PIONEER VENUS

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Foreword

When Galileo Galilei first pointed a telescope at the stars, he made two important discoveries that once and for all settled the scientific controversies over the Copernican model of the Solar System. He discovered (in 1610) that Jupiter had satellites and that Venus displayed phases much the way the Moon does in its monthly traverse of the sky. In the Jupiter system, therefore, Galileo had convincing evidence that smaller satellites can indeed rotate around a larger body. He had before his very eyes a small model of what the Solar System must actually look like to an outside observer. In the case of Venus, his interpretation of the phases which he observed was that Venus executes an orbit around the Sun inside that of the Earth, thus lending further evidence to the idea that both Venus and the Earth are satellites of the Sun.

It is interesting that astronomers lost interest in Venus after this first momentous discovery, and it is not hard to understand why. Soon after Galileo's startling discoveries, Christiaan Huygens, as well as many other people, looked at Mars with better telescopes and there they saw markings on the surface of the planet that were startlingly similar to features on the Earth – the polar caps, the seasonal changes, the period of rotation all suggested that Mars was very like the Earth. By the end of the nineteenth century, even serious astronomers were speculating on the possibility of "canals" on the Martian surface that were created by intelligent beings living on the planet. On the other hand, a closer look at Venus during the three and a half centuries from 1610 to 1960 revealed almost nothing of more than scientific interest. When people looked at Venus more carefully they saw no features, and this was correctly interpreted as being caused by a dense layer of clouds that permanently hid the surface of the planet from view.

It has only been in the last few decades that the roles of Mars and Venus as "twins" of the Earth are slowly reversing as a result of observations with the Mariners, the Vikings, the Veneras and, of course, Pioneer Venus itself. Mars has turned out to be a barren desert on which it is doubtful that much ever occurred that was similar to what happened here on Earth. In the case of Venus, however, the establishment of similarities between the Earth and Venus has been the most important result of the recent exploration of Venus and has now led to some really tantalizing speculations. Both planets are roughly the same size, a fact which was known earlier but which is still supremely important. Both planets have a stable and a dense atmosphere, and Venus very probably has volcanic activity just as the Earth does. Pioneer Venus showed that the atmosphere of Venus could be treated using theoretical models similar to those used to understand the atmosphere of the Earth. At the same time, Pioneer Venus added greatly to our knowledge of the detailed properties of the planet and of the great differences that also exist between Venus and the Earth in spite of the similarities. There is the poisonous atmosphere, the furnace-like temperature of the surface, and the different atmospheric flow patterns that are due to a lack of a short diurnal period on Venus.

It is, I believe, in understanding these differences that the real import of the exploration of Venus becomes apparent. Venus and the Earth must have been very similar when both were formed in the primordial Solar System three and a half billion years ago. What happened to make them diverge? What caused the "greenhouse" effect on Venus and why did it not happen on Earth? Was there ever any water on Venus and, if so, what happened to it? These are some of the major questions that were posed by the findings of Pioneer Venus, and these are then the really lasting results of the mission. They are important because the answers will shed light on the most important question of all, and that is the ultimate fate of our own world.

Hans Mark
Deputy Administrator, NASA


ORIGINAL PAGE
COLOR PHOTOGRAPH

Preface

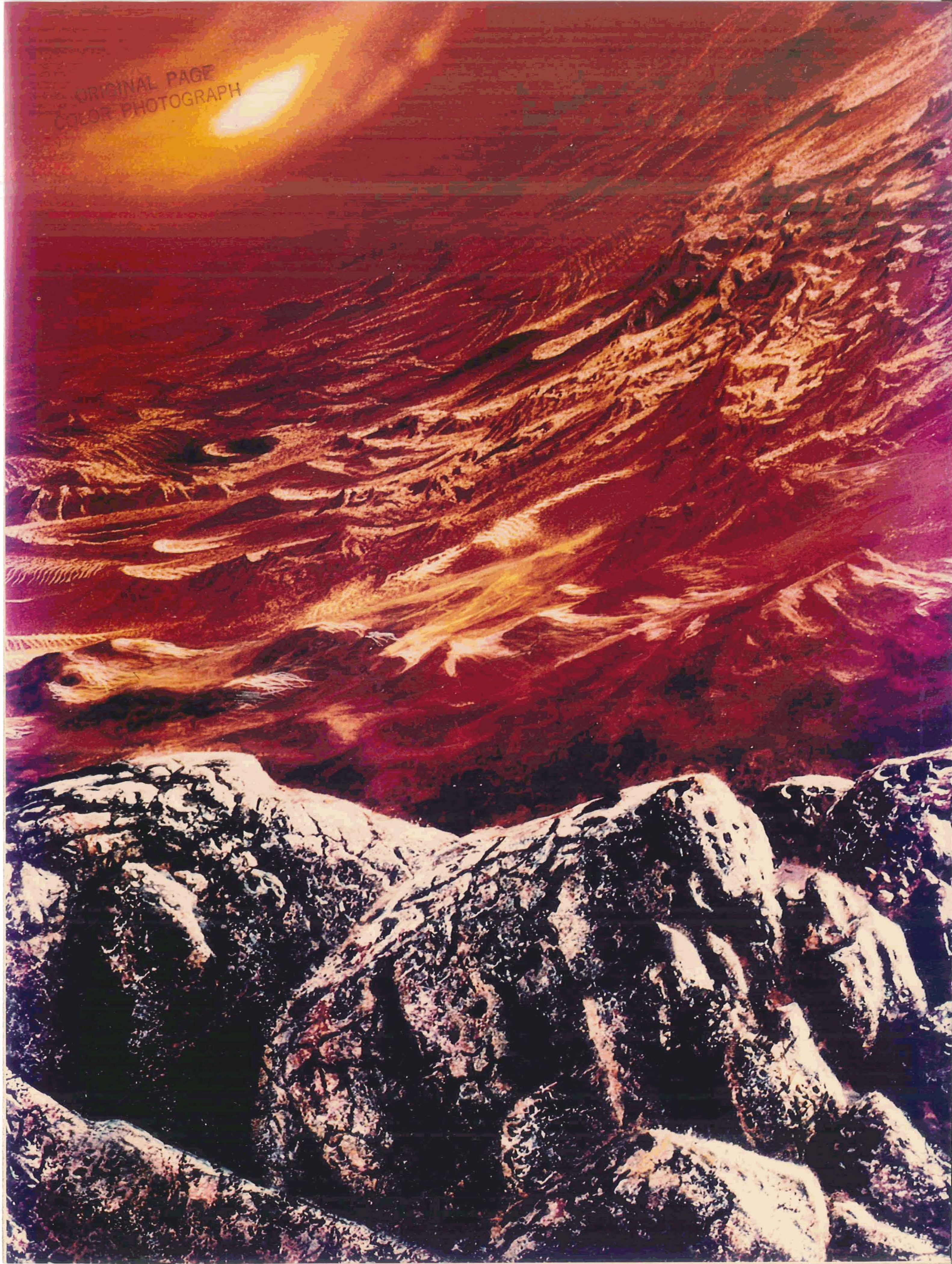
During the month of December 1978 no less than ten separate, scientifically instrumented, unmanned spacecraft assaulted the planet Venus. They were the United States Pioneer Venus Orbiter, the component craft of the Pioneer Venus Multiprobe (Bus, large (sounder) probe, three small probes (day, night, north)), the two fly-bys, and two descent/lander craft of the USSR Venera 11 and Venera 12 missions. The US and USSR missions were not coordinated, although each nation knew of the other's plans in some detail for many months prior to their respective launches. Following the encounters, formal exchange of scientific results was accomplished. These cooperative efforts were fostered by the Joint US/USSR Working Group on Near-Earth Space, the Moon, and Planets.

Nine of the ten craft completed their missions successfully within about 90 minutes of initial planetary encounter. The Pioneer Orbiter continues to collect valuable scientific data and should continue to have this capability through 1992 when the spacecraft will enter and be destroyed in Venus' upper atmosphere.

This NASA Special Publication narrates the story of Pioneer Venus – its history, the spacecraft, the scientific experiments, and the people involved. It is co-authored by an engineer, a scientist, and a science writer.

We thank the many present and former Pioneer staff members and scientists from the Pioneer Venus Science Steering Group for their contributions and help in reviewing the various portions of the manuscript. We are grateful to our Soviet colleagues who graciously supplied a manuscript which we have included as chapter 7. Chapter 7 describes their Venera program that so importantly complements our own. Furthermore, we extend our congratulations to them on the outstanding success of their most recent Venera 13 and Venera 14 missions. Finally, we would like to acknowledge en masse, the hundreds of talented people who contributed their individual expertise to accomplish a highly successful planetary program – Pioneer Venus.

Richard O. Fimmel
Lawrence Colin
Eric Burgess



Introduction

The Pioneer Venus program has gone far beyond the singular objective of investigating the planet Venus. It has offered planetary scientists a significant opportunity to examine theories of comparative planetology, essential to a better understanding of Earth. Pioneer Venus is the latest of a long series of low-cost pioneering missions into the interplanetary medium and to the planets of the Solar System. The series began at Ames Research Center with the Interplanetary Pioneers that investigated the inner regions of the system, continued into the first missions to Jupiter and Saturn, and reached toward interstellar space (Pioneer, First to Jupiter, Saturn, and Beyond, NASA SP-446).

With the successful arrival of the two Pioneer Venus spacecraft in December 1978 it was clear that Venus would be investigated on a global scale for the first time, and that the entire planetary environment could be examined from *in situ* and remote sensing instruments. Earlier research at Ames Research Center with the Planetary Atmosphere Experiments Test spacecraft had demonstrated the practicality of making significant measurements from a spacecraft speeding into a planetary atmosphere. These experiments had paved the way to the development of the four probe spacecraft carried by Pioneer to Venus.

Aside from the Sun and Moon, Venus is often the brightest object observed in Earth's sky. It is ironic that the significant cloud cover that veils the surface of Venus from eyes of the Earth's geologists is also responsible for its brilliancy. A major part of the programmatic thrust for the Pioneer Venus project in the early 1970s was to define the composition of the planet's cloudy atmosphere, and further, to penetrate that atmosphere so that we could identify and study surface features that had been invisible from Earth.

After many alternatives were considered and the constraints of launch dates and funding were carefully weighed, the mission design crystalized as an Orbiter and a Multiprobe spacecraft, each launched separately in 1978.

The Orbiter was designed to carry out experiments dealing with particles and fields and the atmosphere, and to map the planet's surface by cloud-penetrating radar. The Multiprobe consisted of a Bus that carried a large sounder probe and three smaller probes designed to gather information about the atmosphere of Venus – from its highest frontiers of interaction with the solar wind to various locations on the surface of the planet.

The Pioneer Venus probes gathered enormous amounts of diversified data during their quick probing mission through the atmosphere; the Orbiter continues to gather data after years of orbiting. These data augmented those obtained by NASA's Mariner 2, Mariner 5, and Mariner 10, and by the USSR's Venera spacecraft to compile a significant scientific understanding of our sister planet. This publication is dedicated to documenting the Pioneer Venus mission, the knowledge and understanding of Venus as a planet, and the Venus environment that it revealed.

The mission operations/data acquisition phase of the Pioneer Venus Orbiter continues as of this writing. New data and information will continue to build upon the foundation generated over the past 20 years of the space exploration of Venus. The scientific community looks to the next decade as a challenge to enhance our knowledge of Venus and of ourselves through the continued exploration of our Solar System. The success of the Pioneer spacecraft has demonstrated the practicality of focused interplanetary missions; we have gathered extensive significant data at a reasonable cost. The experience we have gained with the Pioneers has significantly increased our potential success in probing the surfaces and atmospheres of other planets and of intriguing large satellites such as Titan. Although Pioneer-class missions are relatively inexpensive, their success assures us an economical means by which planetary scientists can continue their exploration of the Solar System.

A. Guastaferro
Deputy Director
Ames Research Center

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Venus Before Pioneer

DECEMBER 9, 1978 – At the Pioneer Mission Control Center, NASA Ames Research Center, California, planetary scientists anxiously await return of data from scientific instruments that had cost them a decade of their scientific careers to produce. The instruments are carried by a fleet of spacecraft about to plunge into the atmosphere of the planet Venus – a Multiprobe Bus, and four probe spacecraft.

These Pioneer Venus probes are about to transmit signals to Earth after a radio silence of over two weeks. Since separating from the Multiprobe Bus that had carried them from Earth, each probe had traveled in silence toward Earth's twin: cloud-shrouded Venus. During this time electronics within each probe had been counting to that instant when transmitters would spring into activity a few minutes before a meteoric entry into Venus' upper atmosphere.

A few days earlier other scientists had experienced similar dramatic moments as they had anxiously waited word from the Pioneer Venus Orbiter. Then excitement had built up as the Orbiter passed behind Venus and a rocket motor was ignited to slow the spacecraft sufficiently for it to be captured into orbit. That vital maneuver had been successful and Pioneer 12 had become an artificial satellite of Venus.

At 10:27 a.m. PST, the first signal from a probe arrives at the ground station. Everyone cheers. Then in a tight sequence, signals from the transmitters on the other probes are received by the great antennas of the Deep Space Network. The phase of the Pioneer mission to probe deep into the atmosphere of Venus has started. The decade of work begins to pay off in a wealth of new scientific data.

This special publication presents the story of Pioneer Venus from its inception. In this chapter the calendar is flipped back to the late 1960s when initial planning for an in-depth exploration of Venus began. Why Pioneer Venus? What was it about Venus that caused a large segment of the scientific community to advocate the Pioneer Venus mission? A review of what was known about Venus before spacecraft could be sent to the planet is important to deriving an answer. Additionally, the new knowledge acquired by earlier missions of US and USSR spacecraft and why it emphasized the need for a Pioneer mission is described.

Pre-Space-Age Knowledge

Mankind has been intrigued by the brilliant planet Venus and has diligently observed it with the naked eye since antiquity. The highly reflecting, cloud-shrouded planet is clearly visible from Earth; it is brighter than all other star-like objects in our skies. The apparitions of Venus are included in many ancient records, from Babylonian clay tablets through Mayan codices. But the motions were not understood until after the Copernican revolution in human thought which acknowledged the Sun as being the center of the Solar System with all the planets, including Earth, revolving around it. The advent of the telescope made possible the study of Venus' apparent angular diameter and the phases exhibited by the planet as a result of its being in an orbit inside that of the Earth.

Venus is the planet of the Solar System most similar to Earth in size, mass, and distance from the Sun. The mass, diameter, and density of Venus are all only slightly less than those of Earth. But there the resemblance ends. Venus might be likened to a twin of Earth that went astray. Its atmosphere is 100 times as dense as that of Earth. Its surface is hot enough for lead to melt. It rotates very slowly on its axis, has virtually no water, and its dense atmosphere consists mainly of carbon dioxide with clouds of sulfuric-acid droplets. Planetary scientists are intrigued by these differences and seek reasons why the two planets have evolved along paths so divergent that life can flourish on one while the other is totally inhospitable to life.

Improved telescopes did not add much to our knowledge about Venus. Its image seen through the best telescope is brilliant but uninteresting, since it reveals no detail. After a relatively brief period during which astronomers tried unsuccessfully to measure the planet's rotation period and to find a satellite, their interest was redirected to other more revealing objects in the Solar System.

In the early 1900s, however, new techniques increased our knowledge about Venus. Photography, radiometry, and spectroscopy permitted an extension of visual observations. With the development of these new observing techniques, instruments, and powerful analytical methods, a revival of interest in Venus occurred. Application of radar, radio, and new optical (visible, ultraviolet, and infrared wavelengths) techniques, including polarimetry, provided much new information. Scientists used infrared wavelengths to characterize the clouds and the overlying atmospheric gases. Information about the surface and the lower atmosphere was derived from microwave emissions. Analysis of radar signals bounced off the planet determined its period of rotation. But the major discoveries about Venus had to wait until the 1960s when spacecraft became available to explore the planet. The first planetary probe, Mariner 2, flew by Venus in 1962 and the space-age exploration of Venus and the Solar System began.

Appendix A lists chronologically some major events in the exploration of Venus by Earth-based observations and by theoretical inferences.

Venus as a Member of the Solar System

Venus is called an inferior planet because it revolves around the Sun within the orbit of the Earth at an average distance of 72.3% of Earth's distance from the Sun. As a result, Venus is seen from Earth as either a morning or an evening "star." Early peoples regarded these two bright

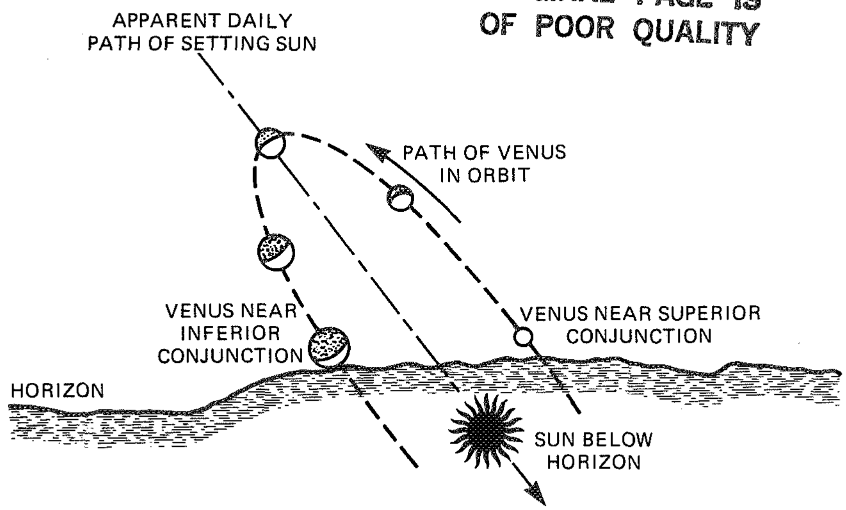
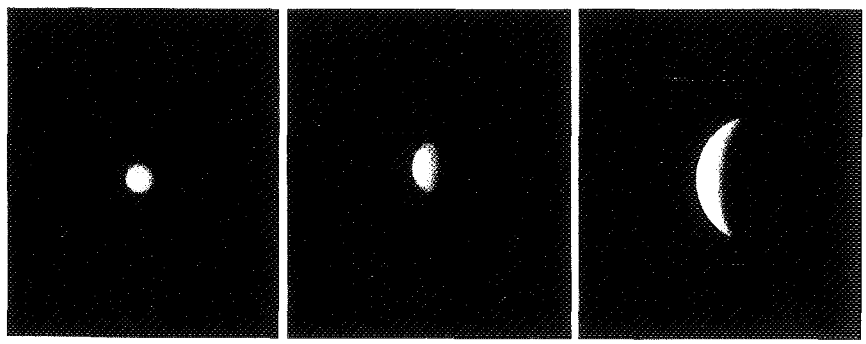


Figure 1-1. Because Venus orbits the Sun within Earth's orbit, it appears to stay close to the Sun in the sky as seen from Earth. At its greatest angular distance from the Sun, Venus is said to be at elongation. The planet is shown at eastern elongation when it sets after the Sun and appears as an evening "star."



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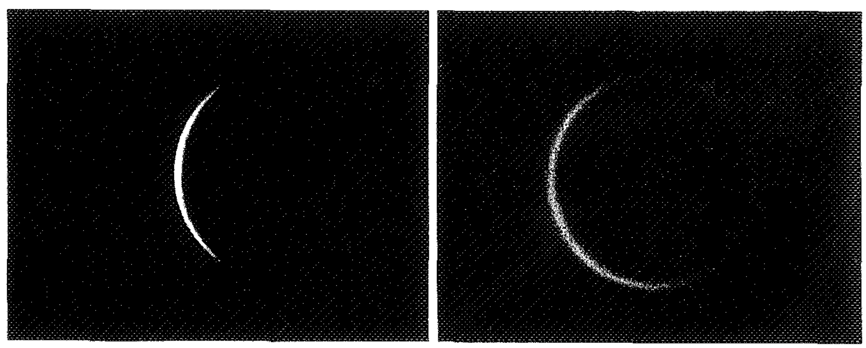

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Figure 1-2. Galileo discovered that Venus, seen through a telescope, shows phases similar to those of the Moon. These photographs from Lowell Observatory show the phases and how the planet looks much larger in the crescent phase as it comes between Earth and Sun.

"wandering stars" as separate objects and named them differently. The Greeks, for example, named them Phosphorous and Hesperus.

Venus appears to move through the constellations of the zodiac, close to the ecliptic – the apparent yearly path of the Sun relative to the stars, which is the plane of the Earth's orbit projected against the stars – and to oscillate east and west of the Sun and never more than 48° from it. The planet's positions at maximum distance east and west of the Sun are termed eastern and western elongation, respectively. At eastern elongation Venus is an evening object. Each day it follows the Sun across the sky (fig. 1-1). At western elongation, Venus rises before the Sun each day. Venus passes from greatest eastern elongation to greatest western elongation in about 144 days, and from western to eastern in about 440 days.

Because it reflects 71% of sunlight which bathes it, Venus is bright enough to be seen at midday if you know where to look. It is brightest about one month before and after inferior conjunction – the time when the planet passes closest to Earth. Venus exhibits phases like the Moon (fig. 1-2) and appears as a fat crescent when at its brightest.

Venus takes 224.7 days to revolve around the Sun in its almost circular orbit of mean radius about 108.2 million km (67.2 million mi.). Because the Earth also moves around the Sun, the periods when Venus is visible at elongations or at conjunctions repeat every 583.92 days. Opportunities to send spacecraft to Venus with minimum energy expenditure repeat also with this same period.

At inferior conjunction (fig. 1-3) Venus is 41.9 million km (26 million mi.) from Earth. When behind the Sun at superior conjunction, Venus is 257.3 million km (159.9 million mi.) from Earth. Earth's orbit is inclined 3.4° to that of Venus, so Venus is nearly always slightly above or below the Sun at inferior conjunction. Infrequently, the planet travels in front of the Sun in what is termed a transit, and it is seen as a small black disc silhouetted on the bright face of the Sun. Transits of Venus, which occur in pairs, are quite rare. The most recent occurred in 1874 and 1882; the next pair are on June 7, 2004, and June 5, 2012.

Astronomers journeyed to remote parts of the world to view transits of Venus to ascertain the distance of Earth from the Sun. They were disappointed. Optical contrast effects distorted the visual shape of Venus and prevented accurate measurements of the time of the transit. The black disc of the planet appeared connected to

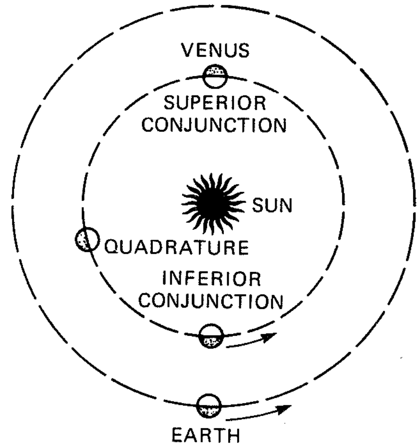


Figure 1-3. When Venus is between Earth and Sun it is said to be in inferior conjunction. When on the far side of the Sun, Venus is said to be in superior conjunction. Sometimes at inferior conjunction the positions of Venus and Earth on their orbits are such that Venus passes in front of the Sun's disc in what astronomers call a transit.

the dark sky beyond the limb of the Sun until the connection became a mere thread, and then snapped (fig. 1-4.). The Russian chemist M. V. Lomonosov correctly interpreted this optical effect as being due to an atmosphere of Venus.

Characteristics of the orbit of Venus are summarized in table 1-1.

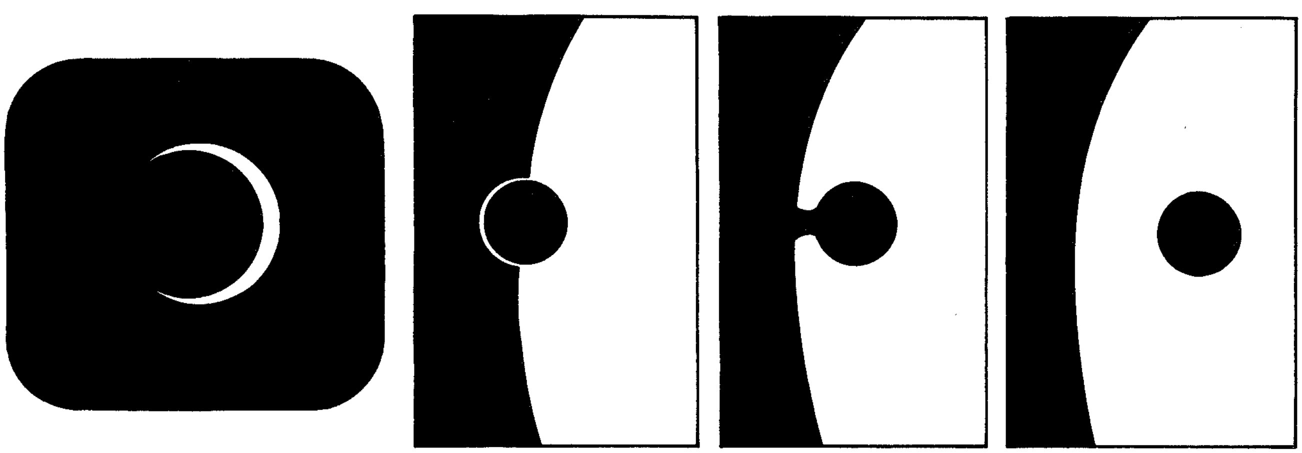


Figure 1-4. Transits are quite rare events. When Venus transits the Sun, the atmosphere of the planet distorts the black spot silhouetted against the bright photosphere. This optical effect shows that Venus has an atmosphere. Also, when Venus is close to the Sun as seen from Earth, its bright thin crescent extends around the dark globe because of the effects of the planet's atmosphere as shown in the second sketch.

TABLE 1-1. – ORBIT OF VENUS

Mean distance from Sun	0.723 AU 108.2 million km 67.2 million mi.
Inclination of orbit to plane of the ecliptic	3.39°
Sidereal period (period with respect to the stars)	224.7 Earth days
Mean synodic period (period with respect to Earth)	583.92 Earth days
Mean orbital velocity	35.05 km/sec 21.78 mi./sec
Closest approach to Earth	41.9 million km 26.0 million mi.

TABLE 1-2.– PHYSICAL DATA ON VENUS

Diameter (solid surface)	12,100 km 7,519 mi. 0.95 Earth's diam
Diameter (top of clouds)	12,240 km 7,606 mi.
Mass	48.8×10^{26} g 0.815 Earth masses
Density	5.269 gm/cm^3 0.96 Earth's density
Axial rotation period (retrograde)	243.1 Earth days
Rotation period, cloud tops (retrograde)	4.0 Earth days (approx)
Period of solar day	116.8 Earth days
Inclination of rotation axis	177.0°
Surface gravity	888 cm/sec^2 0.907 G
Surface atmospheric pressure	9,616 kPa 1,396 psi 95 Earth atmospheres
Surface temperature	750 K (approx) 480°C (approx) 900°F (approx)
Reflecting capability (albedo)	0.71 1.82 Earth's albedo
Stellar magnitude when brightest	-4.4

Venus as a Planet

Why should Venus be so different from Earth? Today the environment on Venus differs significantly from that on our planet; its surface is much hotter and its atmosphere is nearly 100 times as dense. Also, its rotation is much slower and is retrograde. The surface of Venus is hidden beneath uninterrupted planet-wide clouds. In ultraviolet light these clouds show markings which appear to rotate about the planet in a period of about 4 days. The predominantly carbon-dioxide atmosphere contains only minute amounts of water vapor. Venus does not have a significant magnetic field, if it has any, so that interaction of the planet with the solar wind is quite different from that of Earth. Venus also has no satellite. Physical data on the planet compared with those of Earth are given in table 1-2.

Period of Rotation

An Earth-based optical telescope reveals no details on the yellowish, brilliant disc of Venus. Some early observers claimed they saw faint, illusive markings which they likened to those expected of vast cloud systems. As late as 1964, Earl C. Slipher, famous planetary photographer of Lowell Observatory, Flagstaff, Arizona, wrote: "All the early efforts to photograph Venus at Flagstaff (from 1904 on) . . . succeeded in registering only faint vague markings, too weak to add new information." The general absence of visible surface features made it difficult (impossible as we now know) for astronomers to measure the period of rotation of Venus. Wildly varying periods were claimed – from 24 hr like that of Earth, to a period equal to the Venus year (224.7 Earth days).

On May 10, 1961, a radar signal from a NASA Deep Space Network antenna at Goldstone, California, was reflected from Venus. Analysis of the returned echo indicated that the planet must rotate extremely slowly. Subsequently, radar astronomers determined that Venus rotates about its axis in 243.1 Earth days in the opposite direction (retrograde) to Earth. Because the axial rotation and orbital revolution are in opposite directions and of comparable periods, a solar day on Venus is 116.8 Earth days: 58 Earth days of daytime and an equally long nighttime, with the Sun rising in the west and setting in the east.

Strangely, the period of rotation of Venus is almost locked to the periods of revolution of Earth and Venus around the Sun. The result is that Venus turns very nearly the same hemisphere to Earth each time the planet passes between Earth and Sun at inferior conjunction.

Why Venus should rotate so slowly is a mystery; most other planets rotate in periods of hours rather than days. The slow rotation of Mercury is attributed to tidal effects from the Sun, but Venus is too far from the Sun for such effects to have been significant over the lifetime of the planet. One speculation is that rotation was slowed by grazing collision of an asteroid-sized body.

Shape of Venus

Venus' shape is almost a perfect sphere. Its lack of oblateness and of a satellite prevented good models of the internal structure and composition of the planet from being developed. Most planetologists assumed Venus' interior as being similar to that of Earth – a liquid core, a solid mantle, and a solid crust.

Surface Features

The surface of Venus was virtually unknown until radar probed through the dense atmosphere to reveal gross features. Large but shallow circular features, most likely craters, were found in the equatorial regions. A major chasm was discovered stretching 1000 km (620 mi.) north and south across the equator (fig. 1-5). Radar observations also indicated a large-scale granular surface structure, suggestive of a rock-strewn desert. Some areas of high radar reflectivity were interpreted as extensive lava flows and mountainous areas.

Despite the dense atmosphere and the clouds of Venus, some sunlight penetrates to the surface, where the solar flux is about equal to that at the Earth's surface on an overcast day in midlatitudes. The amount of solar radiation at the surface when the Sun is about 30° from overhead was measured as an integrated flux of about 14,000 lux. Photographs from one

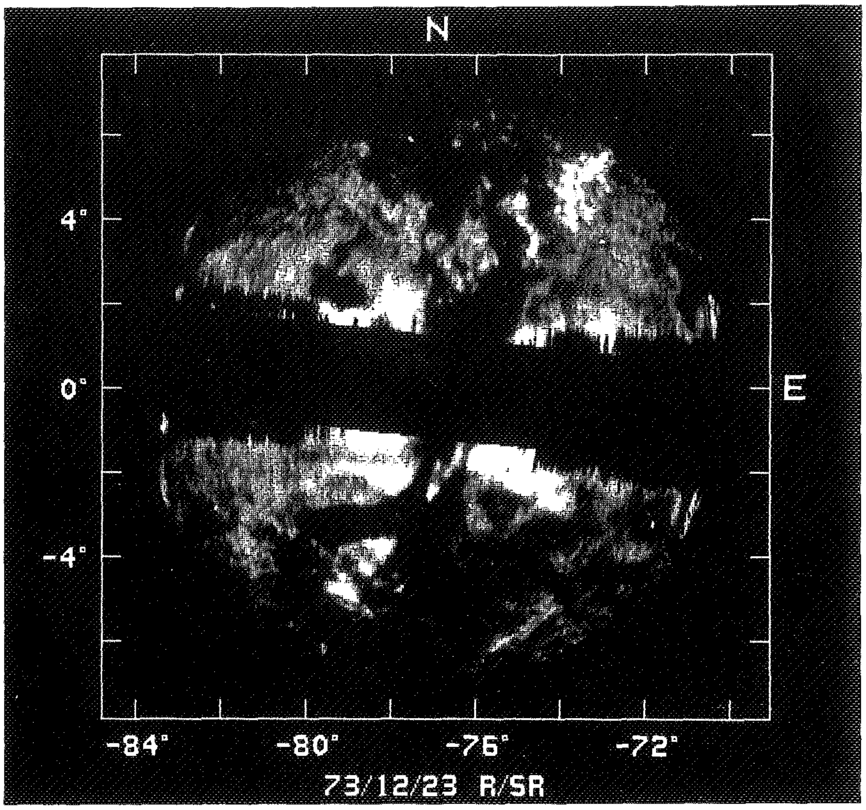


Figure 1-5. While it is not possible to see through the clouds of Venus at optical wavelengths, radar can penetrate to the surface. Radar maps of Venus have been produced to show many surface features. R. M. Goldstein of the Jet Propulsion Laboratory obtained these results with a large antenna of NASA's Deep Space Network located at Goldstone, California. A vast chasm or canyon, over 1000 km long, has many of the features of large canyons on Mars.

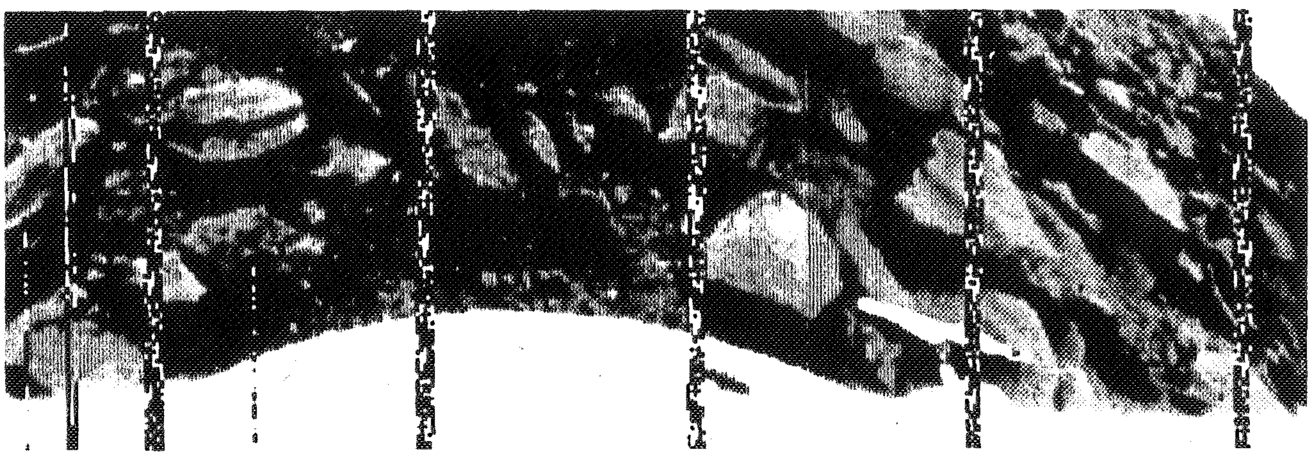


Figure 1-6. The first picture from the surface of Venus, obtained by the Soviet spacecraft Venera 9 in 1975, shows a rocky surface and a clear view to the horizon. The rocks appear to have been fractured and broken in a geologically recent time.

Soviet lander spacecraft (fig. 1-6) confirmed a dry rocky surface that has been fractured and moved about by unknown processes. A second lander produced a picture of rocks with rounded edges and pitted surfaces. Measurements made by the spacecraft indicated that the surface rocks have a density of between 2.7 and 2.9 g/cm^3, which is typical of terrestrial basaltic rocks, and implied that Venus has differentiated into a core, mantle, and crust.

Other early spacecraft results showed that Venus has little water. What happened to oceans if there ever were any? One speculation was that the water rose as vapor into the high atmosphere where solar radiation dissociated it into hydrogen and oxygen. The hydrogen escaped into space from the top of the Venus atmosphere, and the oxygen oxidized the crustal rocks. But Venus may have formed close enough to the Sun for a higher temperature of the solar nebula to prevent water from condensing and incorporating into the material of the planet. If so, Venus would never have had enough water within its rocks to form early deep oceans like those of the Earth. On Earth our oceans played a role in the formation of carbonate rocks by the action of water on the carbon dioxide of the terrestrial atmosphere. The carbon dioxide of Venus remains mainly in its atmosphere.

On Venus, because of high surface temperatures, reactions between rocks, minerals, and the atmosphere were expected to occur much faster than on Earth. However, on our planet the action of running water continually exposes new rocks to the action of the atmosphere and aids reaction between the rocks and the atmosphere. It seemed unlikely that such processes would take place on Venus, and if fresh rocks were not exposed, the atmosphere of Venus could achieve equilibrium with surface materials.

Atmospheric Composition

Although the atmosphere of Venus was discovered in the 16th century, its extent and composition remained unknown until comparatively recently. The atmosphere consists of three distinct regions: that above the visible cloud tops which includes the ionosphere and the exosphere; the clouds; and the part from the base of the clouds to the surface.

In the 1930s infrared spectroscopy revealed absorption bands of carbon dioxide in the spectrum of Venus. This gas appeared to be much more abundant in the atmosphere of Venus than it is in the atmosphere of the Earth. Later, high-resolution spectroscopy confirmed that carbon dioxide is the dominant gas and there are traces of water, carbon monoxide, hydrochloric acid, and hydrogen fluoride. But spectroscopy could not reveal the exact amount of carbon dioxide. Space probes that penetrated the Venusian atmosphere confirmed the Earth-based observations, and the Soviet Veneras 4 and 5 showed a concentration of 97% carbon dioxide. Radio-occultation data confirmed the *in situ* measurements made by the probes. But temperature and pressure measurements made by probes differed from radio-occultation measurements in a way that seemed best explained by there being only 70% carbon dioxide. Also, if the atmosphere had significant amounts of argon, the amount of carbon dioxide could be as low as 25% and still satisfy all the measurements made from Earth.

The amount of carbon dioxide in a planetary atmosphere affects how the microwave spectrum of the planet is interpreted. With accepted percentages of carbon dioxide, microwave observations permitted as much as 0.5% of water vapor below the clouds. Some instruments on Veneras 9 and 10 provided data that suggested an amount of 0.1% water vapor below the clouds. At the cloud tops, however, only 0.0001% was indicated. Should the atmosphere contain another gas that was a poor absorber of microwaves, the planet's atmosphere could contain even more water. In that way the larger amounts of water measured by Veneras 4 and 5 at the surface might

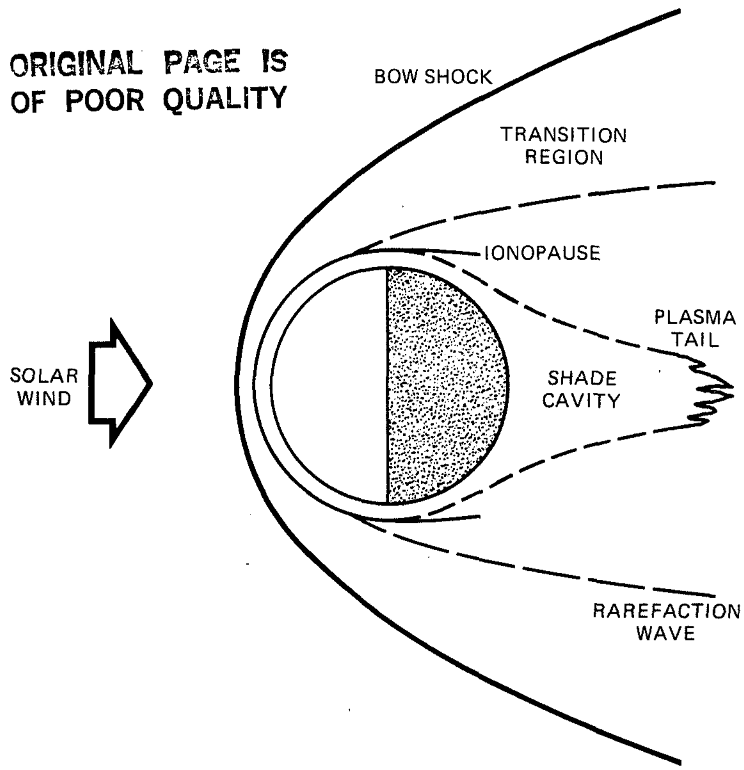


Figure 1-7. Because Venus does not have a magnetic field it interacts much differently with the solar wind than does the Earth.

be explained. On the other hand those measurements might have been erroneous as a result of contamination of the instruments during passage through the clouds of sulfuric acid.

Carbon dioxide is also significant to the evolution of the atmosphere of the planet, and to the radiative properties and dynamic characteristics of the present atmosphere. Despite the preponderance of carbon dioxide, the total amount of this gas seems to be about the same as that forming the carbonate rocks of Earth's crust.

Upper Atmosphere

The atmospheric region above the cloud tops was investigated by observations from Earth and from flyby and orbiting spacecraft. In contrast to the lower atmosphere, this region was found to be colder and, above 150 km (90 mi.), more rarefied than Earth's atmosphere.

Because Venus lacks a significant magnetic field, the solar wind interacts directly with the upper atmosphere and the ionosphere (fig. 1-7). The ionosphere of Venus is thinner and closer to the surface of the planet than is that of Earth. Like the terrestrial ionosphere, that of Venus has layers at which the number of electrons/cm^3 (electron density) peaks (fig. 1-8). Peak electron density in Earth's ionosphere is about 100,000 to 1,000,000 electrons/cm^3 at about 250 to 300 km (153 to 184 mi.). The major ion is atomic oxygen. On Venus, by contrast, a peak of about 600,000 electrons/cm^3 at about 142 km (87 mi.) had been measured, and the major ion appeared to be molecular oxygen.

NASA's Mariner 10 spacecraft which flew by Venus on its way to Mercury found two clearly defined layers in the nighttime ionosphere – a main layer at 142 km (87 mi.) and a lesser layer at 124 km (76 mi.). The lower layer had a peak density about 78% of the higher layer. The spacecraft data revealed a sharp boundary (ionopause) to the dayside ionosphere at 350 km (214 mi.) compared with the 500 km (306 mi.) altitude obtained by measurements from the earlier Mariner 5 spacecraft. The ionopause is believed to be caused by interaction of the solar wind with the atmosphere. On the planet's nightside the ionosphere extended high into space and probably into a plasma tail stretching away from the Sun.

Radio-occultation data also allow temperatures to be measured in regions above the visible cloud layers. Higher still, the temperature of the exosphere was derived from density variations with altitude found by the ultraviolet airglow experiments. Temperatures measured at the top of the Venusian ionosphere required the presence of a gas substantially lighter than carbon dioxide. Scientists speculated that this gas was helium. At the temperature of about 127°C (260°F) as calculated for the exosphere from Mariner 10 data, thermal escape of helium gas would be negligible. If helium had outgassed from the rocks of Venus as it did from the rocks of Earth, it might have accumulated in the upper atmosphere of Venus. Finally, it was discovered that a corona of hydrogen atoms begins at about 800 km (480 mi.) and contains up to 10,000 atoms/cm^3.

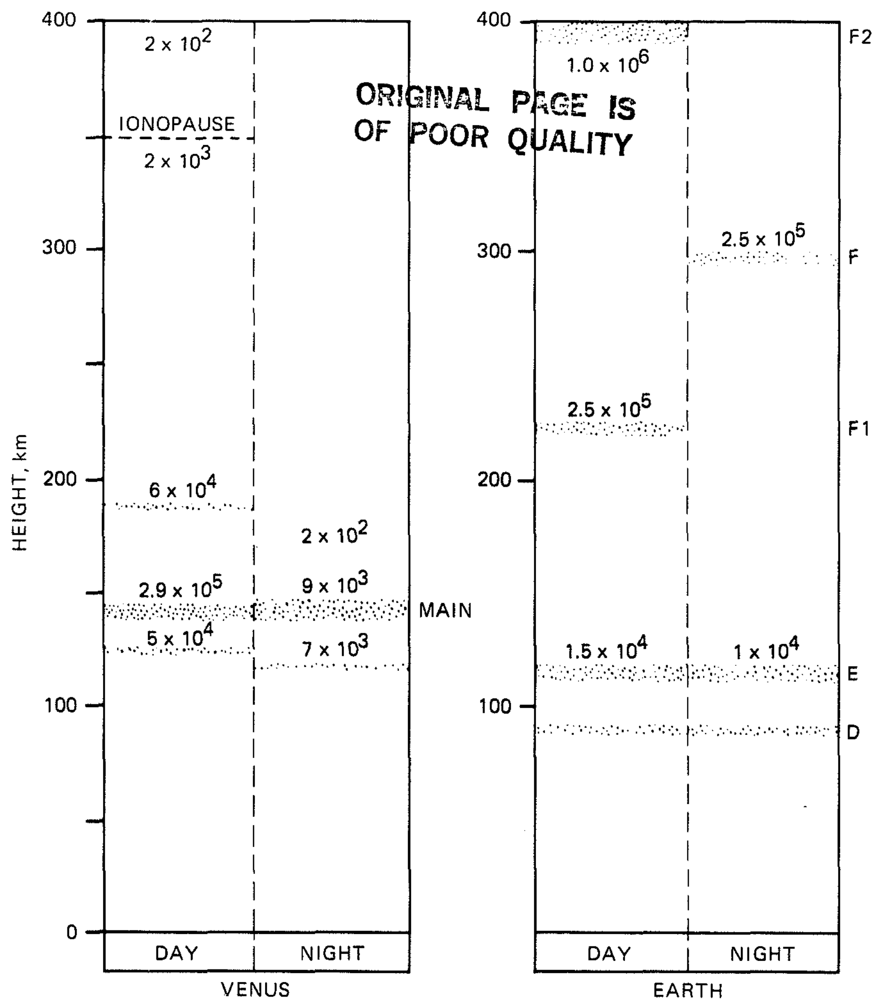


Figure 1-8. Characteristics and layers of the ionospheres of Earth and Venus as revealed prior to Pioneer Venus.

Clouds

Above the main cloud deck at least two stratified layers of extremely tenuous haze – probably aerosols – were photographed by Mariner 10 in the region 80 to 90 km (50 to 56 mi.)

above the planet's surface. The layers extended from equatorial regions to higher latitudes.

Composition of the particles making up the main cloud layers was not understood until comparatively recently. At one time the speculation was that they were dust, and extended down to the surface. Another speculation was that they were condensation clouds with a clear atmosphere beneath them. Suggested constituents included ammonium nitrate, carbon suboxide, formaldehyde, nitrogen dioxide, polymers of hydrocarbonamide, and hydrochloric acid.

From polarization studies scientists concluded by 1971 that the cloud particles must be spherical and about 1 to 2 μm in diameter, and that they were not grains of dust. Nor did they seem to be ice or water droplets, or droplets of hydrochloric acid or carbon suboxide.

The now accepted sulfuric acid composition of the cloud droplets was determined in 1973 through measurements of the infrared spectrum of Venus with instruments carried high in Earth's atmosphere aboard a Learjet aircraft. This composition had been suggested independently by two theorists who had pointed out earlier that concentrated sulfuric acid is a very effective drying agent and could account for the dryness of the atmosphere above the cloud tops.

The droplets consist of about 75% acid-water solution and are close to 1 μm in diameter. Sulfuric-acid clouds can remain as clouds over a wider range of temperatures than can water clouds. Below the bottom of the main cloud layers of Venus the temperature becomes high enough for sulfuric-acid droplets to evaporate into water and sulfuric-acid vapors.

While the clouds of Venus seem opaque from Earth, they are, in fact, very tenuous. Veneras 9 and 10 determined that visibility within the clouds is between 1 and 3 km (0.6 to 1.8 mi.). The clouds are more like thin hazes than typical terrestrial clouds. They form a very deep layer some 15 to 20 km (9 to 12 mi.) thick (fig. 1-9) – more than twice that of cloud layers of Earth. Venera spacecraft passed through several layers and emerged from the lower boundary of the cloud deck at about 49 km (30 mi.).

Characteristic forms of dark ultraviolet markings on the clouds have been studied from Earth (fig. 1-10). These are probably the same as the optical markings noted by early observers. Horizontal psi-shaped features have an extension of the equatorial bar through arms which are sometimes angular and at other times circular. Features that look like a reversed letter C appear more often near the evening terminator than the morning terminator. Horizontal Y-shaped features sometimes have a tail stretching round the planet. Sometimes there are two parallel equatorial bands. Patterns are almost always symmetrical about the equator. Arms of the various features open in the direction of their

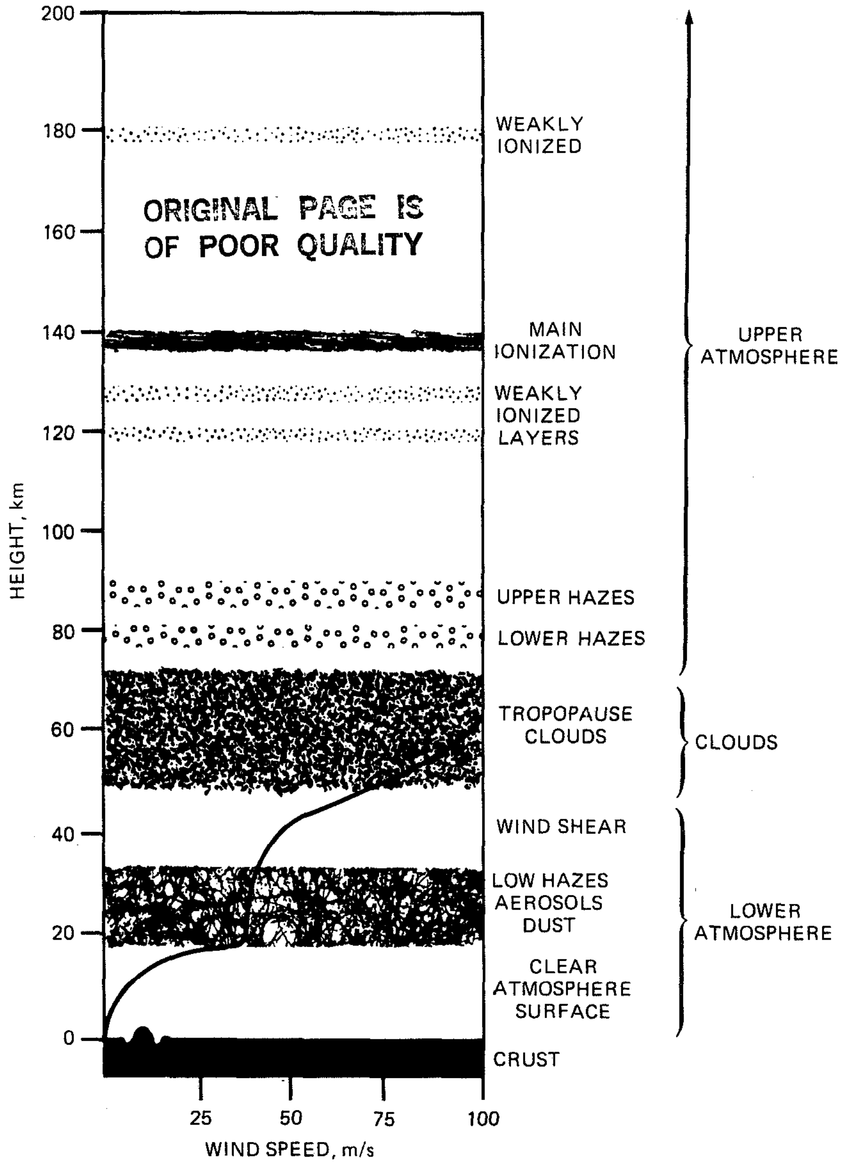


Figure 1-9. Three distinct regions of the atmosphere of Venus that show quite different characteristics of what we knew about the atmosphere before the mission of Pioneer Venus. The regions are the high atmosphere above the clouds, the thick layer of clouds, and the clear atmosphere beneath the clouds. A profile of the wind velocity is shown to illustrate how the wind velocity changes abruptly at the base of the clouds.

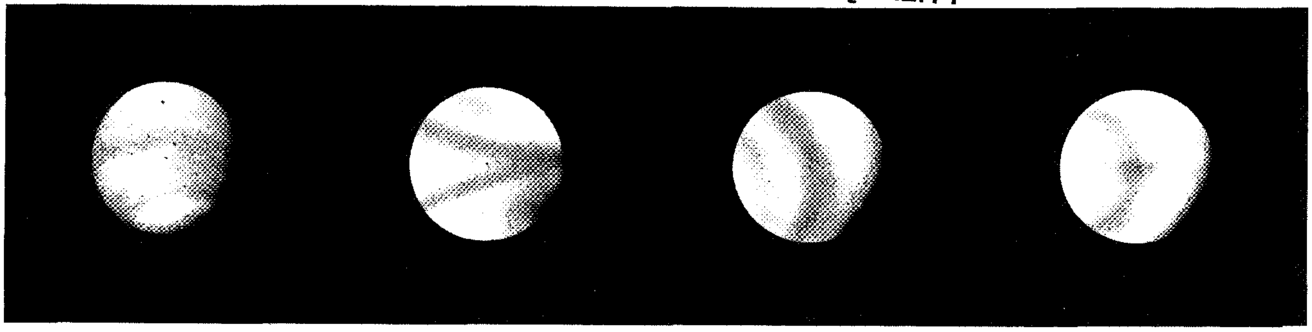


Figure 1-10. Characteristic cloud markings on Venus. The C-, Y-, and psi-shaped markings were observed from Earth and confirmed by Mariner 10 photographs of Venus.

retrograde motion, which varies between 50 and 130 m/sec (164 and 427 ft/sec). A big question about the cloud motions was whether they resulted from actual movement of masses of atmosphere or were merely a wave motion.

Winds

Prior to the Pioneer mission it had been determined that the stratosphere of Venus appears to have a continuous zonal motion averaging 100 m/sec (328 ft/sec), so that its rotation period is approximately 4 days, 60 times more than the planet itself. Relative to the planet's surface high-velocity winds were blowing continually in the high atmosphere. Deeper in the atmosphere the wind velocities became appreciably less, dwindling to a relative calm close to the surface. The Soviet probes showed a division between high- and low-wind velocities at about 56 km (35 mi.) altitude, near the base of the clouds. Over the whole of the planet there are meridional winds with the atmosphere rising at low latitudes and sinking toward the poles.

Thermal emission from the upper atmosphere was found to differ very little between night and day and between low and high latitudes, thereby indicating strong dynamic activity within the atmosphere and heat in substantial amounts being transferred around the planet horizontally from day to night and from equator to poles. Whereas diurnal heating is important above 56 km (34 mi.), dynamic effects predominate below that altitude.

Magnetic Field

The lack of a magnetic field of Venus is another important difference between Earth and Venus. Whereas Earth has a strong field amounting to about 0.5 gauss at the surface, the first spacecraft to fly by Venus, Mariner 2, in 1962, discovered that Venus has no significant field – the field strength is less than 1/10,000 that of Earth. How magnetic fields of planets are generated and maintained is poorly understood. Earth's field is attributed to a self-sustaining dynamo in a fluid core in which convection currents give rise to electric currents. These currents produce the external magnetic field. This theory, which seems to apply to Jupiter and Saturn also, predicts that slow-spinning satellites and planets without molten cores do not have magnetic fields. However, this dynamo theory did not predict the magnetic field of slow-spinning Mercury, discovered by the Mariner 10 spacecraft.

Lack of Satellite

Although several astronomers in the 1800s claimed discovery of a satellite of Venus, all the claims turned out to be observations of faint stars. Venus does not have a satellite.

Early Spacecraft Missions to Venus

Prior to the Pioneer Venus mission the planet had been the target for 13 spacecraft of which 3 were American and 10 were Russian. Five were flybys and 8 were landers. Several Russian missions consisted of flybys and landers that separated prior to arrival at Venus.

Initial Soviet attempts to reach Venus with spacecraft failed. Then came the spectacular 190-day voyage of NASA's Mariner 2 in 1962 when the first interplanetary spacecraft flew by the planet at a distance of only 34,833 km (21,645 mi.).

During the rest of the decade of the 1960s two different methods of exploring Venus were used by Russia and America. The Russians, with greater booster capability, flew probe and lander missions to Venus as well as flybys. The US used flybys only. Conflicting information about Venus was sometimes obtained. A Soviet Venera 4 lander spacecraft recorded a surface temperature of 265°C (510°F) in 1967, while in that same year the Mariner 5 flyby experiments indicated a surface temperature of 527°C (981°F). Calculations of atmospheric pressure did not agree either. Later it was shown that the Venera 4 probe did not reach the surface but had been crushed by atmospheric pressure at an altitude of about 34 km (21 mi.).

The 1969 Soviet landers, although built to resist high pressures, still did not survive the enormous pressure of the atmosphere at the hot surface, but in 1970 Venera 7 did land successfully and it returned data for 23 min. Later in the 1970s landers returned pictures of the rock-strewn surface. The Soviet program is described in chapter 7. The major findings of the three American flybys are summarized below.

Mariner 2

A flyby spacecraft, Mariner 2 was launched August 27, 1962. Closest approach to Venus of 34,833 km (21,645 mi.) took place on December 14, 1962. Mariner 2 discovered that Venus is blanketed by cold dense clouds about 25 km (15.5 mi.) thick with a top at about 80 km (50 mi.), the surface temperature is at least 425°C (800°F) on both day and night hemispheres, and the planet has virtually no magnetic field and no radiation belts.

Mariner 5

A flyby spacecraft, launched June 14, 1967, Mariner 5 passed Venus at 3391 km (2480 mi.) on October 19, 1967. Occultation experiments provided temperature and pressure profiles extrapolated to 527°C (981°F) and 100 atm at the surface. Detailed ionospheric structure was determined at two locations on the planet. Unexpected and difficult to explain exospheric temperatures were observed by an ultraviolet photometer.

Mariner 10

A spacecraft bound for Mercury, Mariner 10 passed Venus en route. It was launched on November 3, 1973 and flew past Venus at 5793 km (3600 mi.) on February 5, 1974. It obtained the first pictures of Venus' clouds from a spacecraft, revealed the structural details of the clouds in ultraviolet light, confirmed the reality of the C-, Y-, and psi-shaped markings, and confirmed the 4-day rotation period of the ultraviolet markings. Significant amounts of helium and hydrogen were found in the upper atmosphere. High-altitude haze layers in the upper atmosphere above the cloud tops were determined from optical limb scanning. Mariner 10 confirmed that Venus does not have a magnetic field of any consequence, determined the structure of the ionosphere, and established temperature and pressure profiles into the upper atmosphere.

Unanswered Questions

Unresolved questions about the atmosphere of Venus included: How does the Venus weather machine work? Is it a greenhouse effect that makes Venus so hot compared with Earth? Or is there a significant dynamic contribution? How did the atmosphere of Venus evolve? Did Venus once have a more moderate surface temperature? What causes the dark ultraviolet markings in the Venus clouds? What are the constituents at the different levels of the atmosphere?

Answers to such questions were expected to help scientists learn more about planet Earth. While many factors complicate Earth's meteorology – mixing of oceanic and continental air masses, partial cloud cover, axial tilt, and rapid planetary rotation – the meteorology of Venus appeared much simpler. The atmosphere has a basic composition of 97% carbon dioxide with hardly any water. There are no oceans to complicate matters, and since the planet has a very slow rotation Coriolis forces are negligible. Since its spin axis is tilted only slightly there are virtually no seasonal effects.

At the time of the Venera landings in 1975 Louis D. Friedman and John L. Lewis pointed out that despite all the missions to Venus, some of the most important and fundamental scientific questions remained unanswered. Very few of the early results helped with the reason why Venus differs so much from Earth. They listed several important questions that need answers if we are to understand that basic dilemma and planetary processes and evolution in general. We needed to know more about the global chemical composition of Venus, its thermal and differentiation history. This requires information about the composition of the crust, the internal structure of the planet, and the ages of crustal rocks. We needed to know if there is evidence of tectonic activity, continental drift, and vulcanism. Mapping of the gravitational field in local regions and geodesy was also important, as was mapping of surface features to determine local geological structures. We needed to know more about detailed atmospheric composition, thermal structure, cloud structure, and the circulation of the atmosphere. In short, these early spacecraft observations had provided intriguing glimpses in some areas, but very little reliable and quantitative information.

By the early 1970s two decades of development of reentry vehicles for intercontinental ballistic missiles had provided the technology base for building scientific spacecraft capable of surviving the high temperatures and high deceleration forces that would be encountered by probes entering the atmosphere of Venus. This made it possible for the highly sophisticated instrumentation that had been demonstrated so successfully on other American spacecraft to be carried through the atmosphere of Venus and down to its surface. A new approach to exploration of the cloud shrouded planet could be taken. Thus the time was ripe for Pioneer Venus, a multifaceted mission to orbit Venus and probe through its dense atmosphere down to the heated surface.

In a presentation to the House Committee on Science and Astronautics on March 15, 1973 in connection with the NASA authorization for fiscal year 1974, Richard Goody of Harvard University repeated a statement he had made to the Royal Society in London on the occasion of the 500th anniversary of the birth of Copernicus.

". . . it is no longer possible or desirable to consider Earth entirely aside from the other planets – planetary science has grown to contain many aspects of the earth sciences and for some geophysicists the aim of enquiry has now become the nature of the entire inner Solar System." He also stressed that some current attempts to model and predict climatic changes on Earth were stimulated directly by observations of planets such as Mars and Venus.

While Pioneer Venus could not answer all the important questions about Venus, it is taking us closer to understanding the planet and why it differs from Earth. Perhaps the most important aspect of this type of planetary exploration is to provide details of extreme cases of conditions that in some ways resemble Earth. Part of the stumbling block to understanding our own planet has been not knowing enough about other planets for valid comparisons to be made. Venus, coupled with Mars, provides the needed comparisons with Earth. NASA's Pioneer Venus program and the Russian Venera program continue to gather the data needed to make such comparisons.

2
Pioneer Venus Mission

THERE ARE DIAMONDS and sapphires on Venus – precious stones that were parts of the Pioneer Venus probes that reached the surface of Venus on December 9, 1978.

Instruments aboard the probe spacecraft were enclosed in pressure vessels to protect them from the fierce Venusian environment. But windows had to be provided for several of the instruments, and these windows had to have many special properties – they not only had to be thick enough to resist the enormous pressures and temperatures of the Venusian atmosphere, but they had to be thin enough to transmit radiation at certain wavelengths in the infrared and optical bands of the spectrum. Moreover, during part of the descent through the Venusian atmosphere, the windows would be exposed to the corrosive action of acid gases and droplets. These requirements presented major design problems (table 2-1).

Some of the windows in the probes were made of sapphire; they would transmit in the optical and ultraviolet bands. For other experiments, in which infrared radiation had to be measured, the original choice for a window material was Irtran-6 (Irtran is derived from infrared transparency). Irtran (manufactured by the Eastman Kodak Co.) has excellent infrared transmissibility characteristics, but it becomes thermally etched when exposed to high temperatures. At temperatures above 200°C (392°F), the material becomes almost totally opaque within a few minutes; as a result, plans to use it for the Pioneer mission to Venus had to be abandoned.

The only material that could withstand the high temperatures and pressures and still transmit in the infrared was diamond. The only acceptable diamond was that called Type IIA (there are about 1500 classes of diamonds). Type IIA diamond is almost perfectly pure diamond, but it has a slight brownish cast and is classified as an industrial diamond.

Members of the Pioneer Venus team responsible for developing the probe instruments soon learned that it would not be easy to acquire the large Type IIA diamond they required. A dealer told them, "You can't go out and buy it, it has to show up in your box." He explained that there are 10 or 12 dealers' boxes in London, boxes of the only persons in the world who deal with the South African diamond producers. Dealers pick up the diamonds that have been placed in their boxes, sort them, and decide how much to offer for them.

TABLE 2-1.– PIONEER VENUS PROBES – WINDOW REQUIREMENTS

Scientific instruments	Size,[a] cm	Number per probe	Wavelength Transmission, μm	Window material
Nephelometer (large and small probes)	1.300 o.d. 1.200 c.a.	2	0.32 to 1.1	Sapphire
Cloud particle size spectrometer (large probe)	1.520 o.d. 1.350 c.a.	1	.6328	Sapphire
Infrared radiometer (large probe)	.743 o.d. .660 c.a.	1	3 to 20	Diamond Type IIA
Solar flux radiometer (large probe)	.375 o.d. .310 c.a.	5	.25 to 1.1	Sapphire
Net flux radiometer (small probes)	.340 o.d.	2	3 to 20	Diamond Type IIA

[a]o.d. = outside diameter; c.a. = clear aperture.

He spoke of rumors that several large diamonds had been found in the sands of the Orange River delta in South Africa, the most likely source of the kind of diamond needed for the probe window. Large stones are rarely found in the diamond mines because they are often broken by the mining techniques used.

The dealer said: "What I'll have to do is go to South Africa and wine and dine people who put the diamonds in the boxes and tell them what my needs are." That is what he did, and the Pioneer Venus instrument designers soon had two large type IIA diamonds from which to make their spacecraft windows.

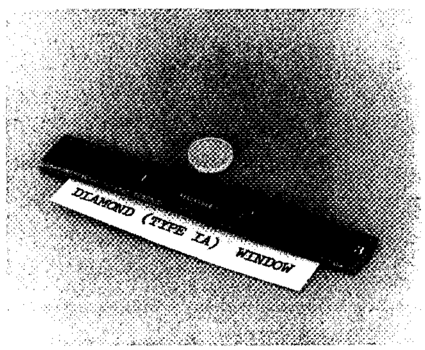
One of the diamonds was cut and ground, and the outside circumference faceted; several windows were made from it. One had 32 facets, another had 16 facets. The outside circumferences were faceted to prevent the microcracks that would develop from grinding the stones into a circular shape.

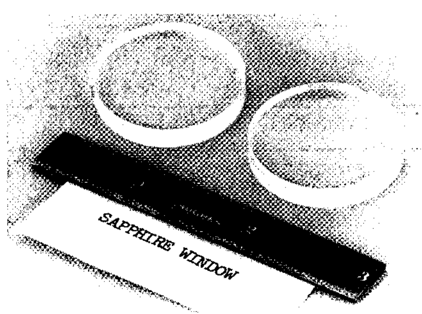
So the large diamond from South Africa became the window (fig. 2-1) through which an infrared radiometer would view the atmosphere of Venus. Other windows for the net flux radiometers were cut from the same stone.

Beginnings

The Pioneer Venus project began shortly after NASA's Mariner 5 spacecraft flew by Venus and the Russian Venera 4 spacecraft probed the atmosphere of the planet in October 1967. Three scientists – R. M. Goody (Harvard University), D. M. Hunten (then of Kitt Peak National Observatory), and N. W. Spencer (Goddard Space Flight Center, NASA) – formed a group to consider the feasibility of a simple entry probe that would investigate the atmosphere of Venus. A study contract was awarded to the AVCO Corporation by Goddard Space Flight Center. In 1968, the Center also began a study to look into the capabilities of small planetary orbiters using Explorer (IMP) types of spacecraft launched by a Thor-Delta launch vehicle. The proposed mission was called the Planetary Explorer. One of the scientists at that time wrote: "We wanted to demonstrate that the objectives on Venus could be rationally thought out, and that they point to a feasible mission, which I hope the U.S. may adopt."

(a)





(c)

Figure 2-1. For a clear view of the infrared spectrum this 13.5 carat diamond window ((a) and (b)) was carried aboard the large probe spacecraft, one of five spacecraft of the Pioneer Venus project that plunged into the thick atmosphere of Earth's twin planet, Venus. Three windows in the wall of the spacecraft were made of sapphire (c), and the diamond windows were used for the infrared radiometer.

In the period 1967–1970, there were few scientific facts available on which planning for a Venus mission could be based. Ground-based observations had contributed very little to man's knowledge of the planet, and the few spacecraft that had flown near Venus had returned comparatively little new information.

Although there was still much speculation about Venus and its environment, it was clear that exploration techniques such as those used for the Moon and Mars would be inappropriate if applied to Venus. The early science study groups first defined the key scientific questions about Venus and then set about defining missions that could be expected to provide the answer. This was a departure from the procedures used previously, in which spacecraft missions were designed mainly on the basis of available technology and what might be accomplished with it; only then were the scientific experiments defined that might be attempted within the limits of the technology. The Venus-mission scientists emphasized that spacecraft payloads should not consist of a group of individual and perhaps unrelated experiments, but that the experiments should be carefully selected to apply to a broad range of mission objectives. When implemented, this philosophy made significant contributions to the success of the Pioneer Venus mission.

Early Studies

By June 1968, a significant study (*Planetary Exploration 1968–1975*) had been completed under the auspices of the Space Science Board of the National Academy of Sciences. It was concluded in that study that planetary exploration should not be undertaken to achieve single goals but instead should be conceived as an overall task covering a broad range of scientific disciplines. Among the missions recommended were those to explore Venus with relatively low-cost spacecraft. A principal recommendation of the Space Science Board was that NASA start a program of Pioneer/IMP-class spinning spacecraft to orbit Mars and Venus at each opportunity, and that additional missions be planned to explore other planets.

In January 1969, Goddard Space Flight Center published the results of its studies and developed a project plan that scheduled the program to commence during fiscal year 1973. The report, *A Venus Multiple-Entry-Probe Direct-Impact Mission,* was authored by R. M. Goody, D. M. Hunten, V. Suomi, and N. W. Spencer. The study was prepared by a consortium consisting of Harvard University, Kitt Peak National Observatory, the University of Wisconsin, and Goddard Space Flight Center. In addition to the authors, some 25 scientists contributed to the study.

Several different approaches for a mission to Venus were considered, including a buoyant Venus station (a balloon that would float in the planet's atmosphere), probes, and orbiters (fig. 2-2). The relative merits of (1) a flyby mission with probe release, (2) a direct-impact bus with separate probes released in advance of the bus reaching Venus, and (3) an orbiter from which probes would be released were also considered. It was concluded that the direct mission afforded a much wider margin of reliability in the collection of scientific data than did the flyby mission (fig. 2-3). A system relying on the release of probes from a planetary orbiter, although offering advantages that derive from lower temperatures during atmospheric entry of the probes, was expensive and required that a large fraction of the total weight of the spacecraft be assigned to the propellants needed to place the probes as well as the orbiter into orbit around Venus. The complexity and cost of large buoyant stations ruled them out as an alternative until more definitive details of the Venusian atmosphere were available.

It was concluded in the Goddard report that crucial problems concerning the nature of the clouds of Venus and the structure, chemistry, and motions of the planet's atmosphere could be solved by using a system of seven entry probes – three small probes and four large probes. Ten days before encounter, three small probes could be launched from a bus to impact near the subsolar point, the antisolar point, and the south pole. During a slow descent to the surface, the three probes could measure atmospheric pressure, temperature, and a component of the horizontal wind. Ninety minutes before encounter and at a distance of 5 Venus radii from the surface, bus science measurements could begin. (The radius of Venus is about 6,000 km (3,700 miles) so 5 radii equates to a distance of about 30,000 km (18,500 miles).) Television and microwave thermal emission pictures could be taken of the planet down to an altitude of 135 km (84 miles). The atmospheric density, electron density and temperature, day airglow, and ion and neutral particle composition could also be measured.

The four large probes could be released from the bus at an altitude of about 135 km (84 miles), just before the bus was destroyed by its high-speed entry into the atmosphere. Two of the large probes could be identical small balloon probes that would carry radar transponders. They could float

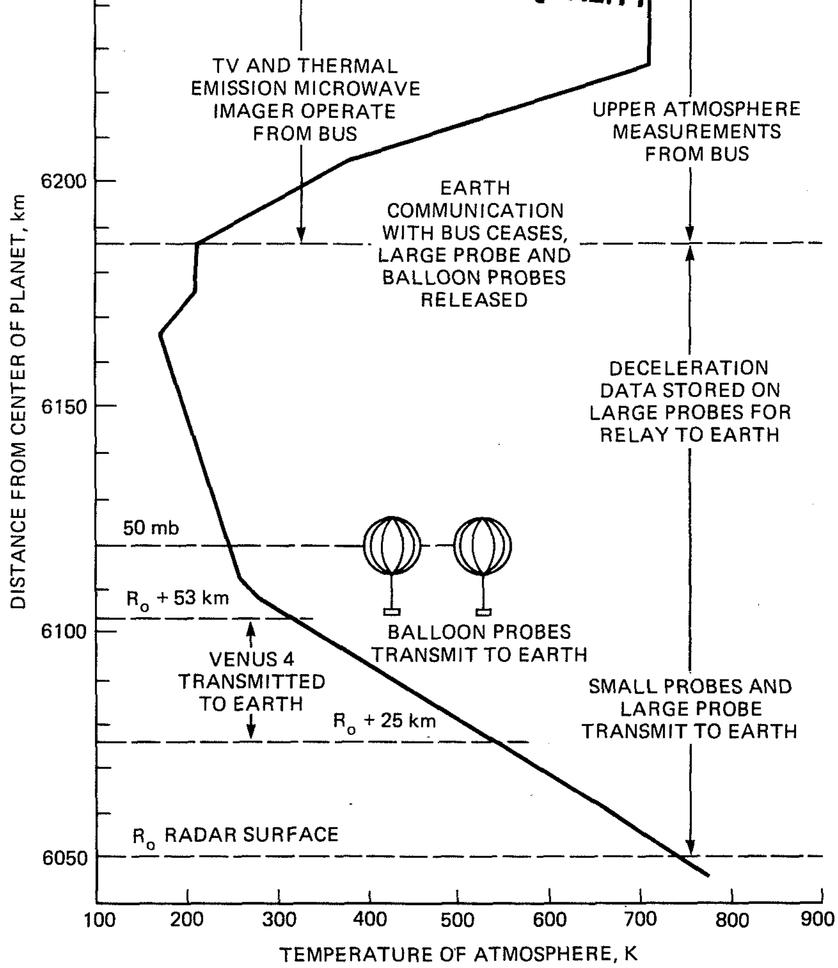


Figure 2-2. Regions of the atmosphere of Venus that could be investigated by various probes, as discussed in the first study of a plan for a comprehensive mission to the cloud-shrouded planet.

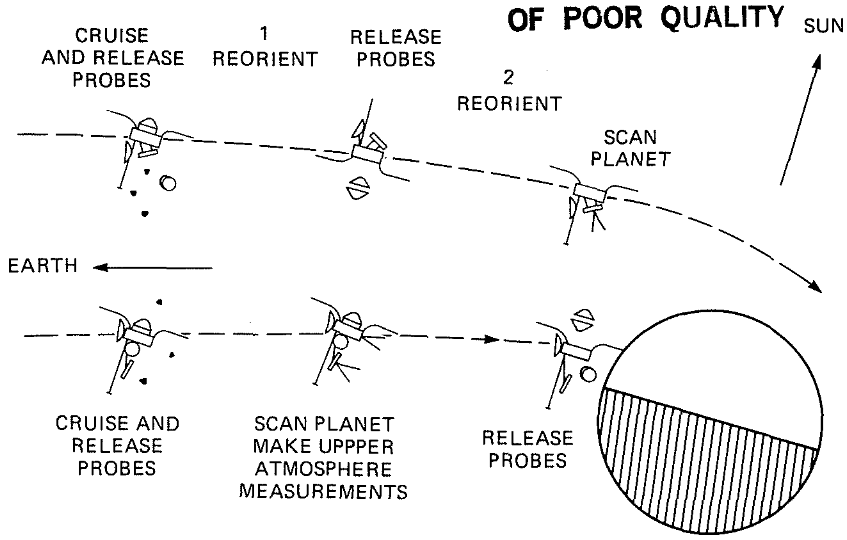


Figure 2-3. The early study compared several mission alternatives, such as a flyby and a direct impact mission for release of probes, and concluded that the latter was more effective.

at a level in the atmosphere where the pressure is about 50 mbar, that is, at an altitude of about 70 km (43 miles) above the surface of Venus; the radar transponders would make it possible to track them from Earth. The balloon probes could measure pressure, temperature, solar radiation flux, and upward thermal radiation flux. The other two large probes could penetrate toward the surface and measure pressure; temperature; gas composition; radiation fluxes; cloud particle composition, number, density, and particle size; and perhaps reveal physical features of the planet's surface.

The Goddard report also stated that the use of probes was the only way to obtain those measurements crucial to an understanding of the atmosphere of Venus. It also concluded that for a given cost the direct-impact probe delivery mission could achieve a substantial advantage over orbiting and flyby probe delivery systems in respect to both comprehensiveness of the atmospheric assessment and reliability in achieving the science objectives.

Consequently, in 1969 Goddard Space Flight Center awarded a follow-on contract to the AVCO Corporation under terms of which AVCO was to study a probe mission to Venus using a Thor-Delta launch vehicle. By the end of that year, NASA had merged the concepts into what was termed a *universal bus,* that is, a combination of the Venus probe spacecraft and the Planetary Explorer Orbiter spacecraft. The idea was that a spacecraft be developed that could be used either to deliver multiple entry probes into the Venusian atmosphere or to send a spacecraft into orbit around the planet.

The "Purple Book"

In 1970, 21 scientists of the Space Science Board and the Lunar and Planetary Missions Board of NASA studied the scientific potential of missions to Venus based on the technology amassed from experience with Explorer spacecraft. They produced a final report, *Venus – Strategy for Exploration,* which came to be known as the "Purple Book" because of its purple cover.

The report recommended that exploration of Venus should be prominent in the NASA program for the 1970s and 1980s, and that the Delta-launched, spin-stabilized Planetary Explorer spacecraft should be the main vehicle for initial missions using orbiters, atmospheric probes, and landers. It was also suggested that the cost of these missions could be reduced if NASA would accept some higher risks than had been the case in previous space missions.

A strategy to explore Venus was developed. No more than two launches would be attempted at each opportunity when the relative positions of the planets in their orbits made a mission possible, given the available launch vehicle and the weight of the payload required. Hybrid missions, such as a spacecraft carrying both an orbiter and an atmospheric probe or a lander, would be avoided because of their added complexity and cost. Identical payloads would be used wherever possible. The report recommended that the scientific value of results be carefully weighed against mission costs. The purpose was to keep mission costs at a minimum (i.e., under $200 million) so that a series of missions to Venus could be planned. Two Multiprobe missions were recommended for the 1975 opportunity, and two Orbiters for the 1976/77 opportunity. Subsequent opportunities were less clearly defined: orbiters, landers, and balloons were candidates. It was suggested that the 1978 opportunity should be used for a follow-on landing mission.

This 1970 study by the National Academy of Sciences on the strategy to be used in exploring Venus also pointed out the seeming paradox of the differences in the evolution of Earth and Venus given the similarities of the two planets. According to the National Academy of Sciences report the study of Venus promised to reveal new insights into the evolution of the planets.

Because of its opaque atmosphere and absence of satellites, less was known about Venus in 1970 than of Mars. Ideally a number of measurements were needed about Venus to determine the chemical composition and mineralogy of the surface materials, the heat flux from the interior, the presence or absence of an iron-rich core, and the variation of elastic-wave velocity with depth and with wave intensity. Making such measurements on Venus would be extremely difficult because of the high temperature at the planet's surface – about 475°C (887°F). Nevertheless, a program of measurements on a scale proposed for Planetary Explorers could allow highly significant measurements to be made. Surface elevations could be measured with a radar altimeter on an orbiter, and some information regarding the distribution of mass in the planet could be obtained from the way in which the orbit of such an artificial satellite is perturbed.

The study by the National Academy of Sciences recommended that NASA should continue to support and develop Earth-based studies of Venus to complement those based on the use of spacecraft. Such Earth-based activities should include thermal mapping of the planet's surface by analysis of radio emissions from the surface, radar topographical mapping, and optical analysis of radiation from the cloud tops. Additionally, the study report asked NASA to set up and maintain a continuing group to plan how Venus should be explored, to advise on strategy for a series of missions to Venus, and to advise on the payloads that should be used for each mission. The study also stressed the need for a wide range of novel scientific experiments, such as those needed to investigate the clouds of Venus. In a summary statement, the scientists responsible for the 1970 report said: "We believe that the combination of scientific goals and the feasibility of contributing to these goals makes the exploration of Venus one of the most important objectives for planetary exploration of the 1970's and 1980's."

Effect of the Soviet Venus Probe, Venera 7

In the fall of 1970, there was no chance of funding a new program for planetary exploration that could meet a launch date suitable for the 1975 opportunity. Consequently, the entire program for the exploration of Venus had to be slipped. The plan was revised to launch two Multiprobe spacecraft during the 1976/77 opportunity, a single Orbiter spacecraft in 1978, and a single Multiprobe (consisting of a floating balloon probe and a lander) in 1980.

Soviet scientists were extremely interested in exploring Venus and sent spacecraft to the cloud-shrouded planet at most of the available launch opportunities (see chap. 7). There were many technical difficulties and several early spacecraft failed. But these failures were more than offset by the partial successes (through Venera 6) of the Soviet efforts to study the atmosphere of another planet and by the worldwide scientific interest they generated.

On December 15, 1971 – soon after the Space Science Board's 1970 report was published – a Soviet spacecraft, Venera 7, successfully entered the atmosphere of Venus and transmitted data from the surface for 23 minutes. In view of the new data made available by Venera 7, the question was asked whether the recommendations of the 1970 study still stood. A special panel of experts was convened to reassess the recommendations. Its conclusion:

"The Planetary Explorer program recommended in the Venus study would be a well-articulated, intensive study of the planet designed to attempt to answer a list of first order questions. Among these are the number, thickness, and composition of the cloud layers; the nature of the circulation; explanation of the high surface temperature; the reason for the lack of water and the remarkable stability of the carbon dioxide atmosphere; the nature of the interaction of the solar wind with the planet; the elemental composition of the surface; the distribution of mass and magnetic field strength; and the measurement of seismic activity. Venera 7 was a highly specialized probe designed to perform only two functions – to measure atmosphere temperature and pressure down to the surface of Venus. It succeeded in obtaining the temperature and confirmed the most widely held expectation – that the surface temperature is high. It has in no way changed the conditions on which the Venus study was based or answered any of the questions that planetary explorers are designed to answer. We can find no reason, therefore, to recommend changes in the scientific objectives set forth in previous Board studies . . . ."

Transfer of NASA's Venus Mission to Ames Research Center

Meanwhile practical work had continued on high velocity entry of spacecraft into planetary atmospheres. By 1970 research scientists at NASA Ames Research Center had accumulated much experimental data about the effects on bodies moving at high speed in an atmosphere. Flight characteristics had been measured by photographing various entry shapes in hypervelocity free flight tunnels at speeds up to 31,000 mph which was higher than the speed needed for entry into the Venus atmosphere.

By 1971 Ames Research Center had designed, fabricated, and tested a spacecraft and most of its instrument systems designed to demonstrate in the Earth's atmosphere selected planetary experiments and instrumentation. This Planetary Atmosphere Experiments Test (PAET) was a vital step in establishing a technical base for advanced planetary exploration of Mars, Venus, and eventually the outer planets. The test spacecraft was launched by a Scout solid-propellant multi-stage rocket. The third and fourth stages of the launch vehicle were used to accelerate the PAET spacecraft back into the Earth's atmosphere at a speed of 15,000 mph.

Launched at 3:31 p.m. EDT on June 20, 1971, the test was highly successful. Instruments scooped up atmospheric gases as planned and PAET demonstrated the capability of selected experiments to determine structure and composition of an unknown planetary atmosphere from a probe entering an atmosphere at very high speed. This was the type of practical data needed for the design of a probe mission into the atmosphere of Venus. The PAET program demonstrated the capabilities of Ames Research Center personnel to participate in such a mission.

Meanwhile an Announcement of Opportunity (AO) for scientists to participate in defining the Venus program had been issued by NASA in July 1971. But in November of that year, the Planetary Explorer program was discontinued at Goddard; by January 1972, it had been transferred to Ames Research Center, Moffett Field, California. At Ames, a study team was quickly organized and the project was renamed Pioneer Venus. The study team, headed by R. R. Nunamaker, included H. F. Matthews, M. Erickson, T. N. Canning, D. Chisel, R. A. Christiansen, L. Colin, J. Cowley, J. Givens, T. Grant, W. L. Jackson, T. Kato, J. Magan, J. Mulkern, L. Polaski, R. Ramos, S. Sommer, J. Sperans, T. Tenderland, N. Vojvodich, M. Wilkins, L. Yee, and E. Zimmerman. This team defined the system and worked closely with a Pioneer Venus Science Steering Group, made up of interested scientists, to define the scientific payloads for the mission.

Science Steering Group and the "Orange Book"

The Pioneer Venus Science Steering Group was established by NASA in January 1972 for the purpose of enlisting widespread participation of the scientific community in the early selection of the science requirements for the Pioneer Venus mission. The Science Steering Group, meeting with Pioneer Venus project personnel over the period February through June 1972, developed in great detail the scientific rationale and objectives for the early missions to Venus. Candidate payloads and spacecraft were conceived and planned, thus providing a useful guide for the NASA Payload Selection Committee and for the contractors who would later have to develop the payloads and spacecraft.

During the first 5 months of its operations, the Science Steering Group held a number of meetings. In 1972, the group published a comprehensive report that became the accepted guide to Venus exploration. Known as the "Orange Book," the report carefully reviewed and endorsed the scientific rationale for missions to Venus in the light of developments since the earlier Space Science Board's report, *Strategy for Exploration,* had been published. These developments included the delay in starting the program, the scientific findings from the Soviet probe Venera 7, new Earth-based observations, new theoretical analyses, and continued analysis of the data gathered by earlier Soviet and American spacecraft. The report recommended that the missions continue with multiple probes in 1976/77 and a single orbiter in 1978 followed by a probe-type mission in 1980.

In the Science Steering Group's report, it was stated that most of the scientific questions concerning Venus required in situ atmospheric measurements below the cloud tops and extending as far as possible down toward the surface. The Science Steering Group defined 24 important questions about Venus (table 2-2).

Since the required technology and scientific instruments were considered at that time to be within the state of the art, a probe mission at the first opportunity was thought to be desirable. A dual launch mission was recommended in case of a failure and because of the opportunity it would provide, if both spacecraft were successful, to retarget the second spacecraft on the basis of experience gained from the first. A third probe was recommended for use at the third opportunity.

The study described the Venus mission for the first launch opportunity as follows. It would consist of two identical spacecraft and payloads launched during the launch opportunity from December 1976 through January 1977. Each spacecraft would consist of a bus, a large probe, and three small probes. The two large probes would be equipped with parachutes; the six small probes would be free-falling and identical. The spacecraft would be spin-stabilized and would use solar power. Cruise from Earth to Venus would take about 125 days, and the probes would be separated from the bus about 10 to 20 days before entry into the Venusian atmosphere. In addition to transporting the probes, the two buses would also enter the Venusian atmosphere (at shallow angles) and send data back until they burned up. Their mission would be to gather data about the upper atmosphere.

The 1978 mission was contemplated as an orbiter mission. It was to consist of a spin-stabilized spacecraft deriving electrical power from solar cells. It would be launched during the period from May to August 1978. After its interplanetary cruise, the length of which would depend on the actual launch date, the spacecraft would be placed in an elliptical orbit about Venus. The spacecraft would be designed to remain active in orbit for a Venus sidereal day (243.1 Earth days). Major objectives would be to produce a global map of the Venusian atmosphere and ionosphere, to obtain in situ measurements of the upper atmosphere and its ionosphere, to investigate the interactions between the solar wind and the ionosphere, and to study the planet's surface by remote sensing.

A third probe mission was still contemplated for 1980. The Science Steering Group anticipated that the details of a 1980 probe mission could be decided upon as the 1976/77 mission became more clearly defined and as results were obtained. The study made no recommendations for a mission in 1982.

It is important to note that at this time (1972), despite Russian entry probes and flybys, we knew very little about the lower atmosphere of Venus. For example, it was not known how many cloud layers there were, how thick they were, or of what they were

TABLE 2-2.– QUESTIONS BY SCIENCE STEERING GROUP FOR PIONEER VENUS MISSION

1. Cloud layers: What is their number and where are they located? Do they vary over the planet?
2. Cloud forms: Are they layered, turbulent, or merely hazes?
3. Cloud physics: Are the clouds opaque? What are the sizes of the cloud particles? How many particles are there per cubic centimeter?
4. Cloud composition: What is the chemical composition of the clouds? Is it different in the different layers?
5. Solar heating: Where is the solar radiation deposited within the atmosphere?
6. Deep circulation: What is the nature of the wind in the lower regions of the atmosphere? Is there any measurable wind close to the surface?
7. Deep driving forces: What are the horizontal differences in temperature in the deep atmosphere?
8. Driving force for the 4-day circulation: What are the horizontal temperature differences at the top layer of clouds that could cause the high winds there?
9. Loss of water: Has water been lost from Venus? If so, how?
10. Carbon dioxide stability: Why is molecular carbon dioxide stable in the upper atmosphere?
11. Surface composition: What is the composition of the crustal rocks of Venus?
12. Seismic activity: What is its level?
13. Earth tides: Do tidal effects from Earth exist at Venus, and if so, how strong are they?
14. Gravitational moments: What is the figure of the planet? What are the higher gravitational moments?
15. Extent of the 4-day circulation: How does this circulation vary with latitude on Venus and depth in the atmosphere?
16. Vertical temperature structure: Is there an isothermal region? Are there other departures from adiabaticity? What is the structure near the cloud tops?
17. Ionospheric motions: Are these motions sufficient to transport ionization from the day to the night hemisphere?
18. Turbulence: How much turbulence is there in the deep atmosphere of the planet?
19. Ion chemistry: What is the chemistry of the ionosphere?
20. Exospheric temperature: What is the temperature and does it vary over the planet?
21. Topography: What features exist on the surface of the planet? How do they relate to thermal maps?
22. Magnetic moment: Does the planet have any internal magnetism?
23. Bulk atmospheric composition: What are the major gases in the Venus atmosphere? How do they vary at different altitudes?
24. Anemopause: How does the solar wind interact with the planet?

composed. And there were at least three significantly different hypotheses to account for the high surface temperature of the planet.

In support of the missions to Venus there was the important need for data to unravel the puzzle of the origin and evolution of the Solar System and the formation, evolution, and current dynamics of planetary atmospheres.

After an independent study of the Soviet Venus program, the Science Steering Group agreed with the Space Science Board's earlier assessment of the Venera program. The previous 11 years of Soviet exploration of Venus had produced in situ measurements of the lower atmosphere, such as pressure, temperature, density, and gross atmospheric composition. The National Academy of Sciences' Venus study, however, exposed a wide range of scientific problems concerning the magnetosphere, the upper atmosphere, the lower atmosphere, and the solid planet that had not been addressed by the Soviet programs.

The Science Steering Group recommended the types of instruments to be carried by the spacecraft, adopting a conservative approach to avoid increasing costs. The group decided that instruments chosen for the Venus mission should have already performed successfully in Earth's atmosphere and that no novel concepts of measurement should be used. Wherever possible, instruments should have been qualified for use in spacecraft or aircraft; if not so qualified, it was essential that the instruments be so simple and rugged that satisfactory performance could be readily proved in laboratory tests.

The Pioneer Venus Mission Crystallizes

The Pioneer Venus program had been initiated as a model, low-cost program replete with innovative approaches to management and an understanding that the total cost would be kept below $200 million. The mission crystallized as a single-opportunity mission – a Multiprobe and an Orbiter that reflected significant and major advances in the sophistication of spacecraft and their instrumentation compared with earlier spacecraft used in missions to Venus.

The Pioneer Venus Multiprobe would produce significant information or make important contributions toward answering questions about cloud layers, forms, physics, and composition; solar heating of the atmosphere, its deep circulation, and driving forces; loss of water, the stability of carbon dioxide, and the vertical temperature structure; ionospheric turbulence, ion chemistry, exospheric temperature, magnetic moment, and bulk atmospheric composition; and the anemopause where the solar wind reacts with the planet's atmosphere.

The Pioneer Venus Orbiter would do likewise in respect to cloud forms, cause of the 4-day circulation, loss of water, gravitational moments, extent of the 4-day circulation, vertical temperature structure, ionospheric motions, ion chemistry, exospheric temperature, topography, magnetic moment, bulk atmospheric composition, and the anemopause.

European Study

Early in 1972, members of the European Space Research Organization (ESRO) expressed a desire to participate in the 1978 Orbiter mission. At a meeting in April 1972, attended by members of NASA and ESRO, a decision was reached to examine jointly the terms on which the two organizations could cooperate in the Venus Orbiter mission planned for 1978. The idea was for NASA to produce and provide ESRO with the Orbiter version of the basic spacecraft, known as the Bus, together with common equipment. ESRO would then adapt the Bus as needed and in particular would provide a retromotor to slow the spacecraft as it approached Venus so that it would enter an orbit around the planet. Also ESRO would provide a high-gain antenna to allow communications at high data rates, and would be responsible for integration of scientific experiments. In addition, ESRO would undertake qualification tests on the spacecraft and its payload. The Orbiter would then be delivered to NASA for launch and flight operations.

A Joint Working Group of European and U.S. scientists was set up to define the objectives of a Venus Orbiter for launch in 1978. The scientists met periodically and issued a report in January 1973, *Pioneer Venus Orbiter.* This report recalled how a series of missions had been proposed since the inception of the NASA Venus exploration concept. A series combining the capabilities of orbiters and probes to the planetary surface appeared to provide the ideal method for exploring that planet's environment. The present mission series was defined by mid-1972 and called for a Multiprobe mission in the 1976/77 launch opportunity and for an Orbiter mission in 1978. The science requirements for the Orbiter mission gave preference to a highly inclined orbit plane – greater than 60° with respect to the ecliptic, the plane of Earth's orbit. Also it was desirable, according to the Working Group, to have a low periapsis (the point in its orbit where the Orbiter would be nearest Venus) of 200 km (125 miles) or less, and located at about lat. 45°, initially in the sunlit hemisphere. Solar gravity would cause the periapsis altitude to increase so that periodic orbital change maneuvers would be needed to maintain the altitude in a desired range. Apoapsis (the point in its orbit where the Orbiter would be farthest from Venus) would be at 60,000 to 70,000 km (37,300 to 43,000 miles). Drag at periapsis would decrease the apoapsis altitude and reduce the period in orbit which would initially be close to 24 hours. Maneuvers would be needed, therefore, to maintain the period.

The experiments were also defined and the required characteristics of the scientific instruments were detailed. Three science payloads were identified, depending on how much scientific payload the spacecraft would be able to carry.

The Working Group stated that in general a model payload should consist of instruments to measure four important areas of interest regarding Venus. *Interaction of the solar wind with the ionosphere* would be investigated by a magnetometer, a solar wind and photoelectron analyzer, an electric field detector, and an electron and ion temperature probe. *Aeronomy and the airglow* would be investigated by a neutral mass spectrometer, an ion mass spectrometer, and an ultraviolet spectrometer/photometer (aeronomy includes investigating atmospheric composition and photochemistry). *The atmosphere's thermal structure and lower atmospheric density* would be investigated by an infrared radiometer and a dual-frequency (S- and X-band) occultation experiment. Finally, *the surface topography, reflectivity, and roughness* would be investigated with a radar altimeter. Several other instruments and experiments were considered: a microwave radiometer to map thermal emission from the surface of the planet; an electric field sensor to detect plasma waves generated by the interaction of the solar wind with the ionosphere; a solar ultraviolet occultation experiment; and a photopolarimeter.

Scientists were extremely interested in determining the gravitational field and geometrical shape of Venus. Such information is important to our understanding of the origin and evolution of the inner planets of the Solar System and in determining why Earth and Venus evolved so differently. Gravitational experiments require an orbiter with a periapsis high enough to avoid any atmospheric drag and one capable of remaining in orbit for a time long enough to provide many data points of tracking. Since there was a conflict between in situ measurements, requiring a low periapsis, and gravitational measurements, requiring a high periapsis, the Working Group recommended that the mission should be extended beyond the nominal 243 days to allow accurate gravity measurements to be made.

Later the Managing Executive Council for ESRO voted not to participate, but only after the European Space Organization had made valuable contributions to the development of the program with important studies at Messerschmitt-Bölkow-Blöhm and by the British Aerospace Company.

During the program a total of 114 scientists were involved, but science management was restricted to a smaller group, which consisted of the principal investigators, a radioscience team leader, a radar team leader, interdisciplinary scientists, and program and project scientists. These individuals (see appendix C) comprised a new Science Steering Group under the chairmanship of T. M. Donahue and cochairmanship of D. M. Hunten, L. Colin, and R. F. Fellows. (Upon his retirement in 1978, the program scientist, R. F. Fellows, was succeeded by R. Murphy, and then H. Brinton.) Various committees were formed among the scientists to deal with specific subjects. Several of these were long standing, including six

Pioneer Venus Science Payload

Meanwhile, during the period of the ESRO study, a decision was made in August 1972 to restrict the program to two flights only, a Multiprobe at the first opportunity (1977), and an Orbiter at the second opportunity (1978). Also, in September 1972, an Announcement of Opportunity (AO) for scientists to participate in the Multiprobe mission was issued. In addition to investigators who would be responsible for developing the hardware for the scientific instruments, NASA, for the first time, invited interdisciplinary scientists and theoreticians to participate. At this time, the Science Steering Group was disbanded to free each of them to respond to the AO if they chose.

The preliminary payload for the Multiprobe mission was selected in April 1973. An Announcement of Opportunity for the Orbiter mission was not issued until August 1973. During the ensuing months a NASA Instrument Review Committee reviewed the instrument design studies for the Multiprobe mission and the proposals for scientific payloads for the Orbiter mission. Recommendations were made to NASA Headquarters in May 1974, and the payloads were finally selected on June 4, 1974.

Twelve instruments were chosen for the Orbiter: seven for the large probe, three identical instruments for each small probe and two for the Multiprobe Bus. In addition, several radioscience experiments were chosen that were applicable to all spacecraft (table 2-3).

TABLE 2-3.– SCIENCE INSTRUMENTS: PROJECT ACRONYMS AND PRINCIPAL INVESTIGATORS[a]

Composition and Structure of the Atmosphere	
	Large Probe Mass Spectrometer (LNMS), J. Hoffman
	Large Probe Gas Chromatograph (LGC), V. Oyama
	Bus Neutral Mass Spectrometer (BNMS), U. Von Zahn
	Orbiter Neutral Mass Spectrometer (ONMS), H. Niemann
	Orbiter Ultraviolet Spectrometer (OUVS), I. Stewart
	Large/Small Probe Atmosphere Structure (LAS/SAS), A. Seiff
	Atmospheric Propagation Experiments (OGPE), T. Croft
	Orbiter Atmospheric Drag Experiment (OAD), G. Keating
Clouds	
	Large/Small Probe Nephelometer (LN/SN), B. Ragent
	Large Probe Cloud Particle Size Spectrometer (LCPS), R. Knollenberg
	Orbiter Cloud Photopolarimeter (OCPP), J. Hansen (later L. Travis)
Thermal Balance	
	Large Probe Solar Flux Radiometer (LSFR), M. Tomasko
	Large Probe Infrared Radiometer (LIR), R. Boese
	Small Probe Net Flux Radiometer (SNFR), V. Suomi
	Orbiter Infrared Radiometer (OIR), F. Taylor
Dynamics	
	Differential Long Baseline Interferometry (DLBI), C. Counselman
	Doppler Tracking of Probes (MWIN), A. Kliore
	Atmospheric Turbulence Experiments (MTUR/OTUR), R. Woo
Solar Wind and Ionosphere	
	Bus Ion Mass Spectrometer (BIMS), H. Taylor
	Orbiter Ion Mass Spectrometer (OIMS), H. Taylor
	Orbiter Electron Temperature Probe (OETP), L. Brace
	Orbiter Retarding Potential Analyzer (ORPA), W. Knudsen
	Orbiter Magnetometer (OMAG), C. Russell
	Orbiter Plasma Analyzer (OPA), J. Wolfe (later A. Barnes)
	Orbiter Electric Field Detector (OEFD), F. Scarf
	Orbiter Dual-Frequency Occultation Experiments (ORO), A. Kliore
Surface and Interior	
	Orbiter Radar Mapper (ORAD), G. Pettengill
	Orbiter Internal Density Distribution Experiments (OIDD), R. Phillips
	Orbiter Celestial Mechanics Experiments (OCM), I. Shapiro
High Energy Astronomy	
	Orbiter Gamma Burst Detector (OGBD), W. Evans

[a]Other scientists involved are listed in appendix A.

Working Groups for each scientific area of investigation. Before launch they developed key questions and afterward synthesized the results received from the spacecraft. Another very active group was concerned with mission operations planning for the Orbiter. This group referred to as the OMOP committee (for Orbiter Mission Operations Planning Committee) consisted of H. Masursky, L. Colin, T. M. Donahue, R. O. Fimmel, D. M. Hunten, G. H. Pettengill, C. J. Russell, N. W. Spencer, and A. I. Stewart.

There were six Working Groups responsible for developing key scientific questions. Chairmanship of these groups varied during the mission but the major leaders were J. Hoffman, composition and structure of the Venus atmosphere; R. Knollenberg, clouds; M. Tomasko, thermal balance; G. Schubert, dynamics; S. Bauer, solar wind and ionosphere; and H. Masursky, surface and interior.

Instruments were procured in a variety of ways. Usually, the principal investigator was responsible for having an instrument built. He either built it in his own laboratory, subcontracted its construction, or used a combination of these alternatives.

In another method of procurement, the Pioneer project office was responsible for contracting and monitoring the development of the instrument by some industrial firm, but still with the principal investigator's participation to assure that it met the requirements of his experiment.

In yet a third method of procurement, the Orbiter's radar mapper was built by the project office for a radar team. Carl Keller, an Ames Research Center engineer, had overall decision-making responsibility, and the radar was built by Hughes Aircraft as a result of an open bid procurement.

There was much talk at the beginning of the program, before the Announcement of Opportunity went out, that only instruments that had flight-proven capability would be used. The instruments had to have been flown in other spacecraft or in Earth's atmosphere. This was intended to save money and improve reliability. But in practice there were very few items of "off-the-shelf" hardware available; even an instrument the same as one flown on an earlier mission usually has to be significantly redesigned to make it suitable for use on a new spacecraft. Most important, redesign is frequently necessary because parts used in an "old" instrument are no longer made. Moreover, there was some need for instrument redesign simply because Pioneer Venus was NASA's first attempt to study the atmosphere of another planet.

The Orbiter electric-field detector is an example. Because it had flown on earlier Pioneer spacecraft, mission planners thought it could likely be flown without modification on Pioneer Venus. Nevertheless, the small ball-like antennas that were used on the detector had to be redesigned. In most cases there was much redesigning to do, particularly for the Multiprobe. No spacecraft similar to the Multiprobe had ever flown. Instruments had to be closely packaged, and many of the measurements had never been made before on any probe. Consequently, many of the instruments were, in effect, new designs that involved several critical development tasks.

From the beginning, the neutral mass spectrometer was the most difficult new design. At the initial selection of the probe instruments more instruments were selected than would ultimately be flown. One example of redundancy was a choice of two mass spectrometers that were then being developed – one at Goddard Space Flight Center and one at the University of Texas at Dallas. Both were funded for a year of continued in-house development. An instrument review committee was appointed to review all the instruments and in particular the two mass spectrometer designs. Eventually the NASA Headquarters Science Steering Committee chose the University of Texas instrument.

There were two other instruments that were chosen initially but those did not fly. One was a radar altimeter to be used on the large probe. After a year's work it became clear that the instrument was too heavy, too complex, and would be too costly. Since altitude as a function of time could be derived from the atmospheric structure experiment the decision was made to remove the radar altimeter experiment. The other instrument was a photometer system from the University of Wisconsin. After a year of in-house study at the University, it became clear to NASA Headquarters that the experiment was neither required nor sufficiently developed for the mission.

Early in the program, preliminary choices were made about experiments and then amended as more information became available. There was nothing unusual about NASA making a preliminary selection of experiments, and then making a final selection some 12 or 18 months afterward. For example, it was never intended that both mass spectrometers would fly. But the photometer and radar altimeter were eliminated on the grounds of payload weight and development studies. If they had been included the weight of the probe would have been too great. On the Orbiter, all the instruments preliminarily selected were finally approved for flight.

Challenges of Instrument Development

Many of the experiments were indeed unique. The big problem for the probes was that of packing all the instruments into a small pressure shell that had to travel through the hostile Venus environment. For the Orbiter it was in ensuring reliability of operation for at least 243 Earth days.

The big challenge in space missions is always that of meeting the scheduled launch date. In the case of Pioneer Venus, all the instruments were ready on time. There was major concern about the JPL infrared radiometer because significant and difficult development problems were encountered. Within a year of launch there was still concern that the instrument might have to be scratched from the payload. However, the development effort was intensified and the instrument was built and tested on time.

There were, of course, many of the usual problems that accompany development efforts, and there were the usual concerns about meeting schedule. But in retrospect there were no problems that seriously affected either mission schedules or the achievement of mission objectives.

The neutral mass spectrometer was a principal development problem. One of the main problems concerned the development of an inlet system for the instrument. Most mass spectrometers used in space applications operate under quasi-vacuum conditions; the Pioneer Venus instrument would operate at pressures 100 times Earth's atmosphere.

Because the ion source of every mass spectrometer has to operate within a narrow range of pressures, the pressure within the instrument has to be kept constant. An inlet system was required that would reduce the pressure from 10^4 torr to the 10^{-5} torr (10^6 Pa to 10^{-3} Pa) required by the ion source – a tremendous pressure reduction. To achieve this range the inlet system had to be built to admit very small quantities of gas, yet quantities that would be sufficient for analysis before the instrument was purged preparatory to the next sample. The University of Texas designed an innovative system consisting of a ceramic microleak (CML) inlet and a variable conductance valve; the valve was controlled by the ambient pressure of the Venusian atmosphere to change the conductance automatically. It was a very difficult development, and at times there were doubts that it could be made to work.

There were problems when attempts were made to adapt the CML for the Pioneer Venus mission. Initially the inlet was formed from stainless steel. When it was tested in sulfuric acid vapor, however, the acid never entered the instrument for sampling; instead, it was trapped in the oxide coating. Since one task was to check for the presence of acids in the Venusian atmosphere, this problem had to be corrected. It took 2 years to develop a suitable ceramic coating with a passivated surface; eventually, the flight CML was made from tantalum instead of stainless steel.

There was also a question about the possibility of aerosol particles in the planet's atmosphere blocking the small inlet opening on the mass spectrometer. The University of Texas developed a narrow slit design to minimize blockages, and a heater coil was installed around the inlet to vaporize such particles. (Nevertheless, there was an inlet blockage during the mission when the inlet was covered for a time with sulfuric acid droplets.)

There was another difficulty still to be overcome. A single inlet would be fine in the lower atmosphere but in the upper atmosphere an additional inlet was needed to provide sufficient gas input. The second inlet was left open until about the time of parachute release, then a pyrotechnic device crushed the line and stopped further entry of gas. Even if the cutoff device failed there would still be a valid set of data although somewhat degraded.

As well as being interesting from the inlet design standpoint, this instrument was the first mass spectrometer of its size that had to survive entry at 400 g.

This instrument also used the first microprocessor to be flown in space: an Intel 4004. The addition of a microprocessor permitted a full spectrum of data to be taken once every minute over the whole mass range of 200 amu. The microprocessor selected the true data point from several data points and adjusted for calibration changes. A high confidence factor was associated with the single data point transmitted. Without the microprocessor it would have been possible to transmit a spectrum only once for every 10-km change in altitude. With the microprocessor, sampling was done at every 1-km change in altitude.

Other instruments also posed some problems. For example, originally it was not proposed to fly a gas chromatograph. However, the original study team developed strong arguments in favor of the gas chromatograph and it was included in the payload package. A gas chromatograph is basically a high-pressure instrument whereas the mass spectrometer is a low-pressure instrument.

At Ames Research Center, Vance Oyama had developed a gas chromatograph for the Viking landings on Mars. Experience gained with that instrument was applied to the design of an instrument for Pioneer Venus. Originally the chromatograph was considered a backup instrument – one that would provide some spectra of atmospheric composition if the mass spectrometer should fail. However, experience with the development of the two instruments soon showed that they complemented each other; for example, the gas chromatograph could measure water vapor which could not be measured reliably by the mass spectrometer.

Robert Knollenberg, a cloud physicist, had developed a small instrument that was being used by the U.S. Air Force to measure the number of ice particles in clouds. This instrument was further developed for the Pioneer Venus mission by Knollenberg and Ball Brothers Research (Boulder, Colorado). This Cloud Particle Size Spectrometer was essentially an optical bench with a laser at one end and a prism at the other; part of the optical bench had to be outside the pressure hull of the spacecraft. Design problems were encountered in safeguarding against twisting and other distortions that would be produced as the pressure vessel heated in the atmosphere of Venus. Lou Polaski, Ames Research Center, who was responsible for development of the probe instruments, determined it was necessary to have heaters on the window in the pressure vessel and on the prism outside the window. Since Hughes Aircraft Company (the contractor for the spacecraft and probes) was responsible for having a good seal, that company also built the faceplate for the instrument through which it would penetrate the wall of the probe. To this faceplate, Hughes attached the parts of the instrument supplied by Ball Brothers, and then the complete unit was aligned by Ball Brothers. Said Polaski: "It was a tremendous challenge to get a very precise optical bench through a wall that was changing relative to the rest of the optical bench. The instrument really worked well but only as a result of a lot of good engineering work ."

Another unique instrument carried by the probe spacecraft was a solar flux radiometer. Its uniqueness derived from the fact that the sensor portion was developed separately from all the electronics. The electronics were built by Martin Marietta, Denver, and the optical head with the sensors was designed and built by the University of Arizona's Optical Science Center.

The infrared radiometer used warm infrared detectors that had to be kept at a constant temperature. So the detectors were packaged in phase-change material (the "blue ice" used for recreational refrigeration), which is known technically as a eutectic salt. This same material was used with the gas chromatograph to control the temperature of the columns of that instrument, and with the solar flux radiometer to control the temperature of its optical head. Salts were picked that would keep the temperature at the required value, just as ice floating in water will keep the water at a constant temperature until all the ice has melted.

It was necessary to ensure that all the salts would be frozen before the probe entered the Venus atmosphere. Much detailed analysis was required to prove conclusively that throughout the period from release of the probe from the Bus to its arrival at the Venus atmosphere – about 3 weeks – the phase change material would remain frozen.

The net flux radiometer flown on each of the small probes had a flux plate that flipped back and forth to measure the up and down flux. This radiometer also required a diamond window, but a smaller window than that provided for the infrared radiometer of the large probe. There were two diamond windows on each side and the instrument hung out over the back of the probe. Its strange appearance resulted in its being referred to as "The Lollipop." The diamond windows were cut from the same stone as the big window. In this way identical infrared transmission characteristics were ensured and correlation of data from the two instruments would be facilitated. Seven diamonds were thus carried to Venus – two diamond windows for each of three small probes and a single large window in the large probe.

For the Orbiter the most significant instrument development was that of the radar mapper. Hughes Aircraft, Culver City, built the radar mapper. There was no principal investigator in the usual sense; instead, there was a team led by Gordon Pettengill of Massachussetts Institute of Technology. The complete instrument incorporated over 1,000 microcircuits, weighed only about 24 lb, and consumed a mere 30 W. This was the first time a complex instrument for radar mapping had been assembled in such a compact package. The responsible project engineer at Ames Research Center was Carl Keller who played a key role in the instrument's development.

The imaging system aboard the Orbiter was a second generation of the imaging photopolarimeter flown on the Pioneer spacecraft to Jupiter and Saturn. For the Pioneer Venus mission it was fitted with an improved telescope and a new interface. The plasma analyzer was also an outgrowth of past programs.

Significantly, the cost of the overall program for instrument development was within estimates. At the beginning of the program a budget for development was established. Some instruments were above cost because problems were encountered in their development, but others came in below cost because problems planned and budgeted for did not materialize. One instrument was very late in delivery, but all were ready in time for the mission. In view of the complexity of the instruments, the financial management of the mission was remarkable.

Designing the Mission and Developing the Spacecraft

Paralleling the development of the science payload, the project had been busily developing the spacecraft. Two concurrent study contracts of $500,000 each were awarded on October 2, 1972; one to Hughes Aircraft Company Space and Communications Group, teamed with General Electric Company, and one to TRW Systems Group, teamed with Martin Marietta. The contracts called for definition of the system by June 30, 1973. After the system was defined, NASA would select a single contractor to design, develop, and fabricate the spacecraft.

There were different approaches by the two contractors. TRW considered the use of different basic spacecraft types for the Multiprobe Bus and the Orbiter. Hughes preferred a single spacecraft design that would serve the dual purpose. The probe designs of the two contractor teams were similar in essentials, although the Orbiter configurations differed significantly. In one (TRW) the spin axis of the Orbiter was aligned parallel to the plane of the ecliptic and pointed toward Earth. The fixed high-gain antenna was also pointed to Earth like that of the TRW-built Pioneer Jupiter/Saturn spacecraft. In this design several instruments were to be mounted on a movable platform so that they could scan the surface of Venus. The Hughes design was to have the spacecraft's spin axis perpendicular to the ecliptic plane with the spin of the spacecraft sweeping the field of view across Venus, and to despin a high-gain antenna and point it toward Earth. This design was chosen for the mission.

Amid the challenge of solving technical problems came a major political disappointment. Congressional authorization could not be obtained for a mission start in the 1974 fiscal year. As a result, it was not possible to meet launch dates for the 1976/77 Multiprobe mission. At this point, August 1972, the mission series was changed. Only two launches would be planned, and both would be slipped to the next launch opportunity. Both the Multiprobe and the Orbiter would use launch opportunities in 1978 and arrive at Venus at about the same time, near the end of 1978.

Overview of the Mission

The two Pioneer flights to Venus were intended to explore the atmosphere of the planet, to study its surface using radar, and to determine its global shape and internal density distribution. The Pioneer Venus Orbiter spacecraft was designed to operate for 8 months or more making direct and remote sensing measurements. The Pioneer Venus Multiprobe spacecraft was designed to separate into five atmospheric entry craft some 12.9 million km (8 million miles) before reaching Venus. Each probe craft was designed to make measurements of the characteristics of the atmosphere from its highest regions to the surface of the planet in a period of a little more than 2 hours at points spread over the Earth-facing hemisphere of the planet.

In celestial mechanics there are two classifications of transfer ellipse trajectories for traveling between planets. A trajectory that carries a spacecraft less than 180° around the Sun on a voyage from one planetary orbit to another is classed as a Type I trajectory. One that travels more than 180° is a Type II trajectory.

For Pioneer Venus, navigators wanted the Orbiter to fly a Type II trajectory to reduce its velocity upon arrival at Venus. As a result, the spacecraft would need much less propellant to slow it into an orbit around Venus – about 180 kg (400 lb) of propellant out of the total spacecraft weight of 545 kg (1200 lb). A Type I orbit to Venus would have required that 50% of the total spacecraft weight consist of propellant. The plan was for the Orbiter to be launched during the period May 20 through June 10, 1978 and to follow a 7-month flightpath to Venus along a trajectory of about 480 million km (300 million miles) (fig. 2-4). The long trajectory, chosen to give a slower arrival speed at Venus, would not only reduce the weight of propellants but also the weight and size of the orbital insertion rocket motor. This path also permitted the periapsis, or orbital low point, to be located at about lat. 20° N on the planet.

For the first 82 days, the Orbiter spacecraft would fly outside Earth's orbit. It would then cross Earth's orbit and plunge inward on a long curving path toward the Sun. It would arrive at Venus on December 4, 1978, 5 days before the arrival of the probes which would follow a shorter flightpath. The Multiprobe spacecraft would be launched a few days after the Orbiter crossed Earth's orbit, during the period August 7 through September 3, and would follow a shorter, Type I trajectory.

On the Orbiter's arrival at Venus the mission plan called for the spacecraft's motor to be commanded to thrust for 28 seconds. This would be the first time a solid-propellant motor stored in the vacuum of space so long (125 days) would be used for an orbit insertion maneuver. The aim was to reduce the velocity of the spacecraft so that it would enter an elliptical orbit with a 24-hour period. The orbit would be oriented 75° to the equator of Venus – somewhat more inclined than suggested in the January 1973 study report. Initially a periapsis, or orbital low point, of 300 km (180 miles) and an apoapsis, or orbital high point, of 66,000 km (41,000 miles) were desired. Later the spacecraft would be commanded into an orbit having a periapsis of 150 km (90 miles).

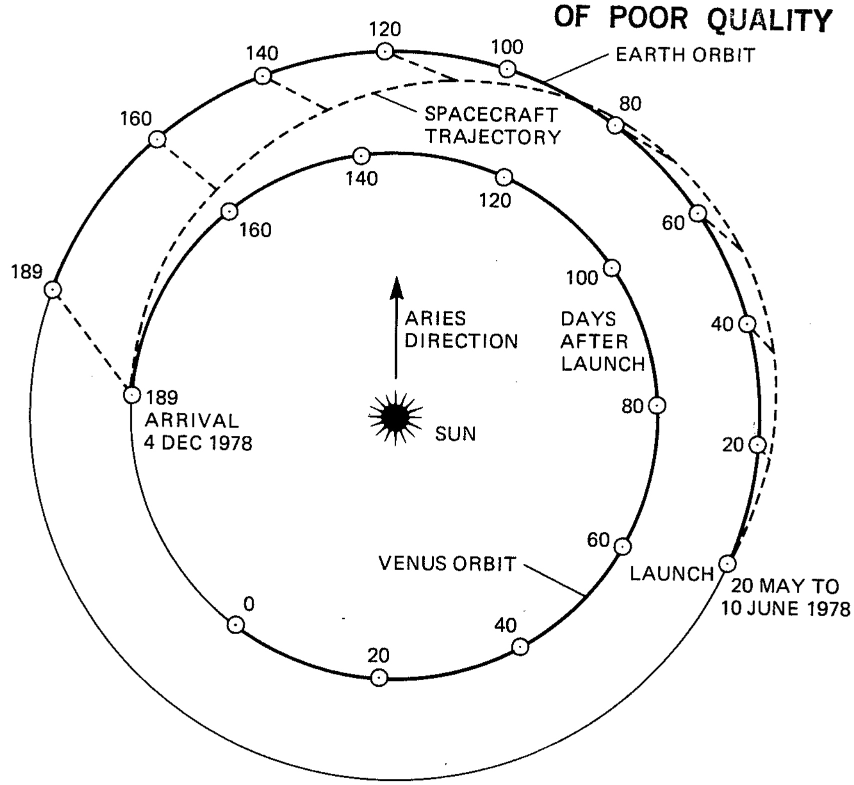


Figure 2-4. The trajectory of the Orbiter carried it first outside the Earth's orbit for nearly half of its journey to Venus. This trajectory minimized the amount of propellant needed to enter into an orbit around Venus.

The 4-month trip of the Multiprobe spacecraft to Venus would result in the spacecraft approaching the planet at about 19,500 km/hr (12,000 mph). The comparative trajectories for the Orbiter and the Multiprobe are shown in figure 2-5.

Twenty-four days before the probes entered the atmosphere of Venus, the Multiprobe spacecraft would be oriented so that its axis would lie along the trajectory that the large probe would follow to Venus. The probe would then be launched to follow its own path to the planet. Next the flightpath of the Bus would be changed to point toward the center of Venus so that the small probes could be released from the spinning Bus when the Bus was 20 days out from the planet. The spin would ensure that the small probes separated along paths that would take them to their individual targets on the planet (fig. 2-6).

Originally an alternative concept had been discussed in which the three small probes might have been individually targetable and separated individually from the Bus. However, to keep the system as simple as possible a simultaneous launch (from the Bus) technique was decided upon. In a one-firing episode all three small probes could be released; separate launches would have been less reliable. However, this single launch episode demanded painstaking computer analysis of where the spin axis should be pointed and at what spin rate the spacecraft should operate for the release so that the probes could be directed to enter the atmosphere of Venus near the limb regions of the planet as viewed from Earth, but not too close to the limb to limit slant-range communications through the planet's atmosphere. A computer program was developed to try different targeting options and to determine the angle of attack of each probe's entry into the Venusian atmosphere. All the probes were stabilized by their rotation, and if one should have entered the atmosphere sideways, its heat shield would not have been effective in protecting it from the heat of entry and the probe would have been destroyed.

On arrival at Venus the four probes would enter the atmosphere. The large probe would take about 55 minutes to descend to the surface, the three small probes, about 57 minutes. None of the probes was designed to survive impact with the surface, which would be at about 36 km/hr (22 mph). The Bus itself would follow the probes toward the planet and would hurtle into the upper atmosphere about 80 minutes after the probes. Unlike the probes, the Bus carried no heat shield; its task was to provide data on only the highest part of the atmosphere.

All probes would send their data directly to Earth as they penetrated the atmosphere of Venus on the hemisphere of the planet that faced Earth at the time of the encounter.

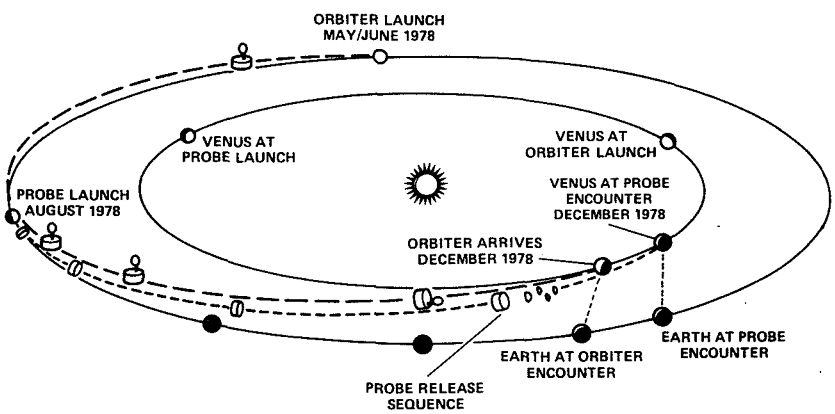


Figure 2-5. The Multiprobe followed a shorter trajectory and arrived at Venus a few days after the Orbiter. The two trajectories are compared on this drawing.

Launch Vehicle

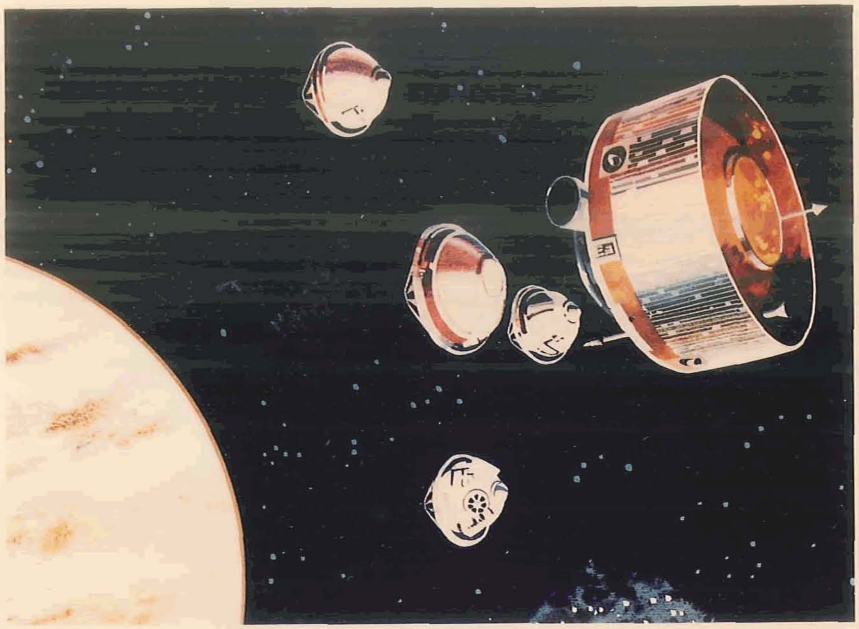
Originally the Thor-Delta launch vehicle was to be used for the Pioneer Venus flight mission. The system definition studies began with this launch capability as a design criterion for the two spacecraft. However, very early in the study effort it became clear that costs were rapidly rising as subsystem designs were severely restricted in weight and size. An attempt was made to reverse this trend by having the competing contractors study an alternative design that removed the weight and size restrictions. This was accomplished by assuming the launch capabilities of Atlas-Centaur and comparing the design and cost estimate results with those for the launch capabilities of the Thor-Delta.

Based on these analyses it was determined that the additional cost of the Atlas-Centaur launch vehicle (approximately $10 million) would at least equal the increased costs that would be required to cover the miniaturization of the Multiprobe and Orbiter spacecraft designs to meet the Thor-Delta requirements. NASA therefore directed the use of the Atlas-Centaur (fig. 2-7), which is NASA's standard launch vehicle for payloads of intermediate weight.

The Atlas-Centaur launch vehicle stands about 40 m (131 ft) high; it consists of an Atlas SLV-3D booster with a Centaur D-1A second stage. Atlas-Centaur was the nation's first high-energy launch vehicle, using liquid hydrogen and liquid oxygen propellants for its upper Centaur stage. Each spacecraft was enclosed in a fiberglass nose fairing to protect it as the launch vehicle sped through Earth's atmosphere.

"New Start" Approval for Fiscal 1975

By July 1973, the system definition studies were completed and a holding contract was issued to each of the teams until, as a result of competitive



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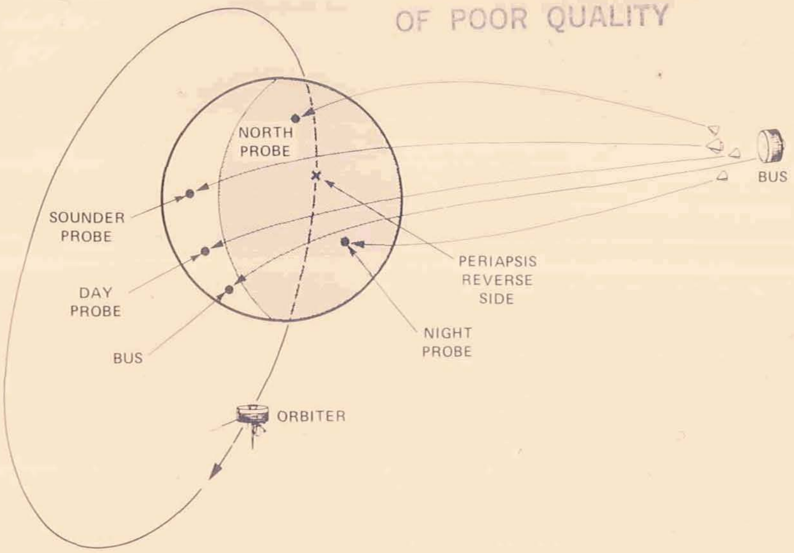


(b)

Figure 2-6. Approaching Venus, the Multiprobe released its four probes toward different target areas on the planet. (a) Artist's concept of the probes and the Bus shortly after their release. (b) Diagram of paths to and entry points on the planet in relation to the orbit of the Orbiter.

bidding following issue of a Request for Proposal in June 1973, Hughes Aircraft Company was selected in February 1974 for negotiation of a cost-plus-award-fee (CPAF) contract for the initial conceptual design phase of the system. The proposed cost of design work for this phase was $3 million, with an option for final design, development, fabrication, and testing of two flight spacecraft, and launch support at $55 million. A contract was awarded in May 1974, but not yet for the hardware (Congressional approval was still awaited for a "new start" – a new authorized space mission for fiscal 1975).

In August 1974 Congress finally approved a new start for Pioneer Venus for fiscal year 1975. Further negotiations took place with the contractor and a final award, including hardware, was made to Hughes Aircraft Company in November 1974. Specifications for the system were completed by February 1975. By the beginning of calendar 1975 work was well under way. The program still had to face major hurdles before the launch of the spacecraft. Said Charles Hall, project manager: "It always seems you don't have enough time and you are trying to find ways to do things faster. You are always having trouble with funding. You may have a total amount of funds that is enough for the program but you never seem to have enough for any particular year. So you are always making small perturbations to your plans to work around funding difficulties."

New Problems of Funding

In June of 1975, during the budget hearings for fiscal year 1976, there was a serious setback to Pioneer Venus. The House of Representatives voted to cut $48 million from the NASA appropriations in connection with the Venus mission. Already $50 million had been spent on the program. The House vote was based on misinformation and a lack of information about the technical problems associated with a delay. If the launch was delayed to the 1980 opportunity, as would have been the case if the funds had been withheld at this time, it would have been necessary to redesign the spacecraft because the 1980 launch opportunity was not as favorable as that in 1978. More launch energy or a lesser payload would have been required. That might have been the end of the program because as much as $50 million additional money – over that originally requested – would have been needed for a mission to Venus at the less favorable launch opportunity.

However, scientists, the national press, and many organizations rallied to the cause of Pioneer Venus. Prestigious scientific groups lent their support. The Nation's most eminent

Figure 2-7. An Atlas-Centaur, NASA's standard launcher for payloads of intermediate weight, was used to launch each of the Pioneer Venus spacecraft.

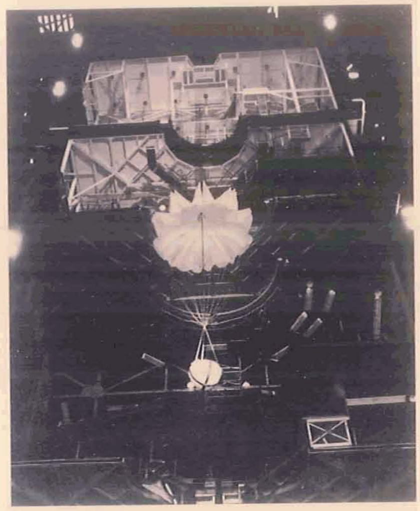


Figure 2-8. The parachute for the large probe was tested initially in drop tests within the large Vertical Assembly Building at the Kennedy Space Center, Florida.

climatologists and meteorologists emphasized the vital need for more and better information about the weather and climates of Venus and Mars. Increases in the world's population make it increasingly important that we should understand Earth's climate better and be able to predict accurately long-term changes that might lead to droughts and poor harvests. They pointed out the mission's importance to Earth sciences and to seeking ways to mitigate the effects of terrestrial climate changes on food production. (For example, one scientist pointed out that a change in Earth's average temperature of only 1.5° could wipe out the whole of Canada's wheat production. If such a change should occur unexpectedly, the effects on world food supplies could be disastrous.) The scientists reiterated that understanding the weather systems on Venus and Mars was essential to a better understanding of Earth's weather systems.

Funds for Pioneer Venus were restored in July 1975 by a Senate subcommittee. This action reversed the House move to slash all but $9.2 million from the project. But the project still faced further hurdles. The Senate Appropriations Committee and then the full Senate had to approve it. If they did, there would still be the need for a joint committee to work out a compromise with the House. The Senate committee acted on the bill later in July and gave support to the mission. Early the next month the Senate also recognized the importance of the program by giving its approval to NASA's requested funding of $57 million for Pioneer Venus during fiscal 1976.

During September 1975 the go-ahead finally came. The Senate-House conference committee restored all but $1 million of the funds for the project to send the two Pioneer spacecraft to Venus in 1978. The Earth-based part of the mission was back on course. Scientists and engineers could again concentrate on the difficult task of having the spacecraft and their scientific instruments ready at the time Venus and Earth arrived at the points in their respective orbits that created launch opportunities.

Parachute Development

By June 1975, final contracts for scientific instruments had been negotiated. By July 1975, problems of how the instruments should be integrated into the spacecraft had been studied and most of them resolved. The first tests of the parachute system, needed for the descent of the large probe into the Venusian atmosphere, had started. This aspect of the Pioneer Venus program made use of the largest structure of its type in the world, the Vertical Assembly Building at NASA's Kennedy Space Center, Florida, originally built for final assembly of the huge Saturn V boosters used to launch Apollo spacecraft to the Moon. The building was used to test the parachute for the large probe. In the test series, full-scale parachutes with pressure vessels of various weights were dropped 135 m (450 ft) in the wind-free environment of the building to determine the aerodynamic trim characteristics of the parachute (fig. 2-8).

The large probe parachute was an important development item. It was essential to the mission because it would delay the descent of the large probe long enough to allow the probe to make a great number of measurements as it settled through the clouds.

"For a time it almost looked as though we were never going to get a parachute," commented Charles Hall after the mission. He related how a newly designed parachute had been taken to the desert near El Centro, California, for a drop-test from an F-4 airplane. The parachute was attached to a pointed cylinder which carried high-speed (200 frames/sec) cameras and test instruments. When the airplane was traveling at high speed and proper altitude the cylinder would be dropped and the parachute deployed, a drogue chute pulling out the main chute.

The day of test arrived. The cylinder was dropped as planned and the drogue chute deployed as expected. Observers were appalled, however, to see no trace of the main chute opening. It literally disappeared. Hall described how when the film records were examined they showed the parachute starting to open and then disintegrating into shreds. The camera speed was 200 frames/sec and the film could be viewed one frame at a time. Said Hall: "You wouldn't believe it, but on one frame the parachute would be intact and on the next frame there would be nothing there. It was not that it was breaking away from the shrouds, the material itself just went into shreds."

It was thought that the test environment was too severe, and another test was planned that exerted a lower dynamic pressure on the parachute. But the results were equally bad. In a split second the parachute was shredded.

A third try also failed. But Hughes engineers, inspecting the pictures more closely, noticed that when the parachute was still intact, in the frame just before complete failure, that many of the parachute gores (the angular sections of the parachute) were missing, even though the chute was fully deployed! This was suspected as the cause of the trouble, since the part that was opened would be subjected to greater stresses than it had been designed to withstand.

One of the parachutes was next deployed in Ames Research Center's 40- by 80-Foot Wind Tunnel. Even there all the gores did not open. The low wind speed in the tunnel was then reduced to a relative breeze so that an engineer could walk inside and watch the opening. When the parachute opened and the gores still stayed folded, he tried to pull them apart but could not do so. The design of the chute was such that the wind load effectively held the gores together. As a result the design of the parachute had to be abandoned in favor of an earlier conical ribbon design.

But time was running out, and some chances had to be taken. The new parachute was manufactured and immediately had to be put through a final system drop-test. There was no time to try it out on airplane drops first. In the earlier tests the falling body had not been a sphere with a heat shield. But because of time constraints, the parachute, the heat shield release mechanism, and other hardware had to be tested on one drop from a high-altitude balloon.

In December 1976, the parachute was tested in a balloon drop at the Army's White Sands Missile Range in New Mexico. The parachute was deployed at an altitude of 16 km (10 miles). At that altitude, the atmospheric temperature and density and the speed of the probe would be close to the conditions that would be encountered on Venus just before the probe descended into that planet's dense, hot, lower atmosphere. The tests were aimed at confirming the deployment of the probe parachute, separation of the atmospheric entry heat shield, and, after 17 minutes of parachute descent, separation of the pressure vessel for its free-fall plunge. The fast descent after release of the parachute would let the probe penetrate deeply into the Venusian atmosphere before high temperatures could destroy its instruments.

The sky was clear at 4:00 a.m. when the balloon gently lifted its load from White Sands Proving Grounds, New Mexico. Ponderously, the great plastic bag carried the test vehicle to an altitude of 31 km (19 miles). At Ames Research Center project leaders waited for the test results. Says Hall: "We got the phone call . . . 'It has been a complete failure.'" When the radio command had been given to release the vehicle, it dropped swiftly from the gondola beneath the balloon as planned. As the probe was released from the balloon, it hit the gondola which caused the probe to turn upside down. Thus, when the parachute was released, it pulled against the parachute clevises in the wrong direction and broke them. The test vehicle plunged to the desert floor. "We were in trouble," Hall said. "We did not have a parachute."

When the photographs were studied at Ames Research Center and after recovered parts of the test vehicle had been carefully inspected, the reason for the failure was discovered. There were structural breakages all over the test vehicle, not from the impact but breaks that had occurred before impact. Structure had been torn out by the way the parachute released. At first it seemed that not only had the parachute failed but that the whole system had not been stressed properly.

Engineers studied the photographs in great detail. They saw that the test vehicle had been tumbling before the parachute deployed at 18,000 m (60,000 ft). In fact, after tumbling part of the way down, the test vehicle became stable, but was falling tail first instead of nose first. When the parachute deployed it came off at an angle that was not designed for. The pictures showed the chute being deployed, and in that split second the chute broke away from the body of the large probe because of its wrong attitude.

The question next to be answered was why the test vehicle had tumbled during its fall from the balloon. For the journey upward it had been carried within a container about 3 m square (10 ft square). At the last minute a test engineer became worried that in the ascent of the gondola to 30,500 m (100,000 ft) the temperature would drop too low and that equipment in the large probe would fail to operate correctly. As a result, a protective blanket, made of 1.3-cm (0.5-in.) fibrous padding, was taped in place beneath the box. When the probe was released and fell through the blanket, one edge of the probe caught on the blanket and the probe was sent tumbling in its fall. Later the design engineers found that the shape of the probe was very stable if it were to fall in a backward direction.

Another test vehicle was built, another drop was made, and success was finally achieved! Pioneer Venus had a working parachute for its large probe.

Spacecraft Development Challenges

There were anxious moments during a thermal vacuum test of the probe spacecraft only 7 months before the launch date. During the test the batteries within the probe spacecraft failed completely. With the launch date so close, this looked like a major disaster for the program.

"In retrospect," said Charles Hall, "All these things look simple, but at the time we had no idea whether it was the test environment or the battery at fault. We made many side tests and had experts give their opinions, and as is generally the case with these problems you can get about as many people on one side as the other."

Investigation showed, however, that the batteries themselves were not at fault. It was the conditions of the test that had caused the failure. During the test the spacecraft had been spun on an axis aligned horizontally. The g force thus varied in direction during each revolution. As a result there was sloshing of the electrolyte within the batteries, a condition that would not occur during an actual mission. This sloshing caused massive failures within the battery cells.

The cable connections within the confined space of the probes also led to difficulties. Within all spacecraft the cable harness nearly always presents problems, and this was particularly so for the Venus probes. The harnesses for these probes were difficult to design because the probes had to be taken apart several times during testing. One of the most difficult problems in testing the spacecraft was associated with assembly and disassembly. Equipment was installed on two shelves and was interconnected by the harnesses. The standard procedure with spacecraft was to first assemble the whole thing and test it, then take it apart again so that the principal investigators could have their instruments for final calibrations in their laboratories. Then the instruments had to be replaced in the spacecraft before it was shipped to the launch area for mating with the launch vehicle.

From a systems integration and test standpoint, the commonality of design on Multiprobe Bus and Orbiter helped ease problems of testing and development of software for the test programs.

Another major problem was that of sealing the probes. On the way to Venus the internal pressure had to be maintained against leakages into the vacuum of space. When a probe entered the atmosphere of Venus it had to resist the tremendous pressures there and leaks inward had to be prevented. During development of the spacecraft many pressure tests were made (fig. 2-9) to make sure that the titanium shell could withstand the pressure and to make sure that the seals did not leak. Two types of seals were necessary for these opposing conditions; they required a unique design and many more tests (fig. 2-10). For the vacuum of space, an O-ring type of seal was used. To resist the high pressure of the Venusian atmosphere there were flat graphoil seals (made of graphite fibers) between flat surfaces on flanges of the spacecraft parts. The system worked well. One probe actually transmitted data after it had landed on the surface of Venus and these data showed no evidence of any leakage.

Sealing the various windows in the spacecraft also presented problems. Many tests had to be made to ensure that the seals would withstand both high pressures and temperatures (fig. 2-11). There were, however, significant development problems encountered in making a suitable seal for the diamond window (fig. 2-12). It was decided early not to braze the window to seal it to the shell of the pressure vessel. Later this decision was reversed, and it was intended to coat the edge and braze it to the diamond. As the program continued, the window sealing presented a very difficult fabrication problem. In fact, it became a pacing item that prevented the flight diamond window, with the full assembly, from being tested with the instruments in the spacecraft.

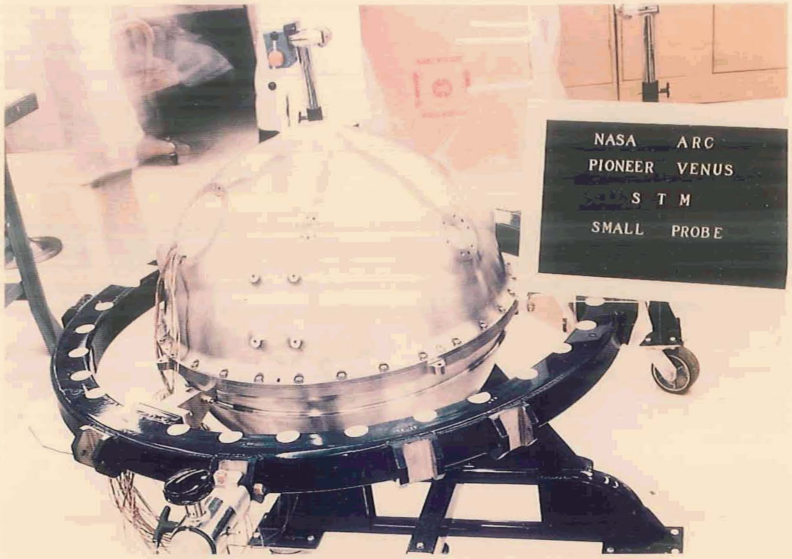
There were many disappointments. The engineers would think they had a solution but when it was tried it resulted in failure. They would try again, but just when they thought a test was being completed satisfactorily, the window seal would spring another leak. Eventually a mechanical flat seal had to be used.

As time for shipment of the large probe approached, engineers decided that the internal pressure might be too low at the time of the probe's entry into Venus's atmosphere and that it should be increased by 6 psia. It was decided to add a nitrogen pressure bottle to the payload of the large probe. This nitrogen bottle had a volume of 110 cm^3 (17 $in.^3$) which, with the nitrogen stored at 4,000 psia, would increase the internal pressure by the required 6 psia. With its attachments it added 3.5 kg (7.8 lb) to the weight of the large probe. The bottle was opened prior to atmospheric entry of the large probe by an electrically fired squib valve that punctured a sealing diaphragm; the rate of release was arranged at 5 psia/min. This addition required wiring changes. And at the eleventh hour the squib valve, when tested, did not puncture the diaphragm, and modifications were required to the ram and valve body.

Mission Operations

Pioneer Venus mission controllers had to operate simultaneously two different spacecraft. Since all Pioneers are relatively unautomated spacecraft, designed that way to minimize costs, mission operations required 24-hour-a-day control and careful analysis and planning at short notice. Although ground-controlled spacecraft provide flexibility in terms of changing plans and objectives during a mission, they require constant monitoring and control. Pioneer Venus control and spacecraft operations were located at the Pioneer Mission Operations Center (PMOC) (fig. 2-13) at Ames Research Center.

Activities at the Mission Operations Center were made somewhat more complicated by the continued operation of previously launched Pioneer spacecraft. Pioneers 6, 7, 8, and 9 continued to circle the Sun and to return interplanetary data. Pioneer 10, which flew past Jupiter in 1973, was heading out of the Solar System and transmitting important



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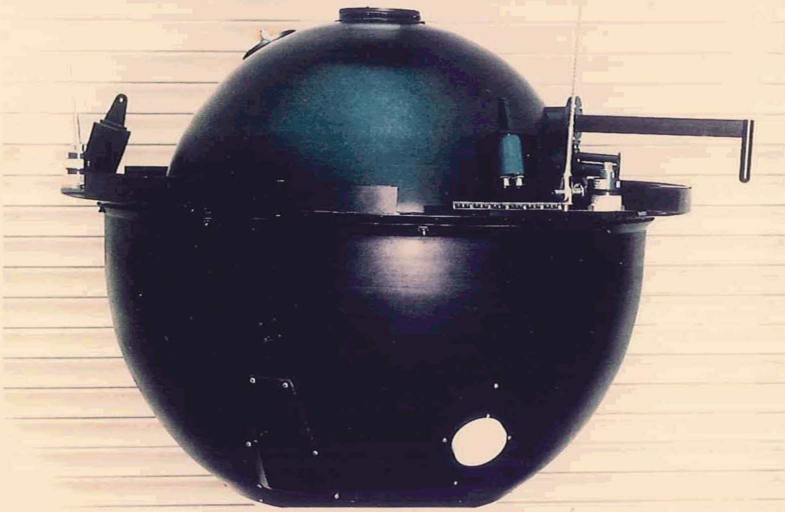

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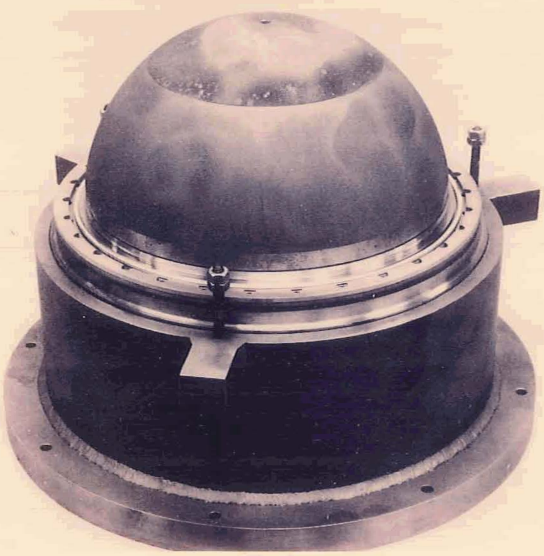


(c)

information from previously unexplored regions of space. Pioneer 11, which flew by Jupiter in 1974, was on its way to the first rendezvous of a spacecraft with Saturn.

All command information originated from the Pioneer Mission Operations Center. It received all telemetry data required for control of the mission and displayed the information as needed. Computers allowed commands to be entered and the stream of data from the spacecraft to be rapidly interpreted for use by flight controllers. The integrated team working at the Center was made up of dedicated individuals from NASA and its support contractor, Bendix.

Because two spacecraft with separate missions were involved, two flight operations groups were needed: an Orbiter group and a Multiprobe group. Both groups had a science-analysis team to determine the status of each instrument and formulate command sequences for that mission. Also they each had a spacecraft performance analysis team to analyze and evaluate the performance of the spacecraft and

Figure 2-9. Many tests were necessary to ensure that the probes would be able to withstand the enormous pressures and high temperatures of Venus' atmosphere. (a) The small probe pressure vessel is shown partially assembled prior to running pressure descent tests. The 2-piece structure was machined from titanium forgings, and weighs approximately 18 kg (40 lb). It is 46 cm (18 in.) in diameter and the wall thickness averages approximately 0.3 cm (1/8 in.). (b) This full-scale mockup of the large probe pressure vessel module was constructed during Phase B to study the packaging problems inherent with spherical geometry. (c) A "buckling indicator" mandril used during buckling tests of probe vessel pressure scale models is shown prior to assembly with a test model. In each test, the mandril supported the inside surface of the pressure vessel model to record the imprint of the buckle pattern on its graphite coated surface after a failure.

Figure 2-10. A metal pressure seal for a probe pressure vessel is shown with its disassembled testing fixture after undergoing a sealing test in a simulated Venusian descent environment.

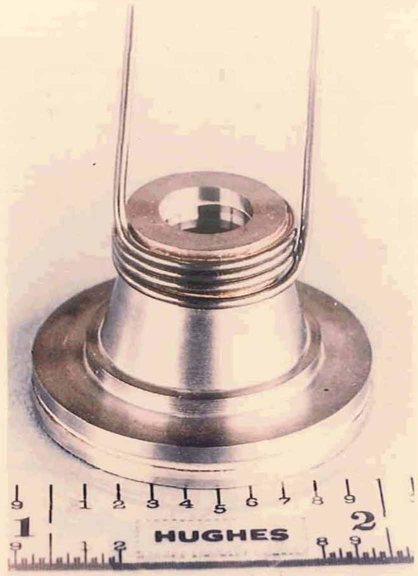
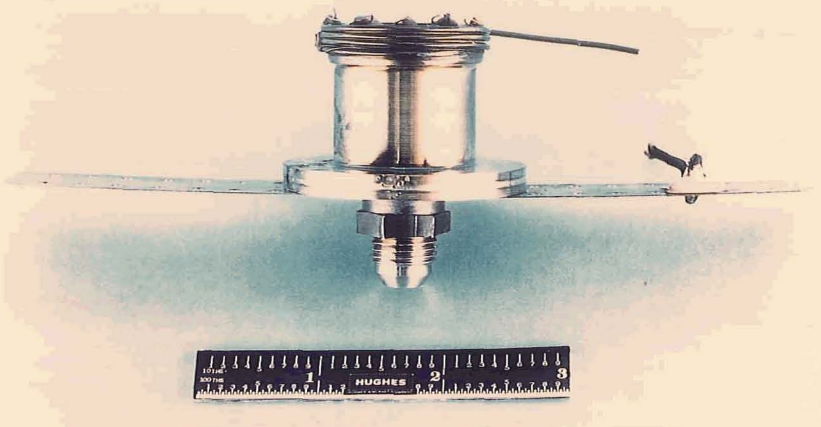


Figure 2-12. This depicts an early configuration of the diamond window and heater assembly. The test article incorporates a 10 mm window and was used to demonstrate a technology of brazing the diamond and heater assembly to a mallory metal mount. Pressure tests conducted up to 2500 psi showed no leak or structural problems at this stage of window seal development.



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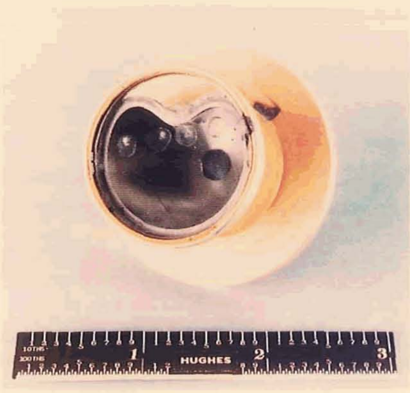


(b)

Figure 2-11. (a) Shown is a side view of the 3.175-cm (1.25-in.) diameter sapphire window assembly after a simulated Venusian descent pressure and temperature test. The assembly consists of an inconel housing with a kovar-sheated heater wrapped around a brazed sapphire window. (b) Shows the result of pressure testing a sapphire window and mount representative of the probe windows. Note that the mount failed prior to the window itself. The test failure pressure was approximately three times the maximum amount expected at the surface of Venus.

to predict how it would respond to commands. There was also a third organizational element that served both spacecraft. This navigation and maneuvers group took care of navigation of the spacecraft, orbital injection and trim, and probe targeting.

The Jet Propulsion Laboratory (JPL) provided computer analysis of the tracking information from the Deep Space Network (DSN) to determine the trajectories of the spacecraft.

Support groups at Ames Research Center and at other NASA facilities assisted the mission operations team in performing computer software development, mission control, and off-line processing of data.

Data Return, Command and Tracking

To track all six spacecraft – the four probes, the Bus, and the Orbiter – the Deep Space Network's global system of large parabolic dish antennas was used. The largest of these antennas at each site was essential for critical phases of the mission (e.g., reorientation of the spacecraft, velocity corrections, orbit insertion, entry of the four probes into Venus's atmosphere) and special science events (e.g., radio occultation experiments).

The Deep Space Network, managed by the Jet Propulsion Laboratory, has facilities located at approximately 120° intervals around Earth (fig. 2-14). As the Orbiter and the Multiprobe appear to set at one station due to the rotation of the Earth, they are rising at the next station. The Deep Space Network had six 26-m (85-ft) antennas, two at Goldstone, in California's Mojave Desert, two at Madrid, Spain, and two at Canberra, Australia. (One at each location is now upgraded to 34 m (112 ft) and the remaining 26-m antennas were shut down during budget cuts in 1981.) There are also three 64-m (210-ft) antennas (fig. 2-15), one each at the three locations. During the critical 2-hour period of atmospheric entry by the Bus and flights down to the surface by the four probes, the 64-m (210-ft) antennas at Goldstone and Canberra were used to receive and record the data coming in simultaneously from all five spacecraft (fig. 2-15). Two additional tracking stations were used to provide special data acquisition for the probes' Differential Long Baseline Interferometry (DLBI) experiment. These were the 9-m antenna stations which are part of the Spaceflight Tracking and Data Network (STDN) and which are located at Santiago, Chile, and at Guam.

During launch, the Deep Space Network, with the help of other facilities, tracked each spacecraft. These other facilities comprised tracking antennas of the Air Force Eastern Test Range and elements of NASA's Spacecraft Tracking Data Network supported by four instrumented aircraft operated by Wright Patterson Air Force Base.

Incoming telemetry was formatted at the Deep Space Network Stations and transmitted over the high-speed circuits of the NASA Communications System (NASCOM) to the Pioneer Mission Computing Center (PMCC). There it was processed by computers to supply various types of real-time display information about the status of all the spacecraft and their experiments. The computers checked for unexpected or critical changes in data and provided information for analysis by specialists experienced in all details of the spacecraft, experiments, and the ground system. Their analyses were used to make sure that the spacecraft were always controlled correctly to get the best science results. Outgoing commands were verified by the computers at Ames Research Center and sent to the Deep Space Network Stations where they were again verified by computer before being transmitted to the spacecraft. Navigation data and trajectory computations for the Pioneer spacecraft were furnished by the Jet Propulsion Laboratory.

Several modifications were made to the Deep Space Network for its use in the Pioneer Venus mission. Receivers

Figure 2-13. From this Pioneer Mission Operations Center at NASA Ames Research Center, California, all the spacecraft were commanded and controlled.

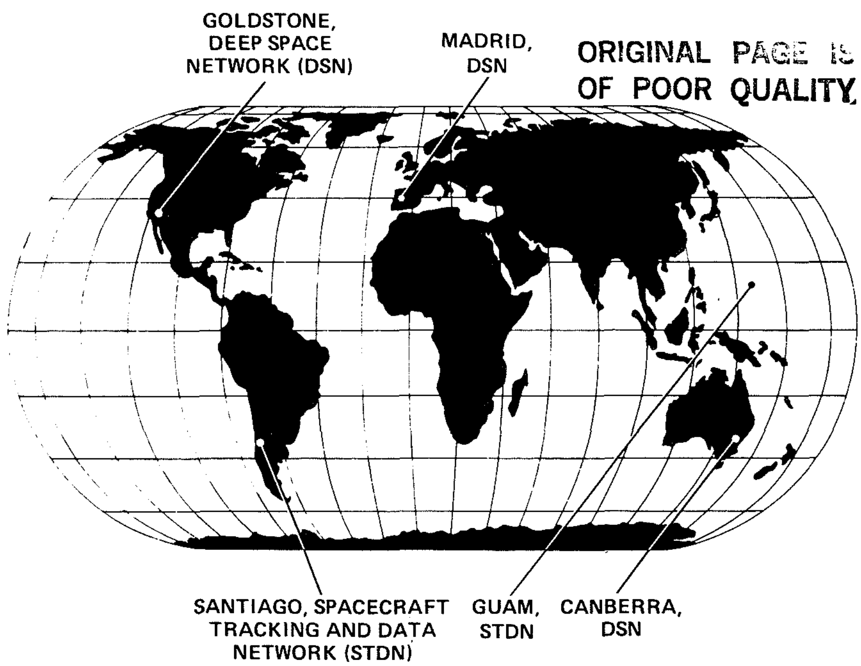
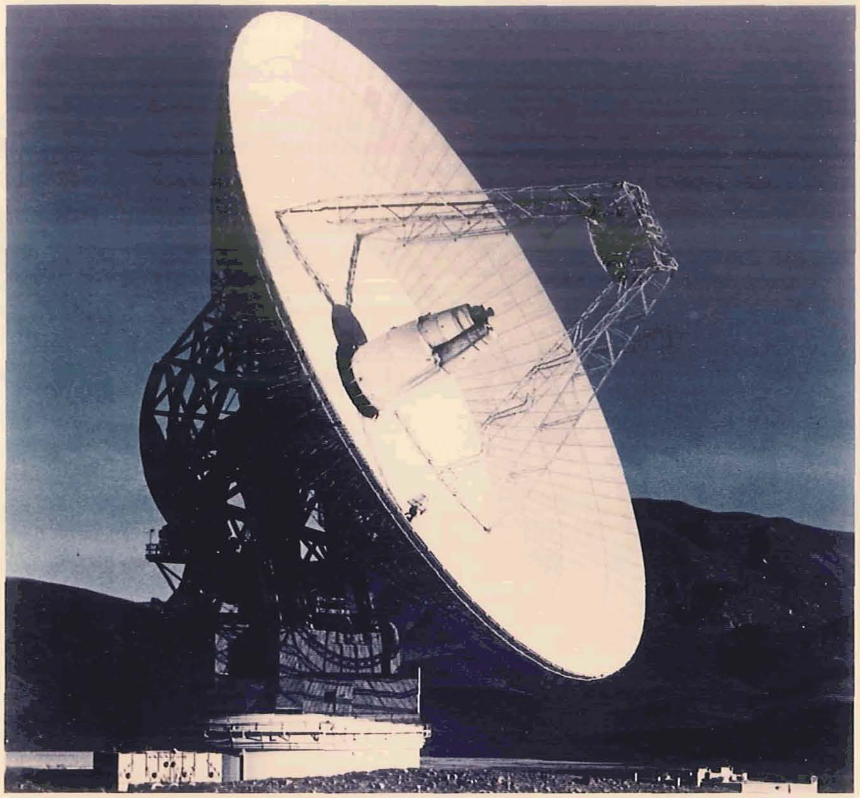
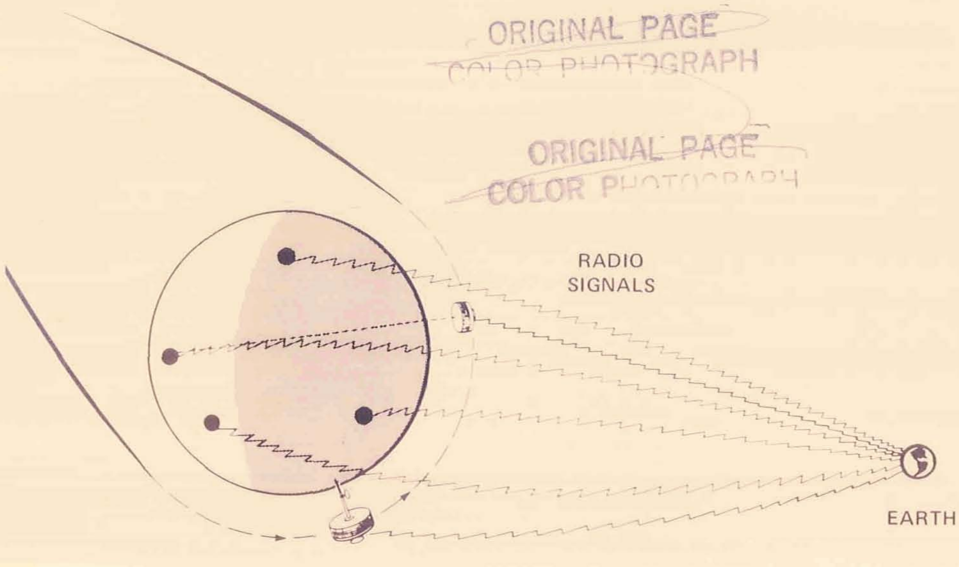


Figure 2-14. The worldwide system of the Deep Space Network was used to communicate with the spacecraft during the mission, to issue commands to some of them and to receive scientific data telemetered from all the spacecraft.



(a)



(b)

Figure 2-15. (a) Two of these big 64-m antennas, at Goldstone, California, and Canberra, Australia, maintained contact with the probes during their penetration of the Venus atmosphere. The two antennas were used at the same time to make sure that none of the data was missed during this one-time descent. (b) During flight of the probes and the Bus through the Venus atmosphere, the Deep Space Network handled six spacecraft at once. All the spacecraft transmitted their information directly to Earth as shown in this diagram.

were added to handle (simultaneously) the five different data streams. Special wideband recorders were required to cope with large frequency drifts caused by changes in probe velocity as the probes entered Venus's atmosphere and by atmospheric effects on signal propagation as the probes descended through the dense hot atmosphere. To make sure that no data were lost as the probes plunged through the atmosphere, the Deep Space Network provided special equipment to tune the receivers to the signals being received from each probe and to record the data in unsynchronized form for special off-line processing.

In addition to providing telemetry for mission operations and quick looks at scientific data, all telemetry was processed at the Pioneer Mission Computing Center to supply Experiment Data Records to each of the principal investigators for distribution to their team members.

Countdown to Launches

Following pre-shipment reviews at the Hughes Aircraft Company's plant in El Segundo, California, during February 1978, the spacecraft were shipped to the launch site at Kennedy Space Center, Florida. The main body of the Orbiter and the high-gain antenna were shipped separately. When they arrived in Florida, the first task was to mate the antenna and the spacecraft. Later, in the checkout area, the complete Orbiter was tested extensively to make certain that all subsystems and scientific instruments were operating correctly.

After these tests had been completed, class B ordnance (ordnance that would not be harmful to the spacecraft or test personnel should it inadvertently be fired) was installed. The spacecraft was then transferred to Building SAFE-2 where the rest of the ordnance and 32 kg (70 lb) of hydrazine propellant were loaded. Hydrazine was the fuel used for trajectory corrections and orientation maneuvers.

The spacecraft was then mated with an adapter (used for attaching it to the launch vehicle) and shipped to launch pad 36 where it was mated to the waiting Atlas-Centaur.

Once the spacecraft was on the launch vehicle, another series of tests was made to verify that the spacecraft and its systems had not deteriorated in any way. Then followed a series of radio frequency interference (RFI) tests to verify that the radar used to track the vehicle during launch would neither interfere with the spacecraft nor affect the data being transmitted from it during the launch phase of operations.

After several practice countdowns, a final test was made with the Deep Space Network to ascertain that the signals being received from the spacecraft were as expected. After 10 days of various tests the "go" for launch was given and the countdown began.

There were no holds. The big Atlas-Centaur lifted the Orbiter into the Florida skies on its way to Venus (fig. 2-16). The launch was precisely on schedule – May 20, 1978, at 1313 UT.

Meanwhile, during April, the Multiprobe had completed its pre-shipment review at Hughes. The large probe was shipped separately from the Bus and the three small probes. As soon as the spacecraft arrived at the checkout area at Kennedy Space Center, the small probes were removed from the Bus and each was thoroughly checked, as was the large probe. During checkout, the flight batteries had to be kept under strict thermal control. They could not be on board the probe spacecraft for testing because they could not be put through charge/discharge cycles. Other batteries were used for the tests, and the flight batteries were the last items to be installed on the probe spacecraft at the end of checkout.

Sealing of the pressure vessels was verified by testing the probes in the thermal vacuum chamber at Martin Orlando. A trace of helium had been placed in the gas within each probe. The contents of the vacuum chamber were sampled for 24 hours. A seal failure would have been revealed by the presence of helium in the samples from the vacuum chamber. None was found for any of the separately tested probes. All passed the leakage test satisfactorily.

Figure 2-16. The First Pioneer Venus spacecraft, the Orbiter, was successfully sent on its way to Venus on 20 May 1978.

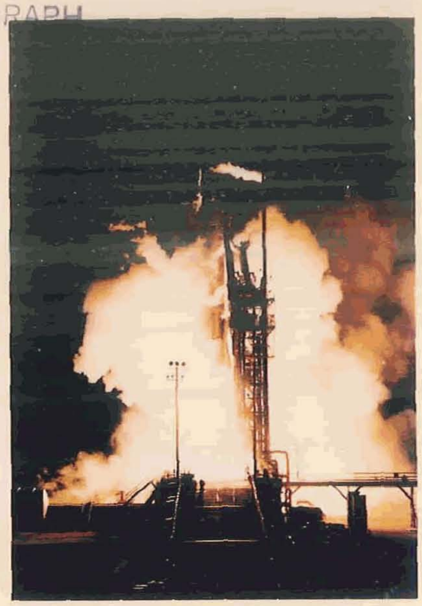


Figure 2-17. Slightly less than three months later the second spacecraft, the Multiprobe, was launched from the Kennedy Space Center, Florida, on 8 August 1978, and followed the Orbiter to a rendezvous with Venus in December of that year.

Back at the Kennedy Space Center the probes were placed on the Bus, and the pyrotechnics were installed – explosive bolts for the large probe and bolt cutters for each of the small probes. These devices would release the probes from the Bus. The hydrazine was also loaded into the Bus for maneuvers.

The Multiprobe was next transferred to the launch pad and mated with the Atlas-Centaur and finally checked out on the launch stand. Only a very brief check could be made of the radio frequency link to each probe. The probes were all warm – near the ambient Florida temperature. However, when they reached the atmosphere of Venus they would be very cold. To avoid exceeding the temperature limits established for the equipment carried within the heavily insulated probes, tests had to be extremely brief. The radio frequency transmitters on each probe were turned on for an extremely short time to verify that there was a signal from them. In the case of the large probe, because the antenna was housed in a support cone, a pickup antenna had to be connected to an outside antenna to relay the signal to the Deep Space Network for the test.

Finally, the Multiprobe countdown was begun. All went well until close to the scheduled launch date of August 6, 1978. Then, as the liquid helium was being loaded into the Centaur, technicians discovered that the helium truck carried less liquefied gas than it should have. As a result, the countdown was stopped. It was resumed on August 7 at 1830 EDT, and the Multiprobe was launched on its way to Venus at 0733 UT on August 8, 1978 (fig. 2-17).

The first U.S. mission into the cloud-shrouded atmosphere of Earth's mysterious sister planet was successfully on its way.

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3
Pioneer-Venus Spacecraft

A NEW ERA DAWNED with an announcement from the Commander, Air Force Missile Test Center, Cape Canaveral, Florida, October 11, 1958:

"The United States launched a three-stage experimental space vehicle at the Atlantic Missile Range at Cape Canaveral, Florida, at 0342 EST this morning. The launching was accomplished by the Air Force under the direction of the National Aeronautics and Space Administration (NASA). It was the second flight test of a number of small unmanned space vehicles designed to gather scientific data as a part of the U.S. International Geophysical Year program which is sponsored by the National Academy of Sciences with the support of the National Science Foundation.

"The vehicle is composed of the Thor intermediate range ballistic missile as the first stage (or booster), a modified Vanguard second stage, and an advanced version of the Vanguard third stage. Topping this vehicle is a highly instrumented scientific payload."

A short while later, another announcement followed:

"The Department of Defense gave the name 'Pioneer' today to the payload of the successfully launched U.S. lunar probe rocket, the first man-made object known to escape the Earth's gravitational field."

This then was the genesis of a series of spacecraft bearing the name Pioneer. The new era of developing spacecraft to explore beyond Earth would lead to vehicles that would be first to visit Jupiter and Saturn, to probe into the outermost reaches of the Solar System, and to penetrate the atmosphere of the mysterious, cloud-shrouded Venus.

Several studies were made in the years after the first Air Force lunar probes to determine how unmanned spacecraft might be developed to explore the Solar System. In early 1960, NASA transferred the solar probe study program to Ames Research Center. There it continued under the leadership of Charles F. Hall and a team appointed September 14 by Smith J. DeFrance, Director of the Center. Other members of the team were J. Dimeff, C. F. Hansen, W. A. Mersman, R. T. Jones, H. F. Matthews, H. Hornby, W. J. Kerwin, and C. A. Hermach. At this time, the concept was for a spacecraft to approach within 44,850,000 km (27,870,000 miles) of the Sun.

In succeeding years, Hall sought support from NASA Headquarters for this idea and won approval from Edgar M. Cortright, then Deputy Director of the Office of Space Science, to develop an interplanetary Pioneer as a step toward a solar probe. Ames management concurred and, in April 1962, a feasibility study was completed by Space Technology Laboratories of Redondo Beach, California. This study developed a concept for a spin-stabilized spacecraft that met design constraints of low weight, low cost, and quick design and fabrication for various missions to explore interplanetary space and its environment.

Contracts were awarded following competitive bidding, and a first launch was planned for 1965. The Pioneer program originally consisted of five spacecraft and their experiments. Ames Research Center managed the project, TRW Systems built the spacecraft, and the scientific instruments were provided by experimenters. The first spacecraft to be launched was Pioneer 6 (fig. 3-1) on December 15, 1965. On August 17 of the following year, Pioneer 7 was launched successfully, followed by Pioneer 8 on December 13, 1967, and Pioneer 9 on November 8, 1968. The final spacecraft in the series was launched August 27, 1969. Hydraulic pressure was lost in the first stage of the Delta booster after 214 sec and the first-stage engine was cut off early. The second stage ignited and the protective fairing on the spacecraft was jettisoned, but the booster began to stray

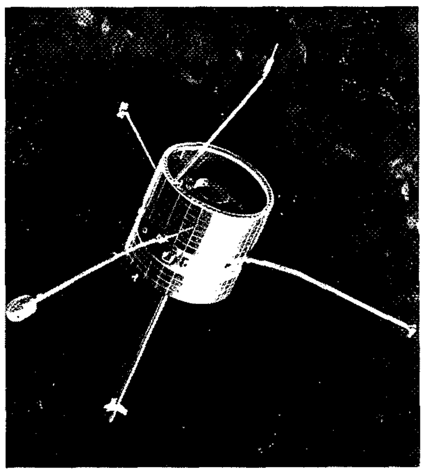


Figure 3-1. The Pioneer series of spacecraft started with the Interplanetary Pioneer 6 launched in 1965, although much earlier the name had been given to an Air Force lunar probe spacecraft series. The Pioneer missions culminated in the Pioneer Venus spacecraft, launched in 1978.

off course. The Range Safety Officer ordered the booster to be destroyed 484 sec into the flight.

All of these spacecraft were designed to orbit the Sun in approximately the plane of the ecliptic, some initially directed inside Earth's orbit, some outside.

The scientific results were impressive. The Pioneer missions confirmed that there is a spiral solar magnetic field imbedded in the plasma that streams outward from the Sun. They also confirmed the structure of Earth's bow shock and of the magnetopause. A geomagnetic tail was mapped, and insights were obtained into what happens in interplanetary space when a solar flare erupts. Energy spectra of solar electrons and positive ions were recorded, and the average electron temperature of the solar wind was shown to be about 100,000 K during times of low solar activity. Cosmic ray telescopes aboard the Pioneer spacecraft showed that, during solar minimum, most of the high-energy cosmic ray particles recorded originated from outside the Solar System. However, even at solar minimum, low-energy cosmic rays were found to be predominantly of solar origin. Shapes of plasma clouds and the electric fields in interplanetary space were also measured.

An important discovery of the Pioneers was that cosmic dust is not a serious hazard to man and spacecraft operating outside Earth's atmosphere as had been previously thought. Also, Solar System constants and ephemerides were improved by accurately tracking the Pioneer spacecraft in their heliocentric orbits. The gravitational constants for Earth and the Moon, the mass ratio of Earth and the Moon, and the distance of Earth from the Sun (the astronomical unit) were all determined with much improved precision.

In 1969, a new class of Pioneer spacecraft originated – a low-cost, lightweight, spin-stabilized spacecraft for flybys of other planets. The first two Pioneers of this class were Pioneers 10 and 11, originally designed to fly by Jupiter. These spacecraft were highly successful in withstanding the intense radiation as they passed through the radiation belts of Jupiter in 1973 and 1974, and in maintaining contact with Earth from the enormous distances of the outer Solar System. As a result, to the mission of Pioneer 11 was added the task to fly across the Solar System high above the ecliptic plane and then to fly by Saturn in 1979 before following Pioneer 10 in the continuing exploration of interplanetary space in the outer Solar System.

Pioneers 10 and 11 showed that spacecraft could safely pass through the asteroid belt and through the Jovian radiation belts. They made significant discoveries about the two largest planets of the Solar System. They found that Jupiter must be a liquid planet and that its atmosphere is heated uniformly from equator to poles and in day and night hemispheres. They discovered that Jupiter's magnetosphere is a pulsating volume of particles and fields stirred by the inner satellites. They discovered three distinct regions and showed that the planet is the source of energetic particles hurtled across the Solar System. They confirmed the intensity and orientation of the magnetic field of Jupiter and Pioneer 11 discovered a magnetic field of Saturn. They imaged the polar regions of Jupiter for the first time and the rings of Saturn observed from the shadowed side. Several new features were discovered in the Saturn ring system, including a thin F ring beyond the A ring, and additional satellites were discovered. The strengths of the magnetic fields of the two planets were measured, and the first images were obtained from a spacecraft of the Galilean satellites and Titan.

The Pioneer Venus spacecraft – the Orbiter and the Multiprobe – were the next steps in the evolution of this highly successful line of trail-blazing interplanetary probes. And one of the Venus spacecraft was to become a true planetary probe in that it carried several spacecraft into the Venusian atmosphere, as opposed to flying by or orbiting the planet. Whereas the previous Pioneers 6-11 were built by TRW Systems, the Pioneer Venus spacecraft were built by Hughes Aircraft Company. Ames Research Center continued in the project management role.

The Orbiter

The Orbiter provides a spin-stabilized platform for the 12 scientific instruments of the orbital mission. It uses the basic Pioneer Bus, common to both the Orbiter and the Multiprobe, to reduce the cost of the mission.

The main body of the spacecraft (fig. 3-2) is a flat cylinder 2.5 m

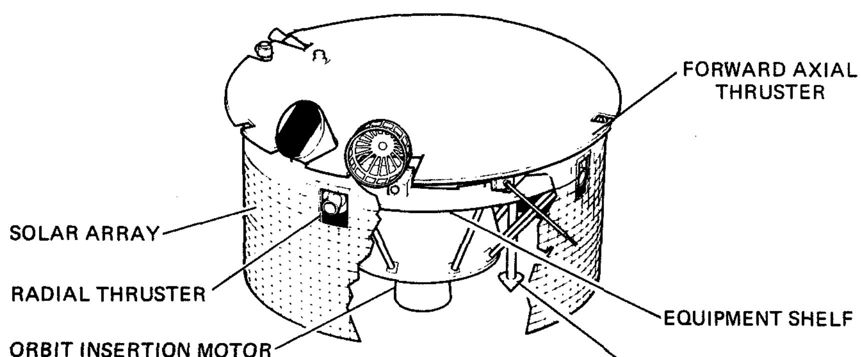


Figure 3-2. The main body of the Pioneer Venus spacecraft is a simple cylinder and it was common design for both Venus spacecraft. It has shelves for equipment, thrusters for maneuvering, an omni-antenna, and, for the orbiter only, a solid-propellant, orbit-insertion, rocket motor.

(8.3 ft) in diameter and 1.2 m (4 ft) high. In the upper or forward end of this cylinder, there is a circular equipment shelf with an area of 4.37 m^2 (47 ft^2) on which all the scientific instruments and electronic subsystems of the spacecraft are mounted (see chap. 4 for descriptions of these instruments). The shelf is mounted on the forward end of a thrust tube that connects the spacecraft to the launch vehicle. Twelve equally spaced struts support the periphery of the shelf from the lower part of the thrust tube. Below the shelf, 15 thermal louvers (fig. 3-3) control heat radiation from an equipment compartment located between the shelf and the top of the spacecraft. A cylindrical solar array (fig. 3-4), attached to the shelf by 24 brackets, formed the circumference of the flat cylinder of the spacecraft.

On top of the spacecraft, a 1.09-m (43-in.) diameter, despun, high-gain, parabolic dish antenna (fig. 3-5) is mounted on a mast so that its line of sight clears equipment mounted outside the spacecraft. The despun design allows the antenna to be mechanically directed to Earth from the spinning spacecraft. The antenna operates at S- and X-bands.

The spacecraft also carries a solid propellant rocket motor (fig. 3-6) that provided 18,000 N (4000 lb) of thrust, decelerating the spacecraft by 3816 km/hr (2371 mph) and placing it into an orbit around Venus. Including the antenna mast, the Orbiter is almost 4.5 m (15 ft) high and it weighed 553 kg (1219 lb) when launched from Earth. This launch weight included 45 kg (100 lb) of scientific instruments and 179 kg (395 lb) of rocket propellant.

A maneuvering system for the basic Bus of the Orbiter controls its rate of spin, makes course and orbit corrections, and maintains the orientation of the spin axis, which is usually kept perpendicular to the plane of the ecliptic. Beneath the equipment compartment and attached to the thrust tube are two conical-hemispheric propellant tanks (fig. 3-7), each 32.5 cm (12.8 in.) in diameter. Initially, 32 kg (70 lb) of hydrazine was stored in these tanks. This hydrazine is used as propellant for three axial and four radial thrusters (fig. 3-8) which changed the attitude, velocity, or orbital period and spin rate of the spacecraft as required during the mission. Two axial thrusters are aligned with the axis of spin and are located at the top and bottom of the Bus cylinder diagonally opposite each other. They point in opposite directions. When the spin axis must be turned, the thrusters are fired in pulses in opposite directions. To speed up or slow down the spacecraft along the direction of its

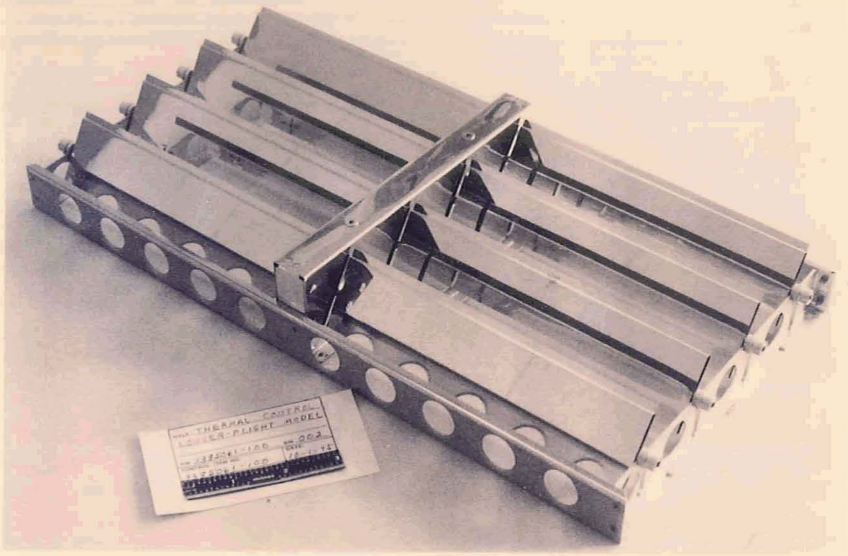


Figure 3-3. Thermal louvers control the internal temperature of the spacecraft. These flight model louvers are shown partially open. Gold strips of kapton film were added to the inboard side of the blades to radiate energy absorbed by the blades to the spacecraft. This reduces blade temperature as required.

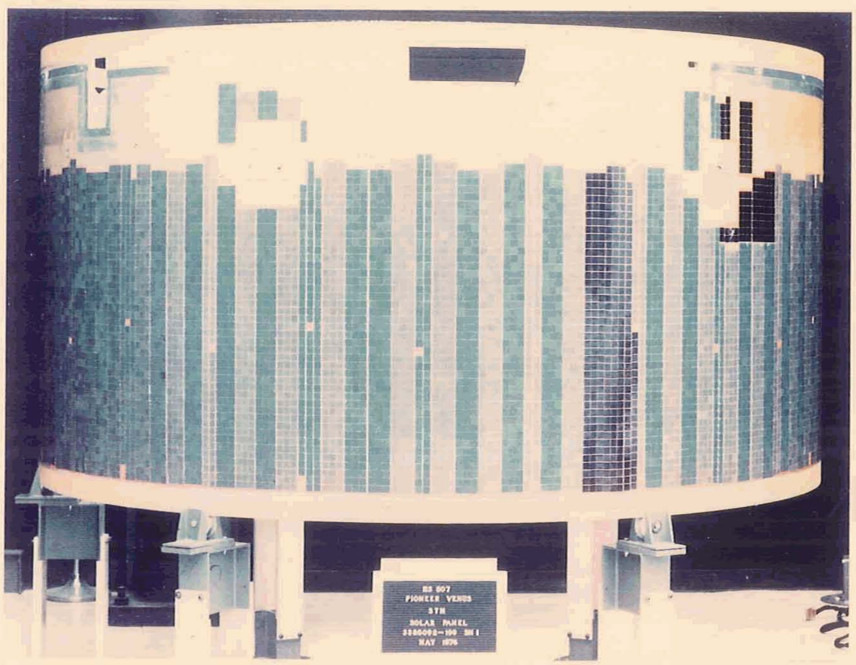


Figure 3-4. A cylindrical solar array forms the circumference of the Bus cylinder and provides electrical energy for the spacecraft and its payload of scientific instruments.

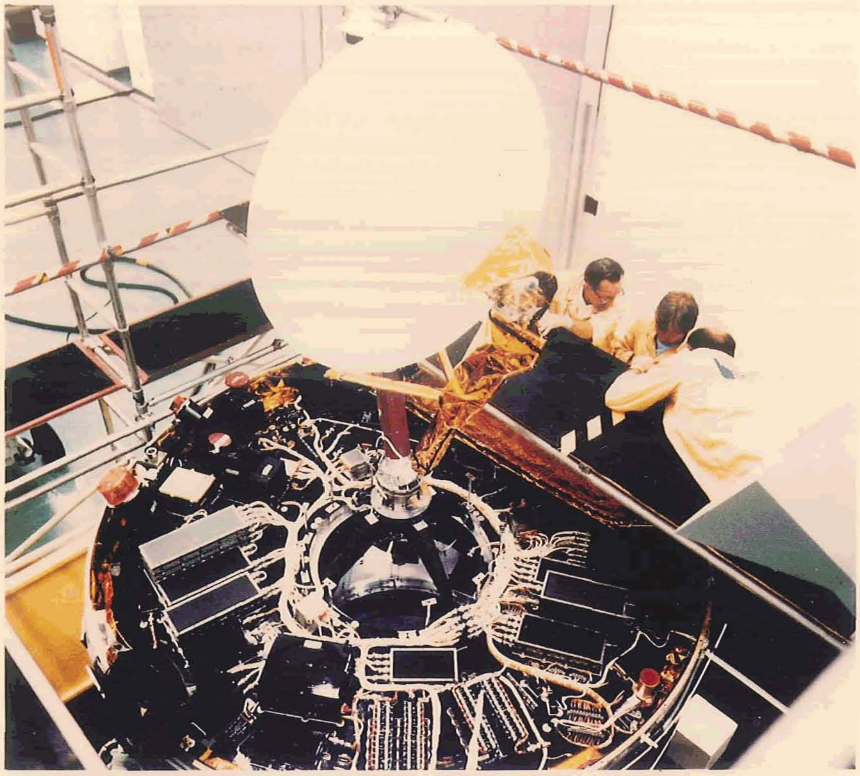


Figure 3-5. A high-gain parabolic dish antenna mounted on a mast can be despun relative to the spacecraft so that it can be pointed toward Earth.

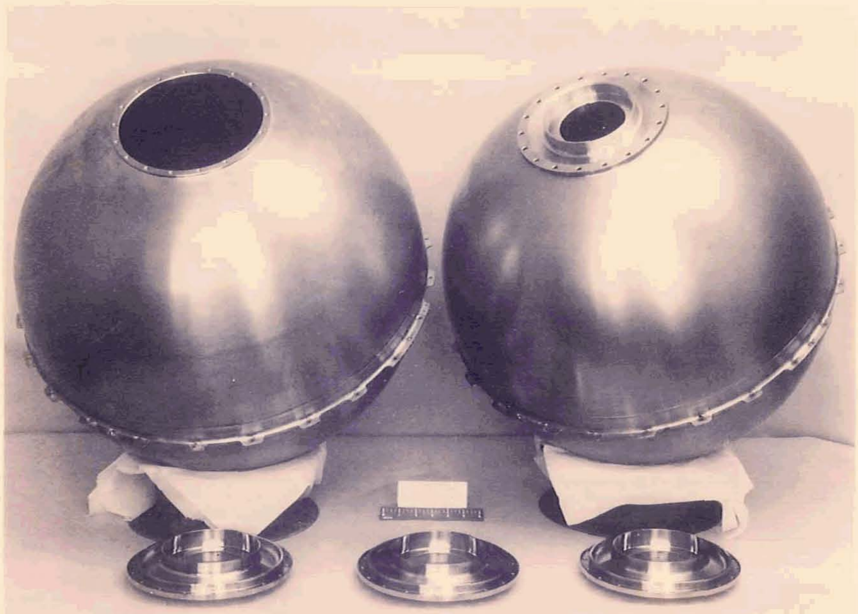


Figure 3-6. A solid propellant rocket motor provided thrust to place the Orbiter into an elliptical orbit around Venus. This orbit insertion motor was supplied by Thiokol Corporation. The picture shows the motor case and the nozzle closure of titanium alloy forgings. The case consisted of two 0.028-inch thick hemispheres joined by a single weld. The nozzle closure, which fastened to the case, was the structural element of the nozzle. Integral bosses allowed attachment of nozzle and igniter, and a scalloped flange was used to attach the motor to the spacecraft.

spin axis, only one thruster is fired in pulses at two points 180° apart in the rotation of the spacecraft. The top or bottom thruster is chosen for this purpose, depending on the direction required for the change in velocity.

A third thruster unit located at the bottom of the thrust cylinder permits continuous firing of two bottom thrusters which allows moves in an axial direction so that the orbit of the spacecraft can be changed.

The four radial thrusters are arranged in two pairs, pointing in opposite directions. They are mounted approximately in a plane perpendicular to the spin axis, a plane that passes through the center of gravity of the spacecraft. The radial thrusters are used to change the spacecraft's velocity in a direction perpendicular to the spin axis. The thrusters are also used to control the spin rate. They are mounted equidistantly around the periphery of the Bus cylinder. Firing two of them 180° apart slows the spin rate; firing the other two increases the spin rate.

A star sensor mounted on the shelf and Sun sensors provided attitude references to control the spacecraft. Each instrument has a slit field of view.

The mechanical features of the Orbiter spacecraft consist of six basic assemblies: the despun antenna assembly, the bearing and power transfer assembly and its support structure, the equipment shelf, the solar array, the orbit insertion motor and its case, and the thrust tube (see fig. 3-9).

The thermal design isolates the equipment from extremes of inputs of heat from solar radiation during the mission. At Venus, the intensity of radiation from the Sun is nearly twice that at Earth. The spacecraft contains electric heaters that can be commanded to turn on to keep critical elements of the spacecraft at the right temperature. Those elements that required temperature control early in the mission were the solid propellant rocket used to insert the spacecraft into orbit and the safeing and arming devices. Thoughout the mission, the

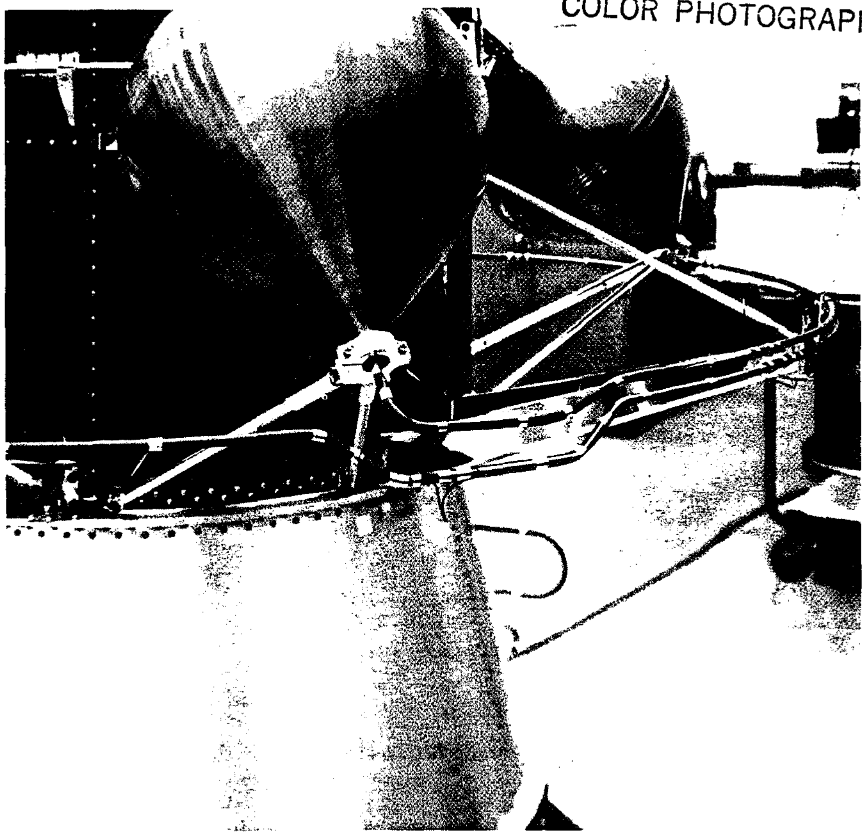


Figure 3-7. Hydrazine propellant for maneuvering thrusters is stored in two tanks within the spacecraft. Each tank, fabricated of titanium alloy, can hold 35 lb of hydrazine under pressure.

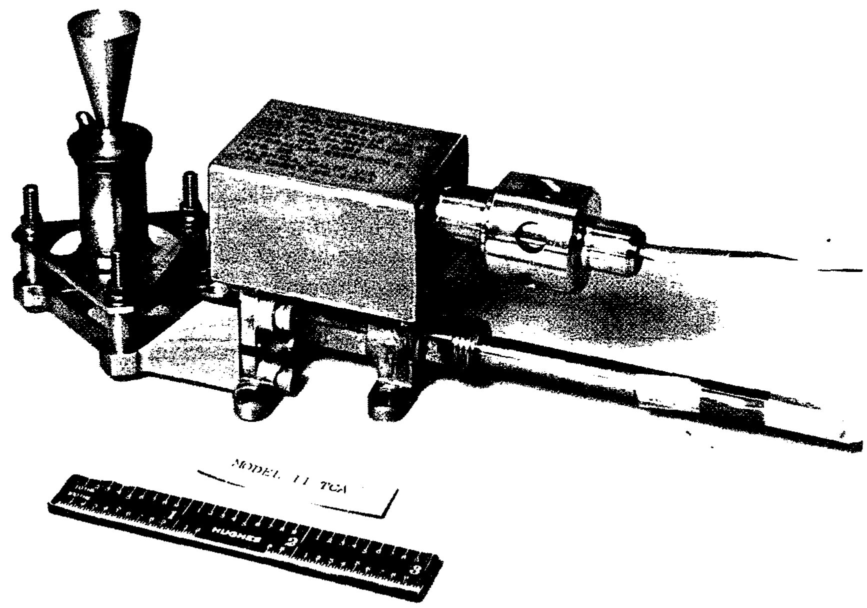


Figure 3-8. Small thrusters are used to control the orientation of the spacecraft and its spin rate. Thrusters are installed in two redundant groups and positioned on the spacecraft so that maneuvers may be commanded to change the spacecraft's velocity, spin rate, and attitude. This photograph shows a thruster assembly.

hydrazine propellant could not be allowed to freeze. There are other heaters that can raise the internal temperature of the spacecraft if for any reason it should fall because sufficient heat is not being developed by its equipment, that is, if a piece of equipment that develops heat during its operation should be turned off for an unexpectedly long period.

Data-Handling Subsystem

A data-handling subsystem (fig. 3-10) within the Orbiter conditions and integrates all analog and digital telemetry data into formats selected by radio command from Earth. Resulting information is routed to the communications subsystem for modulation of the downlink (spacecraft-to-Earth) S-band carrier. Twelve telemetry storage, playback, and real-time data rates between 8 and 2048 bits/sec are available. A rate of 1024 bits/sec was used during interplanetary cruise.

The data-handling subsystem includes a data memory consisting of two data storage units, each of which has a capacity of 524,288 bits, which is equivalent to 1024 minor frames of telemetry. It is intended primarily for use during an Earth occultation when the spacecraft is behind Venus and is not able to communicate with Earth. During this period, which can last for up to 26 min, the data memory can store just over 1 million bits of data. The memory capacity allows data to be taken and recorded during a 26-min occultation at an average maximum rate of 672 bits/sec, or for shorter occultation periods at higher bit rates. Data are stored or read out at the commanded bit rate. The on-board data storage can also be used if for any reason the Deep Space Network cannot receive data from the spacecraft.

The Orbiter data-handling system accepts information from spacecraft subsystems and the scientific experiments in serial digital, analog, and one-bit bilevel (on/off) form. It converts

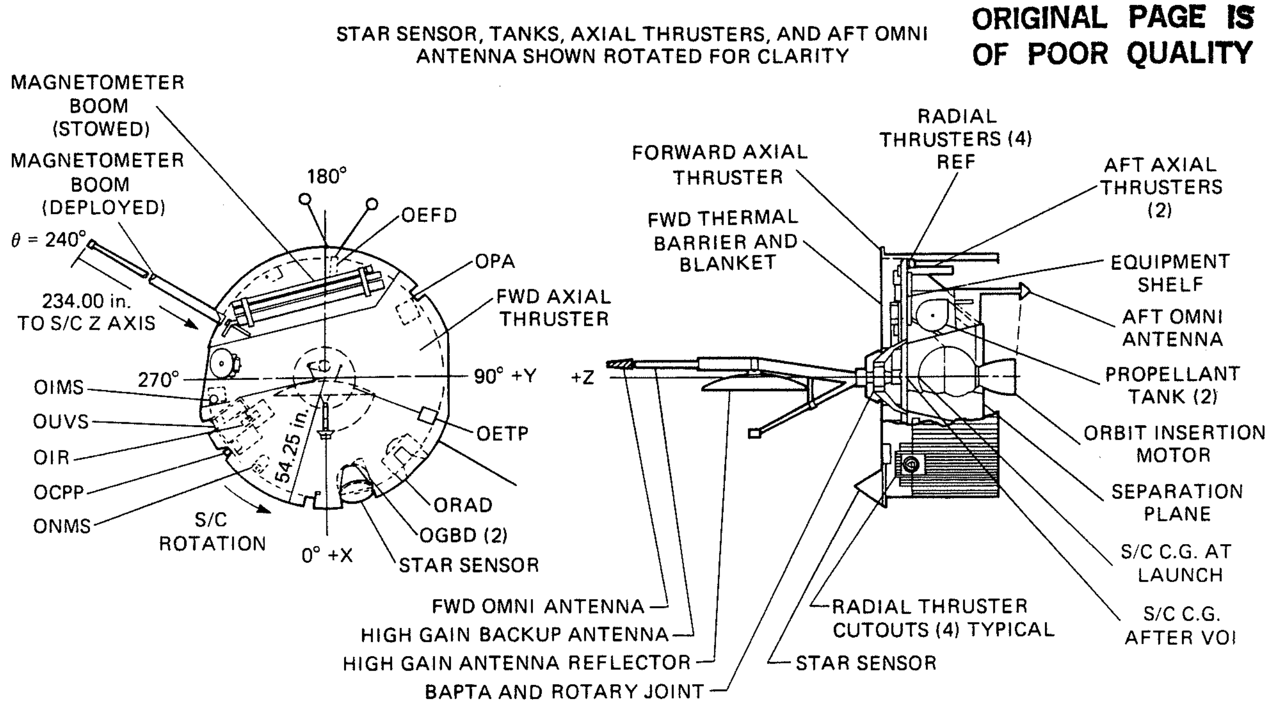


Figure 3-9. Principal elements of the spacecraft are identified on this cross section and side view of the Orbiter.

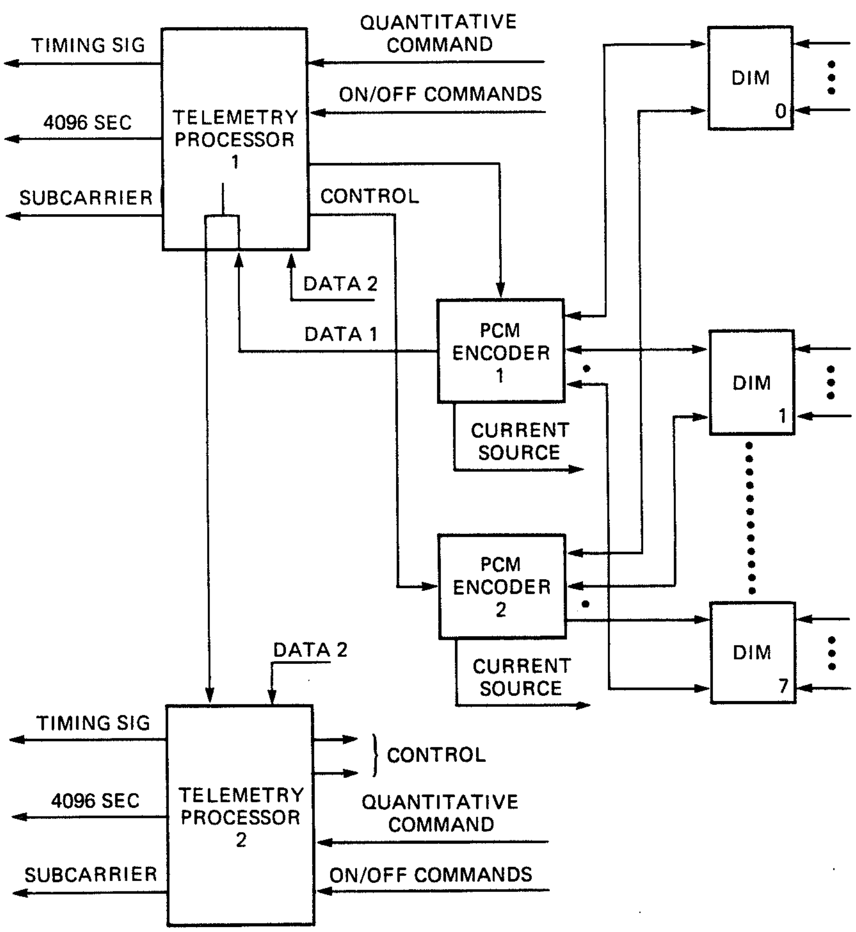


Figure 3-10. This block diagram shows the basis elements of the data handling subsystem common to the Orbiter and the Multiprobe.

analog and one-bit data to serial digital form and arranges all information in formats for transmission to Earth. This transmission consists of a continuous sequence of major telemetry frames, each composed of 64 minor frames. Each minor frame contains 64 eight-bit words, a total of 512 bits per minor frame. The words of a minor frame are arranged into 1 of 13 formats (see boxed inset) as selected by radio command from Earth. Each minor frame contains science and engineering data at the commanded bit-rate, subcommutated data, spacecraft ID data, and frame synchronization data. Three subcommutated data formats are assigned to each minor frame. One is for slowly changing science and science housekeeping data, and the other two are for slowly changing spacecraft engineering data.

The Orbiter has a total of 14 telemetry formats. Five formats, PERA, PERB, PERC, PERD, and PERE, are periapsis formats designed to allow changing the emphasis for part or all of a periapsis period. Two formats, APOA and APOB, are for measurements during apoapsis when the spacecraft is relatively distant from Venus.

The Launch-Cruise, LACR, format is designed to furnish a higher rate of engineering data while at the same time permitting measurements by those instruments capable of interplanetary type observations. The Playback, PBK, and the Data Memory Read Out, DMRO, formats permit reading out data stored in the Data Storage Unit, DSU; however, PBK reads with realtime scientific data, while DMRO exclude them. The Command Memory Read Out, CMRO, format permits a verification check of the command memory load. There is also an engineering format to furnish high rate engineering data for diagnostic purposes and an attitude control system format, ACS, to furnish high rate data from the ACS. The 14th format is on programmable by command to furnish high rate data of a few selectable parameters for diagnostic purposes.

The formats including realtime scientific data are summarized in figure 3.11.

Commands

The basic command system accepts a pulse-code-modulated, frequency-shift-keyed, phase-modulated (PCM/FSK/PM) data stream at 4 bits/sec – the incoming commands from Earth via the radio receivers. Such commands are received at a fixed rate of 4 bits/sec. Each command word consists of 48 bits, including 13 bits for synchronization, which results in a one-in-a-million probability of the spacecraft accepting a false command. The system has a total of 192 pulse commands and 12 magnitude commands. Command demodulators activate the system, convert the signal to a usable binary bit stream, and pass it to cross-connected command processors. Each command is either routed as received to the addressed destination within the spacecraft to be executed immediately or is stored for later execution. Each of the two command memories can store up the 128 commands or time delays. Each assigned command is either completely decoded by the command subsystem and an execution command generated, or is partially decoded to be finally decoded at its destination. Spacecraft units receive commands from redundant command output modules.

Antenna Systems

The Orbiter carries a despun, high-gain, parabolic antenna. At S-band, this antenna directs a 7.6° beam toward the Earth throughout the mission. The antenna dish is 109 cm (43 in.) in diameter and it concentrates the signal from the Orbiter 316 times by directing it into the narrow beam. During the mission the distance between Earth and Venus changed by 203 million km (126 million miles) and the high-gain antenna was designed to return data at high data rates over the greatest distance experienced during the mission.

PIONEER VENUS ORBITER FORMAT ASSIGNMENTS

PROJECT ACRONYMS	WORDS PER FRAME									BITS/FRAME
	PERA	PERB	PERC	PERD	PERE	LACR	PBK	APOA	APOB	SUB D
ORPA	5	3	3	–	–	1	–	–	2	42
OIMS	18	9	9	–	–	1	–	–	2	65
OETP	10	8	5	–	–	–	–	–	2	18
OUVS	11	7	7	–	18	7	1	–	1	41
ONMS	–	14	6	–	–	–	–	–	2	17
OCPP	–	8	–	8	–	–	–	43	–	33
OIR	–	–	4	47	4	–	–	–	–	41
OMAG	4	4	4	–	4	4	4	4	12	41
OPA	3	2	3	–	–	3	5	3	12	17
ORAD	–	–	10	–	28	–	–	–	1	54
OEFD	4	–	4	–	1	4	4	4	4	1
OGBD	–	–	–	–	–	1	1	1	17	82
SCIENCE SUBTOTAL	55	55	55	55	55	21	15	55	55	452
MRO	–	–	–	–	–	–	40	–	–	–
ENGINEERING	–	–	–	–	–	34	–	–	–	–
OVERHEAD	6	6	6	6	6	6	6	6	6	*60
SUBCOMS	3	3	3	3	3	3	3	3	3	–
TOTAL	64	64	64	64	64	64	64	64	64	512

*SPARE BITS

Figure 3-11. Assignment of data formats for the Orbiter are listed in this figure. PER refers to periapsis portion of the orbit, APO to apoapsis. PBK is for playback. The various scientific instruments are listed by their project acronyms given in table 2-3.

The high-gain antenna dish, a sleeve dipole antenna, and a forward omnidirectional antenna are all mounted on a mast which projects 2.9 m (9.8 ft) along the spin axis from the top of the basic cylinder of the spacecraft (fig. 3-12). The sleeve dipole radiates in a flat pattern perpendicular to the spin axis. It provides a backup if the dish antenna cannot be pointed toward Earth if the despin mechanism should fail.

Each of the two omnidirectional antennas – one on the antenna mast and the other aft of the spacecraft – radiates in a hemispherical pattern, thus providing low-gain radiation in all directions around the spacecraft. At any orientation, the spacecraft can receive commands from and communicate at low bit-rates with Earth.

The three antennas mounted on the mast are despun relative to the spinning spacecraft by one of two electric motors. The mast is attached to a flange of a bearing assembly which is mounted on the upper end of the Bus thrust tube. The three antennas are connected electrically to the transmitters in the spinning spacecraft by a series of transfer switches through a dual frequency rotary joint (fig. 3-13). These switches are commanded by pulse commands through slip rings and brushes on the bearing and power-transfer assembly that supports and rotates the mast relative to the spacecraft.

A control system provides redundant electronics to control the despin mechanism and to drive either one of the two electric motors. Motor torque commands are generated by despin control electronics based upon signals from the Sun and star sensors. The parabolic antenna can be pointed in elevation by a motor-driven jackscrew.

For radio experiments during occultation the Orbiter carries a 750 mW X-band transmitter. The signal frequency of this transmitter is maintained at 11/3 times that of the main S-band transmitter. Both X- and S-band signals are transmitted by the dish antenna. This antenna can be directed to point 15° from the Earth-line as the Orbiter passes behind Venus. As the radio waves pass through the atmosphere of Venus they are refracted toward Earth. Without repointing the antenna the radio signal would be refracted away from Earth, thus it allows the radio beam to dip deeply into the atmosphere of Venus and still reach Earth despite refraction by the Venusian atmosphere. Radio occultation data are thus obtained at atmosphere levels closer to the surface of the planet.

The X-band signal cannot be modulated and it is used solely so that atmospheric effects on radio signals at two different frequencies can be studied, thereby providing many more details of the characteristics of the planet's atmosphere.

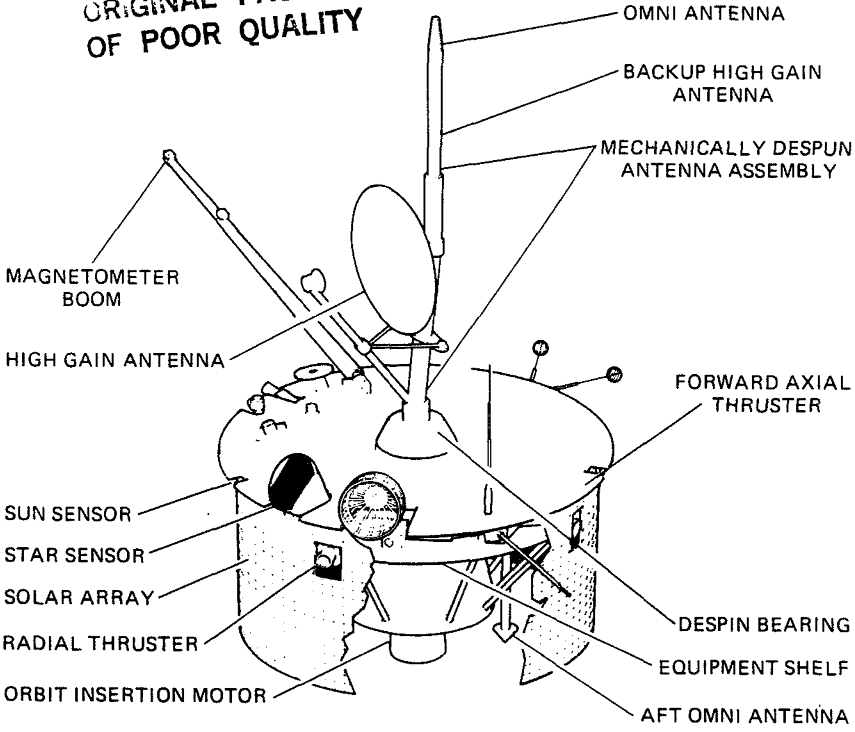


Figure 3-12. The antenna mast carried several antennas as well as the parabolic dish as identified on this diagram.

Communications from Earth

Commands from Earth can be received in any spacecraft orientation through two redundant S-band transponders connected to the omnidirectional antennas. Each transponder receives the radio signal from Earth and tunes the transmitter so that the frequency of the outgoing radio signals from the spacecraft bears a constant ratio to the frequency of the incoming signals. This coherent mode of transponder operation makes it possible to measure precisely the Doppler shift in the radio frequency arising from the motion of the spacecraft relative to the Earth both on the outgoing and incoming radio signals. Thus, it is possible to measure the velocity of the spacecraft to 3 m/hr.

The receiver portion of each transponder responds to only certain frequencies. If no command is received from Earth in a period of 36 hr, the receivers are automatically reversed. Thus, if one receiver should fail the other would automatically take over within 36 hr.

The uplink (Earth-to-spacecraft) command capability is maintained by modulating the S-band carrier of

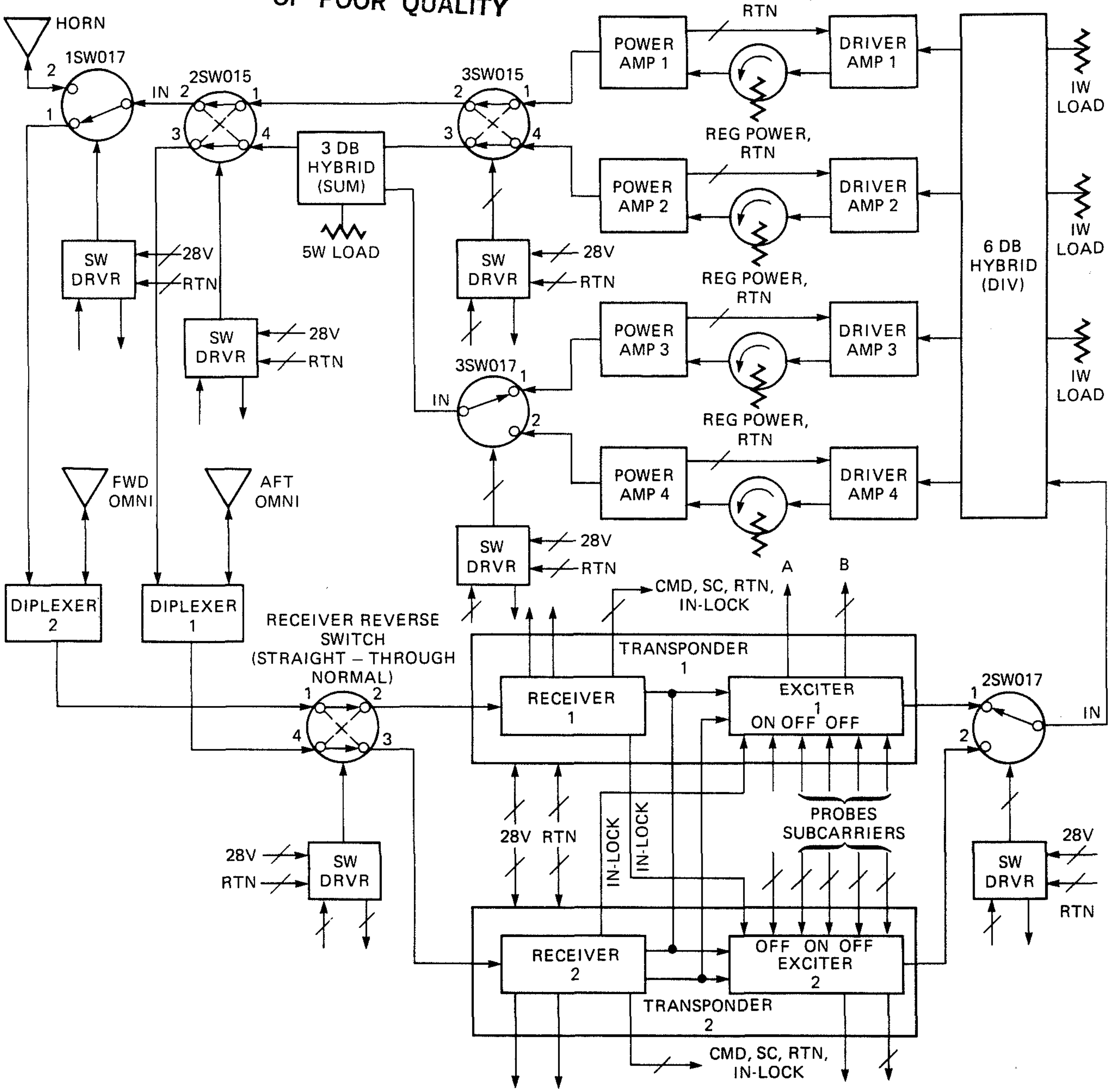
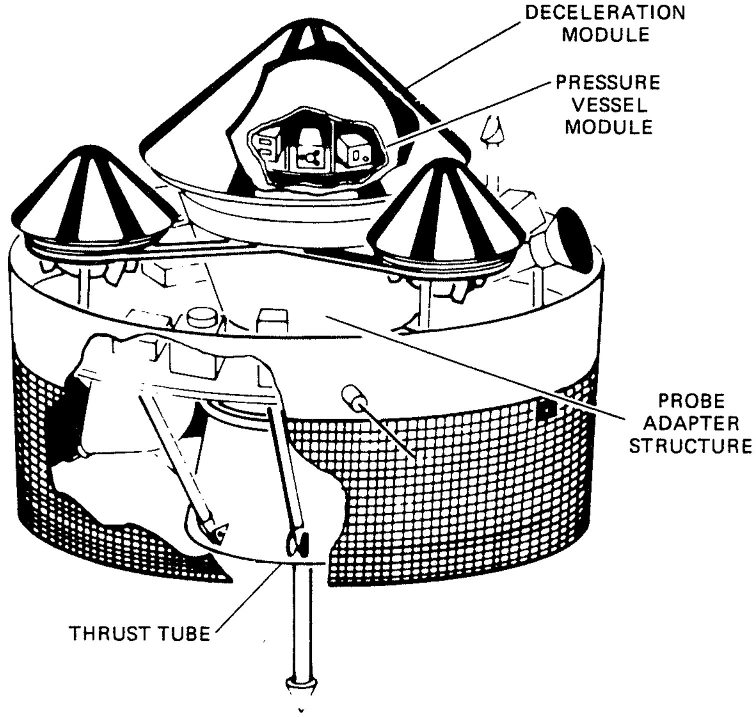


Figure 3-13. The communication system of the common Bus used for Orbiter and Multiprobe is diagrammed to show how the antennas can be connected to the redundant receivers and the transmitting power amplifiers.

approximately 2.115 GHz. The downlink telemetry modulates an S-band carrier of approximately 2.295 GHz.

Power

The power subsystem of the Orbiter spacecraft provides a semiregulated, 28 V direct current to all the electrical loads of the Orbiter, including its science instruments. The primary source of power is the solar array which has 7.4 m^2 (80 ft^2) of solar cells, each cell being 2 cm^2 (0.79 in.^{2}). At Earth's orbit the solar array provided 226 W, and at Venus, it is 312 W. When the output from the array is insufficient, such as during periods when the spacecraft is in the shadow of Venus or when the Sun is not shining directly enough on the solar array, two nickel-cadmium batteries come into operation automatically. This takes place when the bus voltage drops below 27.8 V. Each battery is rated at 7.5 A-hr. The batteries are recharged through a small solar array. Excess solar power over that required is dissipated by seven shunt limiters that keep the bus voltage at 30 V or below.

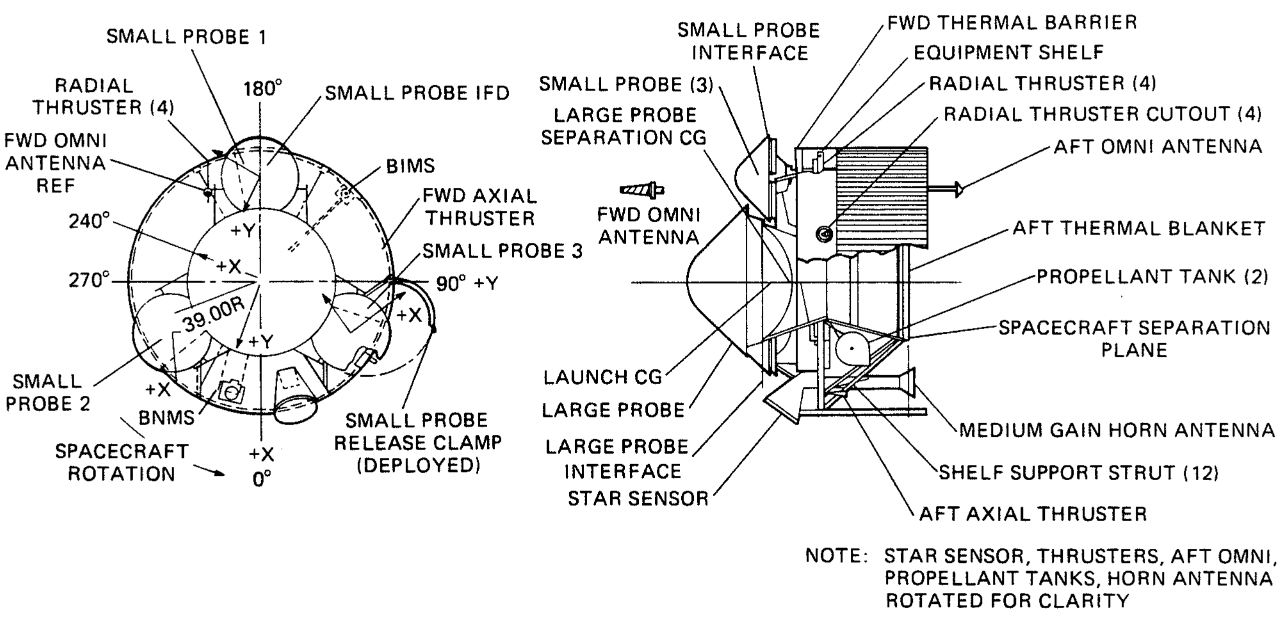


(a)

A power-interface unit switches power as needed by propulsion unit heaters and other heaters in the spacecraft. The unit contains protective fuses. Power is distributed through the spacecraft on four separate power buses. If more current starts to flow than is safe for the spacecraft, loads are removed to prevent a catastrophic failure. First, the scientific instruments are disconnected; then the switched loads such as control and data-handling units, and finally the transmitter are disconnected. Only those loads that are absolutely essential for the spacecraft to survive, such as the command units, heaters, receivers, and power conditioning units, are left in a continuous power-on mode.

Multiprobe Spacecraft

The Multiprobe (fig. 3-14) consisted of the basic Bus, like that of the Orbiter, a large probe, and three identical small probes. It did not carry a despun, high-gain antenna like that of the Orbiter. The weight of the Multiprobe was 875 kg (1930 lb), including



(b)

Figure 3-14. The Multiprobe spacecraft. (a) General view showing major parts. (b) Detailed cross section and side view giving dimensions.

32 kg (70 lb) of hydrazine for correcting the trajectory and orienting the spacecraft spin axis. The total weight of four probe spacecraft it carried was 585 kg (1289 lb). The Bus itself weighed 290 kg (641 lb).

The basic Bus design for the Multiprobe was similar to that used in the Orbiter and it made use of a number of common subsystem designs. Mechanically, the Bus consisted of five subassemblies: a support structure for the large probe, a support structure for the small probes, an equipment shelf, a solar array around the periphery of the cylindrical basic Bus, and a central thrust tube. The spacecraft diameter was 2.5 m (8.3 ft). From the bottom of the Bus to the tip of the large probe mounted on it the Multiprobe measured 2.9 m (9.5 ft).

During flight to Venus (fig. 3-15) the four probes were carried on a large inverted cone structure and three equally spaced circular clamps surrounding the cone. These attachment structures were bolted to the thrust tube of the Bus which formed the structural link to the launch vehicle. The large probe was centered on the spin axis of the Bus and was launched from the Bus toward Venus by a pyrotechnic-spring separation system. The ring support clamps that attached the small probes were hinged. To launch the small probes the Multiprobe was first spun up to 48 rpm and then the clamps were opened by the firing of explosive nuts which thereby allowed the probes to spin off from the Bus tangentially.

The forward omnidirectional antenna of the Multiprobe extended above the top of the Bus cylinder. An aft omni antenna extended below it. Both these antennas had hemispherical radiation patterns. A medium-gain horn antenna was attached to the instrument shelf and radiated aft of the spacecraft. It was used during critical maneuvers when the aft of the spacecraft pointed toward Earth at the time the probes separated from the Bus.

The instrument-equipment compartment, as in the Orbiter, carried the scientific experiments and electronics for the spacecraft subsystems. The solar array provided electrical power from solar radiation. It contained the batteries and a power distribution system, Sun and star sensors, propellant storage tanks, and thrusters for maneuvering and stabilization. The Bus also carried radio transmitters and receivers, data processors and a command and data handling system.

The thermal design was essentially the same as that of the Orbiter. In addition, however, the Bus required protective surfaces in the vicinity of the small probes to keep them at the required temperature during the cruise and to protect the Bus itself from heating after the probes had separated from it.

Except for not having to position a high-gain antenna as on the Orbiter, orientation controls for the Multiprobe were the same as those for the Orbiter. The propulsion system was identical to that of the Orbiter except the Multiprobe only had one aft axial thruster. The Multiprobe did not, of course, carry a retrorocket.

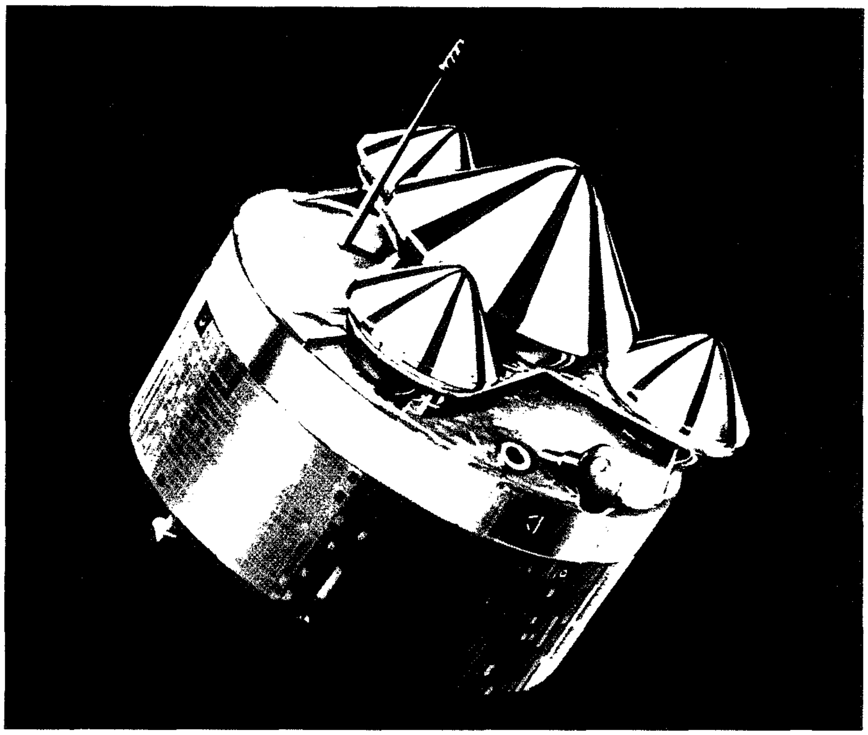


Figure 3-15. During flight to Venus the four probes were carried on the Multiprobe Bus in the configuration shown.

Data Handling System

The data handling system for the Multiprobe was virtually identical to that of the Orbiter except it had no data memory. Data formats were organized to meet the special requirements of the Multiprobe mission. Before separation of the probes from the Bus, the Multiprobe handled data for the Bus and all probes. After separation, the probes used their own data systems which are described later.

The data system of the Multiprobe accepted engineering and selected information required for mission operations information from the four probes as well as data from the Multiprobe Bus itself and from the experiment carried on the Multiprobe Bus. It converted analog data to serial digital binary form and arranged all the information for transmission to Earth. Each telemetry major frame contained 64 minor frames composed of 64 eight-bit words. These words were arranged in several formats. Each minor frame contained high-rate science or engineering data, plus subcommutated data, spacecraft data, and

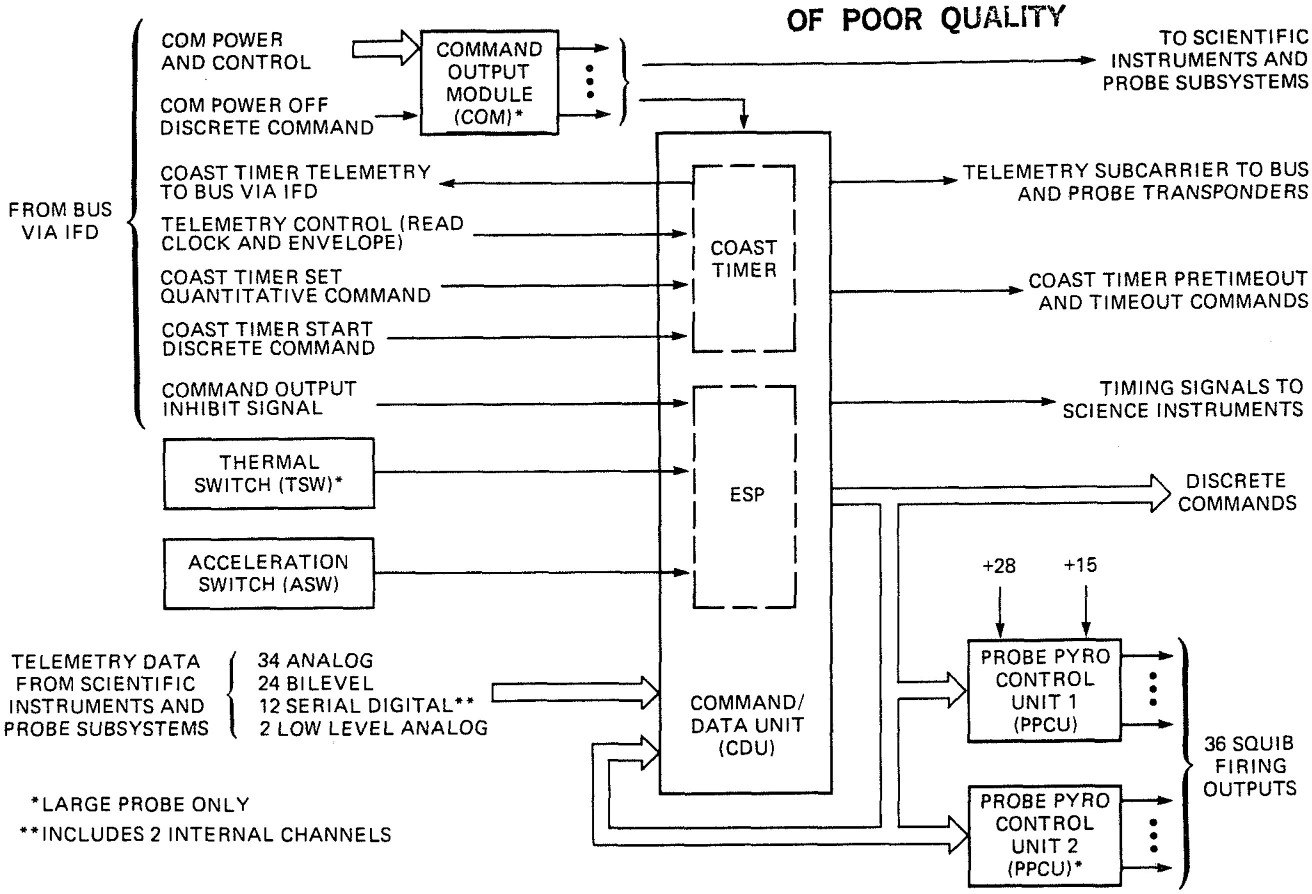


Figure 3-16. The command data subsystem for the Multiprobe spacecraft is outlined in this block diagram.

frame synchronization data. One subcommutated format carried low bit-rate science and science housekeeping data; two were for low bit-rate information from the spacecraft subsystems. Twelve real-time data transmission rates between 8 and 2048 bits/sec were used. Like the Orbiter, the Multiprobe also had high bit-rate formats for attitude control during maneuvers, for engineering data, and for reading out the contents of the command memory. A single format for use during entry into the Venus atmosphere transmitted science data at 1024 bits/sec.

Commands, Communications, and Power

The command subsystem and communications subsystem were similar to those of the Orbiter. The command subsystem decoded all commands received via the communications subsystem of the Multiprobe at a fixed rate of 4 bits/sec. These commands were either stored for later execution, or routed as they reached their destination within the spacecraft and the probes where they were implemented. The communications subsystem provided reception and transmission for radio communications from and to Earth (fig. 3-16).

Also, the power system for the Multiprobe was essentially the same as that for the Orbiter spacecraft. There was, however, a power interface unit that allowed power to be sent to the probe heaters and the probe checkout buses, and for relay drivers for each of the probes. Thereby, the probes could be powered from the Bus without depleting their own batteries during the interplanetary cruise to the vicinity of Venus. The solar array of the Multiprobe, consisting of 6.9 m^2 (74 ft^2) of 2 X 2 cm cells, provided 214 W near Earth and 241 W at Venus.

The Probes

The high pressure in the lower regions of the atmosphere of Venus – about 100 times that of Earth's atmospheric pressure at sea level – the high temperature of about 480°C (900°F) at the surface, and the corrosive constituents of the atmosphere, such as sulfuric acid, presented a tremendous challenge to the designers of the probes. Moreover, these probes had to enter the atmosphere at a speed of about 41,600 km/hr (26,000 mph) or 43 times the speed of a typical commercial jet.

The large and small probes were similar in shape. The main component of each probe was a spherical pressure vessel, machined from titanium and sealed against the vacuum of space and the high pressure within the atmosphere of Venus. Within this pressure vessel were housed the scientific instruments and the various subsystems needed to operate the probe.

Each spherical pressure vessel was housed within an outer structure consisting of a conical aeroshell and an aft shield. The aeroshell, shaped as a 45° cone with a hemispherical blunt tip, was a one-piece aluminum structure with integrally machined stiffening rings. The heat shield of the aeroshell protected the probe from the heat generated as it entered the atmosphere at high speed. The aeroshell also acted aerodynamically to keep the probe stable on its flight into the atmosphere. The aft cover of fiberglass honeycomb had a Teflon flat section transparent to radio waves. It protected the aft hemisphere of the pressure vessel during entry into the Venusian atmosphere. Spin vanes kept the probes spinning during descent to maintain stability.

All instruments within the pressure vessels of the probes required either observations or direct sampling of the hostile atmosphere of Venus. Providing such access was a major design problem. The large probe had to have 14 sealed penetrations through the walls of its pressure vessel: one for the antenna, four for electrical cables, two for access hatches, and seven for scientific instruments. Each small probe required seven such penetrations: one for the antenna, three for electrical cables, one for an access hatch, and two for scientific instruments. Special windows of diamond and sapphire were used to admit light or heat at wavelengths required for several of the science experiments.

The Large Probe

The large probe (fig. 3-17) weighed about 315 kg (695 lb) and was about 1.5 m (5 ft) in diameter. It consisted of a forward aeroshell heat shield, a pressure vessel, and an aft cover.

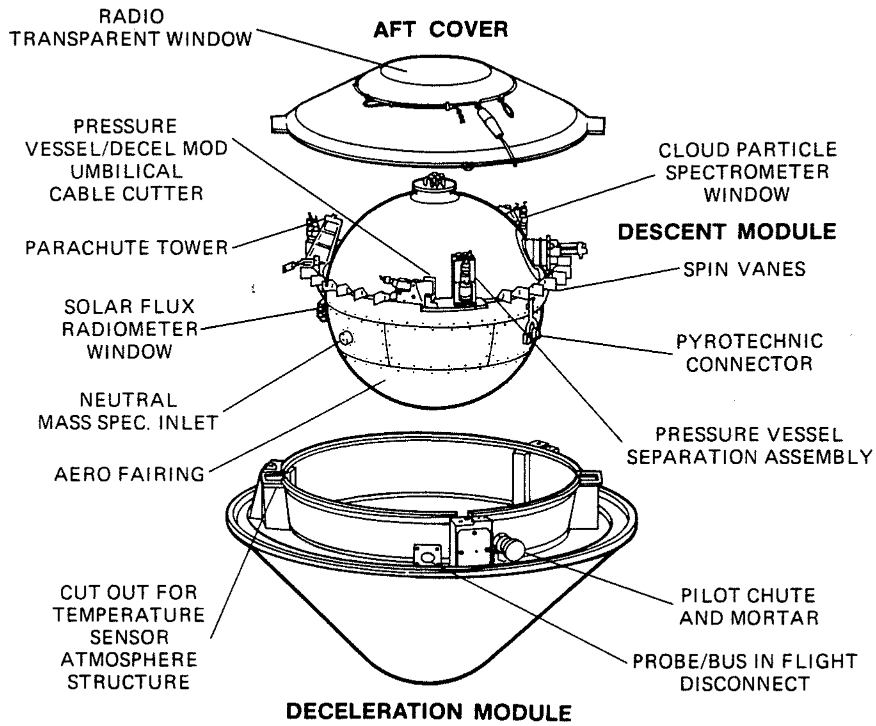


Figure 3-17. The Large Probe is detailed in this drawing which identifies the pressure vessel, the protective nose cone and the aft shield.

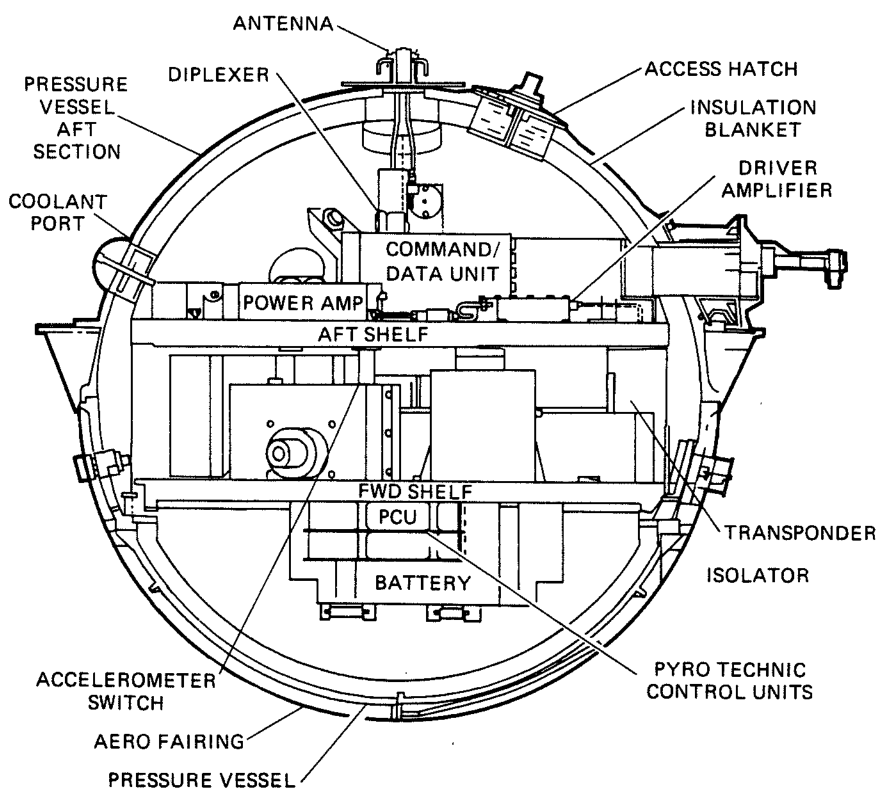


Figure 3-18. The pressure vessel for the Large Probe and the arrangements of scientific instruments and spacecraft components within it.

Precisely machined from titanium to achieve high strength at high temperatures and still be lightweight, the pressure vessel (fig. 3-18) was 73.2 cm (28.8 in.) in diameter. It was made in three flanged pieces – an aft hemisphere, a flat ring section, and a forward cap. These were bolted together with seals between the flanges. The seals were a combination of O-rings to prevent leakage of the 102 kPa (15 psia) nitrogen atmosphere of the probe during transit to Venus, and graphoil flat gaskets to prevent inward leakage of the hot atmosphere of Venus during descent to the surface. A pressure bottle was mounted on the forward shelf of the large probe. The bottle was fired by a stored command to increase the probe internal pressure by 41 kPa (6 psi). Inside the pressure vessel two parallel shelves made of beryllium served as supports and as heat absorbers for the instruments and spacecraft systems mounted on them. Equipment inside the pressure shell was further protected from the heat encountered at Venus by a 2.5-cm (1-in.) thick blanket of multilayered Kapton that completely lined the interior.

Four scientific instruments used nine observation windows through four of the pressure vessel penetrations mentioned earlier. Eight windows were of sapphire and one of diamond. All scientific instruments are described in the next chapter. Three vessel penetrations were inlets for direct atmospheric sampling by a mass spectrometer, a gas chromatograph, and an atmospheric structure experiment. At the aft pole of the pressure vessel was an antenna with a hemispherical radiation pattern. This provided communications with Earth when the probe had separated from its Bus. Extending 10 cm (4 in.) on one side of the pressure vessel, two arms held a reflecting prism used in the cloud particle observations. On the opposite side of the pressure vessel a single arm carried a temperature sensor on its tip.

Three parachute-shroud towers were mounted above aerodynamic drag plates that were spaced equidis-

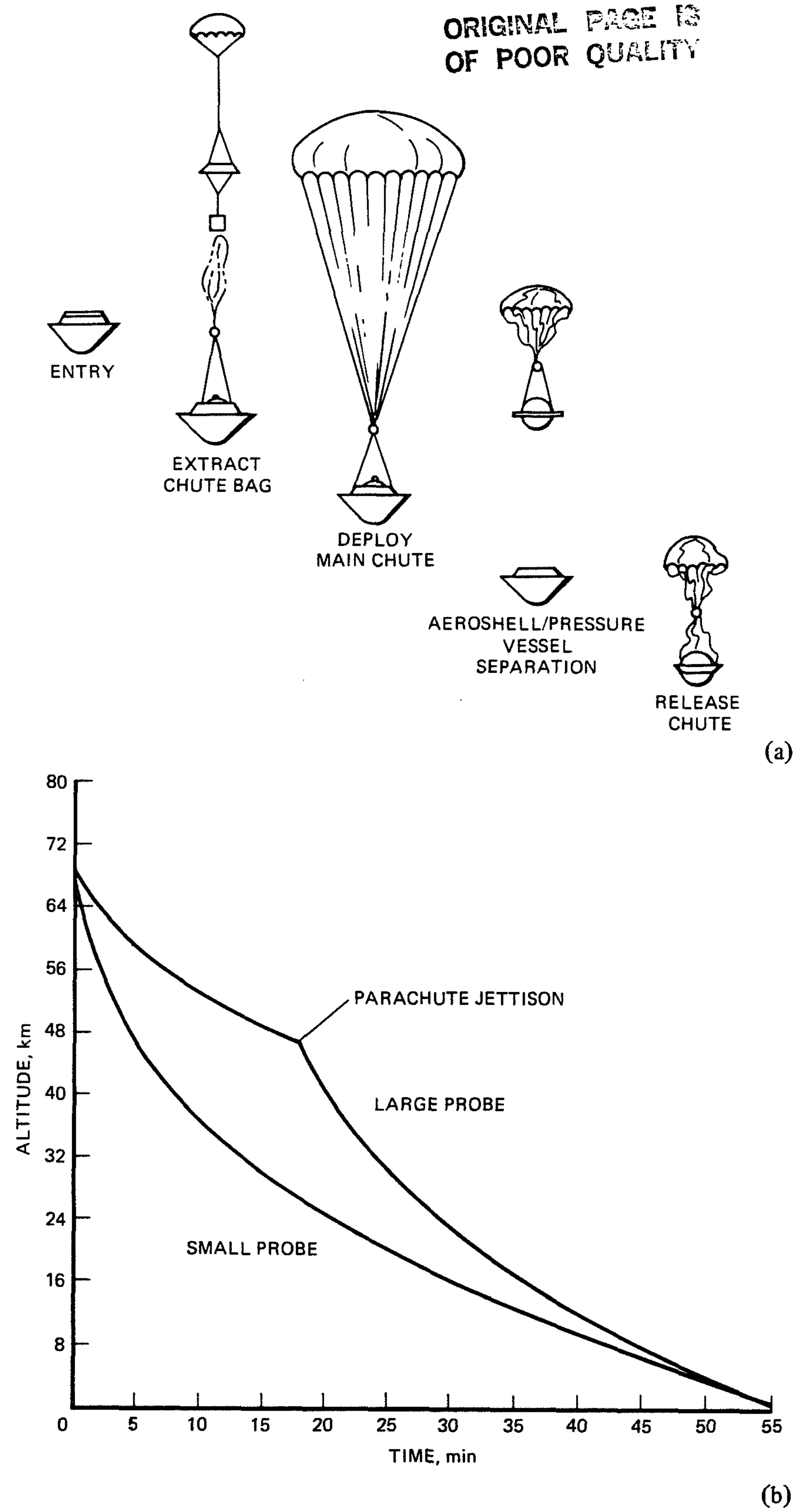
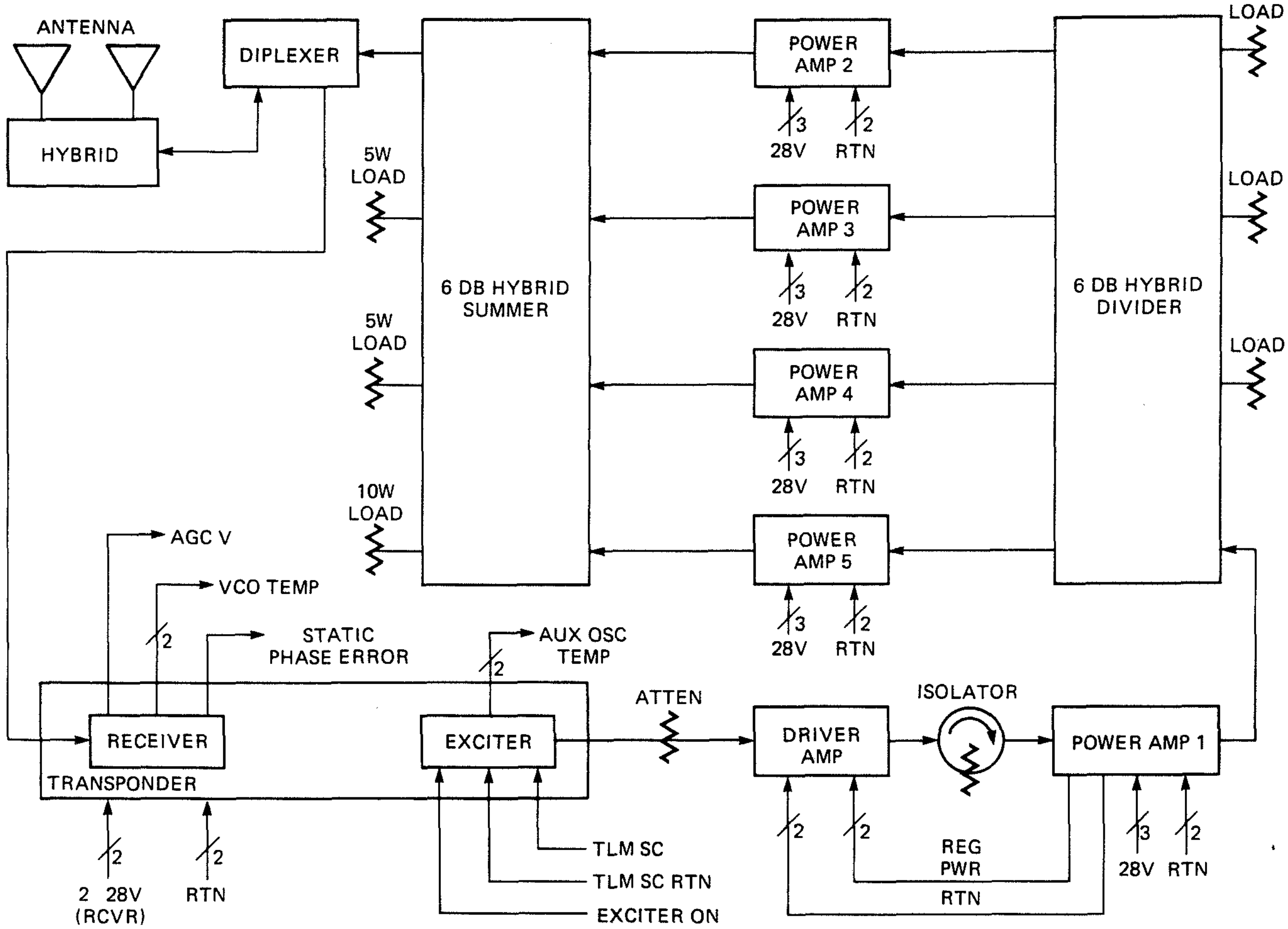


Figure 3-19. (a) The sequence of release of the parachute is depicted in this series of drawings. (b) Altitude plotted against time for the Large Probe is compared with that for each of the Small Probes. Both Large and Small Probes take about the same time to reach the surface of Venus.



NOTES:

1. $\not{}_{n}$ DENOTES (n) INTERCONNECTING LINES SHOWN AS SINGLE LINE GROUP
2. 28V (RCVR) IS SEPARATELY SWITCHED ON BY POWER INTERFACE UNIT FOR RECEIVER ON
3. ALL OTHER 28V LINES ARE SWITCHED ON TOGETHER BY POWER INTERFACE UNIT FOR RF ON

Figure 3-20. Components of the communication subsystem of the Large Probe are identified in this block diagram.

tantly around the equator of the spherical vessel. Of two access ports, one was used for electronic checkout of the system before launch. The other provided a cooling port also used during ground tests.

During entry at high speed into the atmosphere of Venus the large probe was protected from overheating by an ablative heat shield of carbon phenolic which was bonded to and covered the outer surface of the forward-facing aeroshell. All other surfaces of the aeroshell and the aft cover were coated with a heat-resisting, low-density, elastomeric material.

The large probe was designed to execute a predetermined sequence of operations when it reached Venus. Communications with Earth started 22 min before entry into Venus' atmosphere. A peak deceleration of 280 g occurred soon after entry, the aft cover was jettisoned and a parachute deployed. A pilot chute was mortar-fired from a small compartment in the side of the aeroshell. This parachute was attached by lines to the aft cover which was separated by an explosive bolt so that it could then be pulled free. The cover, in turn, was attached to the main parachute. The pilot chute then pulled the main chute from its compartment within the conical aeroshell. As soon as stability was obtained, mechanical and electrical ties to the aeroshell were severed by explosive nuts or by cable cutters, and the main chute then pulled the pressure vessel free from the aeroshell (fig. 3-19).

The heat shield was jettisoned about 67 km (42 miles) above the surface. About 47 km (30 miles) above the surface the parachute was released and the probe fell freely so that it reached the surface about 55 min after first entering the atmosphere. Spin vanes around the pressure vessel spun it at less than 1 rpm during its descent. Stability was maintained by a forward-facing aerofairing, a conical skirt, and sectional drag plates.

The communications subsystem of the large probe (fig. 3-20) had a solid state transmitter to return a stream of data directly to Earth at 256 bits/sec.

Four 10-W amplifiers provided a transmitter power of 40 W. A transponder received an S-band carrier from Earth at 2.1 GHz and set the probe's transmitter to send at 2.3 GHz via the crossed dipole antenna located on the aft hemisphere. The transponder receiver was used for two-way Doppler tracking only. The incoming signal carried no information and the large probe did not receive commands from Earth.

Power for the probe was provided by a 40 A-hr silver-zinc battery, the output from which was maintained at 28 V direct current during the descent. The power system consisted of the battery, a power interface unit, and a current sensor. Before the probe separated from the Bus it received power from the Bus for checking and heating the probe during transit to Venus. During this time the internal battery was open-circuited by switches in the probe's power interface unit.

Once the large probe had separated from the Bus, its internal electronics provided all commands needed to operate it. The command subsystem consisted of a command unit, a pyrotechnic control unit, and sensors to service the command unit, such as measurements of the deceleration being experienced by the probe. The internal command subsystem provided 64 separate commands for the spacecraft itself and for its payload of scientific instruments. It contained a coast timer which was the only part of the spacecraft to operate during the period from separation from the Bus to entry into the atmosphere of Venus. During this period all other subsystems within the probe were shut off. There was also an entry sequence programmer and a command decoder. The entry sequence programmer was preprogrammed to transmit 53 discrete commands in a fixed sequence. Commands were initiated by the coast timer or by an acceleration switch that sensed the deceleration of entry. A temperature switch provided a backup for the timer when the parachute was jettisoned.

The pyrotechnic control unit was made up of 12 squib drivers that provided current to fire explosive nuts for the aeroshell to be separated, the aft cover to be jettisoned, and the parachute deployed. There were also actuators for the cable cutter, the pilot chute mortar, and for releasing the protective cover of the mass spectrometer inlet port.

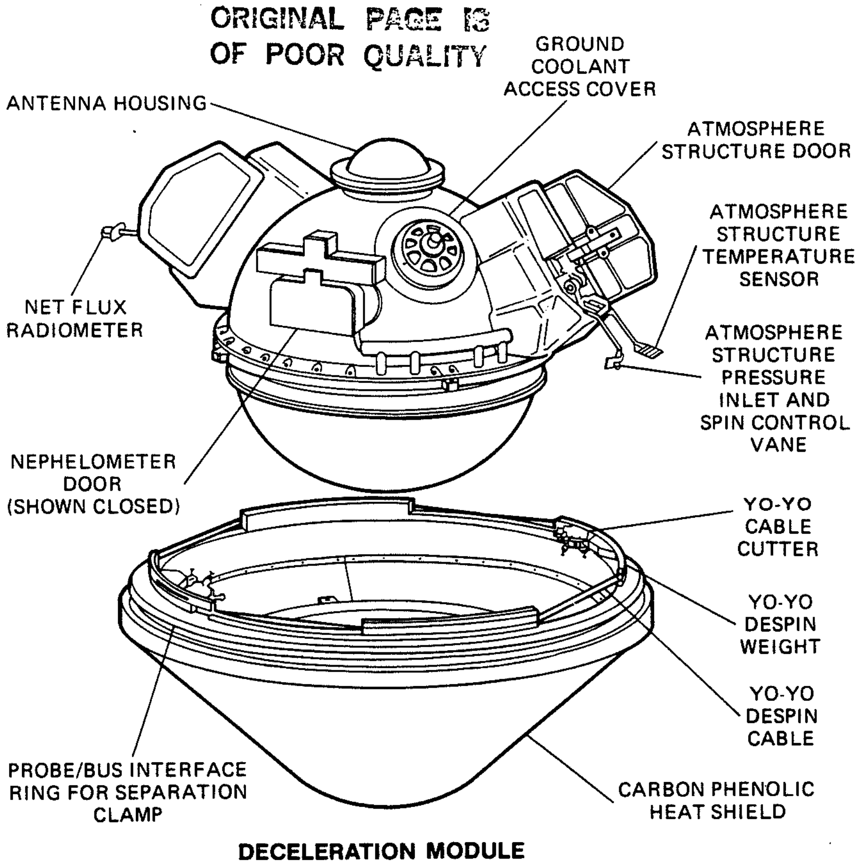


Figure 3-21. The three Small Probes, one of which is shown in this diagram, were identical.

Data Handling Subsystem

The data subsystem of the large probe handled 36 analog, 12 serial digital, and 24 bilevel (on/off) status channels from scientific instruments and from the subsystems within the probe. The unit converted all data into major telemetry frames consisting of 16 minor frames for time-multiplexed transmission to Earth. Each minor frame consisted of a series of 64 eight-bit words for a total of 512 data bits per minor frame.

The data handling subsystem provided two data formats: one for use during radio blackout by the plasma sheath during entry, and the other to be used during normal descent after the probe slowed down. There was a solid-state memory with a storage capacity of 3072 bits so that data gathered during communications blackout could be stored and transmitted afterwards. Data were stored in the memory at 128 bits/sec but were read out afterwards at a rate of 256 bits/sec, the normal bit-rate for transmission of data to Earth during the descent. (For 5 min before entry to 30 sec after entry the transmission bit-rate was only 128 bits/sec.) The full bit-rate was allocated among the experiments at 16 to 44 bits/sec for each of seven experiments. The nephelometer and atmospheric structure experiments were, however, able to use the blackout storage format of 4 and 72 bits/sec, respectively. Two subcommutated formats for low bit-rate phenomena also provided housekeeping data, and additional data for the atmospheric structure, nephelometer, cloud particle spectrometer, and solar flux radiometer experiments.

The Small Probes

The three small probes (fig. 3-21) were identical. In contrast to the large probe they did not carry a parachute; they were slowed down only by aerodynamic braking. But like the large probe, each small probe consisted of a forward heat shield, a pressure vessel, and an afterbody. The heat shield and the afterbody remained attached to the pressure vessel all the way to the surface. Each probe was 0.8 m (30 in.) in diameter and weighed 90 kg (200 lb).

The pressure vessel (fig. 3-22), precisely machined from titanium in two flanged hemispheres that were joined by bolts with seals between the flanges, nested within the aeroshell and was permanently attached to it. The seals were of two types as with the large probe: O-rings to maintain internal pressure during the journey through the vacuum of interplanetary space, and graphoil flat gaskets to prevent the hot atmosphere of Venus from leaking in. The afterbody was also permanently attached to the pressure vessel, its shape closely matching that of the pressure vessel. The interior of each small probe was filled with xenon at a pressure of approximately 102 kPa (15 psia). This was used instead of nitrogen (as used in the large probe) to reduce the flow of heat from the pressure vessel walls to the instruments and the probe spacecraft systems. This flow was further impeded, as in the large probe, by a protective blanket lining of Kapton. Instruments and spacecraft subsystems were mounted on two beryllium shelves that absorbed heat.

The aeroshell had the same basic 45° blunt cone design as that for the large probe, and it used a bonded carbon phenolic ablative coating as a heat shield. Because it had to protect the pressure shell all the way to the surface, the aeroshell was fabricated of titanium, as contrasted with the aluminum aeroshell of the large probe. It used a stressed skin or monocoque construction.

The sequence of entry of the small probes started with communications being initiated 22 min before entry. About 5 min before entry two weights were cut loose by a pyrotechnic cable cutter allowing them to swing out like yo-yo's on 2.4-m (8-ft) cables. As a result, the spin rate of each probe was reduced from about 48 rpm to 17 rpm. The weights and cables were then jettisoned. This reduction in spin rate allowed aerodynamic forces to line up the probes so that their heat shields could protect them from the heating of entry. All probes entered the atmosphere at a speed of about 42,000 km/hr (26,000 mph). The probe making the steepest entry underwent a peak deceleration of 458 g, the others somewhat less. The probe making the shallowest entry decelerated the least at about 223 g. Three doors on the afterbody then opened at an altitude of about 70 km (44 miles) to provide access to the atmosphere by three instruments. Two of the doors opened from each of two protective housings – one for the atmospheric structure experiment and the other for the net flux radiometer experiment. The housings projected like ears from each side of the sphere of the pressure vessel. The temperature sensor and atmospheric pressure inlet for the atmospheric structure instrument extended 10 cm (4 in.) from the door of one housing, and the net flux radiometer sensor extended similarly on the opposite side.

When the doors of the housings opened after atmospheric entry they were retained rather than jettisoned and they served to slow the spin rate of the spacecraft. However, a small vane attached to the pressure sensor inlet kept the spacecraft spinning throughout its descent so that the instruments could scan around the probe. A cover over the nephelometer folded down after it opened. Each small probe fell freely for about 53 to

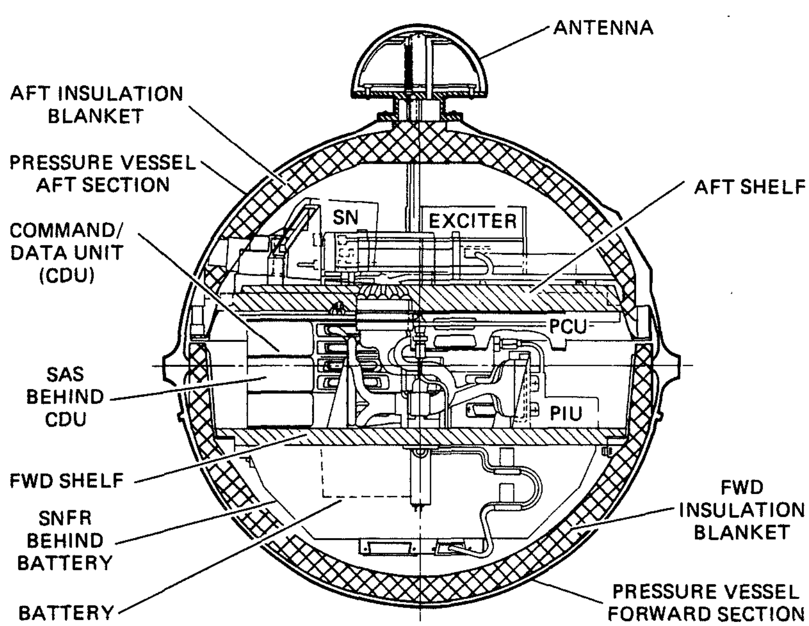


Figure 3-22. Scientific instruments and spacecraft systems of each Small Probe were carried within a titanium pressure vessel as with the Large Probe.

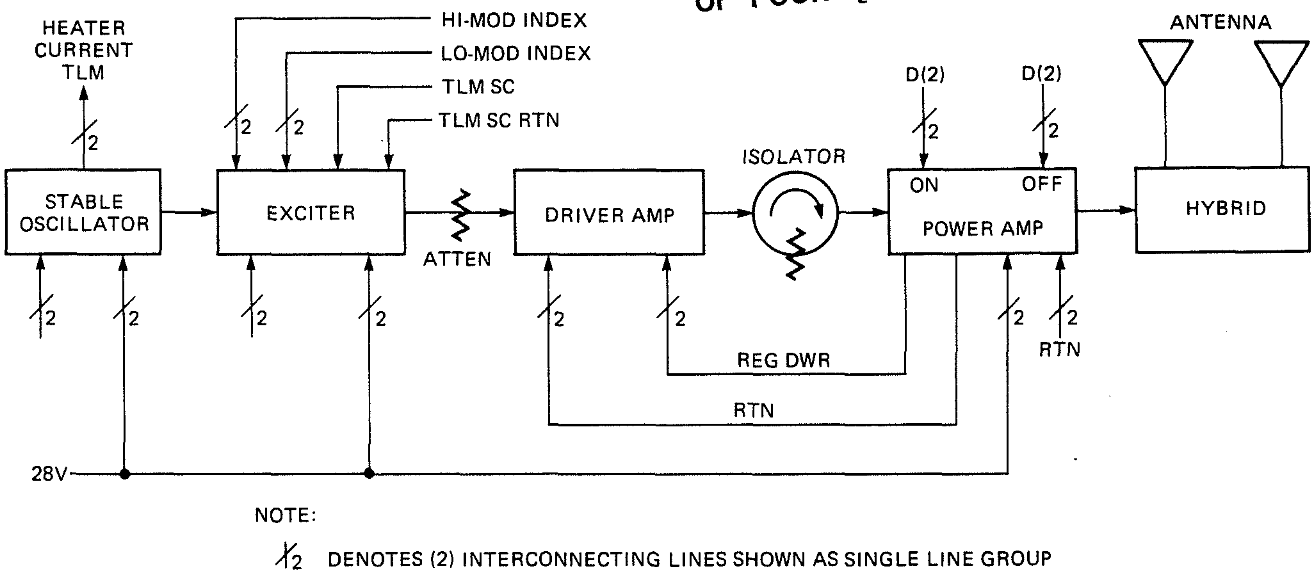


Figure 3-23. Components of the communication subsystem of each Small Probe are identified in this block diagram. The subsystem has only one power amplifier compared with the four of the Large Probe, and it does not have a receiver.

55 min until it reached the surface of Venus.

Communications for each small probe (fig. 3-23) consisted of a solid state transmitter and a hemispherical-coverage antenna, as for the large probe. This antenna was mounted at the aft pole of the pressure vessel sphere and radiated through a teflon window. Each transmitter had one 10-W amplifier, that is, one-quarter the power of the transmitter of the large probe. Data could be received by the large 64-m (210-ft) antennas of the Deep Space Network at a rate of 64 bits/sec until the probes penetrated to about 30 km (19 miles) above the surface of Venus. From there on the data could be received at 16 bits/sec only. The small probes did not carry a receiver for two-way Doppler tracking. Instead tracking was achieved by use of a stable oscillator carried by each probe. This provided the reference frequency for the Doppler measurements used in the ground computations.

Each probe carried an 11 A-hr, silver-zinc battery. This provided 28 V direct current during the descent. As with the large probe, the power system had a power interface unit and a current sensor.

The command subsystem was identical to that on the large probe. No uplink (Earth-to-probe) command capability existed. After separation, all probe commands originated from their respective coast timers, programmers, and acceleration switches. Control was maintained by the coast timer. It started the entry sequence programmer which was preprogrammed to transmit 41 commands in a fixed sequence from the start of the programmer until impact of each probe with the surface of Venus.

Components of the data handling subsystem on each small probe were the same as those on the large probe. Three major data formats were used (upper descent, blackout, and lower descent), each containing 16 minor frames of 64 eight-bit words. As on the large probe, a 3072 bit solid-state memory was used to store data during the short period when communications with Earth were blacked out by the plasma sheath generated on entry. These data were transmitted later when the probes had slowed down and the plasma sheath had dissipated.

4
Scientific Investigations

Haec immatura a me jam frustra leguntur; O.Y.

GALILEO'S MESSAGE in 1610 reported his first scientific observation of Venus, an observation that broke centuries of man's failure to see what in retrospect is quite obvious: Earth is not the center of the Universe. When rearranged and translated into English, Galileo's message said:

> *The mother of the loves emulates the phases of Cynthia.*

that is, Venus exhibits phases like the Moon.

In the centuries that followed Galileo's observation, many more discoveries were made about the cloud-shrouded planet. And there were equally as many speculations about the true nature of the planet, ranging from its being a dust-ridden world, a world of swamps, or one of seas of hydrocarbons. Many of the earlier speculative theories had been disproved by observations made from Earth, using highly sophisticated new instruments and techniques of data reduction, and by data obtained from several flybys of Venus and the landing of some Russian probes on the surface. There were still many unknowns about Earth's sister planet. The six Pioneer Venus spacecraft with their advanced scientific instruments provided a new opportunity to revise our notions about Venus as drastically as the observations of Galileo changed the opinions of many of his contemporaries. For the first time, scientists were able to look through the thick cloud layers on a global basis, sample the constituents of the dense Venusian atmosphere, and make long-term observations of changes within that atmosphere and of its ultraviolet cloud markings for several planetary revolutions around the Sun. The resulting new viewpoints will undoubtedly influence comparative planetologists and other scientists as they work to refine theories that attempt to explain the evolution of the Solar System and its planets.

The scientific payloads of the Pioneer Venus Orbiter and Multiprobe spacecraft were designed to obtain new information about Venus, particularly about its atmosphere and its interactions with the solar wind; the stream of electrons and protons emitted by the Sun that moves outward in all directions through the Solar System.

ORBITER OBJECTIVES

The Orbiter was designed to investigate Venus in four important ways. First, investigate the clouds of the entire planet by using information provided by special sensors aboard the spacecraft and by observing the way in which radio signals from the spacecraft to Earth are affected by Venus' atmosphere when it is between the spacecraft and Earth. Second, measure the characteristics of the upper atmosphere and the ionosphere over the entire planet and detect how the solar wind interacts with the ionosphere. Third, by using a radar instrument to penetrate the Venusian cloud layers, obtain information about the planet's surface. Finally, determine the general shape of the gravitational field of Venus and detect local anomalies in the field by measuring how the field affects the orbit of the spacecraft.

To achieve these science objectives, the spacecraft carries a complement of 12 scientific instruments. Three instruments provide information to answer basic questions about how Venus interacts with the solar wind: a magnetometer measures magnetic fields, a plasma analyzer measures the solar wind, and an electric field detector measures electric fields. An ultraviolet spectrometer measures the intensity of ultraviolet radiation at various wavelengths, with the aim of checking how sunlight is reflected and scattered from the clouds and the haze layers of the Venusian atmosphere. This instrument is also used to detect day and night glows in the upper atmosphere caused by the action of solar radiation on the gases there and recombination of molecules when the solar radiation is absent during the night. The instrument is also used to investigate a corona of hydrogen gas surrounding the planet.

The infrared radiometer measures radiation at selected wavelengths within the infrared or thermal portion of the electromagnetic spectrum and is therefore sensitive to the emitting temperature of the atmosphere at several levels. The instrument also detects and maps the distribution of water vapor in the atmosphere and detects and maps reflected solar radiation.

The radar mapper penetrates the cloud layers to determine the surface topography and scattering properties, thereby revealing details obscured by the cloud layers. It also provides information on the radar brightness of the surface by side-looking mapping. The clouds themselves are mapped by an ultraviolet spin-scan imager; the imager makes a series of narrow scans across Venus to build a picture, in somewhat the same way a television picture is built by a series of lines across the tube face. The mapper also measures the intensity and the polarization of light reflected from the clouds of Venus. Rotation of the spacecraft sweeps the viewpoint of the instrument across the planet, and the motion of the spacecraft along its orbit places the scan paths side by side to build up the images. In addition, the mapper (when operating in a polarimetry mode) provides information about the size, shape, and types of particles making up the clouds and haze layers.

When the Orbiter is closest to Venus – at orbit periapsis – it passes briefly through the ionosphere and upper atmosphere. During those periods, several instruments are used to measure the composition of the atmosphere – a mass spectrometer that identifies the neutral (uncharged) particles of the atmosphere and another that measures the composition and concentration of positively charged thermal ions. A retarding potential analyzer and electron temperature probe measure the abundances of charged particles in the ionosphere and in the layers between the ionosphere and the region of the solar wind, such as ion composition and the energy (temperature) of electrons and ions.

The Orbiter also carries an experiment that is not connected with Venus but is intended to provide a second platform to complement experiments being conducted near Earth. The instrument used in this experiment is designed to measure bursts of gamma rays coming from space. The source of these recently discovered bursts cannot be determined from Earth, but an observation platform in orbit around Venus can provide a second set of data which can be used in conjunction with the Earth-orbiter observations in a triangulation arrangement to allow the source of these mysterious gamma rays to be pinpointed.

MULTIPROBE OBJECTIVES

The Multiprobe spacecraft was also designed to investigate Venus in four major ways. First, its instruments were used to study the nature and composition of the clouds of the planet by direct sampling within them. Second, its science experiments determined the composition, structure, and thermal balance of the planet's atmosphere from high altitudes down to the surface by direct sampling and measurements of radiation. Third, it checked how the atmosphere circulates about the planet. And fourth, it was used to investigate further how the planet interacts with the solar wind.

To achieve these science objectives, the Multiprobe spacecraft carried 18 scientific experiments: 2 aboard the bus, 3 on each of the three identical small probes, and 7 on the large probe.

One instrument on the Bus was a neutral mass spectrometer used to measure the density and to analyze the composition of the gas in the upper atmosphere. The other was an ion mass spectrometer (identical to that carried by the Orbiter) used to determine the composition of thermal ions in the upper atmosphere and to measure their concentration and temperature.

Each small probe carried an instrument to detect the presence of and to measure the optical properties of particles at various levels in the atmosphere of Venus. Each probe also carried an instrument complex to measure the temperature and pressure of the atmosphere. These sensors not only defined the properties of the atmosphere and clouds from an altitude of about 65 km (38 miles), but also enabled the investigators to determine the altitude of the probe at which each measurement was taken. A third device monitored the amount of sunlight penetrating to different levels of the atmosphere and the amount of planetary infrared radiation emitted back to space.

The large probe also carried the first two of the above experiments to determine atmospheric and cloud structure. In addition, it carried a neutral mass spectrometer designed to measure the composition of the neutral components of the atmosphere from an altitude of about 65 km (42 miles). This instrument was expected to identify the vapors that condense to form the clouds of Venus. It also measured the number of isotopes of rare gases in the atmosphere, which is important in tracing the history of the planet and the evolution of its atmosphere. This investigation was extended through another instrument, the gas chromatograph, which measured the abundances of atmospheric gases.

The large probe included an instrument that provided information related to the way in which solar radiation penetrates the atmosphere and reaches ground level. Such measurements are important to our understanding of why Venus is so much hotter than Earth. Another instrument measured the infrared part of the solar radiation flux at all levels in the atmosphere. It was used to detect the presence of clouds and water vapor. Finally, the large probe carried an instrument to measure the sizes of particles in the clouds and in the lower atmosphere and to determine the concentration of such particles at various levels.

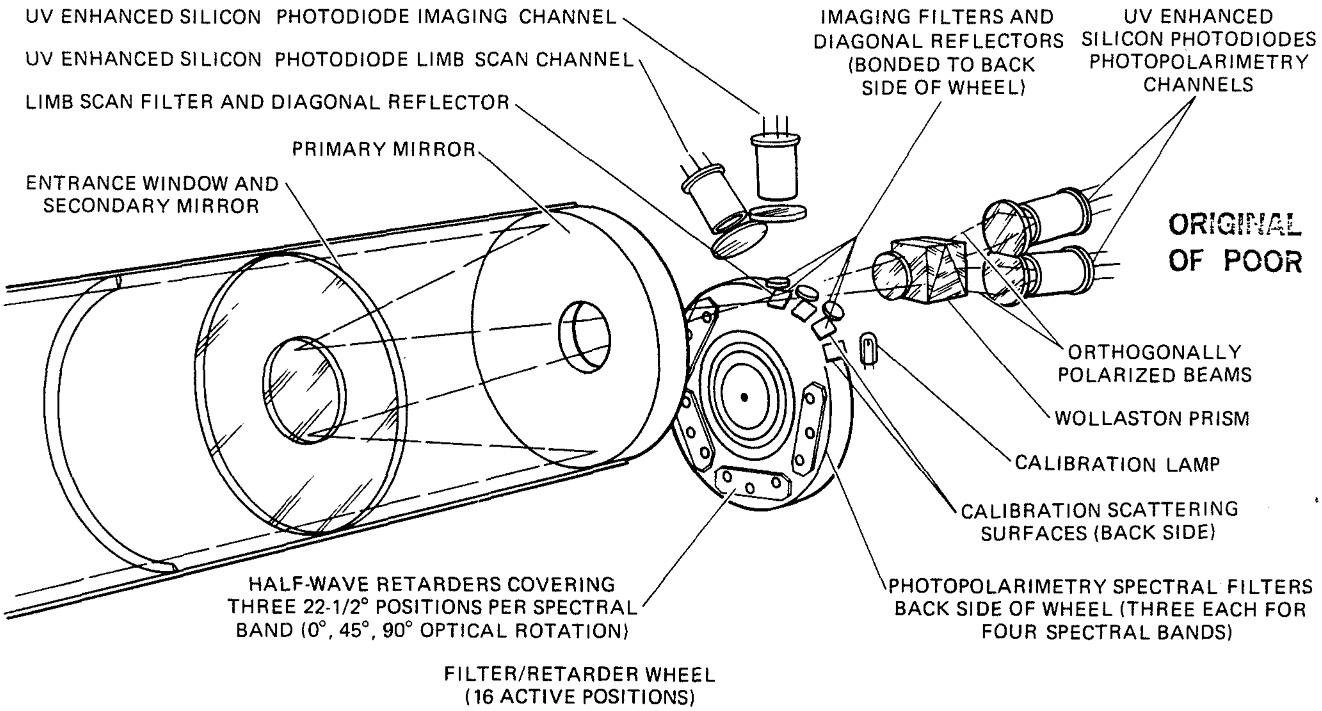
Radio signals from all the probes and from the bus were received at Earth stations. They were used to make extremely accurate measurements of the velocities of the various probe spacecraft and thus to determine wind speeds and circulation patterns in the Venusian atmosphere.

ORBITER INSTRUMENTS AND EXPERIMENTS

Cloud Photopolarimeter

The photopolarimeter is used to measure the vertical distribution of cloud and haze particles and to observe ultraviolet markings and cloud circulations. The ultraviolet images obtained with this instrument provide visual references for data from other Orbiter experiments and for the polarization readings obtained with this instrument. The principal investigator for this instrument is L. Travis, NASA Goddard Institute for Space Studies.

The photopolarimeter (fig. 4-1) weighs 5 kg (11 lb) and requires 5.4 W of electrical power. It consists of a 3.7-cm (1.5-in.) aperture telescope with a rotating filter wheel. There are 16 active positions on the filter wheel – three filters for each of four spectral bands (255-285, 355-380, 540-555, and 930-945 nm), limb-scan filters, and imaging filters. A Wollaston prism directs the beams of light for the photopolarimetry channels to two silicon photodiodes enhanced to detect ultraviolet light. Diagonal reflectors at two positions on the back of the filter wheel send the beams to two other silicon photodiodes, one for the imaging channel and another for the limb-scan channel. With this telescope, the planet is observed at fixed angles, using the Orbiter's rotation to lay scans across the planet and using the



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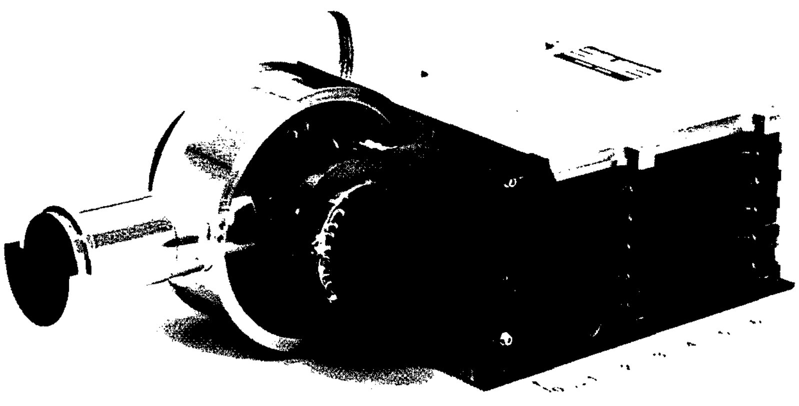

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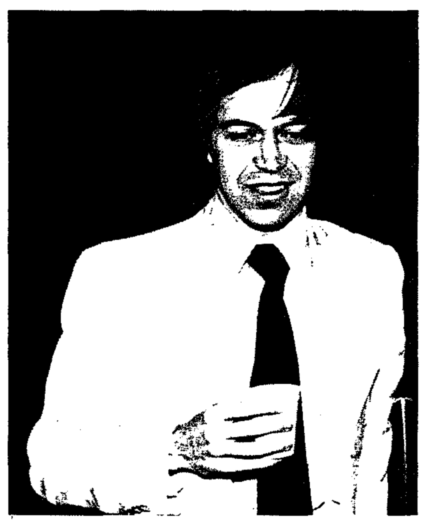

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Figure 4-1. Cloud photopolarimeter (OCPP). (a) Optical system of the instrument; its telescope, filter/retarder wheel, and photodiodes. (b) OCPP. (c) J. Hansen, Principal Investigator for the OCPP. (Note: L. Travis was principal investigator later.)

motion along the spacecraft's trajectory to set these scans side by side. The angle of the telescope to the spin axis of the spacecraft can be set by command from the ground. By this means, the telescope can be directed to observe the planet from any point along the elliptical orbit of the Orbiter.

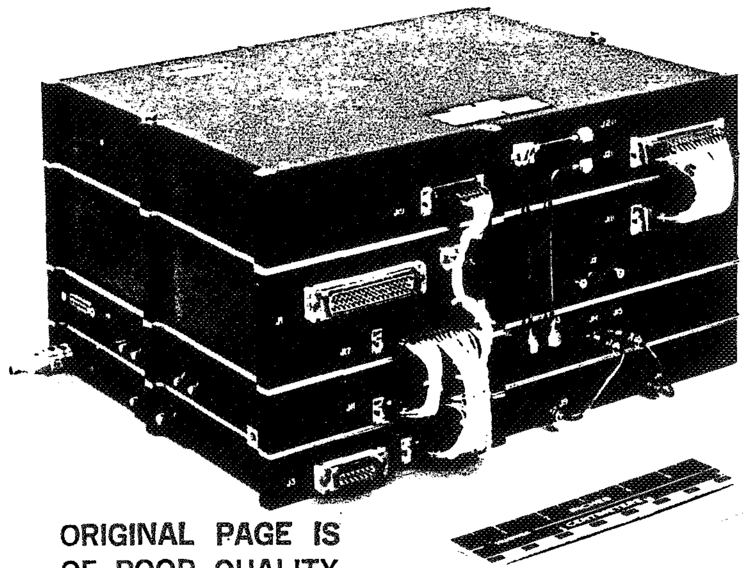
In the imaging mode of operation, when only the intensity of the received radiation is measured, the field of view of the polarimeter is about 0.5 mrad, corresponding to a resolution of about 30 km (19 miles) directly below the Orbiter. In this mode, approximately 3.5 hr are required to record an image of the full disk of Venus. The instrument uses an ultraviolet filter to reveal the fast-moving cloud markings that appear only in ultraviolet pictures of Venus. A maximum of five full-disk planetary images can be made during each orbit of the spacecraft.

In the photopolarimetry mode, the field of view of the instrument is close to 0.5°, which corresponds to a resolution of about 500 km (310 miles) directly below the Orbiter. The four passbands are used in this mode. The instrument measures polarization of scattered sunlight, the characteristics of which depend on the size, shape, and density of particles in the clouds and hazes. The vertical distribution of cloud and haze particles in relation to atmospheric pressure is extracted from these data.

When the Orbiter is near periapsis, the instrument can be used to observe in visible light the high haze layers of the atmosphere by programming the telescope to scan across the limb of the planet. In this mode, the field of view is about 0.25 mrad, which corresponds to an altitude resolution of about 0.5 to 1.0 km (0.3 to 0.6 mile). Such observations are used to obtain information about layers above the main cloud deck of Venus.

Surface Radar Mapper

The radar mapping instrument (fig. 4-2) weighs 9.7 kg (21.3 lb) and requires 18 W of electrical power. (The



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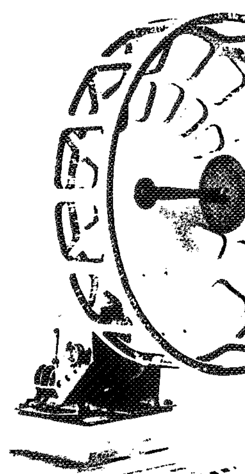

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Figure 4-2. Orbiter radar-mapping instrument (ORAD). (a) Packaging of the electronics. (b) 38-cm diameter, short backfire reflector antenna together with its supporting structure and single-axis positioning motor. (c) Gordon Pettengill, team leader for the radar-mapping experiment.

radar team leader is G. Pettengill, Massachusetts Institute of Technology.) The experiment is designed to produce the first maps of large areas of Venus that are unobservable from Earth by radar. From observing the radar echo, experimenters derive surface heights along the suborbital trajectory to an accuracy of 150 m (492 ft) and a good estimate of global topography and shape. Surface electrical conductivity and meter-scale roughness can also be derived from the radar data.

A low-power (20-W peak pulse power), S-band (1.757 GHz) radar system observes the surface. The antenna is mechanically moved in a plane containing the spacecraft's spin axis to view the suborbital point on the planet's surface once during each roll of the spacecraft. Measurements are made whenever the Orbiter is below 4700 km (2920 miles), subject to constraints set by the spinning spacecraft and competition with other experiments for the limited telemetry capacity. The echoes are processed on board the spacecraft so that the telemetry requirements are minimized. With the spacecraft spinning at a rate of about 5 rpm, the radar observations occupy about 1 sec out of the total rotation period of 12 sec. The instrument automatically compensates for Doppler shift caused by radial motion of the Orbiter toward and away from the planet during each elliptical orbit. When the spacecraft is closer than 700 km (435 miles) to the surface, the received frequency can be stepped to allow range measurements to be made of the areas lying just ahead and behind the path of the spacecraft.

The observed distance between the Orbiter and the surface is subtracted from the spacecraft's orbital radius (obtained from tracking of the spacecraft by the Deep Space Network) to find absolute topographical elevations. Surface resolution is best at periapsis. It is then 23 km (14 miles) along the track and 7 km (4.3 miles) across the track.

Relatively long pulses are used to obtain a good signal-to-noise ratio from each pulse.

The functional parameters used for altimetry measurements are changed when the radar is operating in its other mode: side-looking radar imaging at altitudes below 550 km (345 miles). The mode uses uncoded pulses at a pulse repetition frequency of 200 Hz to avoid ambiguities in range and surface mapping. A sequence of surface brightness measurements is made with the antenna pointing to one or both sides of the ground track, as selected by command from Earth. The illuminated surface area is effectively divided into 64 picture elements or pixels; the size of each is about 23 km (14.3 miles) square when the spacecraft is close to periapsis.

Infrared Radiometer

The infrared radiometer (fig. 4-3) weighs 5.9 kg (13 lb) and requires 5.2 W of electrical power. (The principal investigator is F. Taylor, Oxford University, England.) A pressure modulation unit and molecular sieve for one channel of the instrument that had to make measurements over a wide range of temperatures and pressures were developed and fabricated by Oxford University, England. Unfortunately, the radiometer malfunctioned on February 14, 1979, after 72 orbits, and is no longer operating.

The radiometer measured infrared radiation emitted by the atmosphere of Venus at various altitudes from 60 km (37 miles) at the top of the cloud deck, where the atmospheric pressure is 250 mbars to 150 km (93 miles) where the pressure is 10^{-6} mbars. This region includes the parts of the Venusian atmosphere where the 4-day circulation takes place, where there is maximum cooling by radiation into space, and where there is maximum deposition of solar energy into the atmosphere. The instrument was used to search for water vapor above the cloud layers, to measure the extent of the heat-trapping cloud layers, and to measure the albedo. The data from the radiometer yielded about 800,000 vertical profiles of temperatures in the upper atmosphere. A temperature sensitivity of better than 0.5 K at 240 K was obtained by keeping the sample time short. Such temperature information was important to discovering the extent and the driving forces of the 4-day circulation of the upper atmosphere.

The radiometer had eight detectors, each sensitive to a different part of the spectrum. Because it covered such a wide range of the spectrum, several different measurement techniques had to be used in the one instrument. Five detectors measured infrared emissions at five selected wavelengths of the absorption band of carbon dioxide near 15 μm. Each wavelength sampled a specific altitude region in the atmosphere, depending on the heat-absorbing characteristics of the carbon dioxide molecule and the variation of temperature with altitude. One detector, centered on the strongest part of the pure rotational band of water vapor at 40 to 50 μm, exclusively detected and mapped the distribution of water vapor in the upper atmosphere. Another, operating in the 2.0-μm bands of carbon dioxide, measured the size and shape of cloud layers, and yet another (the wide-band albedo channel from 0.2 to 4.5 μm) measured the total solar reflectance.

A 48-mm (1.9-in.) aperture parabolic mirror gathered radiation for all eight channels of the instrument. This telescope was set at 45° to the spin axis of the Orbiter so that its field of view scanned across the planet by the rotation of the spacecraft. When looking at the limb of the planet, the instrument provided a vertical resolution of 5 km (3 miles) at periapsis.

Airglow Ultraviolet Spectrometer

The airglow ultraviolet experiment is designed to map and make spectroscopic analyses of ultraviolet light scattered or emitted by the clouds and gases in the Venusian atmosphere. (The principal investigator is Ian Stewart, University of Colorado.) The

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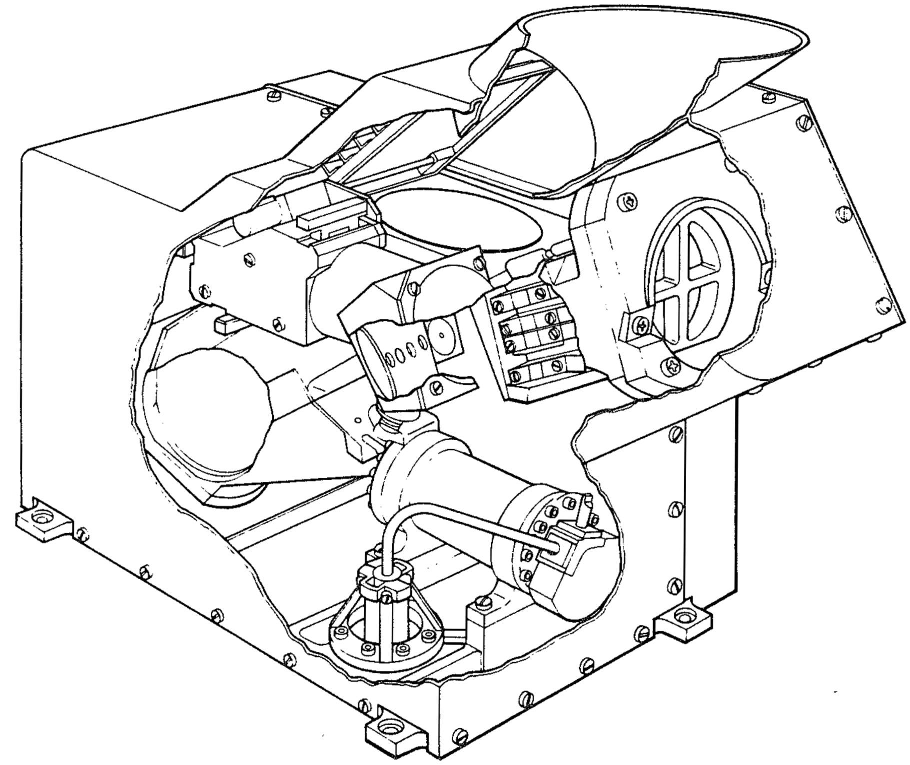

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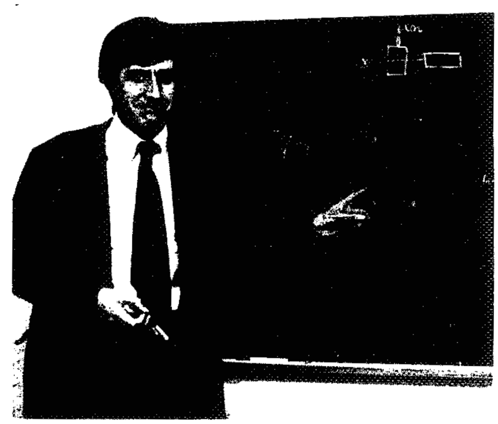

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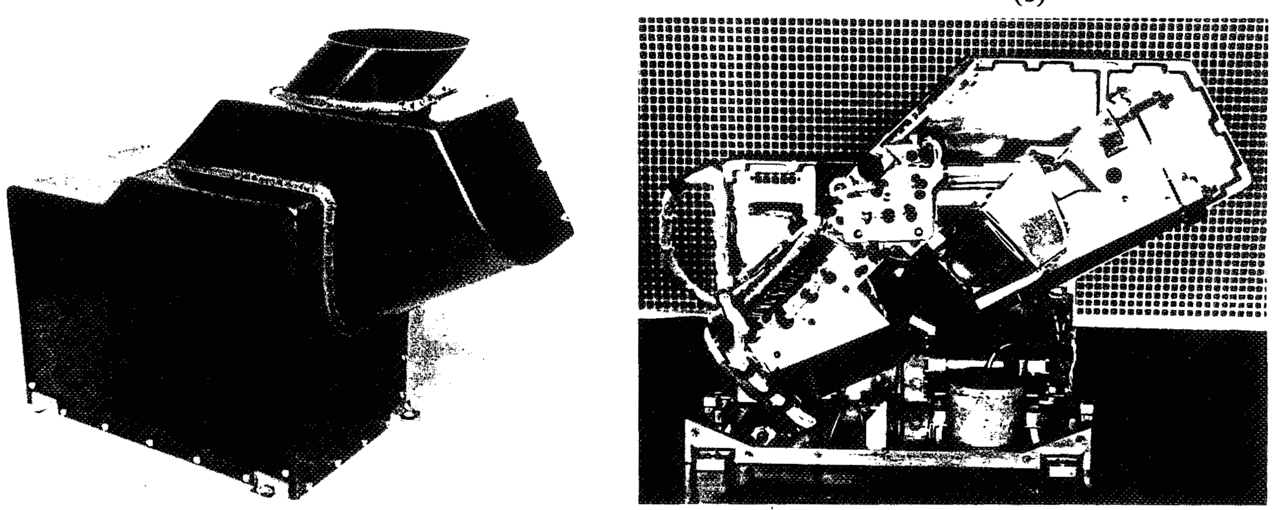

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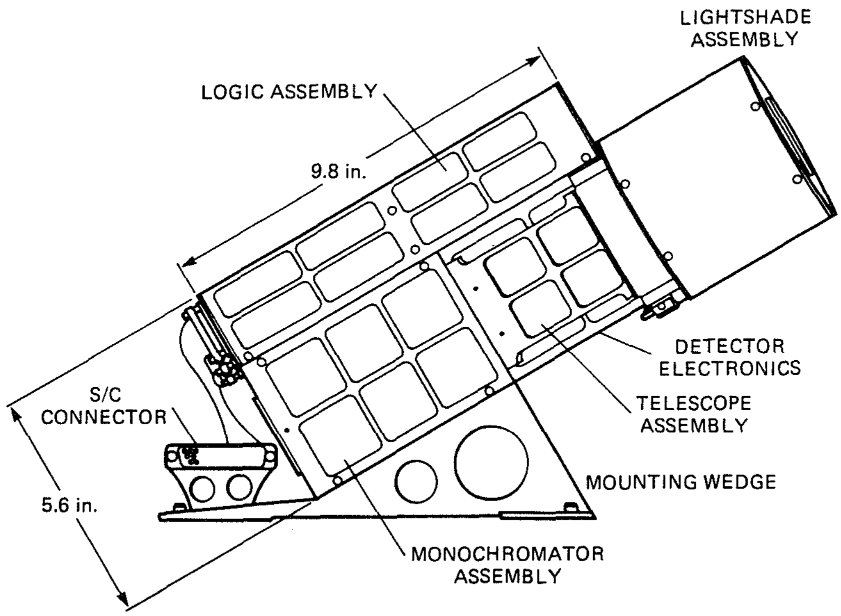
Figure 4-3. Orbiter infrared radiometer (OIR). (a) Cutaway drawing of the instrument related to the outline of its housing. (b) F. Taylor, principal investigator for the experiment. (c) Packaged radiometer and the instrument without its housing.

ultraviolet spectrometer (fig. 4-4) weighs 3.1 kg (6.8 lb) and requires 1.7 W of electrical power.

The manner in which ultraviolet sunlight is reflected by the planet's clouds and atmosphere depends on the details of the size and makeup of cloud aerosols and on the distribution of ultraviolet-absorbing gases. Both the spectral intensity (how the brightness of the light varies with its wavelength) and maps, or images, carry the "fingerprint" of these factors, and analysis reveals the details of the distribution of clouds, hazes, and gases in three dimensions. The variations and movement of bodies of gases and cloud markings (which can be seen only in ultraviolet light) can be traced in images made on successive days.



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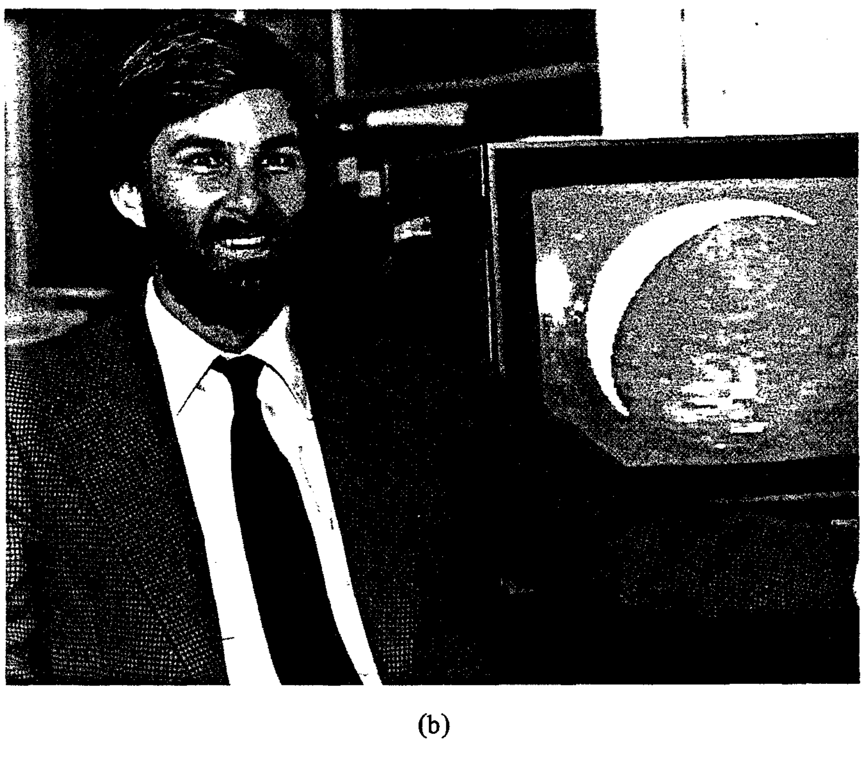

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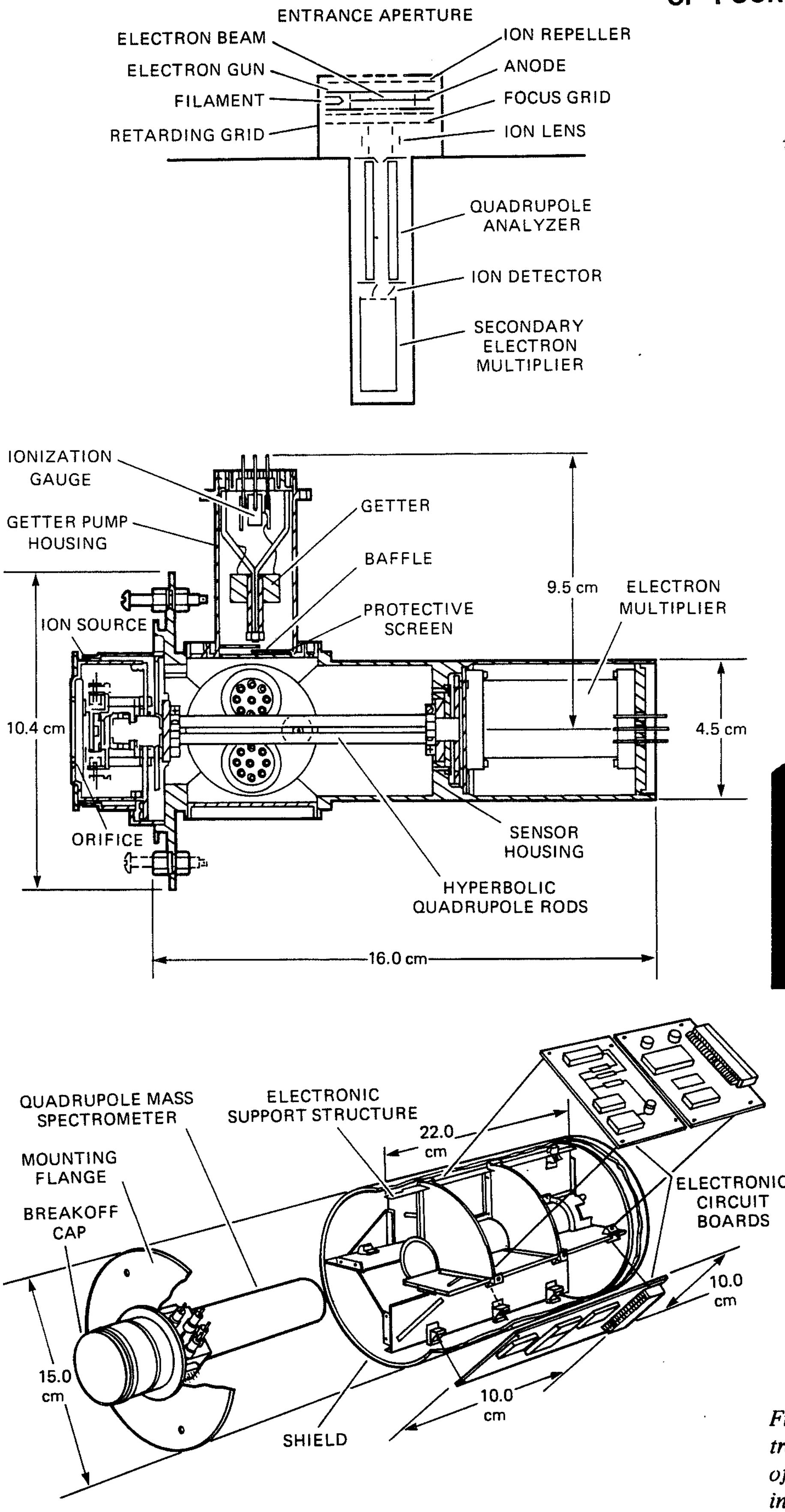
Figure 4-4. Orbiter ultraviolet spectrometer (OUVS). (a) Various assemblies. (b) A. I. Stewart, Principal Investigator for the experiment.

Absorption of extreme ultraviolet radiation from the Sun by the gases of the upper atmosphere causes fluorescence, known as airglow. Each gas has its characteristic emissions, and each of the many physical and chemical processes involved in the fluorescence has its characteristic stamp as well. By measuring the emissions, the experimenters seek to learn about the processes by which the Sun's radiation modifies the composition and temperature of the upper atmosphere.

The ultraviolet spectrometer measures the emission of Lyman-alpha radiation from hydrogen atoms that form a corona around Venus, thereby ascertaining the amount of hydrogen escaping from the top of the planet's atmosphere. This information is important because escaping atomic hydrogen is the last step in the process by which a planet loses water. Water is broken down into hydrogen and oxygen by photolytic processes; the oxygen is too heavy to escape from a planet the size of Venus, but hydrogen can escape into space from the top of the atmosphere. One of the big mysteries about Venus is why it lacks water.

The spectrometer features a 5-cm (2-in.) aperture f/5 Cassegrain telescope (protected by a light shade) and an f/5, 12.5-cm (5-in.) focal length monochromator of Ebert-Fastie design. The monochromator uses a diffraction grating with 3600 grooves per millimeter, driven by a programmable step motor commanded from Earth to select the desired wavelength for observation. The spectral resolution is 13 Å and each grating step is 4.4 Å. (An angstrom (Å) is a commonly used unit of wavelength equal to 10^{-8} cm, approximately the diameter of a hydrogen atom.) Two exit slits pass the dispersed light from the monochromator to two photomultiplier tubes, which convert the light from



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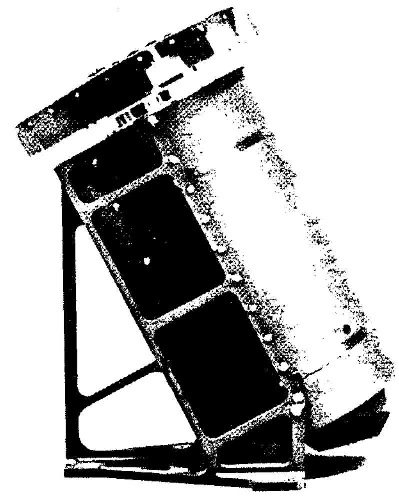

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Figure 4-5. Orbiter neutral mass spectrometer (ONMS). (a) Exploded view of the sensor. (b) General view of the instrument. (c) H. B. Niemann, principal investigator.

Venus into electrical impulses that are then telemetered back to Earth. One photomultiplier has a cesium iodide cathode with a lithium fluoride window; it is sensitive to the wavelength range from 1100 to 1900 Å. The other has a cesium telluride cathode and a quartz window and is sensitive to the range from 1800 to 3400 Å.

The instrument can be operated in several modes. The spectral mode scans the complete spectrum in four 256-word sections; each section is acquired in 1.0 sec and requires one or more complete spins of the spacecraft for transmission to Earth. Mapping and imaging are performed in the wavelength mode, in which the grating position (wavelength), the detector tube, and the length and location of the data arc are selected by command from Earth. Backup modes with lesser capabilities are available to ensure collection of data in the event of a failure in the instrument command system or data memory.

On a typical orbit, the ultraviolet spectrometer views the planet during the period from 150 to 35 min before periapsis and again 15 min before periapsis to 10 min after. The first period is used for airglow and cloud imaging; the second is used for the study of limb airglow profiles and limb hazes. For the rest of the orbit, the instrument observes bright, hot stars for calibration purposes. Lyman-alpha (atomic hydrogen) measurements may be made throughout the orbit.

Neutral Mass Spectrometer

The neutral mass spectrometer (fig. 4-5) is one of two mass spectrometers carried by the Orbiter. It weighs 3.8 kg (8.4 lb) and requires an average of 12 W of electrical power. It is used to measure the densities of neutral atoms and molecules in an upper atmosphere range that extends from near periapsis to a maximum altitude of 500 km (310 miles). (The principal investigator is H. Niemann, Goddard Space Flight Center, NASA.) Information about the vertical and horizontal distributions of neutral gas molecules is important to defining the chemical, dynamical, and thermal state of the upper Venusian atmosphere. Moreover, by comparing the densities of inert gases at the altitudes accessible to Orbiter with those ascertained below 150 km (93 miles) by the large probe and the bus, researchers determine the height above the planet's surface at which atmospheric mixing ends.

Noble gases, other nonreactive gases, and chemically active gases up to 46 atomic mass units are identified and measured. A quadrupole mass spectrometer, with an electron-impact ion source and a secondary electron multiplier ion detector, is used. Gas molecules are ionized and then separated by a quadrupole mass filter according to their mass. The ion source is located inside a chamber, which is connected to the outside atmosphere via a knife-edged orifice. It is designed to operate in two modes alternately: a closed-source mode and an open-source mode.

In the open-source mode, only those ions that result from ionization of free-streaming particles are analyzed. Such particles have a large kinetic energy with respect to the Orbiter, which is moving through the atmosphere at nearly 10 km/sec at periapsis. For atomic oxygen, this kinetic energy is about 8 eV; it is about 0.025 eV for surface-reflected particles. A retarding potential analysis is used to discriminate between surface-reflected and free-streaming particles after they have been ionized by the electron beam. For this mode to be effectively used near periapsis, the axis of the mass spectrometer must point in the general direction of motion of the Orbiter once per spin period. This is accomplished by mounting it on the instrument platform of the spacecraft so that its axis is 27° from the spin axis. Concentrations of chemically active gases such as atomic oxygen are measured in this mode.

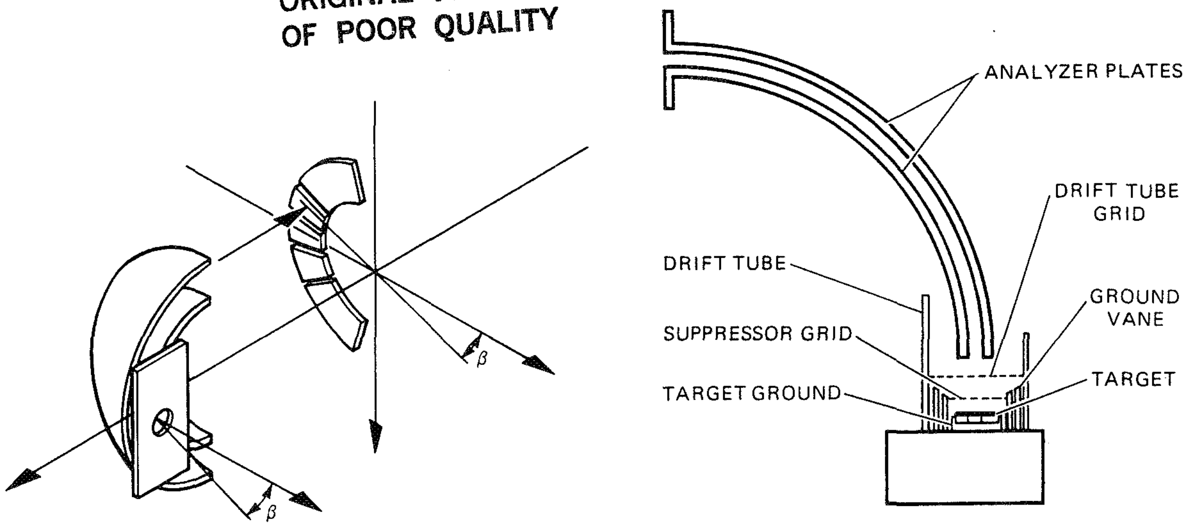
In the closed-source mode of operation, essentially all the particles analyzed by the instrument are surface-reflected particles. The gas density in the ion source is significantly enhanced because the inflowing gas stagnates in the source chamber. This mode is suitable for determining the concentrations of noble gases such as helium and of nonreactive gases such as carbon dioxide and molecular nitrogen. The surface-reflected particles accommodate to the surface temperature before making multiple passes through the ionization region. As a result, this mode has enhanced sensitivity which permits measurements to much lower concentrations than is possible in the open-source mode.

To keep the internal surfaces clean and to allow testing of the instrument during launch preparations and cruise, the ion source was covered by a metal-ceramic breakoff cap which maintained the internal pressure below 10^{-4} Pa (10^{-6} torr). The cap was removed by a pyrotechnic actuator after the spacecraft was inserted into orbit.

The mass spectrometer can be programmed by ground command to scan continuously from 1 to 46 atomic mass units or to scan any combination of eight masses within that range. The kinetic energy of the ionizing electrons can be chosen by ground command to be 70 or 27 eV so that constituents of equal mass can be discriminated during analysis.

Solar Wind Plasma Analyzer

The solar wind plasma analyzer (fig. 4-6) weighs 3.9 kg (8.6 lb) and requires 5W of electrical power. It measures certain properties – velocity, density, flow direction, and temperature – of the solar wind and its interactions with the ionosphere and upper atmosphere of Venus. This information is useful in determining not only how the solar wind interacts with the upper atmosphere but also how it might affect weather patterns on the planet. (The principal investigator for the solar wind plasma experiment was initially John H. Wolfe, Ames Research Center, NASA; he was succeeded by Aaron Barnes, also of Ames Research Center.)



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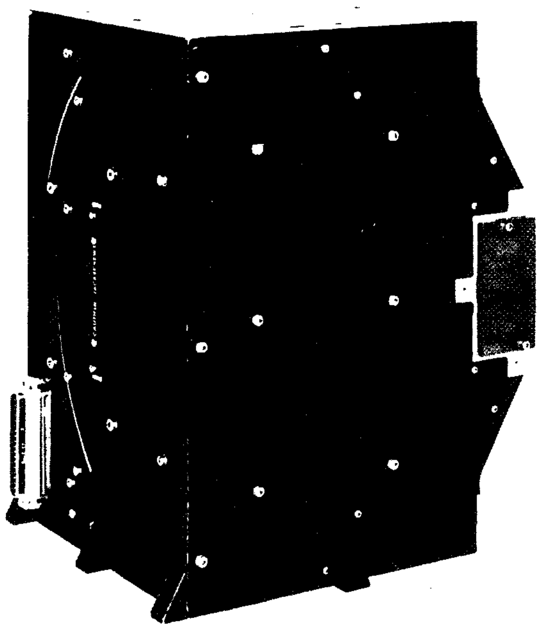

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Figure 4-6. Solar-wind plasma analyzer (OPA). (a) Quadrispherical plates of the electrostatic analyzer. (b) Instrument enclosed in its housing. (c) A. Barnes, principal investigator.

The plasma analyzer is an electrostatic, energy-per-unit-charge spectrometer. The instrument is mounted near the outer edge of the equipment shelf so that its field of view is normal to the spin axis and rotates with the spacecraft. The rate of flow of the solar wind, its flux, is measured by the deflection of in-rushing particles subjected to an electrostatic field between two metal plates. If the particles are within the range of energy and incidence direction determined by the aperture orientation and voltage between the plates, they exit to hit one of five detectors. Which target detector the solar wind particle hits depends on the direction of the wind. By varying the voltage between the plates, the instrument is also able to yield a complete solar wind particle velocity distribution.

The analyzer section of the instrument is a nested pair of quadrispherical plates with a mean radius of 12 cm (4.72 in.); the plates are 1.0 cm (0.39 in.) apart. Charged particles, such as protons and electrons, that pass through the entrance aperture of the instrument enter the region between the charged plates. There they are deflected by the electrostatic field into a curved path and are subsequently collected by the array of five current collectors located at the exit end of the curved plates. Each target is connected to an electrometer amplifier.

The instrument has two modes of operation that can be commanded from Earth, a scan mode and a step mode. The scan mode first finds the maximum flux over one rotation of the spacecraft for each voltage step and identifies the collector and spacecraft azimuth at which this maximum flow occurs. The energy/charge range is normally 32 logarithmically equal steps over the range of 50 to 8000 V for high-energy positive ions, or 15 steps from 3 to 250 V plus a zero step at 0.25 V for electrons and low-energy positive ions. Then a polar scan and an azimuthal scan are made at the four consecutive steps beginning with the step before the one in which the peak flux is measured. Each polar scan measures the flux at all five collectors at each step. Each azimuth scan measures the flux in 12 sectors centered on the peak flux direction. In the step mode, only the maximum flux scan occurs, with only about 1 sec allocated to each voltage.

Magnetometer

The magnetometer, which was designed to investigate the very weak magnetic field of Venus, weighs 2 kg (4.44 lb) and requires 2.2 W of electrical power. (The principal investigator is C. Russell, University of California, Los Angeles.) The instrument – a fluxgate magnetometer – searches for surface-correlated magnetic features, such as regions of crust that might have been magnetized in the past when Venus might have had a field more like that of Earth. Although the field of Venus is extremely weak, scientists thought that it might play an important part in the interactions between the solar wind and the planet. The instrument is designed to clarify whether the solar wind is deflected by a field intrinsic to Venus, by an induced field, or by the ionosphere itself.

The instrument consists of three sensors mounted on a 4.7-m (15.4-ft) boom; the boom isolates the sensors from the magnetic field of the spacecraft sufficiently to permit the measurement of very small fields – fields in the nanotesla (nT), or gamma range. (The field of Earth at the surface is about 50,000 nT.) Two sensors are mounted at the end of the boom; one parallel to the spin axis and the other perpendicular to it. An inboard sensor, mounted one-third of the way down the boom, is tilted 45° to the spin axis. The inner sensor is used to measure the Orbiter's magnetic field, which is subtracted from the readings of the outboard sensors to correct them for the presence of the spacecraft. Each sensor consists of a ring, around which is wrapped a ribbon of permeable metal to form the core of the sensor. It is surrounded with drive, sense and feedback coils. Any external field causes the core to produce an electrical signal. A feedback signal then cancels the external field so that the magnetometer always operates in a zero-field condition. The strength of the feedback signal needed to produce the zero-field condition is a measure of the external magnetic field.

The magnetometer is designed so that gain changes are not needed when the instrument is moved from low- to high-field regions and back again. The range of the instrument remains fixed at 128 nT, but the resolution changes from 1/16 nT to plus or minus 1/2 nT in response to changes in the field.

Electric Field Detector

The electric field detector (fig. 4-7) is designed to answer questions concerning the characteristics of the interactions between Venus and the solar wind. The instrument weighs 0.8 kg (1.76 lb) and requires 0.7 W of electrical power. (The principal investigator is F. Scarf, TRW Systems.) It provides information about how the solar wind is deflected around Venus, the extent to which the solar wind heats the ionosphere, the extent of ionization caused by the exosphere-solar wind interaction, and about the turbulence of the solar wind. It also allows measurements of the variable locations of the bow shock, the ionopause, and the wake-cavity boundary.

The electric field detector measures electric components of plasma waves and radio emissions in the frequency region from 50 to 50,000 Hz. Currents are induced in a 66-cm (26-in.) long, V-type electric dipole antenna and are amplified to derive information relayed to Earth. Four 30% bandwidth channels, centered at 100, 730, 5,400, and 30,000 Hz, are used. Each is useful at different points along the orbit of the spacecraft, as the Orbiter passes through varying densities of the solar wind.

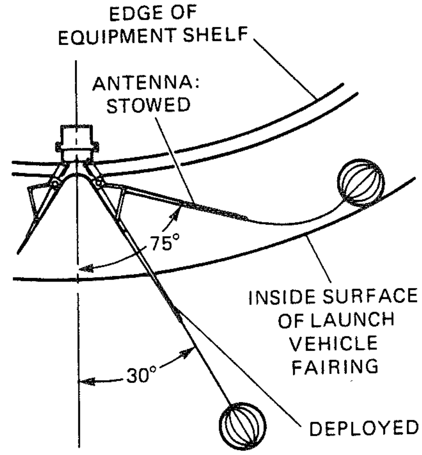
The instrument also searches for "whistlers," which are electromagnetic disturbances that travel along a magnetic field line. At Venus it was anticipated that electron whistler mode signals could be detected in the 100-Hz channel at all orbital locations.

Electron Temperature Probe

The electron temperature probe measures the thermal characteristics of the ionosphere of Venus – electron temperature, electron concentration, ion concentration, and the spacecraft's own electrical potential. Such measurements are needed to help scientists understand the ways in which the ionosphere obtains its heat; heating at high altitudes by the solar wind and at lower altitudes by solar ultraviolet radiation were believed to be two such sources. (The principal investigator for the electron temperature experiment is L. Brace, Goddard Space Flight Center, NASA.

The probe (fig. 4-8) weighs 2.2 kg (4.76 lb) and requires 4.8 W of electrical power. It consists of two cylindrical Langmuir probes, an axial probe and a radial probe. The former is mounted parallel to the spacecraft's spin axis at the end of a boom that is 40 cm (15.75 in.) long. The latter is mounted at the end of a 1-m (39.37-in.) boom that extends radially from the periphery of the spacecraft. Each probe is 7 cm (2.8 in.) long and 0.25 cm (0.1 in.) in diameter. Each has its own power generator but shares in-flight data analysis circuitry.

A sawtooth voltage sweeps each probe twice each second and is electronically adapted to match the exist-



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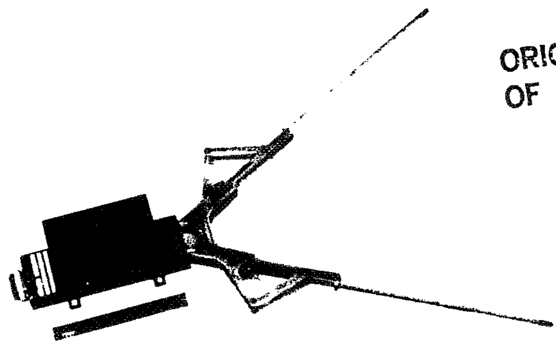

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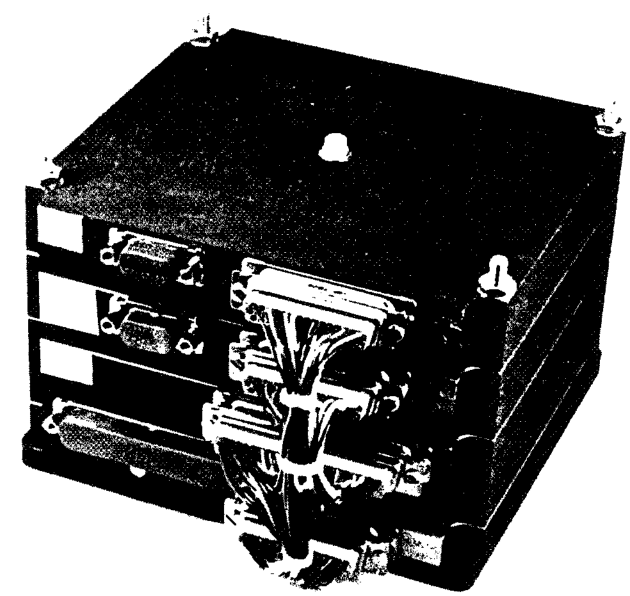
Figure 4-7. Electric field detector experiment of the Orbiter spacecraft (OEFD). (a) V-type antenna. (b) Antenna in the stowed and deployed positions. (c) Principal investigator for this experiment is F. Scarf.



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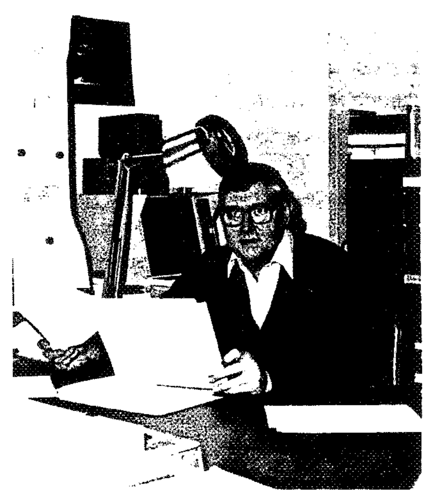

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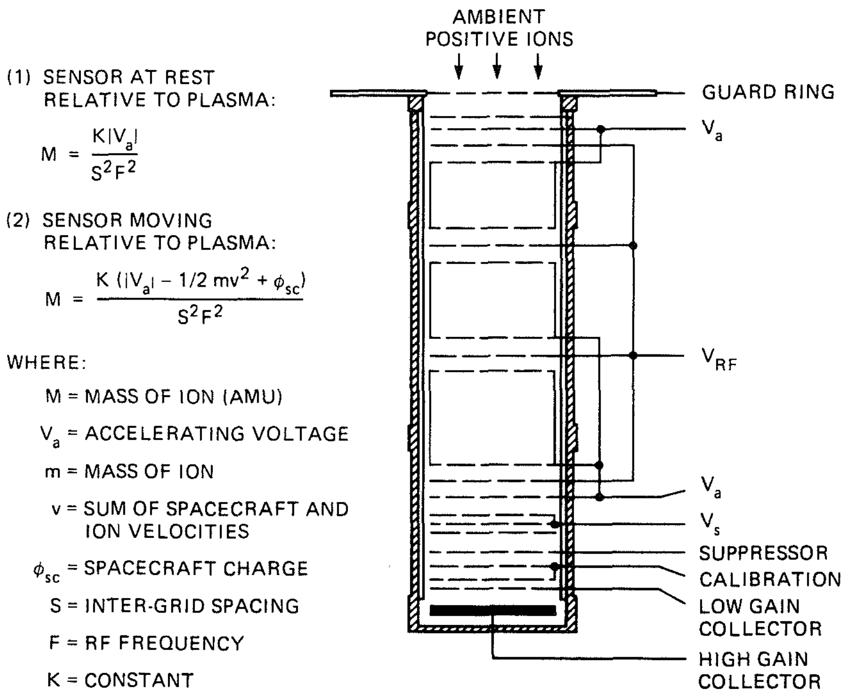
Figure 4-8. Electron temperature probe (OETP). (a) Two Langmuir probes mounted outside the spacecraft and the electronics package. (b) L. Brace, principal investigator.

ing electron density and temperature being measured. The sweep amplitude is varied automatically over the range of 0.5 to 10 V, depending on the electron temperature being measured. Suitable bias voltages are added to compensate for the potential of the spacecraft. At the beginning of each sweep, automatic current-ranging circuits sample the ion current and adjust the electrometer gain to a value suitable for the variations in concentration of the ions. The design of the instrument includes these adaptive functions so that the resolution can be as large as possible over a wide range of electron concentrations and temperatures.

A commandable mode is provided to permit sampling of either one of the two probes instead of alternating between the two. This allows the experimenters to take advantage of having two probes that respond differently (because of their orientation) to changes in the concentration of electrons while maintaining high spatial resolution.

Ion Mass Spectrometer

The ion mass spectrometer (fig. 4-9) weighs 3 kg (6.6 lb) and requires 1.5 W of electrical power to measure the distribution and concentration of positively charged ions in the atmosphere of Venus above 150 km (93 miles). It is similar to the instrument that was used in the Multiprobe bus. (The principal investigator for both ion mass spectrometers is H. Taylor, Jr., Goddard Space Flight Center, NASA.) The instrument directly measures ions in a mass range from 1 (protons or hydrogen ions) to 56 atomic mass units. The data



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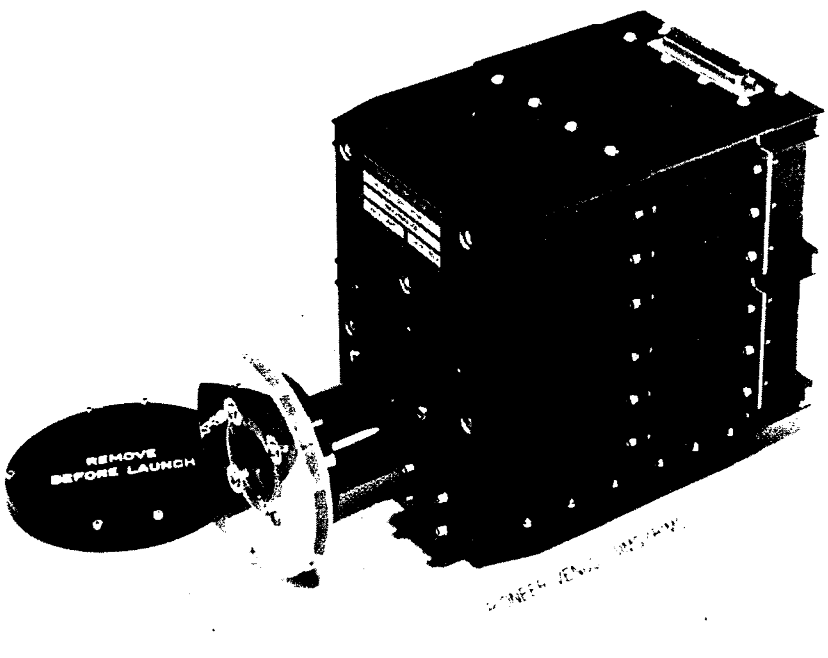

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Figure 4-9. Ion mass spectrometer (OIMS/BIMS) used on the Multiprobe Bus and the Orbiter. (a) Sensor and mass analysis equations used. (b) Photograph of the instrument. (c) H. A. Taylor, principal investigator for this experiment.

gathered by the instrument are important to gaining a greater understanding of the ionosphere of Venus and its interaction with the solar wind.

The basic measurement cycle is 6.3 sec. The instrument first makes an exploratory sweep of 1.8 sec (explore mode), during which a search is made for up to 16 different ions. It then makes a series of sweeps for 4.5 sec (adapt mode), repeating the sampling of the eight most prominent ions identified during the exploratory sweep. As used in the Orbiter, the instrument has commandable modes for regulating the explore-adapt logic circuit. This allows the number of prominent ions for adaptive repeats to be reduced from 8 to 4 or 2. There is also the commandable option to remain in the explore mode only.

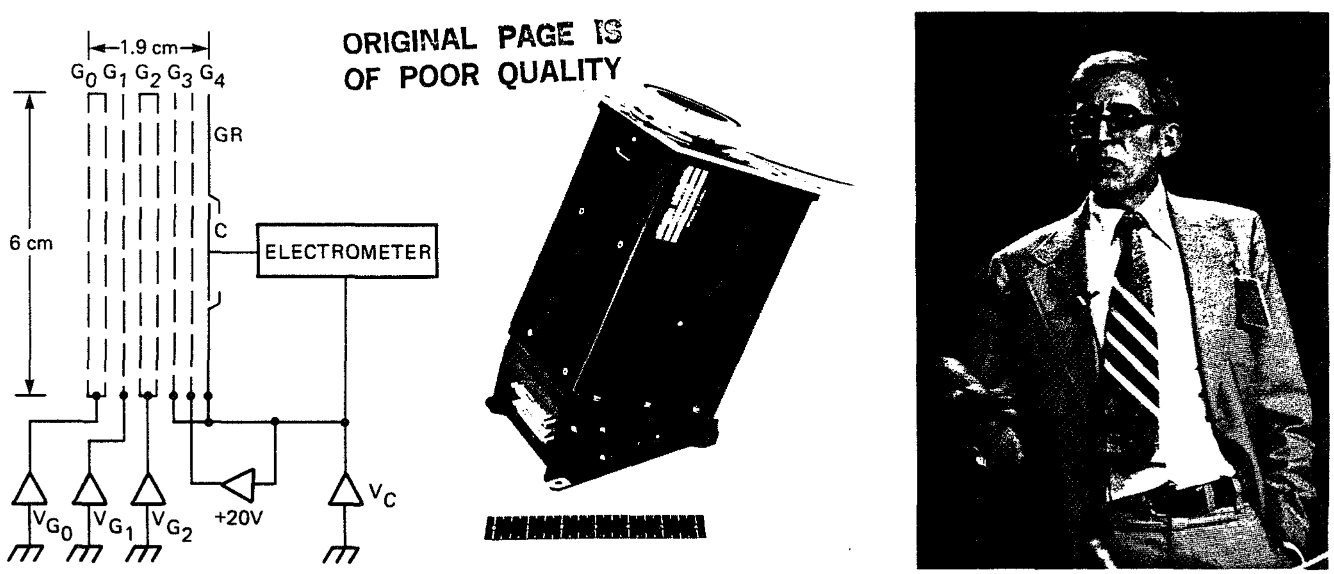
In flight, the sensor – a Bennett-type radio-frequency ion mass spectrometer tube – is exposed to a stream of atmospheric ions which flows into an aluminum cylinder enclosing a series of parallel wire grids. Each ion species is subsequently accelerated along the axis of the spectrometer by a variable negative-sweep potential, which is programmed to step and then dwell at voltage levels needed to detect the particular ions. In this way, the ions that pass through the radio-frequency analyzer stages in phase with the applied voltage gain sufficient energy to penetrate a retarding direct-current field and impinge on a collector at the rear of the sensor cylinder. The ion stream's accelerating voltages yield the identity of the ions, and its amplitude reveals their concentration. The ion currents are detected by a dual collector system, a low-gain grid collector and a high-gain solid disc collector.

Charged-Particle Retarding Potential Analyzer

The charged-particle retarding potential analyzer measures the temperature, concentration, and velocity of the most abundant ions in the ionosphere. It also measures the concentration and energy distribution of photoelectrons in the ionosphere, the temperature of thermal electrons, and spacecraft potential. It provides important data on plasma quantities in the ionosphere, the planetary tail, and the boundary layers surrounding Venus. The instrument weighs 2.8 kg (6.2 lb) and requires 2.4 W of electrical power. (The principal investigator is W. Knudsen, Lockheed Missiles and Space Company. The sensor portion of the instrument was developed and fabricated by the Fraunhofer Institut für Physikalische Weltraumforschung, West Germany.)

The instrument (fig. 4-10) is designed specifically to detect low-energy plasma particles in the ionosphere of Venus, as opposed to the much more highly energized solar wind particles. Nevertheless, the analyzer can provide data concerning the interaction between the ionosphere and the solar wind at an altitude of 400 to 500 km (250 to 310 miles) at the level where the solar wind streams into the ionosphere.

Because of their varying electrical potentials, collector grids (6 cm (2.4 in.) diameter) selectively allow various ionospheric particles to strike a detector. Current induced in the detector is amplified by an electrometer. Large entrance grids and a collector guard ring provide a uniform flux radially from the axis of the instrument. The collector samples the central region of this flux. Systematic error is kept low by using multiple retarding grids coated with colloidal graphite. Surrounding the entrance grid there is a 30-cm (11.8-in.) diameter ground plane, which ensures that



(a) (b) (c)

Figure 4-10. Charged particle retarding potential analyzer (ORPA). (a) Grid system. (b) Assembled instrument. (c) W. Knudsen, principal investigator for the experiment.

the plasma sheath is planar even at a low concentration of electrons.

By application of control voltages and a special program, the instrument is operated in three modes, an electron Langmuir probe mode, an ion mode, and a photoelectron mode. Instrument logic-performing onboard data analysis selects the optimum point in the rotation of the spacecraft at which to sample the plasma. Each scan is completed in a small fraction of a spin period. Scans are taken repeatedly, and the scan for which the instrument is optimally oriented is sensed, stored, and transmitted to Earth. Scans are typically spaced at 120-km (75-mile) intervals along the orbital path.

Vector ion velocity is measured by recording three scans with the instrument pointing to three different celestial longitudes in three successive spin cycles. A special mode of operation can be commanded so that total ion concentration can be measured at 20-m (66-ft) intervals.

Gamma Ray Burst Detector

The gamma ray burst detector is not intended to obtain information about Venus, but to make use of the Pioneer spacecraft in orbit about the planet to provide another set of data concerning the intense short-duration (from one to a few tenths of a second) bursts of high-energy photons from beyond the Solar System. These were first observed in 1973 and their source was a mystery. The gamma ray bursts occur randomly, roughly 10 per year. Because the Orbiter is separated from Earth it provides a means to obtain a direction for the bursts by correlating observations from Venus with simultaneous observations from Earth satellites.

The instrument (fig. 4-11) weighs 2.8 kg (6.17 lb) and requires 1.3 W of electrical power. It consists of two sodium-iodide photomultiplier detector units mounted to provide a near uniform sensitivity over a wide field of view. These detectors are sensitive to photons having energies between 0.2 and 2.0 MeV. To accommodate

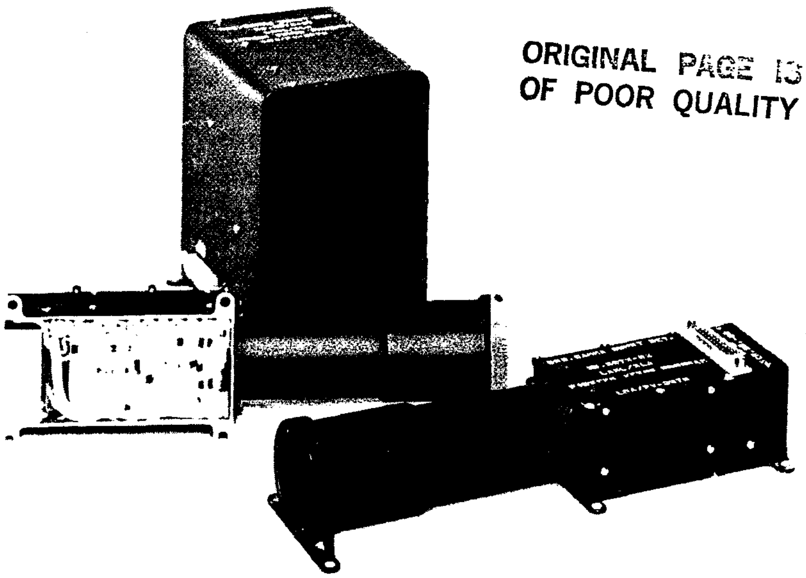


Figure 4-11. Orbiter gamma ray experiment (OGBD).

the very high data rates that occur during intense gamma ray bursts, the experiment includes a buffer memory of 20 kilobits for storing the data until it can be read out later at a lower rate. (The principal investigator for the gamma ray experiment is W. Evans, Los Alamos Scientific Laboratory.)

ORBITER RADIO SCIENCE EXPERIMENTS

In addition to the experiments connected with instruments on the spacecraft, there are a number of experiments that make use of the radio signals exchanged between the Orbiter and Earth. The team leader for these Orbiter radio science experiments is G. H. Pettengill, Massachusetts Institute of Technology. The radio science experiments comprise the following: occultation studies by A. Kliore, Jet Propulsion Laboratory, and T. Croft, SRI International; the internal density distribution of Venus by R. Phillips, Jet Propulsion Laboratory; celestial mechanics by R. Reasenberg, Massachusetts Institute of Technology; atmospheric and solar wind turbulence by R. Woo, Jet Propulsion Laboratory; solar corona by T. Croft, SRI International; and atmospheric drag by G. Keating, Langley Research Center, NASA.

The radio science experiments make use of the spacecraft Doppler tracking system. A microwave signal at about 2.1 GHz is transmitted from an antenna of the Deep Space Network. At the spacecraft, the frequency of this signal is phase coherently multiplied by 240/241 and the signal retransmitted. This frequency multiplication is needed to allow the spacecraft receiver to detect the incoming signal while its transmitter is operating, that is, to discriminate between the two signals. The frequency multiplication also serves a similar purpose for the ground station.

The signal received at the Deep Space Network is then mixed with another locally generated signal to produce a video signal, offset by a known frequency from that resulting from the Doppler effects. The Doppler shift can thus be reconstructed from this biased Doppler video signal. Cycles of the biased Doppler signal are counted at the ground station. The differences between uniformly spaced samples of the cycle count, divided by the count interval and corrected for the effects of the known frequency offset, provide the primary Doppler data. These data approximate the (average) rate of change of the range between the ground station and the spacecraft and thus contain information about acceleration experienced by the spacecraft.

Most of the observed Doppler shift is due to the relative motions of Earth and Venus. The mean elliptical trajectory of the Orbiter accounts for the greater part of the remaining Doppler shift. A significant part of the remaining Doppler shift is attributed to perturbations of the spacecraft's trajectory, a small part to the direct effects of the propagation media. The trajectory perturbations are caused by the other planets and the Sun, by the effects of atmospheric drag, and by irregularities in the gravitational potential of Venus. Analysis of the Doppler data provides a model of these irregularities.

The Doppler shift caused by the propagation media has several components, each of which is derived from a different location: the troposphere and ionosphere of Earth; the solar corona and the plasma that flows from it; the interplanetary medium; and, for some geometries, the neutral atmosphere and ionosphere of Venus. Some of the radio science experiments concern the characterization of components of the propagation media.

In addition to transmitting an S-band signal, the spacecraft can transmit an X-band signal that is also phase coherent with the S-band signal. This X-band signal is received and processed on the ground in the same way as the S-band signal. Since the propagation delay at a given frequency caused by the charged particles (plasma) is inversely proportional to the square of the frequency, the dual-band spacecraft transmissions can be used to measure the change of the total charged particle content of the path from the spacecraft to the ground station.

Internal Density Distribution Experiment

In the internal density distribution experiment, the shape of Venus and the gravitational perturbations of the spacecraft are used to study the relationship between surface features and internal densities. The two-way Doppler tracking data of the Orbiter are used to infer the gravity field of the planet. When used with topographic data obtained from the radar experiment, the gravity data provide a constraint on the internal density distribution. Further, these data are used to investigate whether there are any continuing physical processes taking place within Venus analogous to those moving Earth's crustal plates.

Celestial Mechanics Experiment

The celestial mechanics experiment makes use of the spacecraft's radio tracking system and its onboard radar system. The Doppler tracking data are used to develop a high-resolution map of the gravitational potential of Venus. This map, which shows the irregularities in the vertical component of gravity at the surface of Venus, is found to be fully correlated with topography derived from the onboard radar. When compared in the spatial frequency domain, the topography and gravity yield the spectral admittance, which provides a convenient constraint on the near surface structure of Venus.

The Doppler tracking data are also used to study the time-variable structure of the upper stmosphere of Venus. Earth-based radar observations of Venus are used to measure the direction of the axis of rotation of the planet.

Simultaneous radio tracking of the Orbiter with extragalactic radio sources allows precise determination of the orbits of Earth and Venus with respect to these sources.

Dual-Frequency Radio Occultation Experiment

The dual-frequency radio occultation experiment provides information about the atmosphere of Venus by observing how the S-band and X-band radio signals from the Orbiter penetrate the ionosphere and neutral atmosphere of the planet just before and after occultations. The amount of information that can be obtained from observation of multiple occultations is much greater than that obtained by observing a single passage of a spacecraft behind a planet during a flyby. Each occultation provides a record of Doppler frequency shift and changes in signal strength caused by refraction and absorption by the medium of the planet's atmosphere.

The path repetitively followed by the Orbiter is practically unchanging in orientation to Venus, but the motion of Venus and Earth around the Sun precesses the occultation points around the limb of the planet. During the nominal mission there were 80 occultations that sampled the atmosphere and ionosphere over all latitudes from the North Pole to about 60° south. Nearly all were, however, in the night hemisphere of Venus; those that were not in the night hemisphere were at polar latitudes. During the extended mission, data on the day side are also acquired.

The high-gain antenna of the Orbiter is aimed during occultations so that the radio signals are directed toward Earth after they have been refracted by the Venusian atmosphere. In this way, maximum penetration of the atmosphere is obtained, and microwave absorbing cloud layers can be identified and defined.

By analyzing the Doppler frequency variations in the radio signals, investigators determine the structure of the index of refraction, temperature, pressure, and density of the atmosphere above 34 km (21 miles). Radio signal refraction at Venus is so strong that any level ray that gets below 33 km (20.5 miles) bends down to hit the surface and is rendered useless for the purpose of this study.

Atmospheric and Solar Wind Turbulence Experiment

The atmospheric and solar wind turbulence experiment is designed to permit observations of turbulence of scale sizes smaller than 10 km (6 miles) in the Venusian atmosphere above 34 km (21 miles). The aim is to determine the global distribution of turbulence in the atmosphere. The experiment also reveals fluctuations in electron density in the ionosphere. Detailed information about the atmosphere is obtained just before and after occultation when the radio signal passes through deep regions of the atmosphere on its way from the Orbiter to Earth. Scintillations of the signals, akin to the twinkling of stars as seen through Earth's atmosphere, reveal variations in the density of the atmosphere and the presence of atmospheric layers.

For this purpose, the ground station makes a wide-band linear recording in the frequency interval known to contain the signal. Subsequently, the signal is detected by digital computer simulation of the phase-lock loop in a receiver acting on a digitized record of that wide-band signal plus noise. The digital approach is superior to ordinary (analog) radio signal detection in many respects that are critical to scientific applications.

Recent advances in the use of phase scintillations and spectral-broadening measurements are applied to study the solar wind. These measurements are made after the nominal mission has been completed and Venus, with the Orbiter, approaches superior conjunction with the Sun. The radio waves from the spacecraft then pass close to the Sun on their way to Earth – an ideal time to investigate the solar wind close to the Sun. Because the wind is variable, repeated observations provide information about its density, turbulence, and velocity. Two stations of the Deep Space Network are used simultaneously to record the fluctuations in the S-band and X-band signals as they pass through the solar wind.

Comparisons of Pioneer Venus data with data from Voyager 2, Voyager 1, and Pioneer Saturn formed the basis for a special period of international collaborative solar corona observations that was the first scheduled event of the Solar Maximum Year.

Atmospheric Drag Experiment

The atmospheric drag experiment utilizes drag measurements made for the first time within another planet's atmosphere. The aim is to model the mean behavior of the upper atmosphere and to search for variations in atmospheric density that correlate with solar wind activity and changes in ultraviolet radiation. In addition, evidence is sought for the 4-day rotation extending into the upper atmosphere.

The effects of drag are extracted from the estimated orbital parameters of the spacecraft, as obtained by the navigation team from the S-band tracking data. Through the use of an ad hoc model, atmospheric density is determined at each periapsis, where the drag is greatest. Evaluation of the atmospheric density model relies on the periodic variation of the spacecraft's periapsis altitude. The drag coefficient in free molecular flow is determined from the spacecraft's orientation relative to the flightpath and from an estimate of the composition of the atmosphere. From the density, the density scale height, and a knowledge of the dominant atmospheric constituents, the temperature and the variation of composition with altitude and time can be inferred. Further analysis yields models of pressure gradients and flow patterns.

MULTIPROBE BUS EXPERIMENTS

After separation of its four probes 20 days before reaching Venus, the Multiprobe bus became a probe itself, providing important information on the density and composition of the high atmosphere of Venus, in particular for the altitude range from 150 to 130 km (93 to 80 miles). For this purpose, the bus carried two mass spectrometer instruments attached to the equipment shelf, with their inlets projecting over the flat top of the bus cylinder.

Neutral Mass Spectrometer

The neutral mass spectrometer measured the various components (atoms and molecules) of the Venusian atmosphere and their vertical distribution from about 700 km (400 miles) to the 130-km (81-mile) altitude at which the bus was destroyed. The bus was not equipped with protective thermal shields to prevent or delay its destruction by atmospheric heating as it plunged at high speed into the upper atmosphere of Venus. The instrument weighed 6.5 kg (14 lb) and used 5 W of electrical power.

From the information gathered by this instrument, scientists anticipated deriving the height of the turbopause, or homopause, the region above which the atmospheric gases do not mix but become stratified as the lightest gases congregate toward the top of the atmosphere. They also expected to determine the chemical composition of the region of the atmosphere in the region where the ionosphere's density is greatest, and to measure the temperature of the exosphere, the outermost fringe of the atmosphere.

The neutral mass spectrometer (fig. 4-12) bombarded the atmospheric components by electrons to ionize them. The ions so produced were separated according to their masses up to 46 atomic mass units by deflecting them magnetically. The instrument featured a fast data sampling and telemetering capability to cope with the 3 km/sec (6700 mph) speed of vertical descent of the bus (at an altitude of 150 km (93 miles)). The bus was traveling even much faster as it entered the atmosphere, but it made a very shallow entry so most of its speed was in a horizontal direction. One day before the bus encountered Venus, a known amount of gas was released from a small glass vial into the instrument for calibration purposes. It provided a reference for the sensitivity of the instrument after its cruise through interplanetary space. (The principal investigator for this experiment was Ulf von Zahn, University of Bonn, West Germany.)

The instrument was a double-focusing Mattauch-Herzog electric and magnetic deflection mass spectrometer. It permitted a small, compact arrangement and provided constant sensitivity at high pressures. The design also permitted the use of a dual collector system to provide a large dynamic signal range.

The spectrometer consisted of four major parts: an ion source, where the atmospheric particles were ionized by electron bombardment; an electric analyzer, for mass separation of the ions; and a collector system, consisting of multiple elements so that ions of more than one mass could be collected simultaneously according to their mass. The two detectors were spiraltron electron multipliers; one detected ions between 1 and 8 atomic mass units, and the other detected ions between 12 and 46 atomic mass units. In addition, a titanium sublimation pump and an ion getter pump maintained a pressure differential between ion source and mass analyzer of more than 1000 to 1.

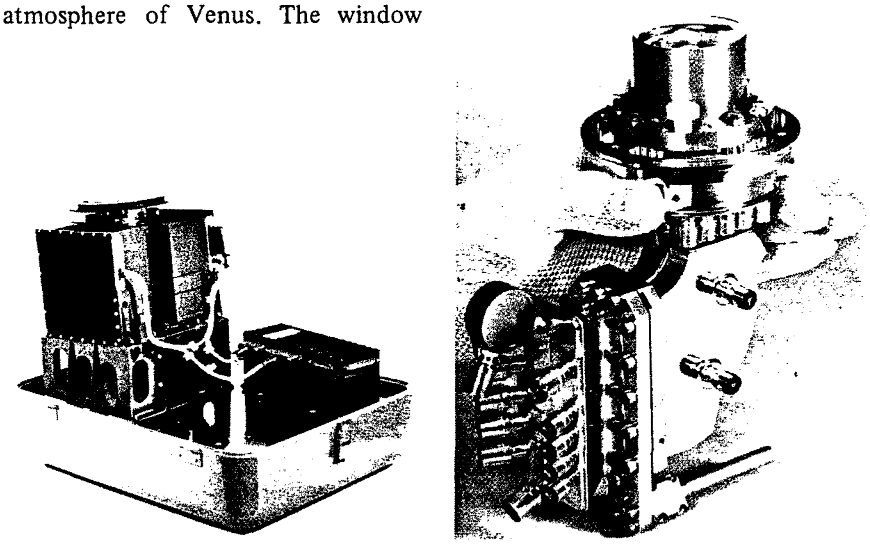
The instrument operated in a peak stepping mode for which only the tops of selected mass peaks and required zero levels were sampled. Below altitudes of about 215 km (135 miles), the instrument operated for about 25% of the time in a fly-through mode, in which only high-energy ions were sampled.

Ion Mass Spectrometer

The ion mass spectrometer used on the bus was identical to the ion mass spectrometer used on the Orbiter. It measured the distribution and concentration of positively charged ions in the upper atmosphere of Venus above 120 km (75 miles). (The principal investigator was H. Taylor, Goddard Space Flight Center, NASA. Taylor was also principal investigator for the ion mass spectrometer experiment described in the Orbiter Instruments and Experiments section.)

LARGE PROBE EXPERIMENTS

There were seven scientific instruments aboard the large probe. A gas chromatograph and a mass spectrometer measured the composition of the atmosphere directly and a group of pressure sensors measured pressure directly, with inlet ports penetrating the shell of the probe. The other five instruments observed through windows in the probe, sensed the motion of the probe, or measured temperature through externally mounted sensors. An infrared radiometer required a diamond window because diamond is the only material transparent to the wavelengths to be observed and also capable of withstanding the high temperatures and pressures within the lower atmosphere of Venus. The window was about 1.9 cm (0.75 in.) in diameter and 0.32 cm (0.125 in.) thick, or about the size of a quarter. It weighed 13.5 carats and was shaped by diamond cutters in the Netherlands from a 205-carat industrial grade rough diamond from South Africa. A nephelometer used two sapphire windows. A cloud particle instrument directed a laser beam through a sapphire window to an outside reflecting prism and then back to its sensor. A solar flux radiometer used five sapphire windows.



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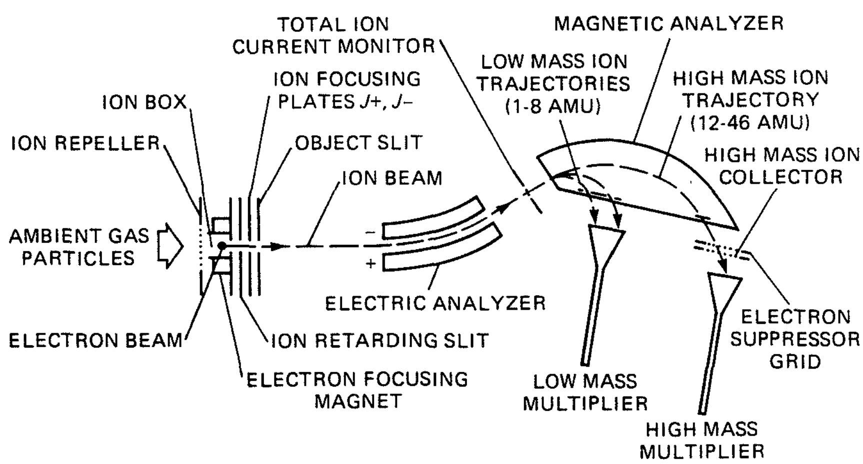

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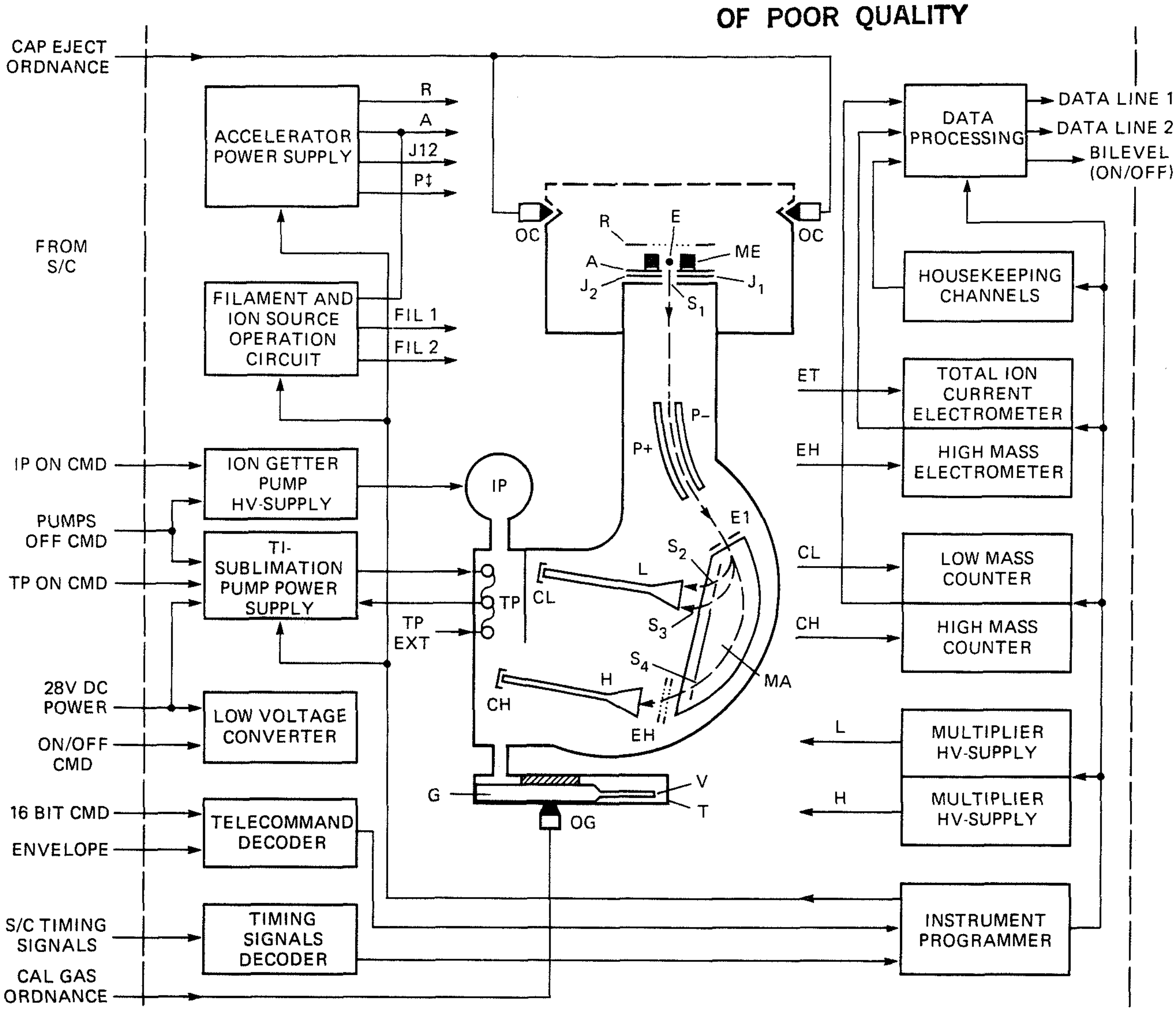
Figure 4-12. Neutral mass spectrometer used on the Multiprobe Bus (BNMS). (a) Mass spectrometer and the electronics package. (b) The path of the ionized gas through the instrument to the detectors. (c) Schematic of instruments. (d) U. von Zahn, principal investigator.



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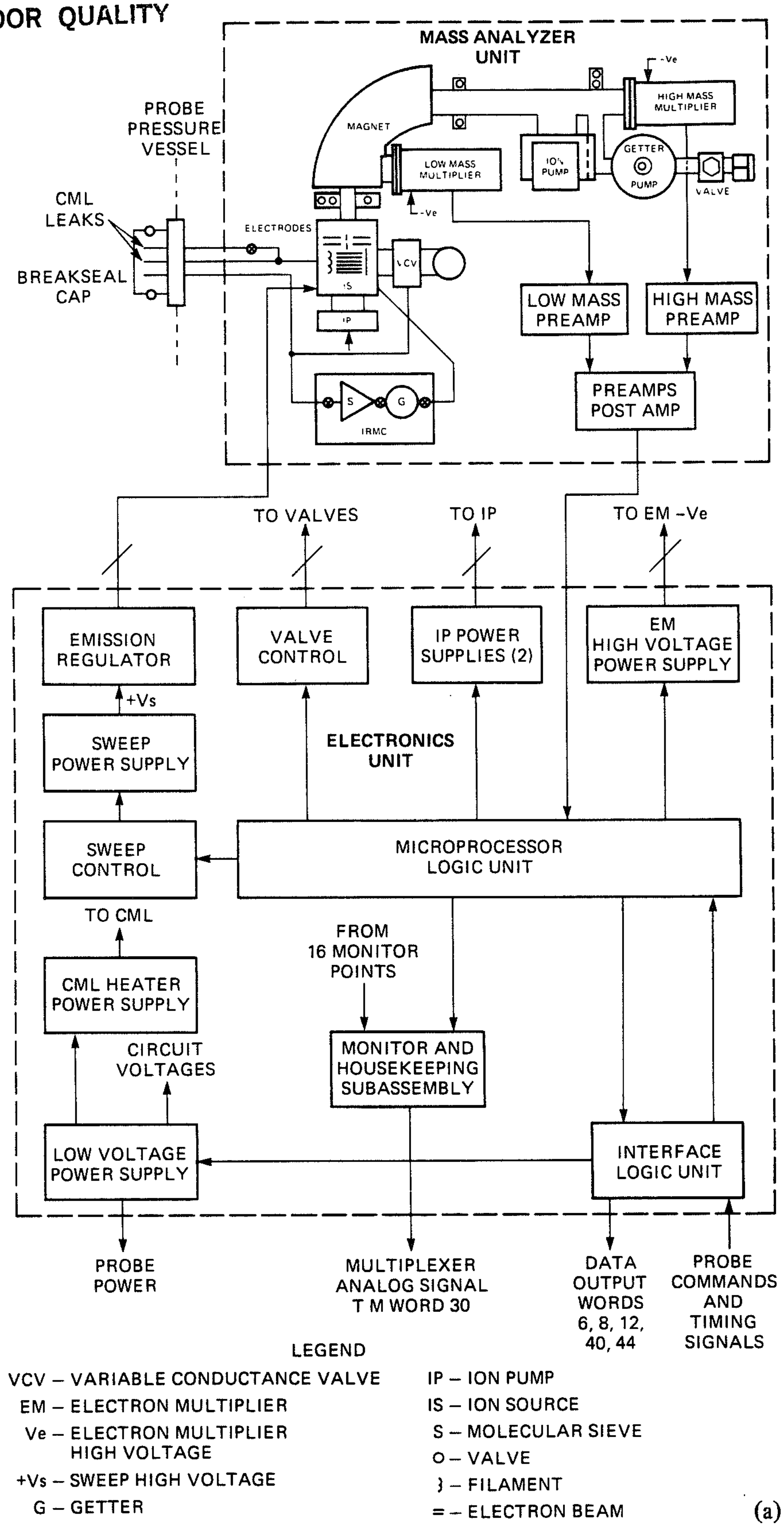
Neutral Mass Spectrometer

The neutral mass spectrometer (fig. 4-13) measured the composition of the lower 62 km (38 miles) of the atmosphere of Venus, most of which was below the cloud layers. Knowledge of the relative abundance of gases in this region is required to gain a better understanding of the evolution, structure, and heat balance of the planet.

The instrument, which weighed 10.9 kg (24 lb) and required 14 W of electrical power, consisted of two units mounted on a single baseplate located on the lower shelf of the probe. A mass analyzer, ion source, pumping system, isotope ratio measuring cell, and valves were in one unit; the electronics were housed in the other. (The principal investigator was J. Hoffman, University of Texas, Dallas.)

The instrument was designed to have wide dynamic and mass ranges to survey the atmospheric gases and determine the composition of the clouds. Special care had to be taken in the design to make sure that chemically active species were not altered by the sampling process. Samples were collected through a chemically passive inlet leak to prevent such alteration.

The inlet consisted of a pair of microleaks, each being formed by compressing the tip of a tantalum tube into a slit. The tubes projected



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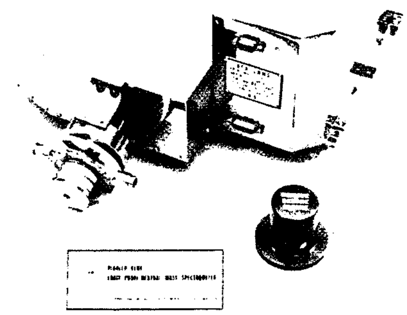
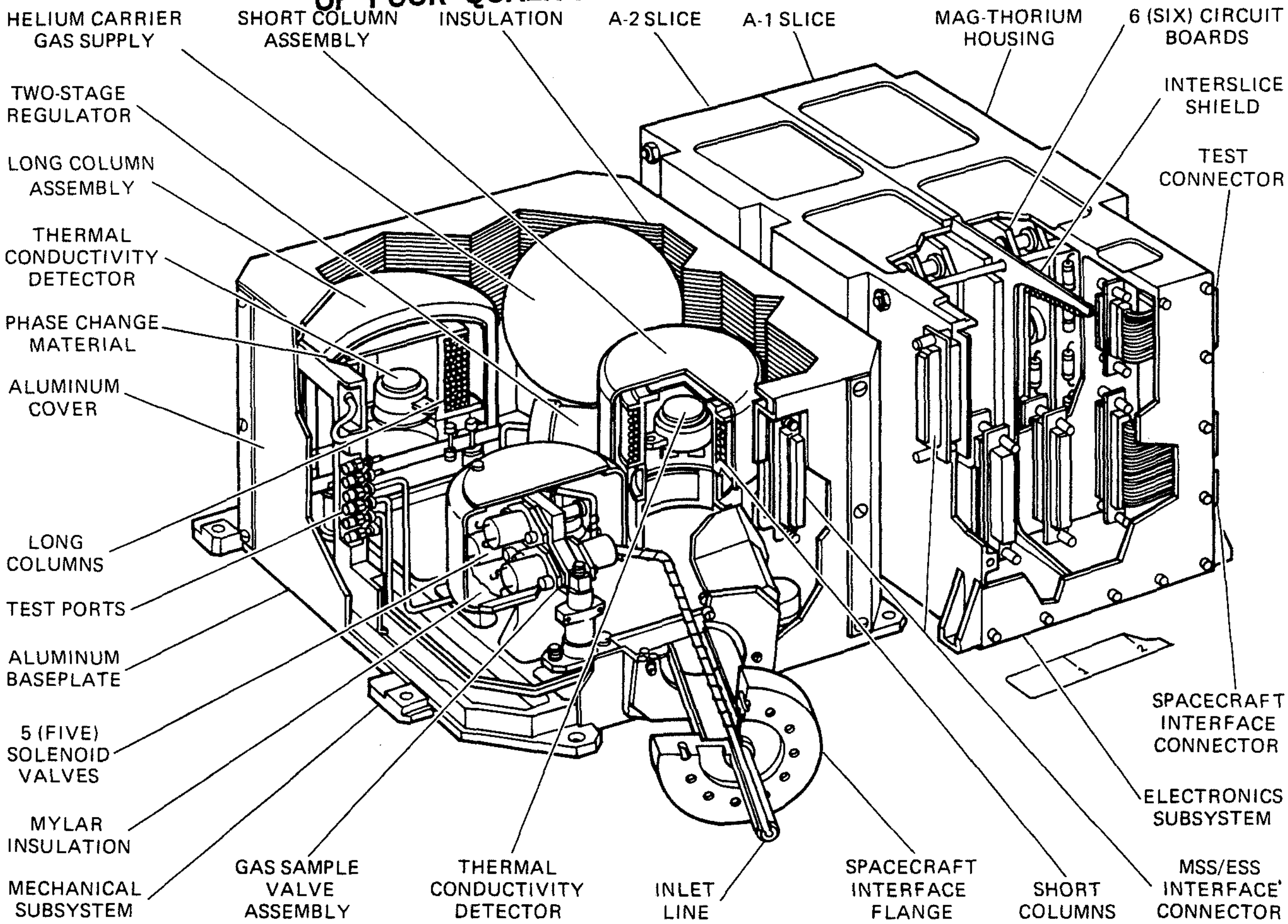


(b)

(c)

Figure 4-13. Neutral mass spectrometer used on the large probe (LNMS). (a) Functional block diagram of the instrument. (b) Electronics unit (right) and the mass analyzer unit. (c) Principal investigator, J. H. Hoffman.

through the probe wall out beyond the boundary layer. The tube with the larger conductance was closed off when the atmospheric pressure reached 1.5 bars to prevent too great a sample deeper within the atmosphere when pressure increased rapidly. Atmospheric gases and vapors passed into an ion source which was pumped through a valve (variable conductance valve) that gradually opened during descent to keep a constant pressure at the ion source. The gas sample was analyzed by a magnetic sector field mass spectrometer, the range of which extended from 1 to 208 atomic mass units and the sensitivity of which was great enough to detect minor constituents present in 1-ppm concentration over the entire descent. The ioniz-



(a)

ing electron energy was stepped through three levels to aid in identifying unknown substances and in separating parent peaks from fragmentary ions.

Each mass spectrum took 64 sec to sample. A microprocessor controlled the mass scan mode, the sequencing of the ion source energy, the accumulation of data, and data formatting. Accumulated counts for each spectral peak were converted into 10-bit, base-2, floating-point numbers. A data rate of only 40 bits/sec was required to transmit to Earth the data from about 50 spectra obtained during the descent. Atmospheric gas densities relative to carbon dioxide were measured. The microprocessor (an Intel 4004) was the first ever flown on a NASA spacecraft.

The instrument incorporated an isotope ratio measuring cell into which a sample was collected shortly after deployment of the parachute. In this cell, the sample was purged of carbon dioxide and other active gases to obtain an enriched sample of inert gases. Then the ion-source cavity was pumped out and the sample was analyzed to determine the isotope ratios of such inert gases as xenon, argon, neon, all of which are important to gaining a better understanding of how the atmosphere of Venus evolved.

Gas Chromatograph

The gas chromatograph experiment also measured the gaseous composition of the lower atmosphere of Venus. It was a modified version of part of the gas exchange experiment carried by the Viking lander spacecraft. It was designed to measure gases likely to be present on Venus, with the aim of answering questions about the evolution, structure, and thermal balance on Venus. (The principal investigator was V. Oyama, Ames Research Center, NASA.)

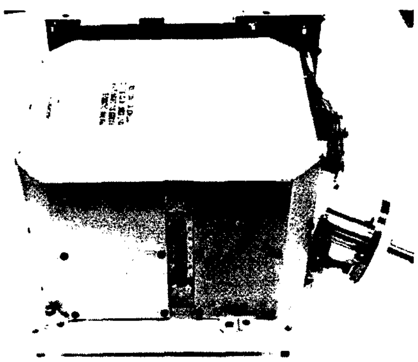


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Figure 4-14. Large probe with gas chromatograph (LGC). (a) Cutaway drawing. (b) Photo of the instrument. (c) Electrical and mechanical schematic. (d) V. Oyama.

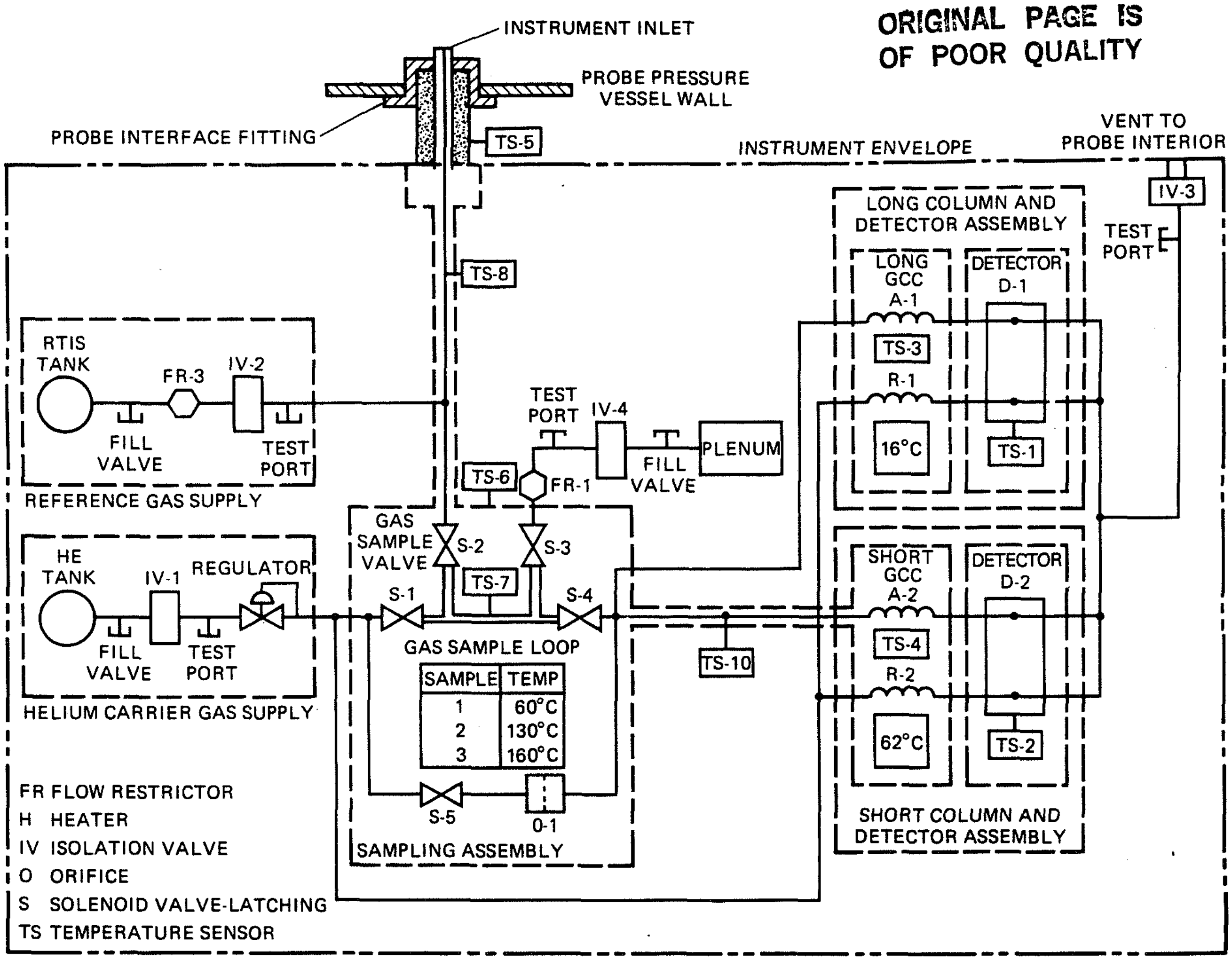

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Figure 4-14.

The instrument (fig. 4-14) weighed 6.3 kg (13.9 lb) and required 42 W of electrical power. It sampled the lower atmosphere three times during the descent of the large probe. During each sampling process, atmosphere flowed through a tube into a helium gas stream which swept the sample into two chromatograph column assemblies. There the atmospheric constituents were identified by the time it took each to flow through the columns. A long column assembly consisted of a matched pair of 1585-cm (624-in.) packed columns bifilarly wound. Each column contained polystyrene (Porapak N) and was operated at 18°C (64°F), the temperature being controlled by a proportional heater surrounded by a shell of phase change material (n-hexadecane). The long columns were used for gases with masses between those of neon and carbon dioxide. There was also a short column assembly consisting of similarly wound 244-cm (96-in.) columns that contained a mixture of polymer spheres (80% polydivinyl benzene, 20% ethylvinylbenzene), kept at an operating temperature of 62°C (144°F). These short columns were used for gases in the mass range from carbon dioxide to sulfur dioxide. As the gases sequentially emerged from the columns, they were passed to a thermal conductivity detector that generated data. These data were stored in a buffer memory awaiting telemetry.

As a calibration check, two samples of freon, a gas not likely to be present in the atmosphere of Venus, were added to the third sample.

Solar Flux Radiometer

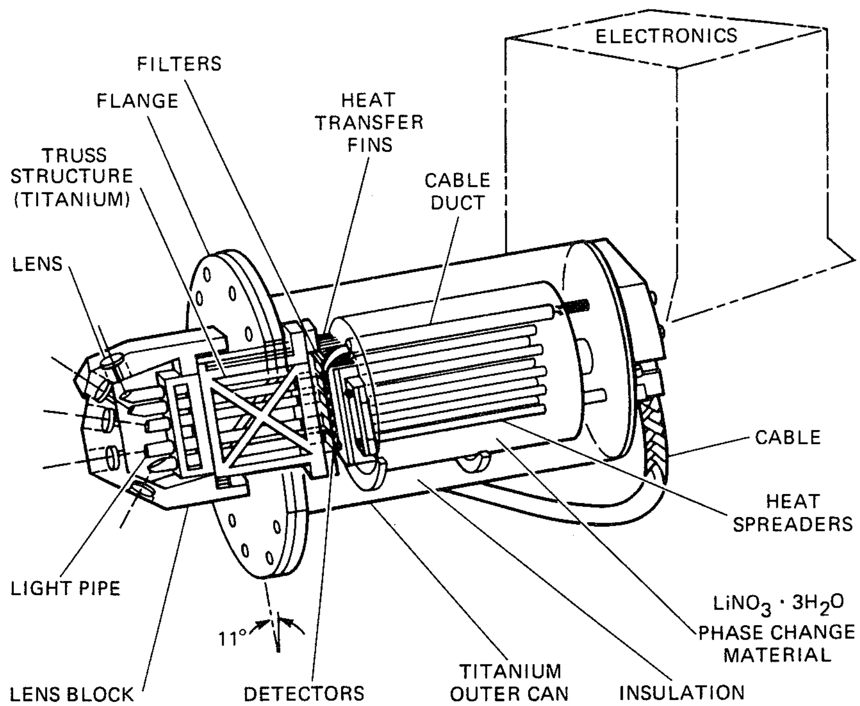
The aim of the solar flux experiment was to measure the height of the region in the Venusian atmosphere at which solar energy is deposited to heat the atmosphere. (The principal investigator was M. Tomasko, University of Arizona.) The solar flux radiometer (fig. 4-15) weighed 1.6 kg (3.5 lb) and required 4 W of electrical power. It revealed how much sunlight was absorbed by the clouds and how much reached the surface, information important to determining if the heating of Venus is a result of a greenhouse effect, with the planet absorbing solar energy efficiently but reradiating it inefficiently.

The instrument continually measured the difference in intensity of sunlight directly above and below the horizon of the probe. Five quartz lenses (3 mm (0.125 in.) in diameter) inside five flat sapphire windows collected the light and transmitted it along quartz rods to a detector array of 12 separate photovoltaic detectors. The intensity of the sunlight was detected over the spectral range of 0.4 to 1.8 μm, where 83% of the solar energy is concentrated. Two broad and flat spectral channels were included at each azimuth and zenith sample; one filtered a channel from 0.4 to 1.0 μm, the other a channel from 1.0 to 1.8 μm. Also, there was a narrow filter from 0.6 to 0.65 μm, that was read at one of the upward-looking zenith samples and one of the downward-looking samples. This channel was used to obtain information about the single scattering albedo and the optical depth of the clouds during descent.

The detector array was cooled by being mounted on a mass of phase-change lithium salt that absorbed heat in melting. The detector head consisted of lenses, quartz rods, filters, detectors, and their supporting structure. There were 12 electronic channels of the detector head, and the electronics package contained 12 logarithmic amplifiers for these channels.

To avoid having either the probe itself or the parachute affect the measurements, the field of view of the instrument was made quite narrow – 5° and only over a selected set of azimuth and zenith angles.

The instrument operated in two modes. To begin with it detected the intensity peak at the solar azimuth and used the time of successive peaks to control a mode-1 azimuth sampling in accordance with preset values. If a period of 16 sec passed without a peak being detected, the instrument automatically switched to a second mode. In this mode-2, samples were collected at each zenith angle as frequently as the telemetry rate allowed; namely, every 8 sec. This provided a vertical resolution of 300 m (984 ft) which was 2.67 times better than that



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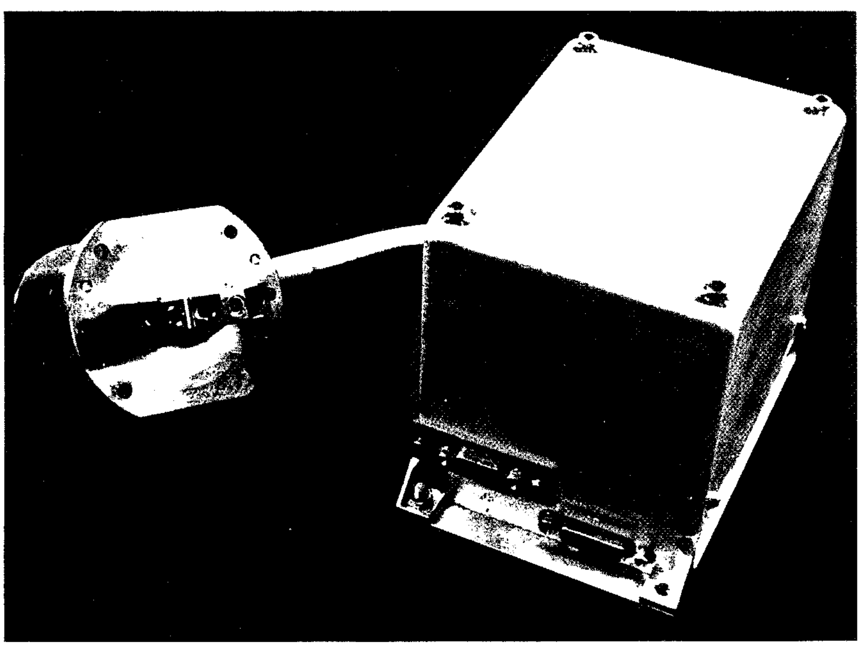


(b)

Figure 4-15. Solar flux radiometer carried by the large probe (LSFR). (a) Detector head of the instrument. (b) Head and the electronics package.

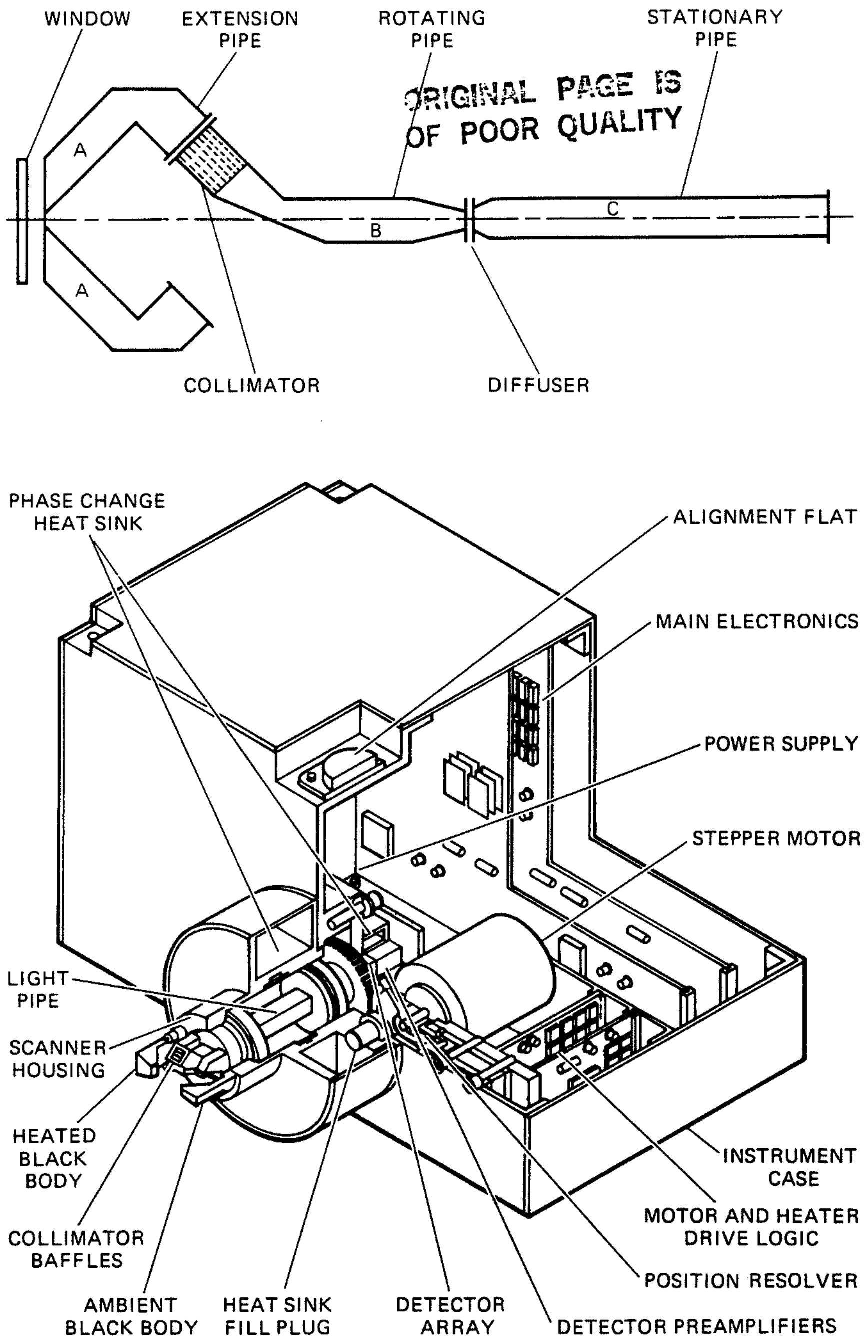
obtained during mode-1 operations. When the probe reached 54 km (34 miles) the instrument was locked into mode-2 for the rest of the descent.

Infrared Radiometer

The infrared radiometer (fig. 4-16) measured the vertical distribution of infrared radiation in the atmosphere from the time the large probe parachute was deployed until the probe reached the surface of the planet. It also detected cloud layers and water vapor, both of which may be important traps for solar heat. The instrument weighed 2.6 kg (5.8 lb) and required 5.5 W of electrical power. (The principal investigator for this experiment was R. Boese, Ames Research Center, NASA.)

The radiometer consisted of two sections: an optical head and an electronics box. It was located on the aft side of the probe's forward shelf and gathered its information through a diamond window, which was heated to prevent contamination during descent through the clouds. The window provided an unobstructed conical field of view of 25° centered at 45° upward and downward from the horizontal.

Six pyroelectric infrared detectors were chosen. Because they require no special cooling equipment, they were well suited to the high temperature conditions of Venus. Each detector viewed the atmosphere via rotating light pipes (to minimize stray light) through a different infrared filter between 3 and 50 μm. These detectors possessed uniform sensitivity throughout the infrared. Although the detectors needed no protection from heating, the preamplifiers, which were closely connected to them, had to be protected. The detector package was surrounded by phase-change material to keep the temperature relatively constant. The six filters for the six channels covered the ranges: 3 to <50 μm, 6 to 7 μm, 7 to 8 μm, 8 to 9 μm, 14.5 to 15.5 μm, and 4 to 5 μm. The first channel allowed measurement of the entire thermal flux. The next two channels were used to search for water vapor. The fourth channel provided information on the opacity of the clouds; the fifth channel was centered in a strong band of carbon dioxide so that it revealed any



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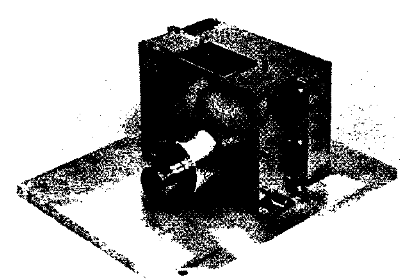

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Figure 4-16. Large probe infrared radiometer (LIR). (a) Schematic configuration of the instrument (top) and diagram of the detector-filter package. (b) LIR.

obscuration of the outer window. The sixth band was used to determine the temperature of the window itself.

Two black bodies within the instrument provided a calibration system since these two bodies were maintained at temperatures sufficiently different to generate a signal-to-noise ratio of at least 100:1 in all the detector-filter channels. The instrument was commanded into this calibrate mode approximately 6% of the time during descent.

An electronics box conditioned power from the spacecraft's electrical system to provide closely regulated voltages needed by items within the instrument. It also conditioned the output signals from the detectors and prepared the data for telemetry to Earth.

Vertical resolution within the atmosphere of Venus varied from about 250 m (820 ft) at the top of the atmosphere to about 90 m (295 ft) near the surface. This was governed by the telemetry bit rate assigned to the experiment, which allowed integration of data over a 6-sec period.

Cloud Particle Size Spectrometer

The cloud particle size spectrometer (fig. 4-17) measured the particle size and shape and density within the clouds and in the lower atmosphere. By measuring particle size and mass, the investigation (under the direction of R. Knollenberg, Particle Measuring Systems, Inc.) provided a vertical profile of particulate concentration for 34 different size classifications, ranging from 1 to 500 μm. Such measurements provided clues to basic cloud formation processes and the interactions between the clouds and sunlight. The spectrometer also was used to determine if ice crystals were present; if they were, the instrument would differentiate them from other crystalline particles by determining if they had the characteristic ratio of particle thickness to size for ice.

With this instrument, the heights of clouds were resolved to within 400 m (1312 ft). Its prime measuring technique was that of optical array spectrometry. This technique covered particle sizes in sequential ranges of 5 to 50 μm, 20 to 200 μm, and 50 to 500 μm, using multiplexed photodiode arrays. Each size range included 10 size classes of equal size width. Also, a scattering subrange used one of the light paths to measure particle sizes from 0.5 to 5 μm.

The instrument, which weighed 4.4 kg (9.6 lb) and required 20 W of electrical power, directed a laser beam onto an external prism supported 15 cm (6 in.) from the outer surface of the pressure vessel of the probe. This prism was mechanically decoupled from the wall of the pressure vessel by a metal flexible bellows. The prism directed the beam back into the pressure vessel to a backscatter detector, where three independent optical paths were generated by a system of lenses and beam splitters. As a particle entered the field of view of the instrument, its shadow was cast onto a photodiode array detector where its size could be measured and recorded. Another way of measuring particle size involved using the light scattered by single particles; this resolved 5-μm particles. A third measurement of particle transit time, that is, the time required for a particle to pass through the beam, determined the average thickness of the particle.

EXPERIMENTS COMMON TO LARGE AND SMALL PROBES

There were two experiments common to the three small probes and the large probe: the atmospheric structure experiment and the nephelometer experiment. Each of the four probes carried identical instruments for these experiments.

Atmospheric Structure Experiment

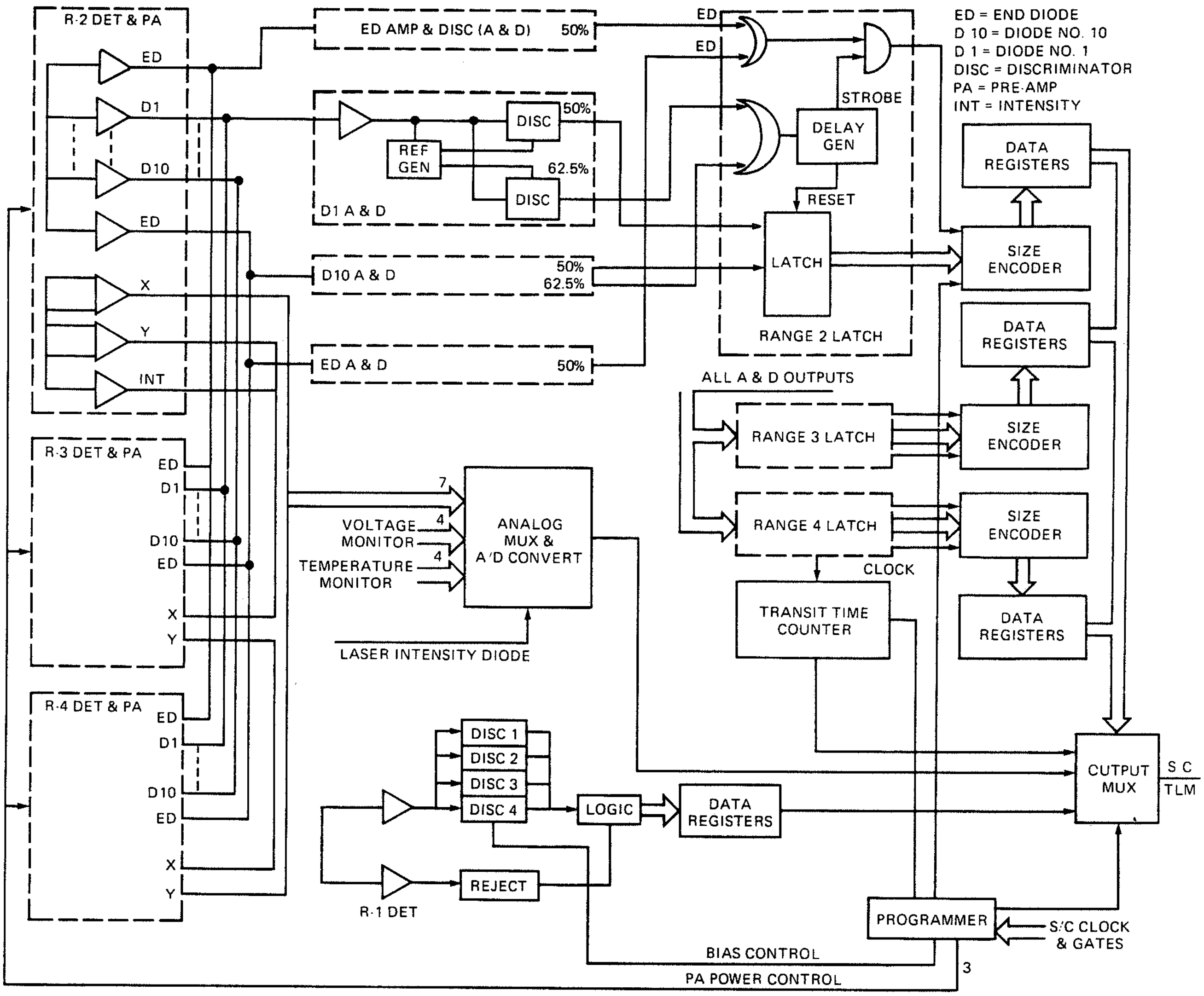
The atmospheric structure experiment was aimed at finding the structure of the Venusian atmosphere from 200 km (124 miles) down to the surface at four well-separated entry sites. Temperature, pressure, and acceleration sensors on all four probes yielded data on the location and intensity of atmospheric turbulence, the variation of temperature with pressure and altitude, the average molecular weight of the atmosphere, and the radial distance from the center of the planet. (A. Seiff, Ames Research Center, NASA, was the principal investigator.)

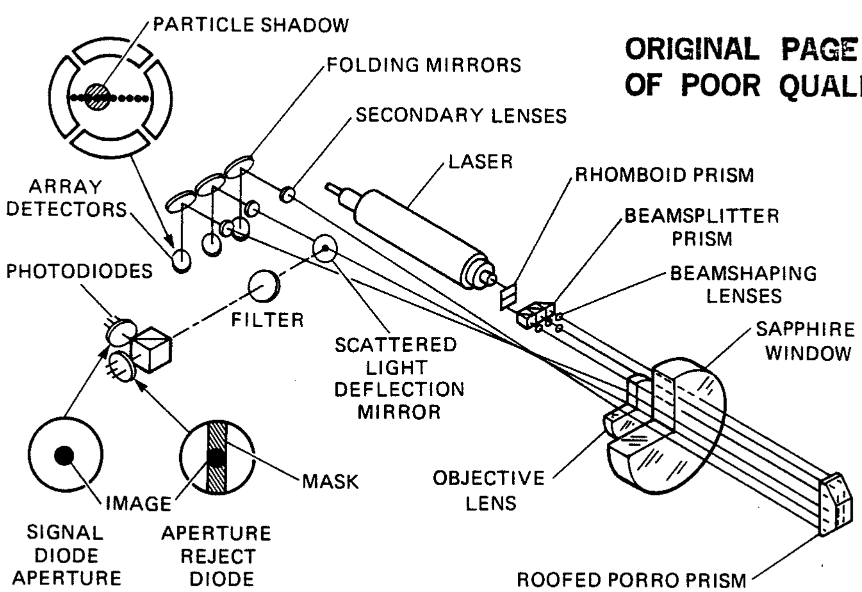
The instruments used for this experiment on the large probe weighed 2.3 kg (5.1 lb) and required 4.9 W of electrical power. The instruments on each small probe weighed 1.2 kg (2.7 lb) and required 3.5 W of electrical power (fig. 4-18).

The temperature sensors were dual resistance thermometers. Each had one free wire element protruding into the atmosphere for maximum sensitivity, and one element bonded to the support frame for maximum survivability. Temperatures from -100°C (-148°F) to +525°C (977°F) could be recorded. The sensor was stimulated by a current source of 10 mA, constant to within 20 ppm, and the potential drop across the sensor was read to provide the measure of temperature.

The pressure sensors were multiple-range, miniature, silicon-diaphragm sensors. They had to operate over a wide dynamic range from 30 mbars to 100 bars. To meet this requirement, 12 sensors were used, each of which was to cover a relatively small range of pressure. These 12 sensors were sampled in a way that preserved data even if one of them should not work properly. Each sensor had a strain element, which was diffusion-bonded onto the pressure side of the diaphragm. The four resistors were arranged as a Wheatstone bridge. Two resistors could deform, two could not.

The acceleration sensors (four on the large probe, one on each small probe) were developed from highly accurate guidance accelerometers. They used a pendulous mass maintained in a null position by the interaction with a permanent magnetic field of a current in a coil inside the mass.





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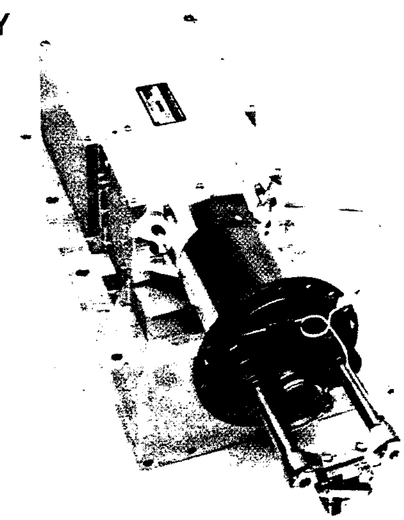

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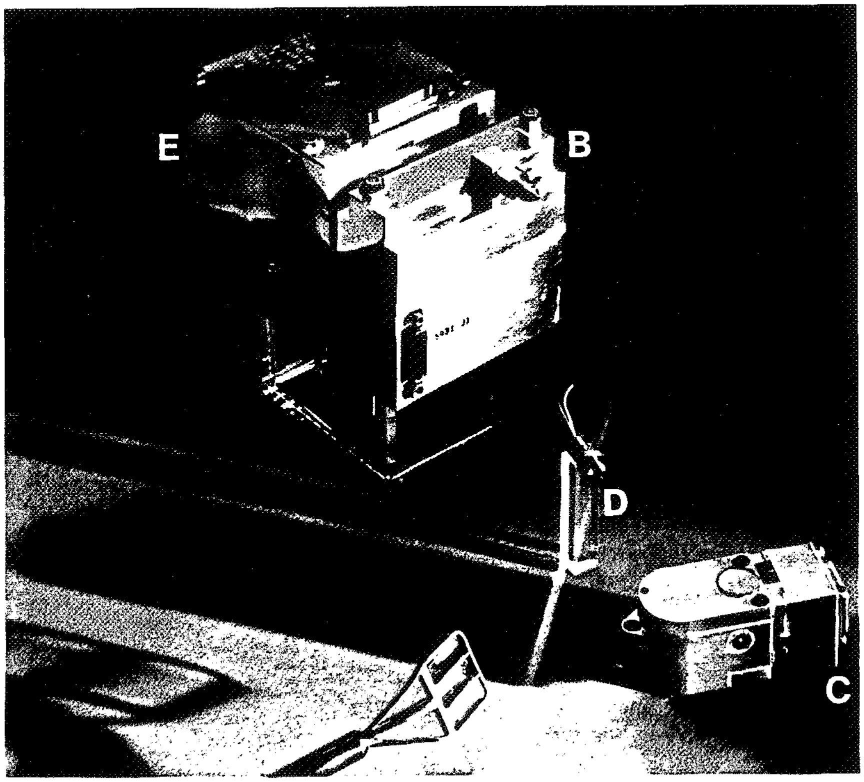
Figure 4-17. Cloud particle size spectrometer (LCPS) carried by the large probe. (a) General arrangement of the spectrometer (top), optical path (bottom). (b) Photo of the instrument.



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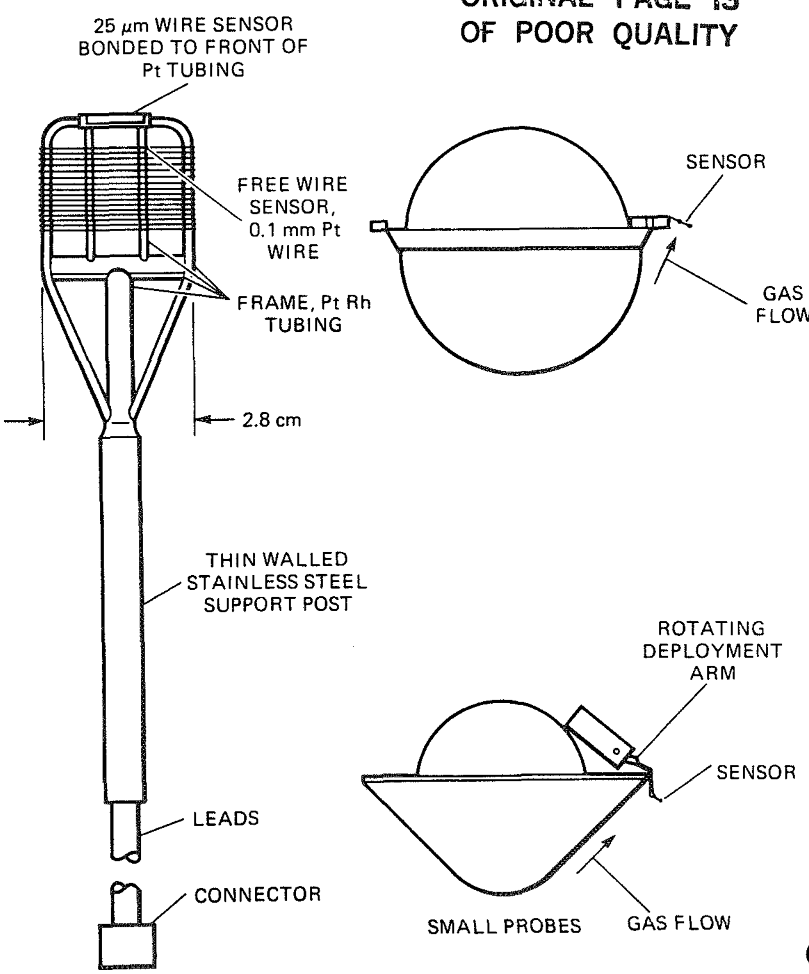

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The amount of current needed to keep the pendulous mass in the null position was a measure of the acceleration. The sensors were range switched from 0.4 microgravity to 600 gravities by changing load resistors and amplifier gain. There were four ranges for use during entry and two for use during descent.

An electronics package distributed power to the sensors, sampled their output, changed their ranges as required, and stored their data ready for telemetry. There were separate data formats for the high-speed entry phase, transition to the descent phase, the descent phase itself, and for use if the probe survived on the surface.

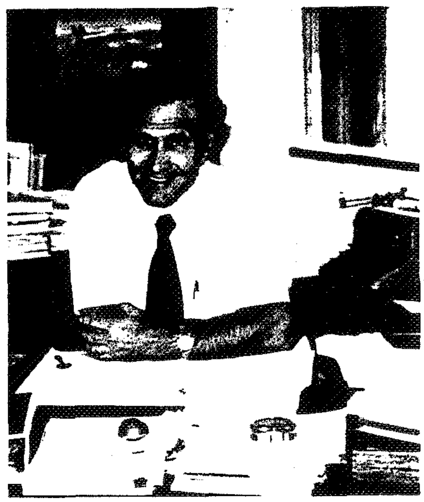

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Figure 4-18. Atmospheric structure experiment carried by all probes (LAS/SAS). (a) Instrument with atmospheric temperature semsor A, a multirage atmospheric pressure semsor B, a single-axis accelerometer C, and the electronics package E. An individual pressure sensor like the 12 which comprise the multirage sensor is shown at D. The large probe instrument was the same as that on the small probes except for the accelerometer which had four sensors like C to measure aerodynamic accelerations in three axes, with a redundant sensor in the direction of the probe axis for symmetry. (b) Temperature sensor and installation on a probe. (c) A. Seiff, principal investigator.

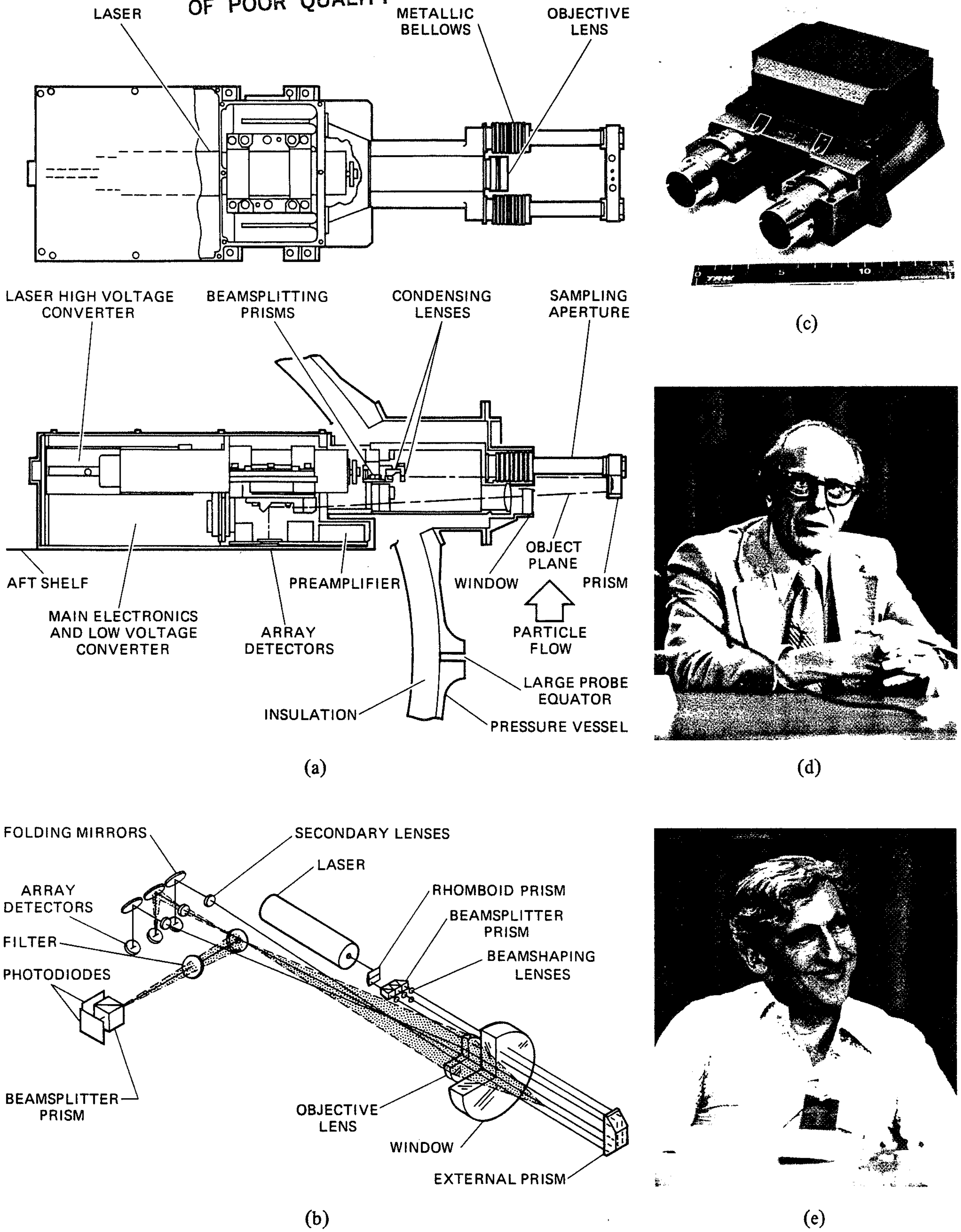


Figure 4-19. Nephelometer (LN/SN) which was used to search for cloud particles as each probe descended through the atmosphere. (a) Details of the instrument. (b) Optical path through the instrument. (c) Photo of the instrument. (d) B. Ragent and (e) J. Blamont, principal co-investigators.

Nephelometer

The nephelometer (fig. 4-19) searched for cloud particles. By providing all four probes with one of these instruments, investigators were able to determine whether cloud layers varied from location to location or were uniformly distributed around the planet. Each instrument weighed 1.1 kg (2.4 lb) and required 2.4 W of electrical power. (The experiment's principal investigators were B. Ragent, Ames Research Center, NASA, and J. Blamont, University of Paris, France.)

To investigate cloud particles, a solid-state emitter operating at 9000 Å was used to illuminate the surrounding Venusian atmosphere near the probe at distances outside the aerodynamically disturbed region. The intensity of the light backscattered by atmospheric particles was measured. On those probes entering the sunlit hemisphere, background solar light penetrating the atmosphere was also monitored at two wavelengths: 3550 Å and 5200 Å. The light-emitting diode (LED) illuminated the atmosphere through a window mounted in the pressure vessel of the probe. Through a second window, receivers measured the intensity of the scattered LED light, focused by a plastic Fresnel lens, and the background solar light. Calibration targets were fixed to the window covers of the small probes and to the aeroshell on the large probe.

The instrument consisted of an optical subsystem and an electronics subsystem. The former consisted of two major optical trains of elements: a transmitter, a receiver, and a lens barrel for each. A fiber optics light pipe, shielded from direct reflections, conducted some of the light reflected from the front surface of the window through which the transmitted light passed from the probe. This light pipe was used to monitor the state of the window and also the condition of the light-emitting diode. There were three solid-state photodiodes to detect the backscattered light, ultraviolet background, and visible background. The lens barrels for each channel gave some thermal insulation and collimated the light. Further thermal insulation was obtained by borosilicate glass elements.

The electronic subsystem converted electrical power to meet the requirements of the instrument. It provided timing and logic control, conditioned the LED pulse power, and compressed the data and prepared it for telemetry. The digital data provided for telemetry included the measurements of the backscattered light and also calibration and monitoring data such as temperature, channel noise, and the window condition.

Investigators used the experiment to construct a vertical profile of particle distribution in the lower atmosphere. In addition, the two small probes descending on the sunlit side of the planet measured the vertical distribution of scattered solar light in the ultraviolet and visible regions of the spectrum.

SMALL PROBE EXPERIMENT

One experiment was exclusive to the small probes – the net flux radiometer experiment, aimed at mapping the planetary positions of sources and absorbers of radiative energy and their vertical distribution, important to our understanding of how the atmospheric circulation on Venus is powered. (The principal investigator for this experiment was V. Suomi, University of Wisconsin.)

The instrument (fig. 4-20) weighed 1.1 kg (2.4 lb) and required 3.8 W of electrical power. It consisted of a sensor assembly mounted outside the pressure vessel of each small probe. This assembly was carried inside a protective enclosure and was deployed only after the probe experienced its maximum deceleration during entry into the atmosphere. The sensor was a net flux detector mounted on an extension shaft which could be rotated periodically through 180° to cancel offsets of the instrument and to reduce the effects of asymmetric heating. The detector also included a temperature sensor and a heater. The latter was included to reduce condensation on the diamond windows of the detector. (The windows – two per detector – were cut from the same stone used for the infrared radiometer window.)

The flux plate was oriented parallel to the surface of Venus. A difference between upward and downward radiant energy falling on the two sides of the flux plate produced a temperature gradient through it. This induced an electric current, which was a measure of the flux difference. The plate was flipped through 180° every second.

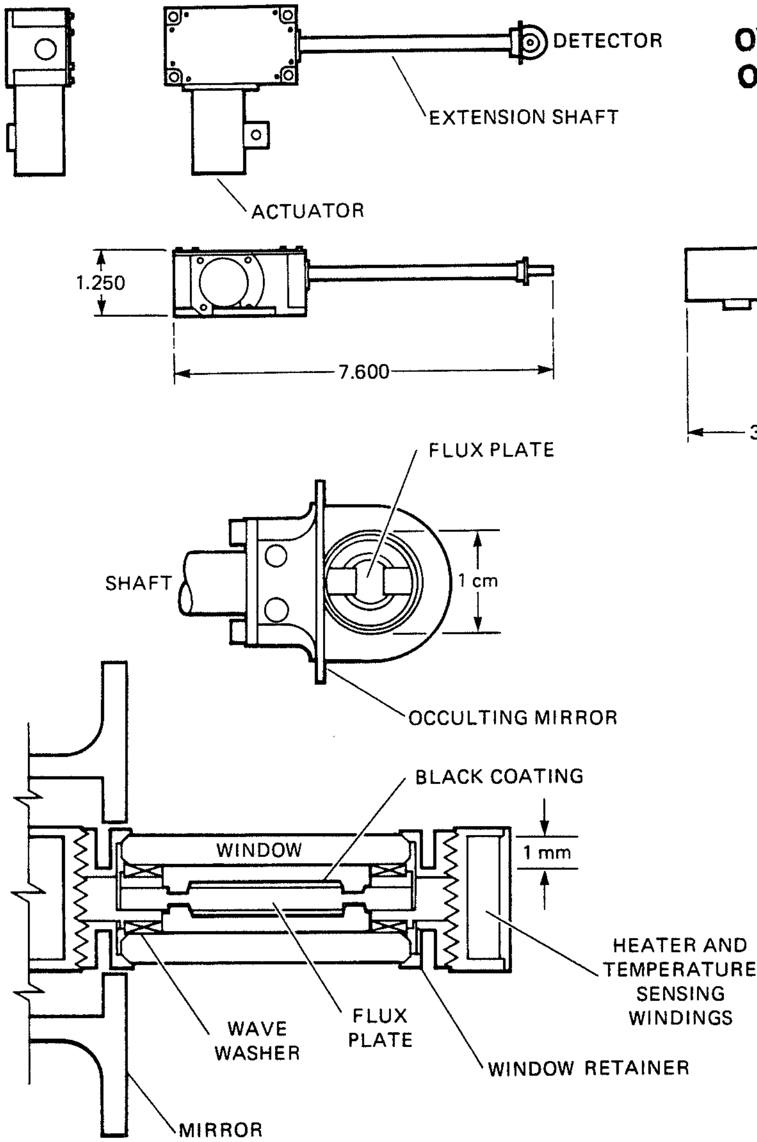
An electronics module processed two flux parameters: the integral, time-averaged flux, and the maximum and minimum values of a periodic input. The system operated over four dynamic ranges and was controlled by internal timing. In addition to the science measurements, the instrument transmitted the detector housing temperature, the amplifier temperature, and the status of the detector and its heater.

MULTIPROBE RADIO SCIENCE

As with the Orbiter, radio signals from the Multiprobe mission, probes, and bus, were used for a number of experiments that did not require instruments to be carried within the spacecraft. These experiments were a differential, long-baseline interferometry experiment by C. C. Counselman, Massachusetts Institute of Technology, an atmospheric propagation experiment by T. Croft, SRI International, and an atmospheric turbulence experiment by R. Woo, Jet Propulsion Laboratory. (See fig. 4-21.)

Differential Long-Baseline Interferometry

The differential long-baseline interferometry experiment measured the velocity and direction of winds in the Venusian atmosphere as the four



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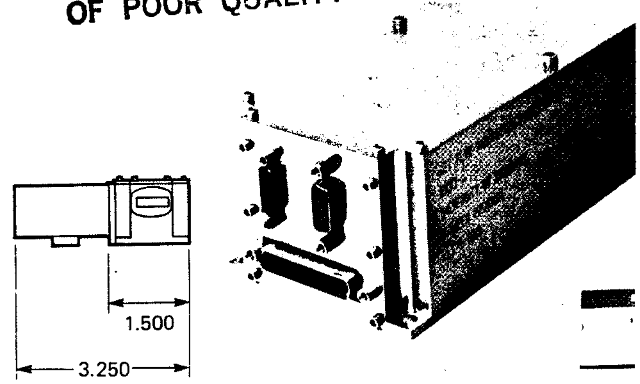

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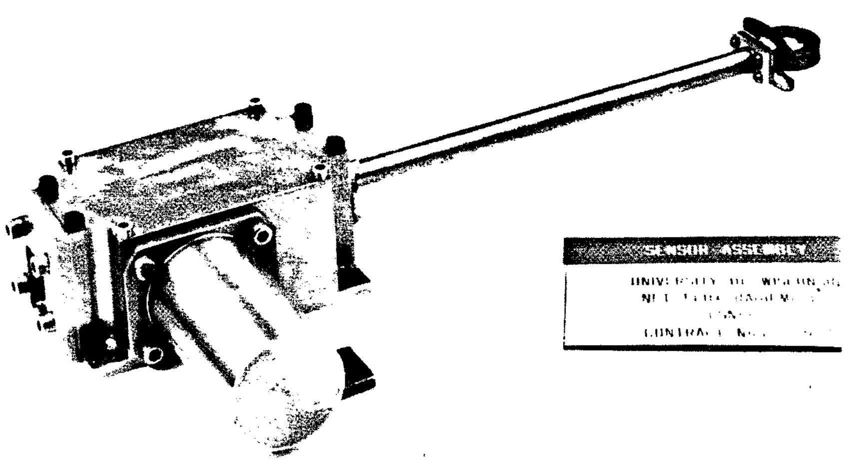

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Figure 4-20. Net flux radiometer experiment (SNFR) carried by each small probe. (a) Sensor assembly (top) and sensor head of the instrument. (b) Sensor. (c) Packaged electronics. (d) V. E. Suomi, principal investigator.

probes descended through it. By comparing the descent paths of the probes with simultaneous measurements of atmospheric temperature and pressure from probe sensors, a better model of the atmospheric circulation was sought.

While the four probes descended to the surface, the bus remained above the atmosphere and followed a ballistic trajectory that could be determined accurately with respect to the planet. Probe velocities were measured differentially with respect to the bus, and velocities relative to the planet were obtained by reference to the known bus trajectory. Deviations of the probe trajectories from the mathematical model of their trajectories in a still atmosphere were attributed to winds.

Two Deep Space Network stations, Goldstone and Canberra, and two Spaceflight Tracking and Data Network stations, Santiago, Chile, and Guam simultaneously tracked all spacecraft. The component of the velocity vector along the Earth-Venus line of sight was inferred from the Doppler frequency shifts of the received signals. Differential long-baseline interferometry was used to find the other two components of the velocity vector of each probe.

Atmospheric Propagation Experiment

The atmospheric propagation experiment attempted to obtain information about the surface and the atmosphere by the effects of the atmosphere on the radio signals from the probes. As the probes descended, some of the transmitted power from the relatively broad antenna beam was reflected from the surface of the planet. This signal was shifted by Doppler effects away from the probe signal by up to 200 Hz. These reflections provided information about the atmospheric winds because they effectively gave a second component of the Doppler shift from a different angle. Data were also obtained from atmospheric refraction and attenuation due to the clouds.

Atmospheric Turbulence Experiment

The atmospheric turbulence experiment (directed by R. Woo) studied turbulence in the Venusian atmosphere by observing the scintillations of the radio signals of probes as each probe penetrated deep into the atmosphere. These data complemented the radio scintillation measurements that are made above 35 km (22 miles) during Orbiter occultations.

INTERDISCIPLINARY SCIENTISTS

For the Pioneer Venus program, several interdisciplinary scientists were selected for both the Multiprobe and Orbiter missions to provide assistance in analyses of the Venusian environment and to generate a broader picture of the results from the individual experiments. These scientists and their affiliations are also listed in appendix A.

The tasks of these scientists (fig. 4-22) included serving as members of a continuing Science Steering Group throughout the nominal and extended missions and analyzing data from different scientific disciplines to provide overviews of the scientific results. Several served as chairmen of working groups. Scientific investigations include developing models for the transport and chemistry of hydrogen, oxygen, and carbon monoxide to resolve questions concerning the stability of the carbon dioxide atmosphere, the theory of the evolution of the atmosphere, and the formation of some of its constituents and clouds (T. M. Donahue). Another interdisciplinary scientist, D. M. Hunten, coordinates the preparation of a monograph on Venus based on two scientific conferences, analyzes the enormous amount of data gathered by the Orbiter concerning the neutral thermosphere, and analyzes data to plan further measurements by the aeronomy instruments carried by the Orbiter.

Siegfried Bauer studies, analyzes, and interprets data from bus and Orbiter experiments to determine the detailed characteristics of the ionosphere of Venus and its interactions with the solar wind by investigating neutral gas composition, thermal structure of both neutrals and plasma, mass transport, and the role of the solar wind and the magnetic field in the physical processes responsible for the origin, maintenance, and variability of the planet's atmosphere.

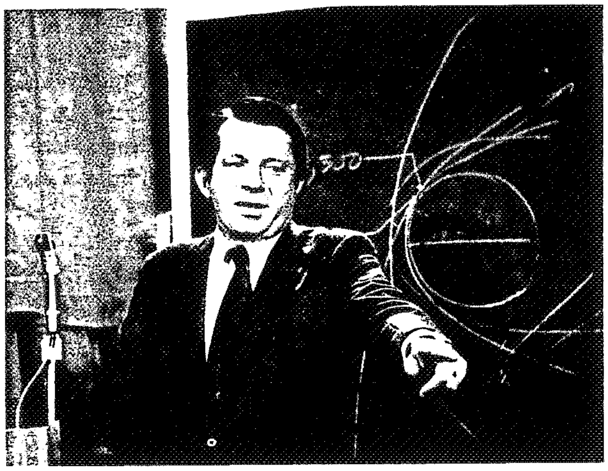
Nelson Spencer concentrates on atmospheric motions by analyzing data from the Orbiter's neutral mass spectrometer to assess probable wind-vector parameters and to calculate atmospheric motions and find out how they correlate with other data and how they relate to basic questions about the atmosphere of Venus.

In a broad study of radar data, G. Pettengill analyzes the data from the radar instrument on board the Orbiter and submits abstract data to the shared data base for use by other scientists. Harold Masursky processes radar data and correlates radar altimetry and image data to produce maps and Venus globes and to perform topical studies of particular regions of Venus and geologic maps of the planet's surface. George E. McGill interprets the topography of Venus by plotting radar altimeter data of selected small regions for detailed analysis of topography and surface properties. He is also studying Venus's tectonics and is generally supporting other scientists working with radar data.

A. F. Nagy develops theoretical models of the ionosphere and performs comparative studies with parametrized models of the planet's atmosphere. He is also chairman of one of the working groups of scientists.

Guest Investigators

Several guest investigators (fig. 4-22) were appointed during the program, their task being to use the data to investigate particular specialized areas of Venus science. S. Kumar, for example, investigates the escape of hydrogen from Venus, and R. S. Wolff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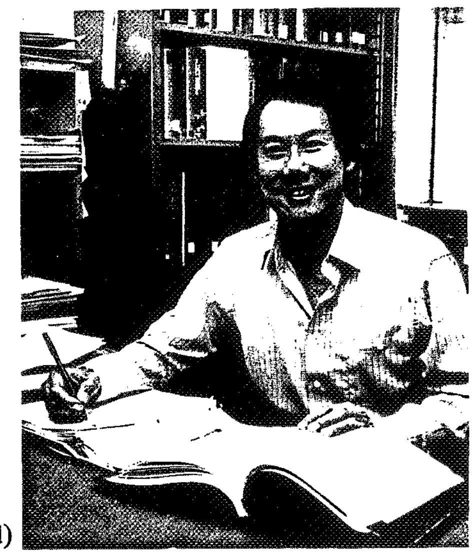
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Figure 4-21. Some of the scientists who used the radio signals from the Pioneer Venus Spacecraft for a number of experiments as described in the text. (a) E. T. Croft. (b) G. Keating. (c) A. Kliore. (d) R. Woo. (e) I. I. Shapiro. (f) R. D. Reasenberg. Others (not shown) are G. H. Pettengill, R. J. Phillips, W. L. Sjogren, R. Prinn, and C. C. Counselman.


(f)

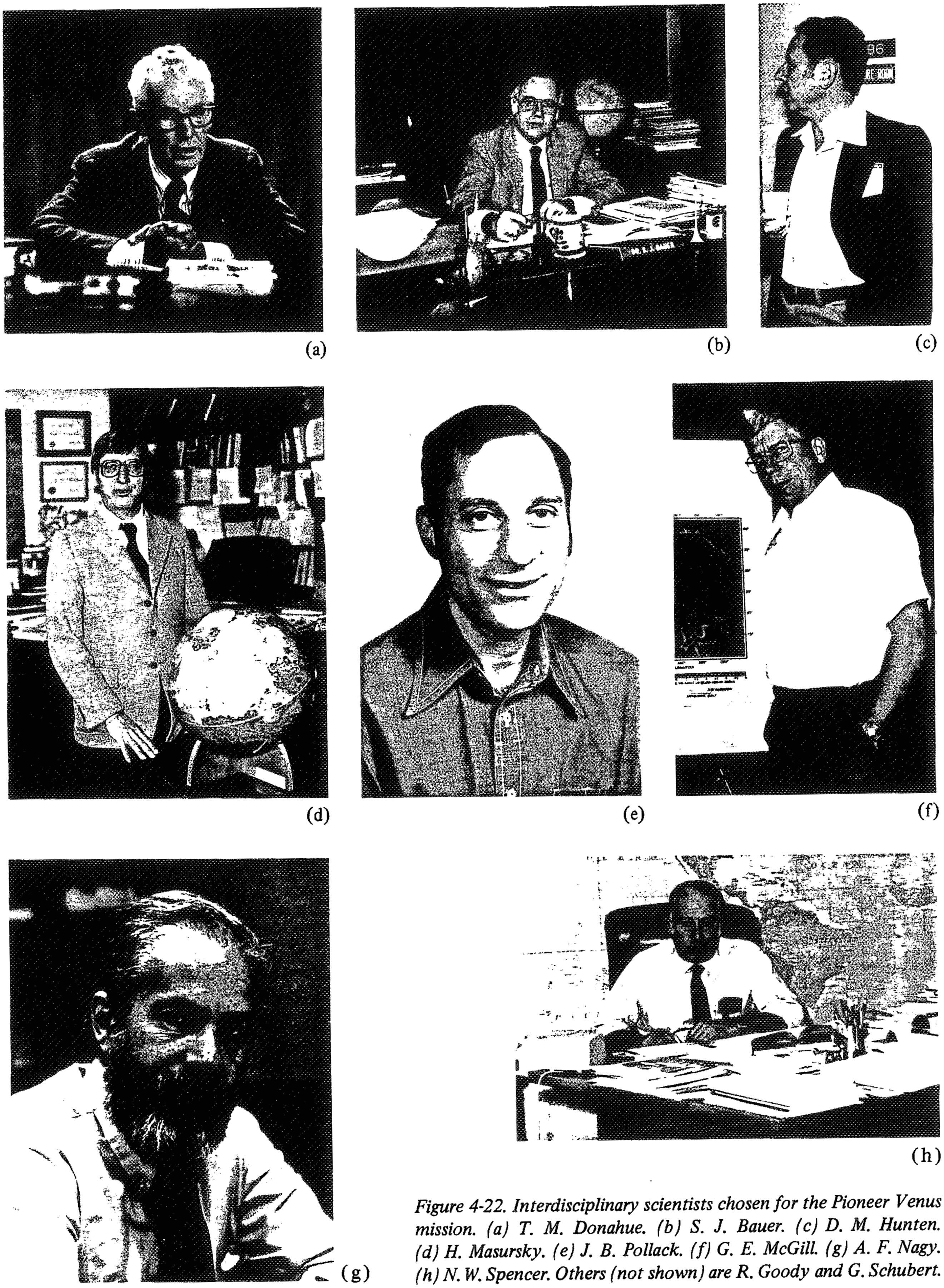

Figure 4-22. Interdisciplinary scientists chosen for the Pioneer Venus mission. (a) T. M. Donahue. (b) S. J. Bauer. (c) D. M. Hunten. (d) H. Masursky. (e) J. B. Pollack. (f) G. E. McGill. (g) A. F. Nagy. (h) N. W. Spencer. Others (not shown) are R. Goody and G. Schubert.

investigates the characteristics and the variability of the dayside ionosphere as a function of solar-wind conditions. A morphological classification of ionospheric density and temperature profiles is correlated with solar-wind dynamic pressure, interplanetary magnetic field direction, sun zenith angle, and planetary latitude. From this classification, a model is constructed to show ionospheric dynamics.

Paul Rodriguez analyzes measurements of plasma waves in the ionosheath to derive the characteristic spectrum of these waves and thereby determine the important wave-particle interactions occurring between the solar wind and the ionosphere. These are compared with conditions in Earth's atmosphere to gain a new understanding of how the solar wind interacts with nonmagnetized planets.

Other guest investigators look at the viscous interaction of the shocked solar wind with the ionosphere of Venus (M. Dryer), the chemistry and transport of thermospheric odd nitrogen (J. C. Gerard), the clouds and atmosphere of Venus (A. T. Young), the role of metastable and doubly ionized species in the chemical and thermal structure of the atmosphere of Venus compared with Mars (J. L. Fox), the morphology and movements of polarization features (S. S. Limaye), and the gravity, topography, and crustal evolution of Venus (C. O. Bowin).

These investigators and their affiliations are listed in appendix A.

C-2

5
Mission to Venus

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BY MID-NOVEMBER 1978, both Pioneer Venus Orbiter and Pioneer Venus Multiprobe were converging on their target. Venus had just passed a closest approach to Earth and was emerging from the Sun's glare, rising as a morning star just before the Sun. Although it had been launched 2-1/2 months later, the Multiprobe was now following closely behind the Orbiter and was being readied for separation of the first of its four probes. On December 4, the Orbiter would be placed in orbit around Venus, and 5 days later the probes from the Multiprobe would make their hour-long descents through the Venusian atmosphere.

There had been dramatic incidents during the long flight through interplanetary space (fig. 5-1), one of which occurred at the time of the Orbiter's first significant ground-commanded maneuver after it left Earth. Soon after it was launched on May 20, 1978, the spacecraft's long magnetometer boom had been deployed, and the dish antenna had been despun so that it could face Earth from the spinning spacecraft. The Orbiter and several of its scientific instruments had been checked and the telemetry indicated that everything was operating as planned. The spin-scan imaging system had been tested by obtaining several pictures of Earth illuminated as a thin crescent.

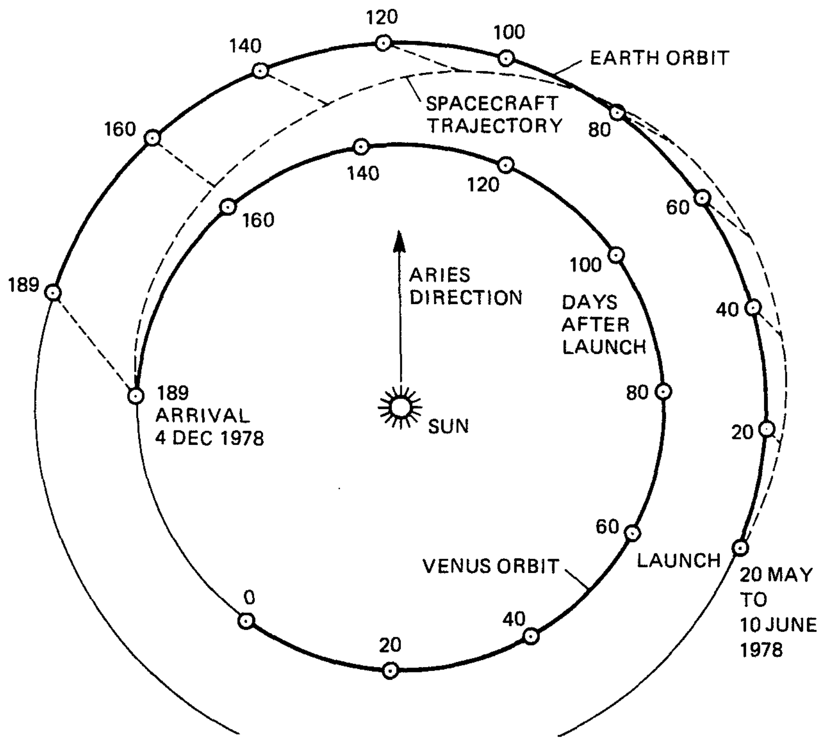


Figure 5-1. Path of Pioneer Venus Orbiter from Earth to Venus carried the spacecraft more than halfway around the Sun on its 7-month journey. At first, the spacecraft moved outside Earth's orbit, crossing inward approximately 90 days after launch and then moving toward the Sun to a rendezvous with Venus in December 1978.

Controllers commanded a first mid-course correction on June 1, 1978, to change the velocity of the Orbiter by 3.33 m/sec (7.8 mph) and to aim it more accurately at the point near Venus where the Orbiter would fire its rocket motor and go into orbit around that planet.

The maneuver was not completed as planned. Although the cause turned out to be trivial, it was the first of many operational lessons that the project engineers controlling the mission would learn during the interplanetary voyage. The roll reference system had been designed with an automatic shut-off, as a safety feature. A servomechanism followed changes about the roll axis at a restricted rate. If the spacecraft changed too quickly, the servomechanism lost synchronization; if this occurred during a maneuver, the protective design halted the maneuver. In this instance, part of the structure of the spacecraft deflected the plume from the thrusters, thereby causing a propeller-like action that changed the roll rate sufficiently to drive the servomechanism too hard. As a result, the first maneuver was automatically aborted. Once the cause had been identified, controllers avoided the problem by issuing commands to disable this automatic cutoff circuit when it was safe to do so.

The first maneuver was then successfully completed, but it required 8 hours and rocket thrusts in two directions. As a result, the scheduled arrival at Venus was changed so that, instead of the Orbiter following its initial course, which would have carried it toward the southern hemisphere of Venus, the spacecraft was directed to the required orbital injection point some 348 km (216 miles) above the planet's northern hemisphere. The change in flightpath was intended to position the spacecraft so that on arrival at Venus it would be able to achieve its planned elliptical orbit, that is, tilted 75° to the equator of Venus. The orbit would take it to within 241 km (180 miles) of the planet and then as far away as 66,000 km (41,000 miles). The maneuver slowed the spacecraft, allowing it to fall toward the Sun. The effect, however, was to speed the spacecraft on its solar orbit so that it would arrive at Venus 6.5 hours earlier at 8:00 a.m. PST on December 4, 1978.

By early June, the Orbiter detected an extremely powerful burst of gamma radiation, thereby obtaining an early and important scientific result from one of its onboard experiments. Such gamma-ray bursts, discovered in 1973, possess enormous energies; they occur on the average about once per month, seemingly from random points in the Galaxy or even from beyond. Two other spacecraft – Vela, a Department of Energy satellite circling Earth, and Helios B, a NASA-European spacecraft orbiting the Sun – also observed this gamma-ray burst. By triangulation of several such observations, scientists expected to be able to locate origins of the bursts and thereby deduce what kind of extraordinary physical event might produce such high-energy phenomena.

During its voyage to Venus, the Orbiter recorded a total of six gamma-ray bursts, two of which were equivalent to the most powerful ever recorded. Later, on March 5, 1979, it recorded a burst of gamma rays that was determined (from triangulation with observations from other spacecraft) to have come from a supernova remnant in the Large Magellanic Cloud.

The Multiprobe spacecraft successfully completed its first course change on August 16, 1978. Without a course adjustment, the Multiprobe would have passed Venus at a distance of about 14,000 km (8,700 miles) from the planet's surface. The course correction required a day-long procedure, which featured a series of timed rocket thrusts in two directions in space, increasing the speed of the spacecraft by 2.25 m/sec (about 5 mph).

There was a minor incident during the interplanetary voyage of the Multiprobe. Both the Orbiter and the Multiprobe carried redundant equipment to provide backup in case a critical piece of equipment failed. For example, there were duplicate power amplifiers for the communications system, either of which could be used if one failed. The redundant receiver on the Multiprobe was used when engineers noted what appeared to be an incipient problem with the operating receiver. The original receiver was never brought back into operation because the backup worked well and the Multiprobe was approaching its rendezvous with Venus. There was no need to switch receivers on the Orbiter because there was no failure (although the command receivers were actually switched for operation purposes).

Splitting the Pioneer Venus Multiprobe into its five independent spacecraft provided two of the most crucial and exciting operations of the entire Venus mission. Rather small errors would have made the probes miss their targets or fail on entry. The large probe was scheduled to be released on November 15, 1978. Even more critical was the scheduled release on November 19 of the three small probes – they had to be ejected within a few hours of a preselected time and within a fraction of a degree in roll.

Separating the probes required that precisely calculated numbers be placed in timers aboard each probe. Each number represented the millions of seconds between the release of a probe and the time when its various systems would commence operating for its entry mission. The probes could be released over a period of 3 or 4 days; however, once a time was selected, the timers had to be set precisely for that time so that systems within each probe would be activated at the preestablished number of minutes before each probe entered the Venusian atmosphere. "It was extremely critical," said Charles Hall. "If the times were set short we would have started using the battery (in each probe) too early and run out of power by the time we reached the atmosphere. If we had set the times too long, we would have missed a lot of data as the probes began to enter the high atmosphere."

The probes themselves were not designed to accept uplink commands from Earth to the spacecraft, and their timers had to be set before each probe was released from the bus that carried them toward Venus. Moreover, that time had to be calculated from the instant when each timer would be started by an on-board clock pulse activated by command from Earth, which meant that allowance had to be made for the one-way travel time (at the speed of light) of signals from Earth to the Multiprobe spacecraft. To minimize human error in those calculations, three people were assigned to derive them independently.

Before the large probe could be separated from the Multiprobe bus on November 15, the bus had to be oriented so that the large probe would separate in the right direction. The spin axis of the bus was kept perpendicular to the ecliptic plane on the journey from Earth to Venus. On November 9, the spin axis was moved through 90° so that the medium-gain, aft horn antenna of the spacecraft could be used to communicate with Earth. The omnidirectional antenna was no longer suitable for Earth communications in checking the probes before their release.

At about 13 million kilometers (8 million miles) from Venus, the spin axis of the bus was aligned so that the entry trajectory of the large probe would permit it to enter the atmosphere of Venus with its heat shield aligned correctly, relative to its entry flightpath. However, when the spin axis had been changed for release of the large probe, tracking data received from the Deep Space Network were startling. Said Charles Hall: "These data did not seem to add up to what we were doing . . . there was some question as to the precise direction the bus was pointing." A decision had to be made on whether a compensating maneuver was needed.

A big problem in orbit determination is to measure the north-south component of velocity relative to Earth. This measurement is made by comparing the difference in Doppler shift from a tracking station in Earth's Northern Hemisphere with another in the Southern Hemisphere. When many maneuvers have to be made – as was true for the Pioneer Venus Multiprobe, with its requirements to reorient the antenna and target the large probe and then reorient for the release of the small probes – very complicated bookkeeping was necessary to keep track of what had been done to a spacecraft's velocity vector and of how the spacecraft was approaching a planet. The long trajectory tracking history during the voyage from Earth was compromised by the preseparation maneuvering. Navigators were concerned that the orientation had not been measured precisely enough, or that the plume of the thrusters had bounced off the structure of the spacecraft, thus creating a sideward kick.

In tracking a spacecraft, navigators build the trajectory to a current position based on the spacecraft's previous positions. The current position is not measured accurately from an angular viewpoint. A spacecraft traveling from Earth to Venus obeys the laws of celestial mechanics and travels along a certain trajectory, as calculated from those laws. But it has to be observed from a tracking station on a rotating Earth, which itself is traveling in orbit around the Sun and wobbling in concert with the Moon. What is done is to model the trajectory and then compare the observations with the model, continuing to refine the model until the two fit. Extraneous effects that are not included in the model only begin to show up after they have influenced the trajectory for some time. Navigators measure frequency shifts resulting from the Doppler effect. Doppler residuals are the differences between the Doppler shift according to the model and the Doppler shift observed in the signal from the spacecraft. These residuals are continually determined, evaluated, and used to update the model trajectory. Accuracies within a fraction of a thousandth of a meter per second are aimed for and achieved.

Before any maneuver is made, the anticipated Doppler effect is calculated. If, after the maneuver has been completed, there is a difference between the observed and the expected Doppler residual, it is attributed to one of two things: the maneuver was not made in the direction planned or the performance of the thruster was not as expected.

Jack Dyer explains: "There is a lot of judgment involved in deciding on the cause. If you know the orientation then the residual must be due to the thrusters. That is especially so if the alignment of the spin axis is, say, 60° from the direction in which you are observing the Doppler effects. It is only when the direction is perpendicular to the line of sight from Earth that there is an unknown situation." So navigators try to do all maneuvers in an alignment that is turned somewhat toward or away from Earth.

The classical way to make a spacecraft turn is to fire two thrusters opposite each other (fig. 5-2). "At my insistence," said Dyer, "we fired only one thruster to cause an unbalanced turn, and allowed the spacecraft to be propelled because we had a very accurate means of determining orientation on the spacecraft and had a capability of very precisely returning from one direction to another a few degrees away. These directions could be measured by the star sensors to within 0.01°. From such measurements, we could calculate very accurately how much impulse had been imparted to the spacecraft and therefore how much velocity had been applied in the maneuever." From launch, all spacecraft maneuvers were made using this technique of unbalance.

To explain the unexpected Doppler data received from the Deep Space Network after the preseparation

Figure 5-2. The classical way to make a spacecraft turn is to fire the thrusters opposite each other, explains Jack Dyer. We fired only one thruster to cause an unbalanced turn and find out very accurately how much the velocity of the spacecraft had changed.

maneuver, Pioneer project management considered the possibility of there being a propellant leak that generated an unwanted thrust sufficient to push the spacecraft from its commanded orientation. An answer was needed before the large probe could be separated. The large probe was scheduled for release from the Multiprobe at 6:00 p.m. on November 15, but Charles Hall decided to hold the release until the problem could be identified. "There were so many unknowns at that time that I decided we had better not separate until we had a better handle on the problem. It took us about 12 hours to see some evidence of what the problem really was. It is amazing how these small things take so long to sort out. It was an all-night session. I can recall that we had a large number of engineers and scientists in the mission control area. It was too noisy to think, so I brought a cadre of top project people into my office and we started going over all the calculations. We pieced the whole story together until it finally appeared that all the diverse facts showed we were on the right track."

Because the large probe could be targeted over a fairly large area of Venus, the precise aiming point was not so critical, but the timer setting was. It was decided not to attempt another correcting maneuver but to choose a timing setting that straddled the situation. But the problem would be very serious with the small probes because they had to be targeted with extreme precision if they were to complete their missions.

The large probe was launched by a pyrotechnically released spring mechanism toward an entry near the equator on the dayside of Venus. Separation was normal and the large probe became a separate spacecraft silently pursuing its path toward the cloud-shrouded planet, its internal timer counting the seconds to activation of its systems just before the probe encountered the rarefied upper regions of the Venusian atmosphere.

With the large probe successfully on its path to Venus, the bus was prepared to launch the three small probes. During the 4 days before scheduled release of the small probes, the Doppler residual uncertainty problem was recognized as probably being an effect of solar radiation. When the aspect angle of the spacecraft was changed during the prerelease maneuver, the force of solar radiation differed from that modeled in the orbit determination program. Because this aspect angle to the Sun had not previously been experienced, and solar pressure modeling had otherwise been successfully treated, the discrepancy was a surprise.

But there was a problem connected with the dispersion of the small probes: their trajectories did not allow for flexibility in targeting, especially for the probe that would enter the Venusian atmosphere in the daylight hemisphere. So careful judgment was needed against the possibility of an incorrect interpretation of the change in Doppler data. One option was to diminish the size of the circle over which the probes would be released by staying inward of the boundaries established as desirable for the scientific mission. Finally, there was enough confidence to release the small probes toward the preselected targets.

There was a recognized design criticality in that alignment of the spin axis for release of the small probes would orient the spacecraft relative to the Sun so that its solar panels might produce too little power to maintain the bus battery. That would have limited the time that the battery could be kept charged at the confidence level needed. So when the spacecraft had been reoriented, the attitude and the spin rate each had to be measured and adjusted, if necessary, and the probes released within a period that would not deplete the battery.

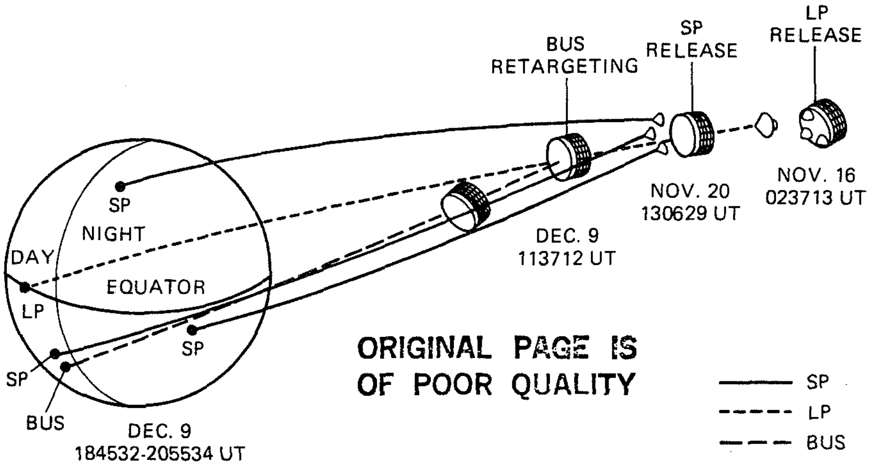
Before separation from the bus, and still 22 days before entry, the small probes were checked out by radio command. All passed their tests. Two days later, the bus was reoriented so that the small probes would be targeted to their entry points (as shown in fig. 5-3) – one on the dayside at midsouthern latitudes (the day probe); the second on the nightside, also at midsouthern latitudes (the night probe); and the third on the nightside at high northern latitudes (the north probe).

The ephemeris (a list of predicted positions) for Venus was well known before the Pioneer Venus mission as a result of earlier flybys of the planet by the Mariner spacecraft. The error in the ephemeris was predicted to contribute about a 30-km (18.6-mile) uncertainty in the arrival of the Pioneer spacecraft at Venus. However, the effect of this uncertainty was reduced by a factor of 2 in its effect on where a probe could be located on Venus because the gravity of the planet would focus each probe toward Venus.

In terms of errors in the downtrack, however, the uncertainty was greater, as much as hundreds of kilometers. Estimating the downtrack uncertainty and then planning the encounter to this uncertainty was a problem. There were targeting options for the five entry vehicles (the bus itself as well as the four probes would enter the Venusian atmosphere). The final selection of entry points was made after much deliberation between the scientists and the mission planners. Maximum science would be obtained by the probes entering at different latitudes and longitudes on the planet; in that way, data could be gathered in day and night hemispheres and at equatorial and high north and south latitudes. There were, however, geometrical and communications constraints. The bus spacecraft was designed to communicate to Earth from a certain angle around the hemisphere of Venus from the point directly facing Earth – the sub-Earth point. The probes had to be targeted inward from a design boundary of communications by enough margin to allow for the estimated downtrack uncertainty.

With the Multiprobe spacecraft oriented correctly and spinning at about 48 rpm, clamps opened to release the three small probes within

(a)



(b)

Figure 5-3. a) Peter Waller explains how the probes were released from the multiprobe bus, a model of which is shown alongside a model of the orbiter. b) Sequence of releasing the four probes. After separation of the small probes the bus was retargeted to enter the Venusian atmosphere.

about a millisecond of each other at a predetermined point in the spin cycle. The spin of the spacecraft and the precise timing of release directed the probes onto the trajectories required to achieve the targeted entries into the atmosphere of Venus. The timers in the probes began counting the seconds to atmospheric entry.

After all probes had left the bus, it was maneuvered for its own entry into the atmosphere. The bus was slowed slightly so that it would reach Venus a short time after the probes. Unlike the probes, the bus carried no heat shield to protect it from the heating effects of high-speed entry and was expected to burn up within a few minutes. But during those few minutes, its two scientific instruments – ion and neutral mass spectrometers – would gather the only data during this mission about the atmospheric composition between the top of the atmosphere and the 115-km (71-mile) level.

One of the most challenging problems presented to the navigators was to direct the bus for its entry into the atmosphere. The problem was to enter at as shallow a flightpath angle as possible (thus reducing the heat load) to extend the lifetime of the bus during its data-gathering operation. However, if the entry angle was too shallow, the bus would skip off the top of the atmosphere without getting the required atmospheric data. The most desirable trajectory would cause the bus to enter the atmosphere, penetrate to the 115-km (71-mile) level, and then skip out again (fig. 5-4), thus providing data along incoming and outgoing paths. Commented Jack Dyer: "We could see that it was not possible to navigate so accurately. The risk would be too great that the depth of penetration needed would be missed. So it was decided to go for as shallow an entry as we confidently could."

The targeted entry flightpath was selected as 9° below the local horizontal at 200 km (124 miles) above the surface of Venus. The navigators attempted to get as close as possible to that path, and the spin axis of the bus had to be set so that the angle of attack would be precisely 5°; at that angle, the atmospheric molecules would enter the scientific instruments

Figure 5-4. Pioneer Venus scientist Larry Colin explains to the press that the bus had to be precisely aimed for its entry into the Venusian atmosphere to avoid plunging too rapidly to destruction or skipping off the top of the atmosphere.

properly. Now all the probes and the bus were on their way to their targets.

Meanwhile, Pioneer Venus Orbiter, was approaching its rendezvous with the planet; it would be placed in orbit before the probes arrived.

On December 4, the Orbiter was injected into an elliptical path around Venus (fig. 5-5). The maneuver took place behind Venus (as viewed from Earth), so the spacecraft was out of communication for almost 23 minutes while this extremely critical milestone was passed. During this time, the spacecraft was slowed by firing a 180-kg (400-lb) solid-propellant rocket motor, thus causing it to be captured by Venus' gravity and go into orbit around the planet. This was the first time a solid-propellant rocket had been fired after being stored in space

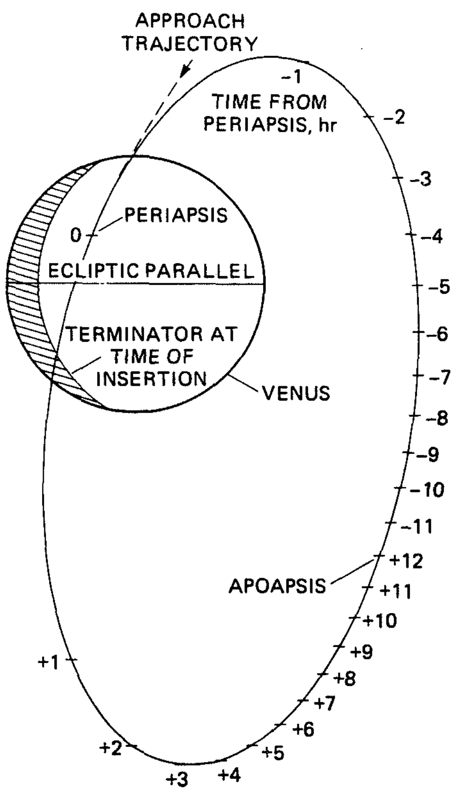


Figure 5-5. Perspective view of the orbit around Venus identifies the orbital insertion point, the periapsis, and the apoapsis relative to the planet. The hour marks along the orbit show how the Orbiter travels fast through periapsis and more slowly around apoapsis.

for 7 months – the time between the launch and arrival at Venus.

On December 2, the Orbiter started maneuvers for its insertion, beginning with orientation so that the rocket nozzle pointed in the direction of travel. The communications bit rate was lowered from 1024 to 64 bits/sec so that communications could be maintained with the omnidirectional low-gain antenna instead of with the high-gain antenna during the reorientation maneuver. Communications were switched to this antenna, and the high-gain antenna was released and spun up to match the spin rate of the spacecraft. The spin rate was then increased to 30 rpm. Next the high-gain antenna was despun and the bit rate returned to 1024 bits/sec.

Although the flight of the Orbiter from Earth had been free of major problems, there had been minor anomalies in the command memories on the way to Venus; the anomalies could have led to serious difficulties in obtaining a correct injection into orbit. High-energy solar cosmic rays had caused "bit-flip" errors in the spacecraft's memories – changing ones to zeros and vice versa. These errors were observed to occur on an average of once every 2 weeks or so, and they could have resulted in a command sequence being interrupted or changed. Fortunately, when these bit-flips occurred, the command could be corrected or the command had already been executed. But if such an error occurred in the command timing sequence to fire the rocket motor, it might have caused premature or delayed rocket firing for the orbital insertion maneuver.

Bit-flip anomalies occurred on both the Orbiter and the Multiprobe in transit to Venus. Although they occurred on the Orbiter in flight before the Multiprobe was launched, it was much too late to make design changes for the Multiprobe. Such events had probably been experienced in interplanetary spacecraft before, but it was only when there was a means of comparing what went into a spacecraft's memory with what came out of it that such problems could be clearly identified. Until Pioneer Venus, there had been no opportunity during a mission to check spacecraft memories for these bit-flip effects. Actually, bit-flips had been discovered on some Earth-orbiting satellites; ironically, they were a result of the high technology that makes it possible to minimize the amount of energy required to flip a digital circuit from one state to the other – a high-energy cosmic ray particle could provide sufficient energy. The problem surfaced so late in the Pioneer Venus program that design changes to overcome it were not practical. To avoid these bit-flips, great care was exercised in deciding how commands were stored in the command logic. Commands that had to be stored for any length of time were checked before execution to make sure that nothing had changed.

A bit-flip could have had serious consequences during the injection maneuver if it had changed the timing sequence to ignite the motor. This sequence leading to motor ignition would be started while the spacecraft was in radio communication with Earth and before the spacecraft went behind Venus. A time delay put into the spacecraft's memory for the total time delay to the ignition of the motor could, however, be changed by a bit-flip, and such a change might have been disastrous. Alternatively, the countdown to ignition could be commanded with a sequence of small time delays whose sum would be the total time. Analysis showed that greater reliability would be obtained from the series of time delays in two redundant command memories. Large extension of the time delay in either parallel memory would have had no ill effect, whereas a jump to early rocket firing by either would have been disastrous.

On December 3 at 11:00 p.m. PST, the two command memories of the Orbiter were loaded with the sequence of commands needed to fire the orbit insertion motor at 7:58 a.m. on December 4 (fig. 5-6). Of over 40 delays commanded, the first few were for 1 hr, the next for 45 min,

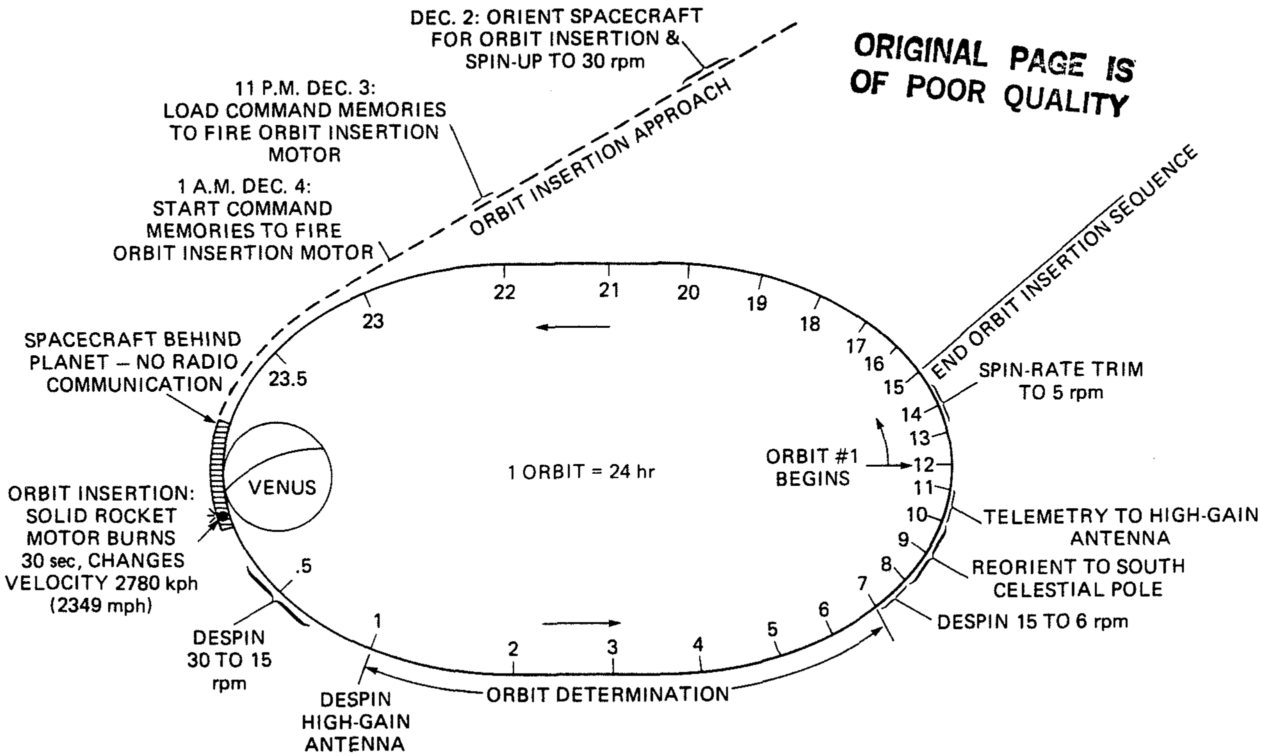


Figure 5-6. Operations of the orbiter spacecraft before, during, and after the period of insertion into orbit.

then 30 min, then delays of 1 min, then another batch of 3 sec each. The command memory countdown started at 1:00 a.m. on December 4. Each time one of the delays was counted out without error the spacecraft signaled the successful timing execution and the readiness to intervene with commands from Earth could be further relaxed.

At 7:51 a.m. on December 4, the Orbiter passed behind Venus and communications with Earth were interrupted. Seven minutes later, the orbit insertion commands stored in the spacecraft's memory would fire the rocket motor, and the motor's propellant would burn for almost 30 sec; this burn would change the spacecraft's velocity by about 23,780 km/hr (2,349 mph). The problem was that, when the orientation of the spacecraft and the altitude of the closest approach of the flyby trajectory had been set, the firing of the retrorocket had to be timed so that the Orbiter would be thrust into an orbit as near as possible to the nominal orbit desired for the mission. Any errors made in retrotiming and total impulse developed by the rocket motor would have to be corrected later. Such corrections would cost propellant and reduce the reserve for maneuvering in orbit, thereby shortening the lifetime over which the Orbiter's periapsis altitude could be controlled to obtain upper atmospheric science from the mission.

As the spacecraft approached Venus, the propellant reserve was more than sufficient (the launch had been early in the launch opportunity). To preserve the desired capability of maintaining orbit for one Venus sidereal day, there was no attempt to stretch the mission to ultimate design requirements. (A Venus sidereal day is different from a Venus solar day. The sidereal day is the rotation period of the planet relative to inertial space, whereas a solar day is the rotation period relative to the Sun. The Venusian sidereal day is 243.1 Earth days; the solar day is 116.8 Earth days.)

Maintaining propellant reserves was important because there were data transmission limits to the mission – experiments could gather more data than could be accommodated by the radio link to send to Earth. It was a foregone conclusion that the experimenters, after the first sidereal day, would want the spacecraft to continue in orbit, gathering and transmitting data into a second sidereal day – an extended mission – with a changed emphasis on the types of data being gathered and transmitted. To preserve this capability, it was important that propellant usage be budgeted and reserves be conserved.

This period of moving into orbit was exciting for project management, said Charles Hall. "We had never done anything like this before. Ignition of the rocket motor behind the planet meant there was always the question of whether or not the motor had ignited." To ensure ignition, another ignition command was sent and timed to arrive at the spacecraft after its emergence from behind Venus. This command was intended to start ignition if it had not taken place behind the planet as commanded . The orbit would not, of course, have been as good from such a late ignition, but the spacecraft would have been prevented from flying past Venus and going into solar orbit.

Hall explained how ignition was confirmed. "If we had ignition, then, when the spacecraft emerged, the frequency of the carrier radio wave (from the spacecraft) would be different from that if ignition had not occurred (because of Doppler effects). I recall that we had two receivers on the ground waiting to pick up signals on one or the other frequency." At 8:14 a.m., the spacecraft emerged from behind Venus, but some 3 min elapsed during which the radio signals traveled the 56 million km (35 million miles) to Earth. Everyone waited for one of the two ground receivers to lock onto the signal from the spacecraft. "When it was clear that the right receiver had locked onto the signal from Pioneer Orbiter, there was a big cheer because we knew then that the spacecraft had gone into orbit."

At 8:30 a.m., the Orbiter's spin rate was adjusted to 15 rpm and the high-gain antenna was despun and pointed toward Earth. Within the next few hours, tracking data were analyzed to determine the parameters of the orbit around Venus. The highly elliptical orbit, inclined 75° to the equator of Venus (105° retrograde) was almost but not quite as expected. Table 5-1 gives the orbit parameters achieved by the injection burn, compared with those planned.

Jack Dyer explained the problems of entering an orbit around another planet. "We had to be very precise with navigation so that the burning of a given weight of propellant would put the spacecraft into orbit. We spent a lot of time determining how accurately we thought the manufacturer of the retrorocket could predict the amount of impulse it would deliver."

The retrorocket performed better than predicted, which was as bad as underperforming. The overperformance had slowed the Orbiter too much and resulted in a lower apoapsis – greatest distance from Venus – and a shorter orbital period, 23 hr 11 min. Also, the periapsis was higher than planned. Consequently, more propellant from the attitude control subsystem would have to be expended than had been planned to correct the period of the orbit to the required 24 hr. The period has to be adjusted at periapsis, and because the first orbits were times of great scientific activity, the adjustment had to be delayed for two orbits. In the meantime, however, a preplanned maneuver to lower the periapsis from 378 km (234 miles) to 250 km (155 miles) would be executed at apoapsis on December 5 by firing two of the spacecraft's thrusters for just over 3 min.

Initial orbital operations followed a carefully preplanned sequence (fig. 5-7). At 3:00 p.m. on December 4, the spin rate was reduced to 6 rpm from that previously established at 15 rpm, and the spin axis was adjusted to point toward the celestial poles. Then, a couple of hours later, the high-gain antenna was pointed toward Earth and communications switched to it from the omni-antenna. In the next hours, some of the scientific instruments were activated – the infrared radiometer, the neutral mass spectrometer, and the electron temperature probe. The radar antenna was unlocked and the boom of the electron temperature probe was deployed. The neutral mass spectrometer and the radar were then put through calibration sequences. Just after the first orbit began, at the first apoapsis after the spacecraft was injected into orbit, the magnetometer and the retarding potential analyzer were activated and the first orbital data-gathering sequence was started. The remaining instruments were turned on later in that first orbit at times requested by the principal investigators.

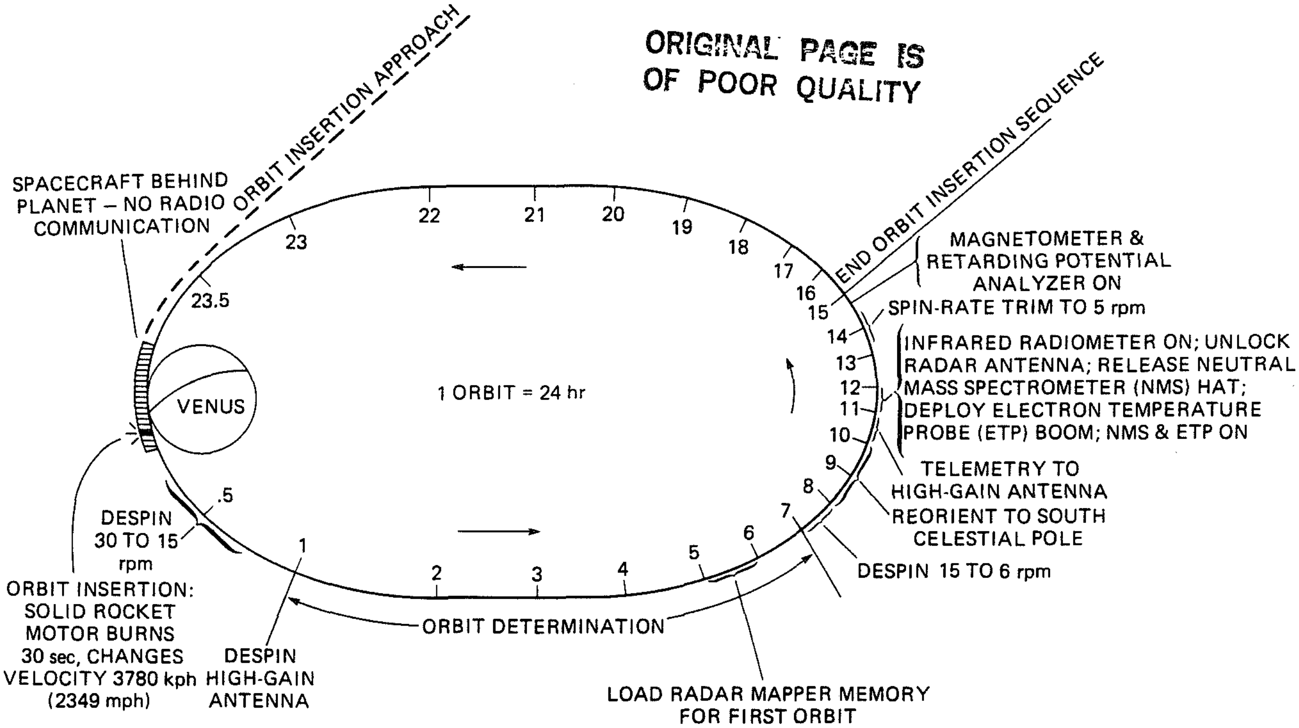
The short orbital period caused the time of periapsis to occur at an earlier time each Earth day than desired, so that it affected assignment of tracking stations. The relative geometrics of the spacecraft, of Venus, and of Earth's tracking stations had to be arranged so that key tracking stations at Goldstone, California, and Canberra, Australia, could receive signals from the spacecraft at a preselected part of its daily orbit around Venus. After two orbits had been completed, the thrusters on the spacecraft were fired at periapsis on December 6, and the orbital period was increased to just over 24 hr so that the time of periapsis would gradually move to that required.

Once achieved, the 24-hr orbit was divided into two segments, reflecting the kind of measurements being taken (fig. 5-8). The periapsis segment was about 4 hr long. The apoapsis segment was 20 hr long. Mission operations used five data formats during the short periapsis segment. The formats were designed to make it possible to emphasize certain instruments when desirable – for example, one for intensive aeronomy coverage at periapsis, another for optical coverage.

Normally, only two data formats are used in the 20-hr apoapsis segment of the daily orbit. The first is for obtaining images of the whole disk of the planet in ultraviolet light to record the cloud features (fig. 5-9). It allocates 67% of the data stream to imaging data and divides the balance of the data transmission among the three

TABLE 5-1.– PLANNED AND INITIAL ORBIT PARAMETERS

Parameter	Planned	Actual
Periapsis altitude, km (miles)	350 (217.5)	378.7 (235.3)
Periapsis latitude, deg	18.5 N	18.64 N
Periapsis longitude, deg	203-223	207.990
Inclination, deg	105	105.021
Period, hr:min:sec	24:0:0	23:11:26



(a)

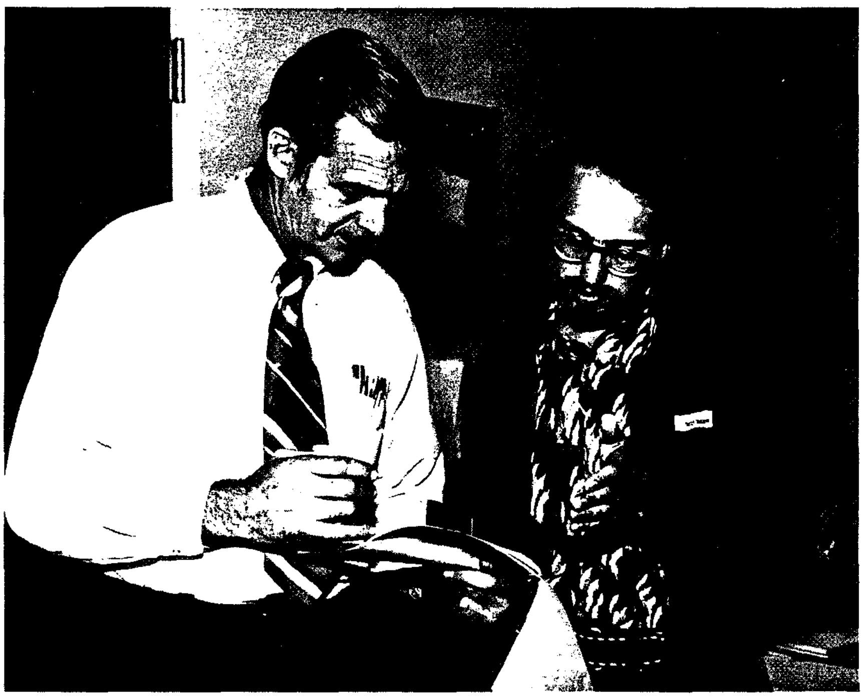

(b)

Figure 5-7. a) The orbit insertion sequence ended 15 hr after achieving orbit, and the first operational orbit began after several instruments had been turned on just before first apoapsis. b) Preparation for the first experiments following orbit insertion are discussed by Marshall Johnson and Ed Tischler.

instruments that measure solar-wind and planet interactions and the gamma-burst detector. The other format allocates data return to all the instruments except the imaging instrument and the infrared radiometer.

By December 6, the first black and white image of Venus (fig. 5-10) had been received successfully and science data were flowing to Earth. All was going well with the Orbiter spacecraft.

When the probes separated from the Multiprobe bus, they went "off the air" because they did not have sufficient on-board power or solar cells to replenish their batteries. There was no way to command the probes from Earth. Preprogrammed instructions were wired into them and their timers had been set before they separated from the bus. The on-board countdown timers were scheduled to bring each probe into operation again 3 hr before the probes began their descent through the Venusián atmosphere on December 9, 1979 at 7:50 a.m. PST. The timers had to turn on heaters to warm the battery and the stable oscillators of the radio transmitters to make sure that the carrier frequencies would be correct when the transmitters began sending signals to Earth shortly before entry. Later, the command unit initiated warmup and calibration cycles for the three instruments on each probe. At 8:15 a.m., the command timer on the large probe initiated warmup of its battery and of the radio receiver to be used to receive

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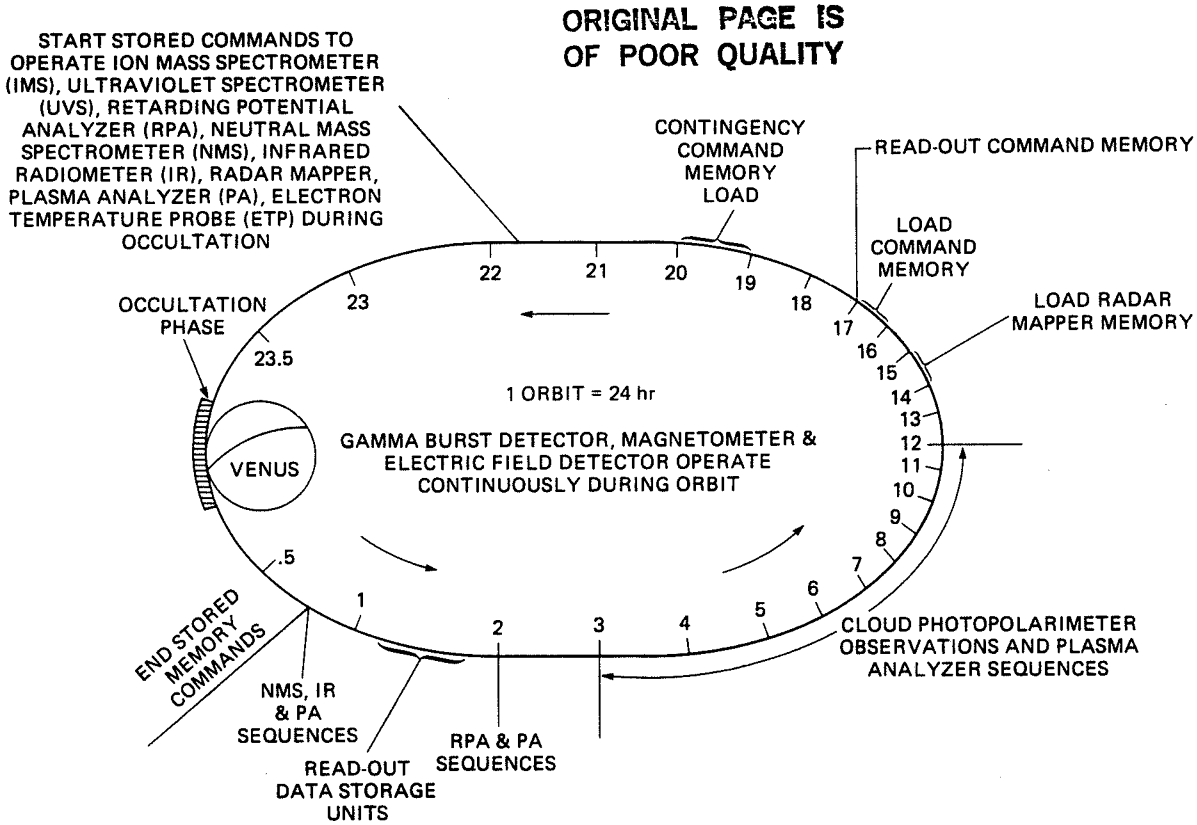


Figure 5-8. Typical orbital operations through the mission.

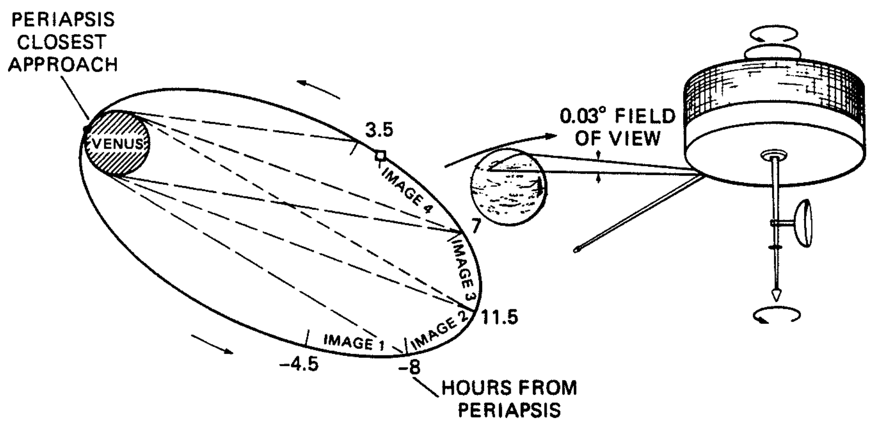


Figure 5-9. Cloud photopolarimeter uses motion along the orbiter's flightpath around Venus and spacecraft rotation to scan the planet in ultraviolet light. The instrument can make five planetary images in each orbit with a resolution of about 30 km (19 mi). It can determine cloud particle characteristics from polarization measurements, and make images of haze layers at the planet edge with a resolution of 15 km (0.3 mi).

an uplink carrier frequency (from Earth to spacecraft) that would provide the reference frequency for the downlink signal (from spacecraft to Earth).

At 10:23 a.m. PST, just 22 min before entry, the large probe began to transmit radio signals to Earth for two-way Doppler tracking at 256 bits/sec. Within the next 11 min, all the small probes started transmitting – first the north probe, then the day probe, and finally the night probe. Seventeen minutes before it hurtled into the atmosphere of Venus at 42,000 km/hr (26,000 mph), each small probe would begin transmitting data at a rate of 64 bits/sec, the large probe at 256 bits/sec.

The 22-min interval was planned as a compromise between consuming precious battery power and providing the Deep Space Network stations with sufficient time to lock onto the signals before the probes began to send entry data.

Charles Hall related how, several months before encounter, a group from the Pioneer project traveled into California's Mojave Desert to visit the isolated Goldstone Tracking Station of the Deep Space Network. There the group reviewed the station's equipment and operating procedures for obtaining data from the probes during their entry into the Venusian atmosphere. The operators at Goldstone went through encounter simulations to

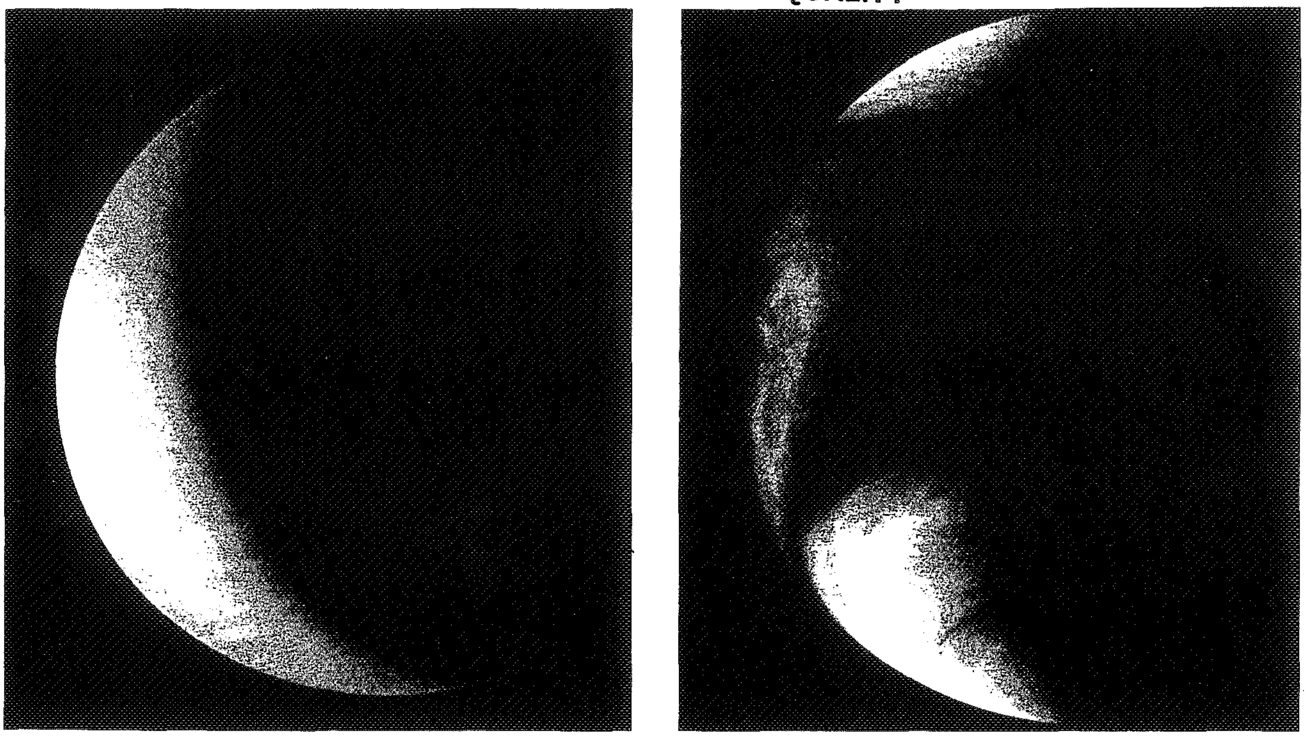


Figure 5-10. First black and white image of Venus from the Pioneer orbiter was received on December 6, 1978. It showed a crescent-shaped image. In subsequent days images with greater detail were obtained, such as the one shown alongside taken on December 25; it reveals great details in the Venus cloud systems.

demonstrate how the actual mission would be performed and to identify and eliminate potential operational and ground equipment problems.

The five frequencies from the five spacecraft – four probes and the bus – were simulated to represent their expected form when they arrived from the distant spacecraft fleet as it approached Venus. Equipment had been designed to receive radio signals from these spacecraft in an open-loop mode, that is, without using the output to correct the input. If the frequency of a carrier emitted by any spacecraft were detected, a small blip would appear among radio noise on a monitor screen. "When I first saw this screen and the blip, it looked like a rowboat in the middle of the Atlantic Ocean during a storm," said Hall. "We could hardly see the blip for all the noise; a crowd of dots moved up and down on the screen and only one of them was still. Highly skilled operators had to be very alert to see the stationary blip.

The operators became very skilled in finding the blip among the noise, homing in on it by reducing the bandwidth so that the blip stood out clearly from the noise, bringing a pointer to the correct frequency and pressing a button. This started an automatic calculation so that the operator of the closed-loop receiver could have information to set into his control dials and get the real-time data flowing from the simulated probes. In this way, the operators were able to change to a closed-loop system and lock onto a simulated signal within seconds."

These extensive practice runs paid off when the probes reached Venus. During the encounter, friendly competition developed between the two tracking stations (Goldstone and Canberra) as to which station would be the first to receive the radio signals at the time the probes entered the atmosphere. Said Hall: "I guess the most exciting part of the mission was to hear the Deep Space Network (audio communications) as the probes were turned on and their signals were received and locked onto." The first radio signal came from the large probe. It was sent from the probe at 10:24 a.m. PST on December 9 and arrived at Earth 3 min later. "When we got the message – 'We've locked up on the large probe' – everyone cheered. Then 3 or 4 min later, we heard 'Forty-three (ID for the Canberra station) has locked up on a small probe,' and so on, right down the line. First one station and then the other announced a lockup. In retrospect, it was a tie between the stations."

One by one, and within a few minutes, each probe reestablished communications with the Pioneer Mission Operations Center at Ames Research Center in California. Shortly after each probe had been acquired, it was sending data to Earth. By 10:45 a.m., the Operations Center reported that all instruments on all probes were operating satisfactorily.

"We had been waiting for 24 days (for the large probe) and for 19 days (for the small probes) and to have them come on within a split second of the times they were supposed to, and particularly to have the ground stations lockup, was quite an achievement," commented Hall. "I think that the lockup of the four probes was probably one of the most difficult tasks that the Deep Space Network has ever had to deal with."

Five minutes before each small probe entered the atmosphere, two cables and weights of its yo-yo despin system were deployed to reduce its spin rate from 48 to 15 rpm. The high spin rates imparted by the bus earlier were needed to disperse the probes to entry points widely spaced over the planet. However, this wide dispersion also meant that the smaller probes entered the Venusian atmosphere somewhat tilted off their flightpaths. The spindown of the probes was needed to make it easier for aerodynamic forces to line up the axes of the probes with the desired flightpaths. This had to occur quickly before heating at the edges of a probe's conical heat shield could become serious. Cables and weights were jettisoned immediately after spindown.

While data transmitted from the last of the probes to begin transmission were on their way to Earth, the probes started entering the atmosphere. They were traveling at about 42,000 km/hr (26,000 mph) at 200 km (125 miles) above the surface of the planet. Expected entry communications blackout occurred as the heated atmosphere flowing around the heat shield was ionized, thus screening the communications signal for about 10 sec. Because the probes were moving more slowly after this blackout, the tracking stations had to acquire their signals again at a different radio frequency. The Deep Space Network successfully relocked on all the probes after each went through its individual radio blackout.

Now the most exciting part of the mission began. Enormous pressure and intense heat coupled with acid chemical corrosion in the atmosphere of Venus were the great environmental challenges in designing and building the probes. The large probe had to jettison its parachute to speed its descent through the thick lower atmosphere; in this way, the probe would be able to send data back all its way down to the surface of Venus. A slower descent would have heated the probe to dangerously high temperatures before it reached the lower atmosphere and would have prevented it from obtaining information there.

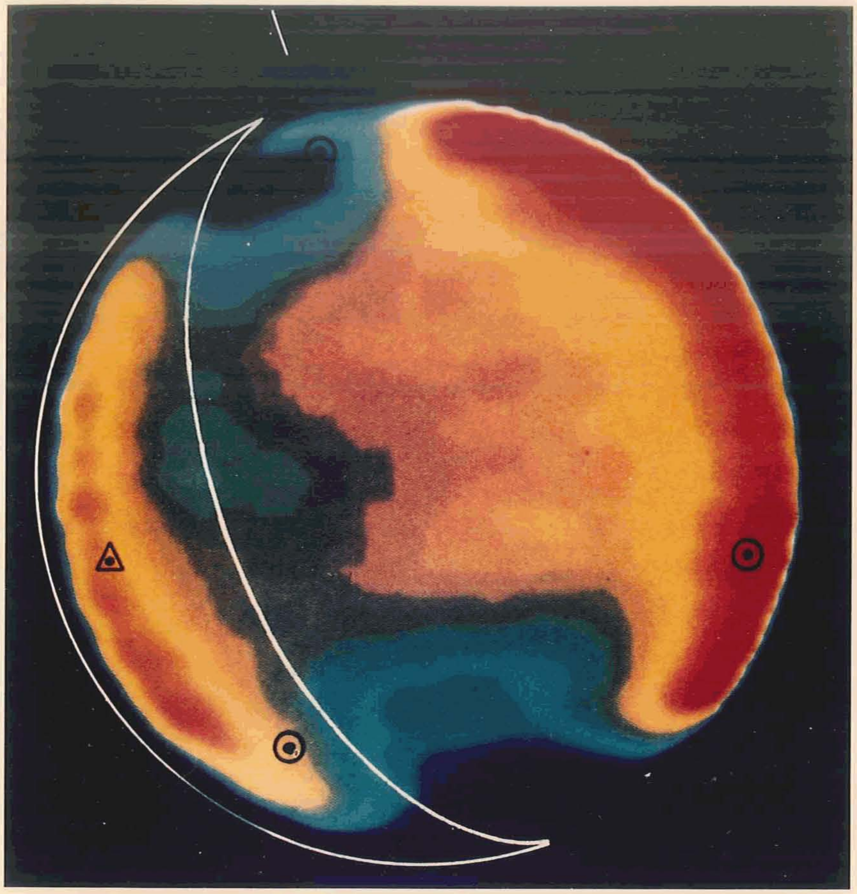
An earlier chapter recounted how the probe pressure vessels were constructed from titanium, a light but strong metal that is, however, very difficult to machine. To enable the probes to withstand the enormous pressures they would encounter deep in the Venusian atmosphere, the designers applied experience gained in building bathyspheres for exploring Earth's deep oceans.

Each pressure vessel had to be equipped with multiple ports so that scientific instruments could have access to the ambient atmosphere. There were 19 such penetrations in the large probe's pressure vessel and 7 in each of the three small probes. Protecting the vessels against the great range of outside pressures had presented many engineering difficulties, and sealing windows against pressure and heat was perhaps the most demanding task. The sapphire windows, which tended to crack when tested at high temperature, had been thickened so they could survive the conditions on Venus. A brazed seal for use with the diamond windows had deteriorated when tested and had been replaced with complex seals of Graphoil, Anviloy (containing 90% tungsten), and Inconel. As the probes plunged toward Venus, engineers anxiously awaited results that would confirm the success of their designs. Although the probes had withstood rigorous tests before launch, there was always the possibility that the environment of Venus could hold some surprises.

The probes were protected in several ways against heat derived from high-speed entry into the atmosphere and the high ambient temperature deep in that atmosphere. Heat shields built chiefly of carbon phenolic protected the probes against excessive entry heating. Transfer of entry heat to the scientific instruments was controlled by mounting the instruments on heat absorbers (sinks) which consisted of beryllium shelves for the large probe and of aluminum shelves for the small probes. Heat transfer was further limited by multilayered protective blankets of thin plastic sheets that were unusually heat resistant. Conduction of heat through the atmosphere inside the small probes was reduced by filling the probe interiors with the inert gas xenon, which conducts only about 21% the amount of heat that air does. The aim was to keep the interior of each probe below 50°C (122°F) in a surrounding environment with temperatures as high as 493°C (920°F).

As the time for entry approached, excitement rose dramatically at the Pioneer Mission Operations Center and at the many contractors' plants involved in the design of the Pioneer Venus vehicles. The years of design and the many ground-based simulations were about to be put to their ultimate test when the four probes plowed through the global haze and sulfuric acid clouds, through the violent winds, and the hot, carbon dioxide of Venus. Entry points are shown on figure 5-11.

Table 5-2 summarizes the sequence of some important events that occurred during the entry of the Pioneer Venus probes. On entry (fig. 5-12), the large probe decelerated from 41,800 to 727 km/hr (26,000 to 452 mph) within 38 sec. During this period, data were stored in its onboard memory for later transmission after the radio blackout. Its parachute opened at 10:45 a.m. to slow its speed of descent further. Its forward aeroshell heat shield was jettisoned to expose all apertures and windows for the descent phase of the operations. Forty-three seconds after entry, at an altitude of about 66 km (40 miles), all instruments on the large probe were operating normally and returning data to Earth. Seventeen minutes later, at 10:02 a.m., and at an altitude of



45 km (28 miles) above the hot surface of Venus, the parachute was jettisoned as planned (fig. 5-13). The probe continued to plunge down – slowed by the dense atmsophere as a huge metal ball would be if sinking into the ocean – rotating slowly under the influence of spin vanes. The aerodynamically stable pressure vessel descended to the surface of Venus in about 39 min after chute jettison. The large probe hit the surface at only 32 km/hr (20 mph), landing near the equator of Venus on the dayside at 10:41 a.m. PST, some 55 min after first encountering the Venusian atmosphere. Its radio signals ended abruptly at impact.

Figure 5-11. Ground-based picture of Venus taken at the time of probe entry by Jay Apt with the 60-inch Mt. Hopkins Observatory telescope, Tucson, Arizona, at a wavelength of 11.5 micrometers. The small probe entry points are indicated by circles, that of the large probe by a triangle.

TABLE 5-2.– IMPORTANT ENTRY EVENTS

Event	Time at spacecraft,[a] hr:min:sec, PST			
	Large probe	North probe	Day probe	Night probe
End of coast timing	10:24:26	10:27:57	10:30:27	10:34:08
Initiate telemetry	10:29:27	10:32:55	10:35:27	10:39:08
200-km (124-mile) entry	10:45:32	10:49:40	10:52:18	10:56:13
Radio blackout began	10:45:53	10:49:58	10:52:40	10:56:27
Signal locked on	10:46:55	10:50:55	10:53:46	10:57:48
Jettison parachute	11:03:28	(None on small probes)		
Impact with surface	11:39:53	11:42:40	11:47:59	11:52:05
Signal ended	11:39:53	11:42:40	12:55:34	11:52:07
Bus entry (200 km; 124 miles)		12:21:52		
Bus signal ended (110 km; 68 miles)		12:22:55		
Durations				
Descent time (entry to impact)	54:21	53:00	55:41	55:52
Blackout time (signal loss to relock)	62	57	66	81
Time on parachute (large probe only)	~17:07			
Surface operations (impact to signal end)	None	None	67:37	02

[a]Earth received times were approximately 3 min later than the above spacecraft times.

Figure 5-12. As the probes and the bus entered the Venusian atmosphere they glowed briefly like meteorites. The bus, as shown in this artists's rendering, was most spectacular because it did not carry a heat shield; as a result, it burned up completely.

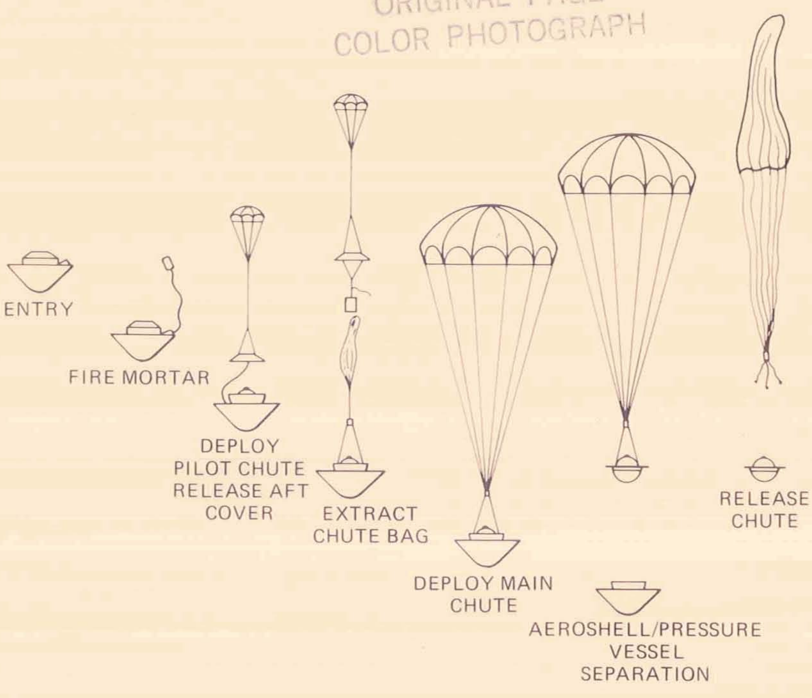


Figure 5-13. Entry sequence of the large probe was more complicated than that of the small probes because its descent had to be slowed, in part, by a parachute, which then had be jettisoned.

Five minutes before the peak deceleration pulse of atmospheric entry was expected for the small probes, the command unit on each probe ordered the blackout format for storage of spacecraft data in an internal memory, together with heat-shield temperature and accelerometer measurements for the atmospheric structure experiment. This was to ensure that there was no loss of data during the 10- to 15-sec communications blackout at entry. These data were transmitted later during the descent.

The small probes, entering the atmosphere within a few minutes of each other between 10:50 and 10:56 a.m., were all quickly slowed down, the atmosphere retarding their fall to the surface without the use of parachutes. Because the flightpath angles of the three small probes varied considerably, each probe's deceleration rate and entry heating also varied widely. Peak decelerations ranged from 200 to 565 g (1 g is 32 ft/sec/sec).

At 10:51 a.m., the window for the nephelometer was opened on the north probe and it began gathering data on locations and densities of cloud layers. The atmospheric structure and net flux radiometer housing doors opened, and these instruments started telemetering to Earth data about the thermal structure of the atmosphere. Instrument booms deployed. Within the next 6 min, similar sequences had started on the two other small probes.

As instrument compartment doors opened on either side of each small probe's afterbody, their drag effects on the atmosphere further reduced the spin rate of the probe. A small vane, mounted on the pressure inlet, prevented the despin rate from falling to zero so that instruments could make observations over a full rotation of the probe.

At this time, the upper descent phase began, with the three probes in the altitude range of 72 to 65 km (43 to 39 miles) and all instruments operating.

The small probes all took about the same time as the large probe (55 min) to reach the planet's surface. As the probes penetrated deeper into the atmosphere, the atmosphere thickened and interfered with radio communication. Signals received at Earth were weakened. At entry plus 16.4 min and at an altitude of about 30 km (18 miles), the bit rate of data transmission from probes to Earth was reduced to 16 bits/sec to avoid missing any data from the lower atmospheric regions. The Deep Space Network had to achieve a third lockup on each probe's transmission. Again, it was highly successful and no data were lost in the process.

From that point on, the three probes descended into the increasingly dense atmosphere of Venus, impacting the surface at 36 km/hr (22 mph) 57 min after their entries. Unlike the large probe, the small probes retained their heat shields to the surface. The density of the atmosphere is so great that the drag of these aerodynamic surfaces slowed the probes to the desired speed of descent.

One of the three small probes (the north probe) landed at 11:47 a.m. in darkness near northern polar regions. Another (the day probe) went into the southern hemisphere on the dayside and landed at 11:50 a.m., kicking up a cloud of dust that took several minutes to settle. The third probe (the night probe) went down in darkness to reach the surface in the southern hemisphere at 11:53 a.m. Although signals from the north probe and the night probe ended at impact, transmissions continued from the day probe for another 68 min (fig. 5-14) before it, too, became silent. Engineering data radioed back from the day probe showed that its internal temperature climbed steadily to a high of 126°C (260°F) before its batteries were depleted and its radio became silent. The internal pressure monitors showed that the pressure within the probe rose just as would be expected for a sealed bottle on the surface of Venus, with the temperature increase gradually causing an increase in internal pressure. There was no evidence of any leakage into the probe from the atmosphere following the impact, the seals had withstood the real-life test of impact with the hot surface of Venus.

Table 5-3 shows the locations on Venus where the probes impacted and the conditions at the impact points. These locations were very close to the points targeted before the probes were released from the bus.

Meanwhile the Multiprobe bus had been hurtling toward Venus close behind the probes. On December 8, the bus had been reoriented to its final entry angle, its instruments had been calibrated, and the cap covering the inlet to the neutral mass spectrometer had been released. Entry was scheduled for 12:21 p.m. on December 9, about 96 min after the first probe entered, and 88 min after the last probe had entered.

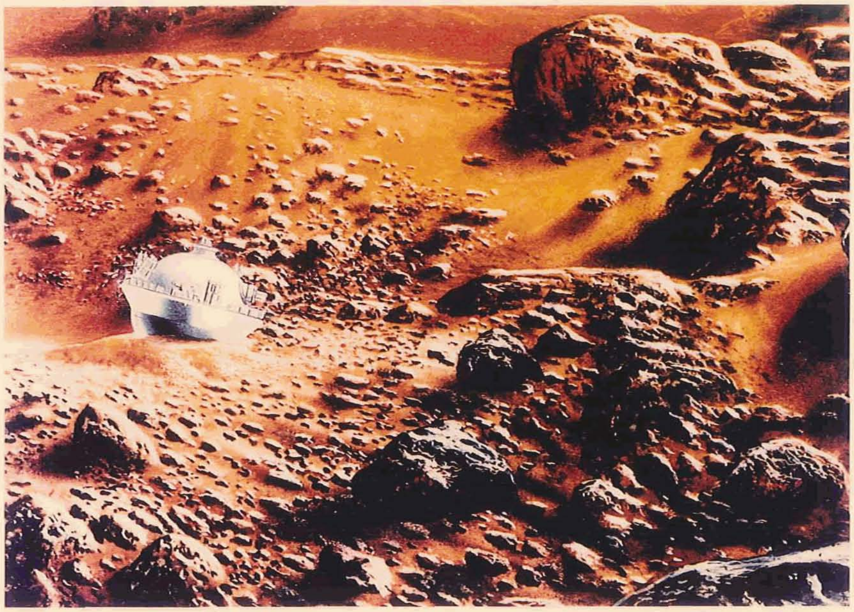


Figure 5-14. Artist's concept of one of the probes on the hot surface of Venus. Although the probes were not designed to withstand impact, there was a chance that one might survive and transmit some data from the surface. A small probe did survive and transmit data for 67 min.

The bus plunged into the atmosphere on the dayside of the planet at a high latitude in the southern hemisphere. Table 5-4 gives the entry position of the bus at an altitude of 200 km (125 miles), and the locations of the subsolar and sub-Earth points (i.e., where the Sun and Earth would appear directly overhead to an observer on Venus).

Since the bus had no heat shield to

TABLE 5-3.– PIONEER VENUS MULTIPROBE IMPACTS

Probe	Latitude, deg	Longitude, deg	Solar zenith angle, deg	Local Venus time, hr:min
Large	4.4 N	304.0	65.7	7:38
North	59.3 N	4.8	108.0	3:35
Day	31.3 S	317.0	79.9	6:46
Night	28.7 S	56.7	150.7	0:07

TABLE 5-4.– PIONEER VENUS BUS ENTRY AND LOCATION OF SUN AND EARTH SUBPOINTS

	Latitude, deg	Longitude, deg	Solar zenith angle, deg	Local Venus time
Bus entry at 200 km	37.9 S	290.9	60.7	8:30
Subsolar	0.5 S	238.5	0	12:00
Sub-Earth	1.6 S	1.7	123.1	3:47

protect it from the high-speed entry, it was expected to burn up within 2 min. Radio transmissions from the bus poured back to Earth carrying scientific data (at the rate of 1024 bits/sec) on the composition of the very high atmosphere of Venus, including the region where the ionosphere is most dense. This region could not be explored by the other probes because they gathered no data from external sensors until they had been slowed by the atmosphere.

When the bus burned up at 12:23 p.m., the uniquely exciting phase of the entry part of the mission was concluded. It had lasted for only 1 hr, 38 min. But in that period the probes and the bus had recorded data for a whole new look at the complex atmosphere of Earth's sister planet (fig. 5-15). During the following few

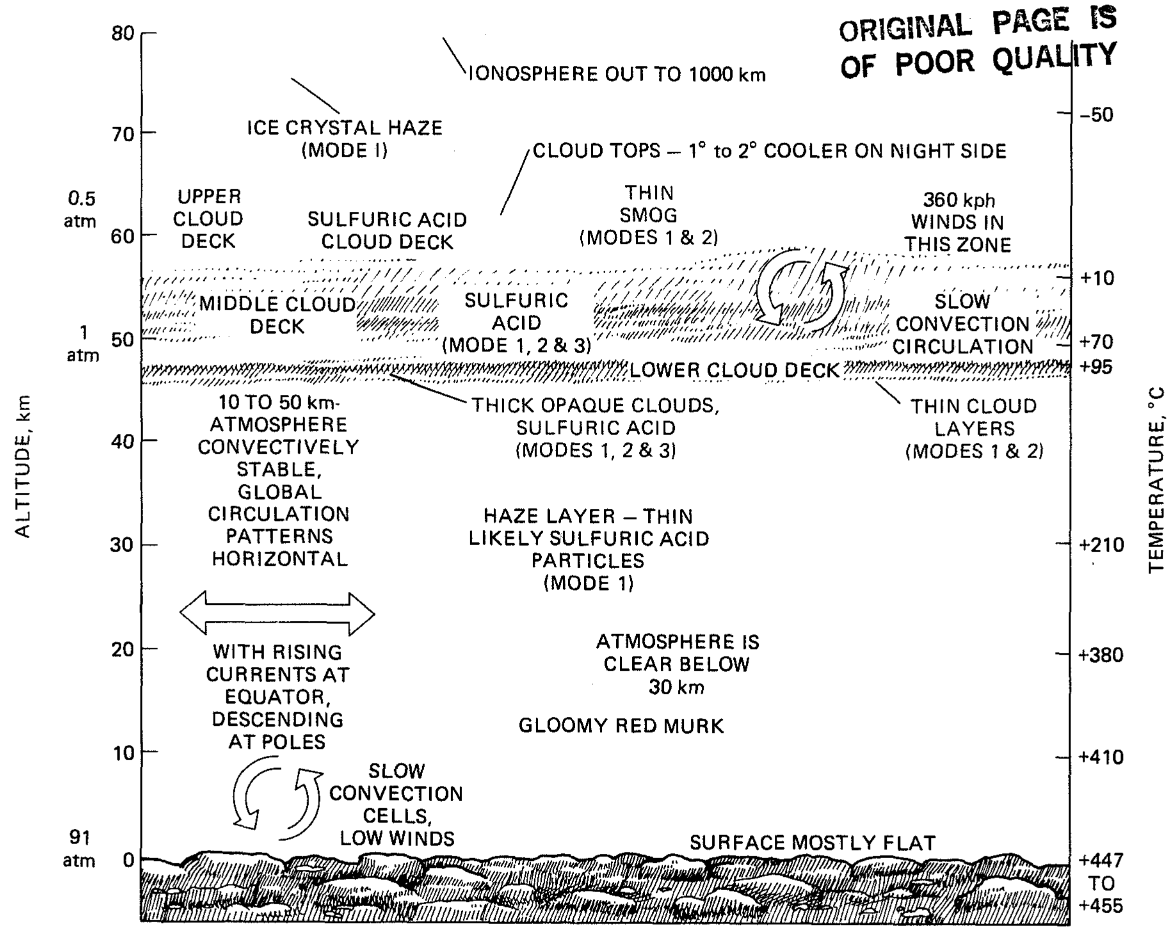


Figure 5-15. The Pioneer Venus mission provided a more detailed and accurate picture of the Venus atmosphere, its cloud layers, composition, and wind systems.

days, scientists completed preliminary initial analyses of the data and announced some startling and unexpected discoveries. Then the mission settled down to the equally fascinating but more lengthy process of observing Venus from the Orbiter over a period of several Venus sidereal days.

There were several major findings from the probes. These results are discussed in detail in the next chapter. Initially, however, there were some discoveries that produced a great deal of excitement in the days immediately following the encounter.

An unexpected result was concentrations of primordial argon and neon several hundred times those on Earth. This finding conflicts with most accepted theories about the origin of the Solar System. Those theories propose that the Sun and planets formed at about the same time, with the planets forming from a gas cloud surrounding the Sun and composed of the same elements as the Sun.

How did the probes and their instruments withstand the rigors of the descent into the atmosphere of Venus? Scientists had been concerned that, when the probes went through the clouds, droplets might condense upon the inlet to the mass spectrometer. As a result, a heater coil had been placed around the inlet in an effort to prevent such condensation; nevertheless, the inlet became blocked. A change was observed in the amount of gas entering the instrument. Later in the descent, when the temperature had risen, peaks of sulfur were seen in the data. It appeared that a large drop of sulfuric acid had blocked the inlet; when it later boiled off, its constituents entered the instruments and were revealed in the data.

There were some anomalies with all the probes. Anomalous events appeared in the engineering data as well as in the science data at approximately the same altitude in all four probes.

The first signs came from the sensors of the atmospheric structure experiment at an altitude between 12 and 14 km (7.5 and 9 miles). Soon afterward, external sensors of the net flux radiometer on the north probe, day probe, and night probe suddenly failed at about the same altitude. In the data from other scientific instruments and from engineering transducers, other anomalies occurred just before, during, and after these failures. These anomalies are summarized in table 5-5.

It seems unreasonable to assume that all these different instruments failed together and at precisely the same condition. A cause other than simple, virtually simultaneous equipment failure seemed likely.

The temperature sensors (fig. 5-16) of the atmospheric structure experiment were exposed to the atmosphere of Venus. But it was clear from the data that the temperature sensors did not physically break; there remained

TABLE 5-5.– ANOMALIES EXPERIENCED BY THE PROBES

Anomaly	Probe			
	Large	North	Day	Night
Temperature sensors apparently failed	X	X	X	X
Changes and spikes in pressure data	X	X	X	X
Apparent failure of net flux radiometer fluxplate temperature sensors		X	X	X
Abrupt changes and spikes in data from net flux radiometer		X	X	X
Change in the indicated deployment status of the atmosphere structure temperature sensor and net flux radiometer booms		X	X	X
Erratic data from two thermocouples embedded in the heat shield		X	X	X
Erratic data from a thermistor measuring junction temperature of the heat-shield thermocouples		X	X	X
Slight variation of current and voltage levels in the power bus		X	X	X
Slight offsets or jumps in the values for temperatures of the forward and aft shelves and the internal pressure		X	X	X
Abrupt changes in cloud particle size laser alignment monitor	X	Not applicable		
Decrease in the intensity of the beam returned to the cloud-particle-size spectrometer	X			
Steady increase in flux readings of the infrared radiometer	X			
Noise in the data from the infrared radiometer	X			
Spikes in the data monitoring the ion pump current of the mass spectrometer analyzer	X			
Abrupt decrease of current in the power bus	X			
Jumps in the receiver (transponder) static phase error	X			
Spikes in the receiver automatic gain control	X			
Spurious reading from thermocouples that had been dropped from the probe in its heat shield	X			

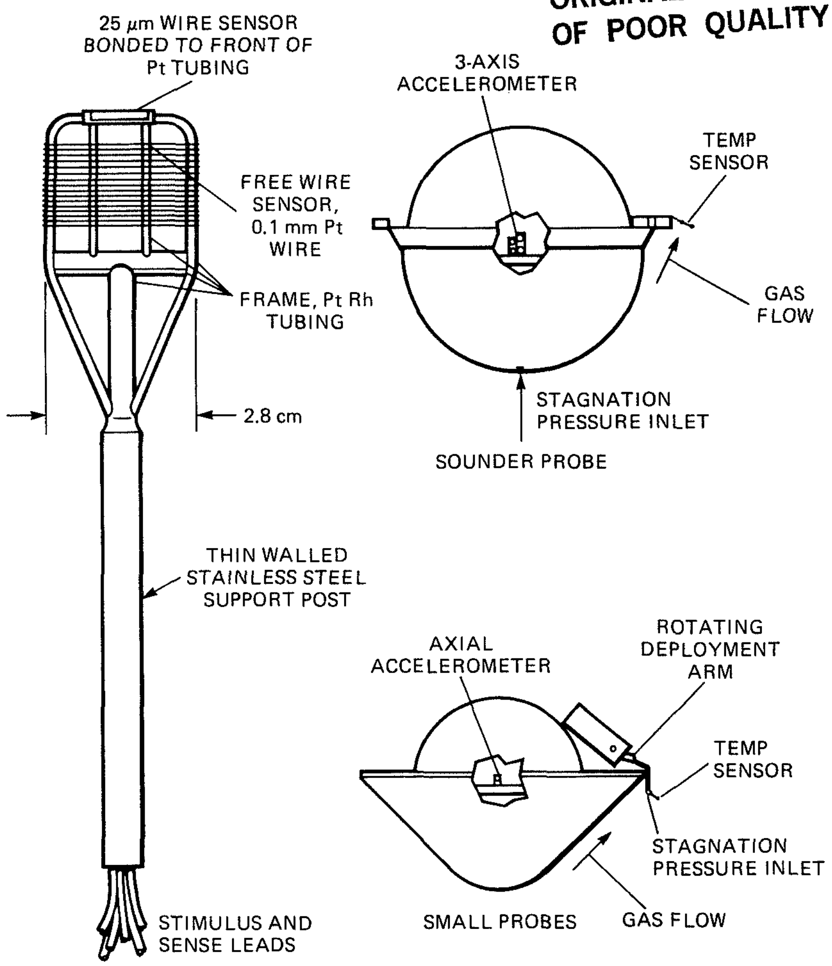


Figure 5-16. As the probes reached deep into the atmosphere unexpected readings were obtained from several instruments, including the atmospheric structure temperature sensors shown here. Sensors of entirely different design produced bizarre results at the same altitude.

an electrical resistance through the sensor of 25 Ω, as expected. The presence of continuous acid films on the sensors was indicated from partial shorting of the insulation of the T1 fine-wire sensors while in the clouds, but this cleared as the probes descended lower into higher temperatures. Also, the shorting effects within the clouds varied for the different probes, but the anomalies later all occurred at the same altitude, that is, at the same temperature and pressure levels in the atmosphere. Moreover, the T1 and T2 sensor elements exhibited anomalies almost simultaneously, although their physical configurations differed. The T1 sensors each consisted of a coil of fine platinum wire wound on a frame. The T2 sensors were more robust. They consisted of platinum wire bonded as a resistance thermometer on top of a thin glass insulating layer. It is important to note that the sensors that failed at almost the same time were made of different materials and that their electronics were isolated from each other.

The telemetered change in position – from deployed to stowed – of the sensor boom for the atmospheric structure and net flux radiometer experiments was a mechanical impossibility. It was concluded from post-flight analysis of identical boom status switches that failure of these switches under conditions of high temperature and pressure was a likely cause.

Anomalies in large probe housekeeping data, particularly the strange readings from the heat-shield thermocouple and thermistor, can best be explained if the probe became covered with a plasma of charged particles. One of the most mysterious events was an apparent reading from a thermocouple in the heat shield of the large probe. The heat shield had, of course, been detached and had fallen separately into the atmosphere. The leads had been severed at the time the heat shield was dropped from the large probe. Somehow an electrical potential had been created between the ends of the severed leads. Readings from these severed leads indicated a potential difference of 0.2 mV, with slight changes during the rest of the descent to the surface. A tantalizing possibility is that the severed leads acted as a Langmuir probe in a plasma.

The other anomalies – power variations, changes in the large probe's transponder static phase error and receiver automatic gain control, jumps in internal pressure and temperature readings – would be consistent with static discharges within or outside the probe, if such were possible.

One explanation suggested was a reaction between sulfur and the materials of the probes. Because each probe was always colder than the atmosphere, sulfur condensed on the outside of the probe pressure vessels and was carried down to regions of higher temperature. There, surface reactions occurred between the sulfur and the materials of the probe; this generated, in turn, an electrical charge. Each probe then acted as a large capacitor because parts of the spacecraft had not been electrically bonded (to avoid heat transfer between them). Moreover, titanium, a poor conductor, would act as a semi-insulator and prevent electrical charges from dissipating once they had been generated.

However, the nephelometer showed a clear atmosphere below 40 km (25 miles); so a major question was how such a charge might be built up in a particle-free atmosphere. Although the atmosphere was optically clear, it might nevertheless be ionized, literally swarming with invisible ions created by chemical reactions at the molecular levels as opposed to the particle level. A charge could be built up in a clear atmosphere by such chemical reactions.

There were anomalous, lower-atmosphere conditions to which the diamond window for the infrared flux radiometer was exposed. Scientists expected that, as more radiation was absorbed in the lower atmosphere, the flux would decrease. What actually happened was that the flux increased at low altitudes. Also, it appeared that the heater for the diamond window did not work as intended. Thus, there would be a rapid change in temperature of the window and it would appear in the data when the heater failed. This may have caused the apparent change in the flux data.

One possible cause of the failure of the window heater is the tantalum heater sheath. At high temperatures, there is a reaction between tantalum, carbon dioxide, and acid; both of the latter are present in quantity in the Venusian atmosphere. Engineers speculate that holes developed in the tantalum heater sheath from such a reaction. The insulation could have then become contaminated enough to provide conductive paths that allowed an electrical short between the heater and the spacecraft ground. This would have shorted the heater circuit and blown its fuse.

A conclusion is that most of the anomalies on the probe can be explained by effects arising from an unexpected electrical interaction between the probes and the atmosphere. Except for the sulfur deposition and the tantalum reaction, the source for a reaction of such widespread effect is, however, still uncertain.

Generally, however, the performance of these probes in the extremely inhospitable atmosphere of Venus was remarkable. A wealth of important new data was gathered as planned by the project scientists, and the technology had been proved for penetrating planetary atmospheres and for gathering data under conditions of enormously high temperatures and pressures. This new technology held the potential for exploring the many bizarre atmospheres of the planets in the outer Solar System.

Meanwhile, preliminary science discoveries were being attributed to the Orbiter experiments. Data from the Orbiter's first radar map (fig. 5-17) suggested that the topography of Venus might be similar to that of Earth, with high mountainlike features and extensive, relatively flat areas. The first preliminary scans by the radar mapper showed that, in a region of Venus previously unexplored by radar – a strip that extends for about 1900 km (1200 miles) – much of the surface appears relatively flat, similar to Earth's surface and quite different from the rough, cratered surfaces of Mars, Mercury, and the Moon.

After the first two dozen orbits, a serious setback occurred: the radar instrument stopped working. Teams of scientists and engineers tried several remedies, but to no avail. This failure was a great disappointment because the radar had started to reveal tantalizing details of the planet's surface. When all corrective measures failed, the radar mapper was turned off while more analysis into the instrument design took place.

However, no additional corrective ideas were discovered and when the radar was turned on again a month later, it worked, although not quite normally. The problem appeared to be of a transient nature, one associated with operating the instrument for periods longer than 10 hr. The instrument had been kept on for the first orbits and not turned off. An electrical charge may have accumulated in its sensitive logic circuitry. The experiment team leader and project personnel decided on new operating modes for the instrument. During each orbit, it was operated for a while and then turned off. This intermittent use resulted in normal operation of the radar mapper within about 10 days; it

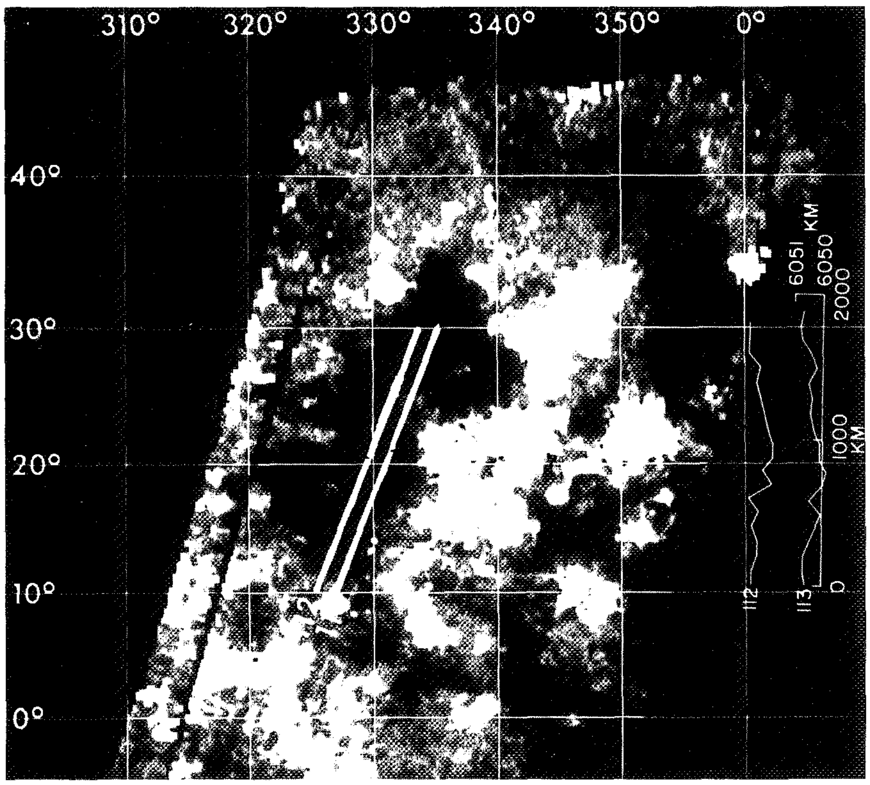


Figure 5-17. First radar scans of Venus from the Pioneer orbiter produced intriguing new maps of the cloud-hidden surface. The instrument also measured elevations, revealing enormous mountains and deep valleys.

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operated satisfactorily for the rest of the mission.

Although a month of radar data was lost by this failure, the areas of Venus missed during that period were later covered in the extended mission.

There was another disappointment with Pioneer Venus, one that was not as happily resolved as the problem of the radar mapper. The infrared radiometer failed when the spacecraft was on about its seventieth orbit. Despite many attempts to correct the failure, the instrument could not be brought back into operation. It is believed that the problem was in the power supply of the instrument. There were some problems with other instruments from time to time, but they were resolved, the instruments recovered quickly, and data were gathered throughout the mission.

The initial altitude of periapsis had been chosen to be high enough that drag on the spacecraft would be negligible during the first orbit. A very conservative altitude had to be chosen because information about the upper atmosphere of Venus was sparse. As information was gained from the spacecraft, 7 periapsis correction maneuvers were performed during the first 16 orbits to reduce the periapsis to the scientifically desired 150 km (93 miles) above the mean surface of Venus, and to achieve the orbital parameters for the nominal mission (table 5-6).

The periapsis position of the orbit is affected by perturbations from the gravity field of the Sun. This required control by use of thrusters to maintain the variations in altitude within predetermined limits. Without corrections to the orbit by use of thrusters, the effect of the Sun's gravity is to push the periapsis out from the planet, that is, to raise its altitude. To keep the periapsis within the range of altitudes desired by the scientists, periodic corrections were required through the entire nominal mission. Figure 5-18 shows a plot of periapsis altitude for the first 9 months in orbit.

TABLE 5-6.– ORBITAL PARAMETERS FOR NOMINAL MISSION

Parameter	Value
Periapsis, km (miles)	150-200 (93-124)
Apoapsis, km (miles)	66,900 (41,572)
Eccentricity	0.843
Average period, hr	24.03
Inclination to equator, deg	105.6
Periapsis latitude, deg	17.0 N
Periapsis longitude, deg (for Orbit 5)	170.2

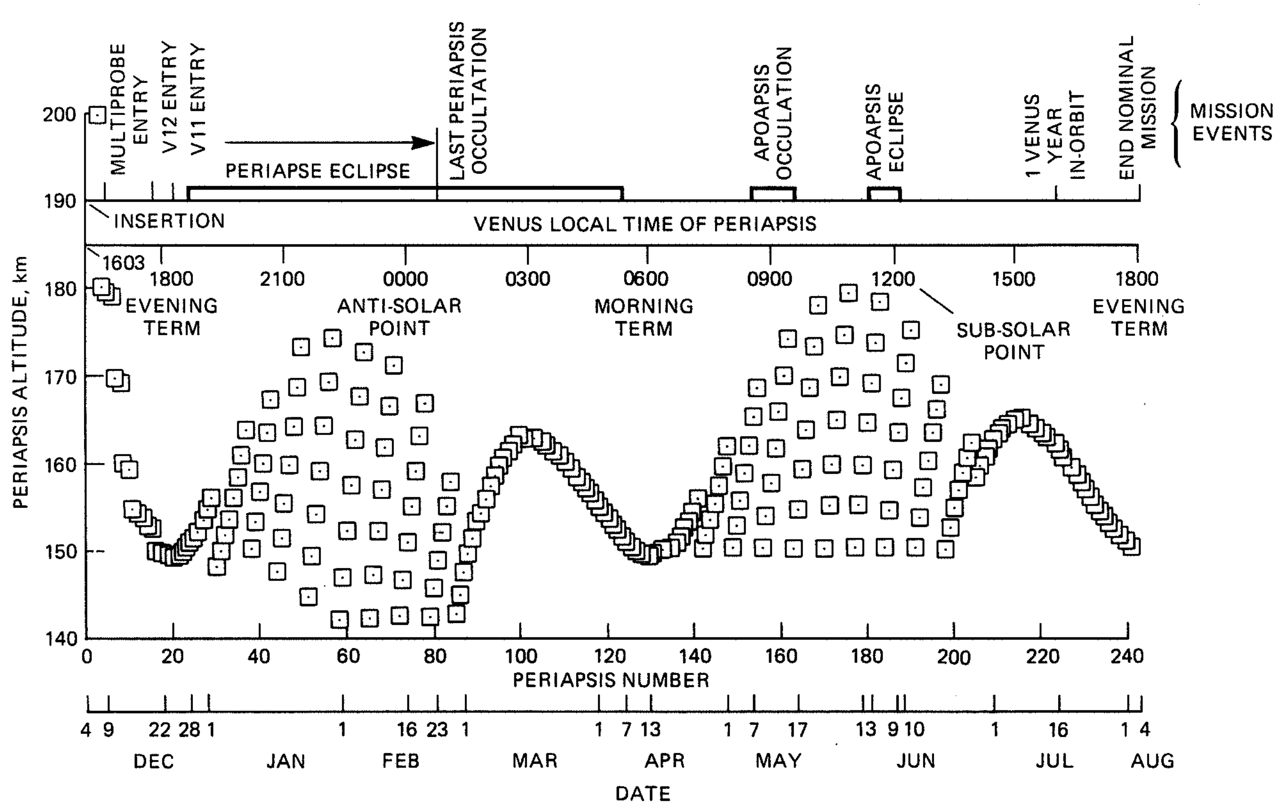


Figure 5-18. Altitude of periapsis during the nominal mission of Pioneer Venus orbiter and partway into the extended mission. Also shown are periods of eclipse and occultation.

Figure 5-18 summarizes how the altitude of periapsis changed through the nominal and into the extended mission. During the first few weeks of the spacecraft's operation in orbit, the periapsis was lowered to 150 km (93 miles) before it passed from the dayside to the nightside of Venus. Because the atmosphere is less dense on the nightside of the planet than on its dayside, the periapsis was lowered several times to 142 km (88 miles) while it was on the nightside so that the spacecraft could sample deeper into the atmosphere.

The Orbiter was oriented so that its spin axis is perpendicular to the ecliptic plane, with the despun antenna to the south end of the spacecraft. This orientation continues through the mission. Because the scientific instruments are located on an equipment shelf near the base of the antenna and because periapsis occurs at a northern latitude, the view of the north polar region is better than that of the south polar region.

Figure 5-19 shows how some orbit relationships varied during the nominal 243-day mission. The Sun-Venus-Pioneer orbit system is shown at four positions in the sidereal year from December 9, 1978, to July 22, 1979. Since the orbit is fixed in an inertial reference frame, the lines of apsides remain "parallel" to one another at each of these four positions. The local time of periapsis increases by 1.6°/day. At periapsis, the Orbiter thereby first sampled the dayside upper atmosphere of Venus. After several weeks of moving at 1.6°/day, the periapsis crossed the evening terminator; the spacecraft was then able to sample the nightside atmosphere and ionosphere at each close approach to Venus. Later the periapsis crossed the morning terminator and the spacecraft sampled the dayside again. The evening terminator was crossed again at the end of the nominal mission. Data at periapsis and along the orbit were thus obtained for all Venus local times in a period of 224.7 Earth days. However, because of the retrograde rotation of the planet on its axis, the longitude of periapsis moves relative to the solid body of the planet at 1.48° per Earth day (i.e., per orbit), so that 243 Earth days were needed to observe all longitudes on the solid planet. Figure 5-20 shows the geometry of several orbits relative to the track of the spacecraft through the bow shock, ionopause, and ionosphere.

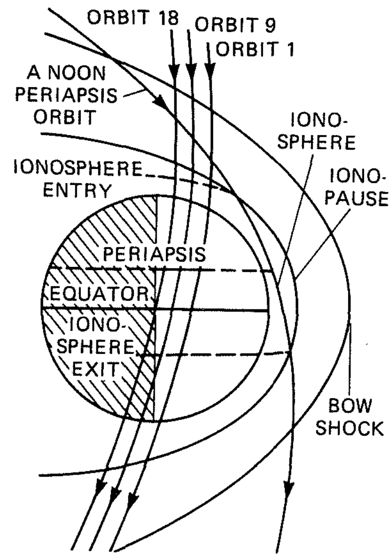


Figure 5-20. Periapsis passages of orbits 1, 9, and 18 carrying the Orbiter spacecraft through the bow shock, the ionopause, and the ionosphere.

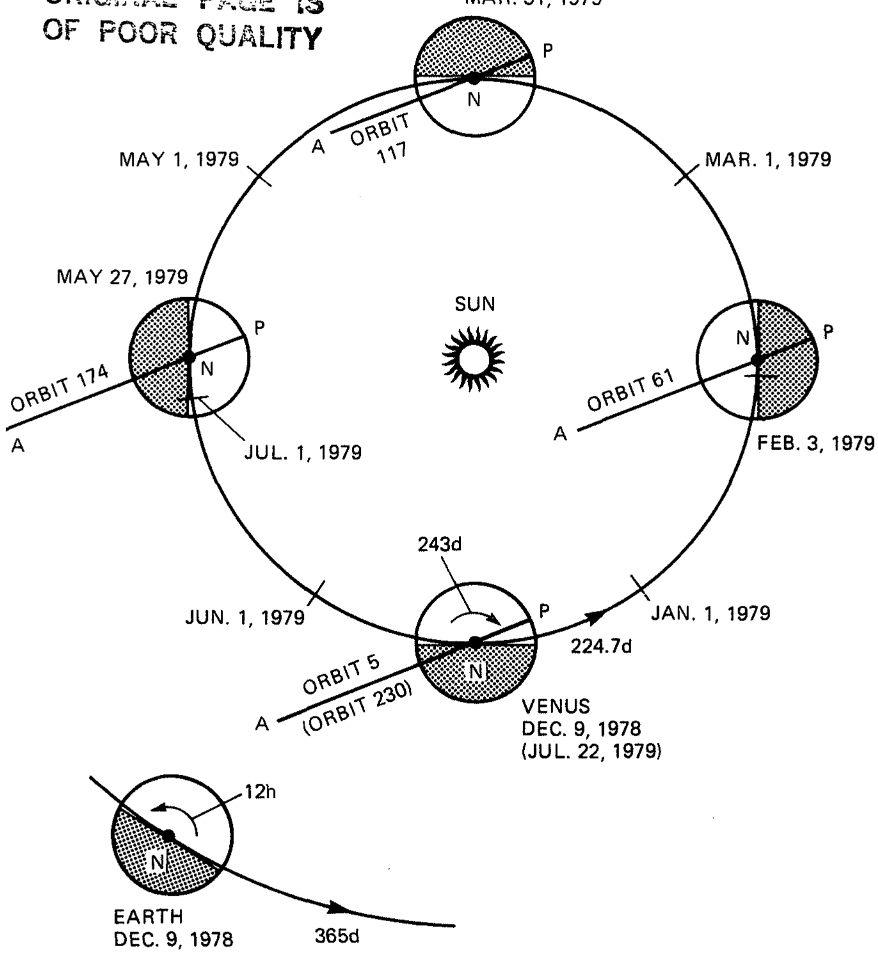
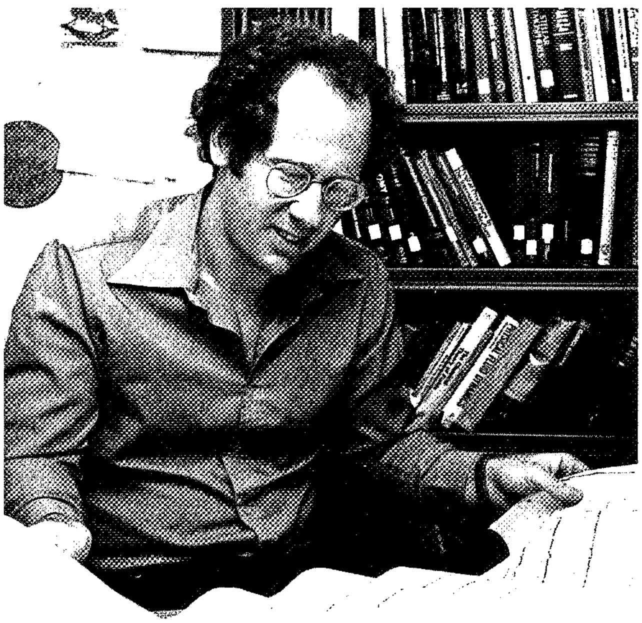


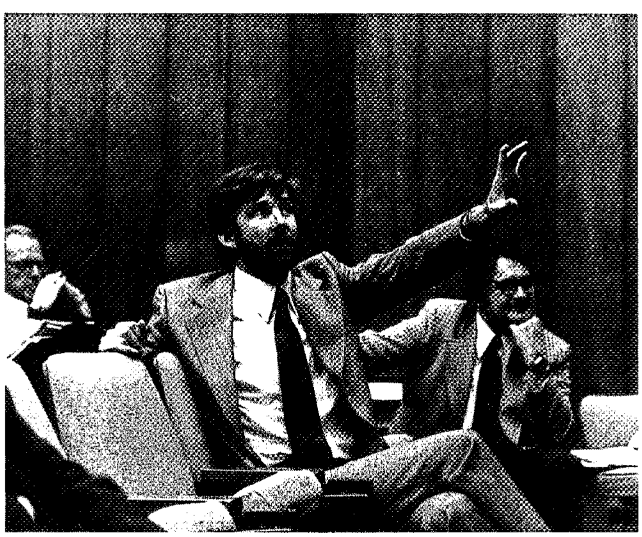
Figure 5-19. Sun-Venus-Orbiter geometry illustrates how the periapsis moves around the planet during the Venusian sidereal year to sample day and night hemispheres. Because the planet rotates in a retrograde direction, it takes more than one Venusian sidereal year for periapsis to move over all longitudes of the planet (as explained in text).

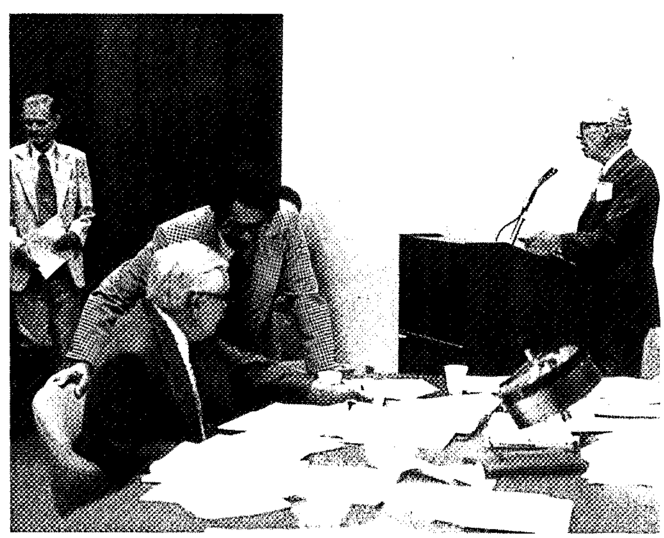
The nominal mission of the Orbiter was completed on August 4, 1979. Propellant had been conserved to the extent that the tanks were still almost half full for an extended mission. In fact, there was enough to keep the spacecraft active in orbit for at least another two sidereal periods of Venus, that is, for another 486 days, thereby providing a tremendous scientific bonus from this relatively inexpensive planetary mission.

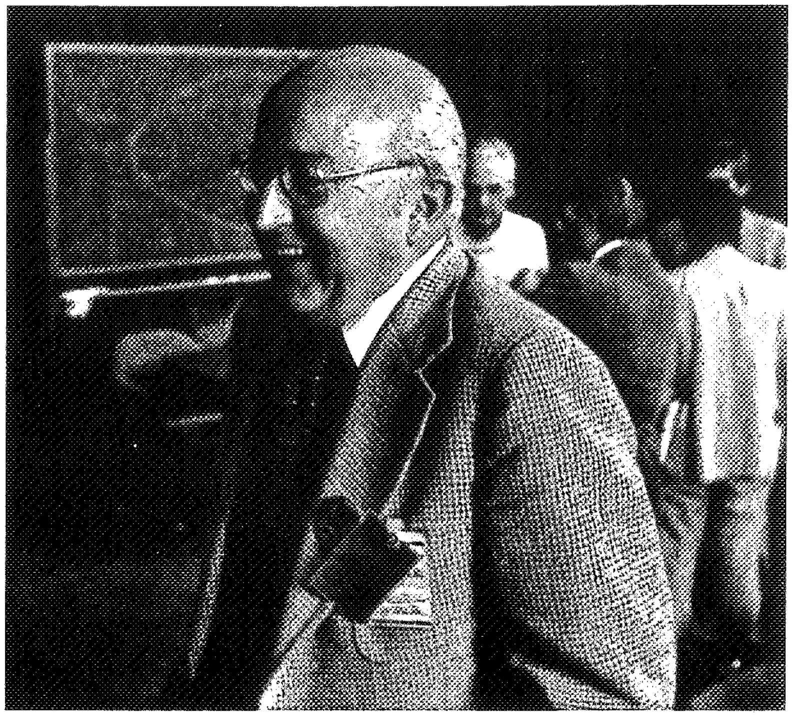
It was decided to continue the basic periodic control of the orbit until about orbit 600 on July 27, 1980, and then allow the periapsis altitude to rise slowly, initially at a rate of 400 km (250 miles) per 243 days and at only 225 km (140 miles) per 243 days by 1984. The apoapsis descends at an identical rate so that the period of the orbit remains constant.

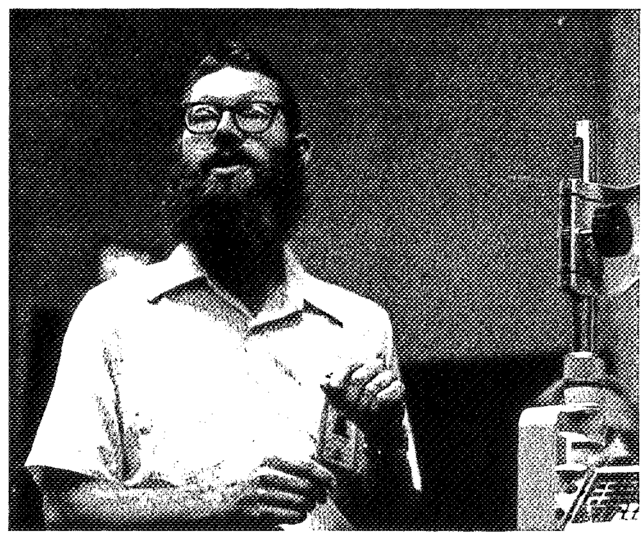
The extended mission thus consists of two operational phases. In the first phase, periapsis was controlled to remain within the Venusian atmosphere so that the spacecraft could continue to gather atmospheric data. During the second phase, large regions of the dayside bow shock and the nightside ionosphere, which could not be investigated in the nominal mission, and the first phase of the extended mission became accessible about 1 month twice each Venusian year. This phase also provided an opportunity to track the spacecraft for improved estimates of the low-order gravity field of Venus since atmospheric drag and spacecraft maneuvering would be virtually negligible.

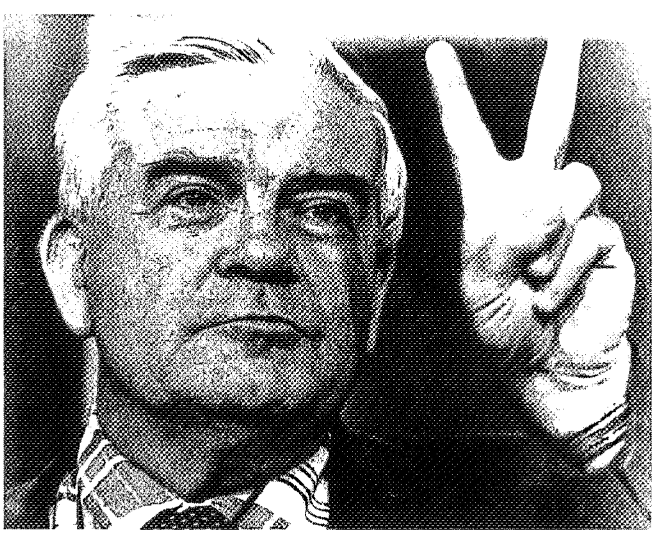












6 Scientific Results

"WE NEVER SEE HER SURFACE; she presents but a dazzling disc, with never a marking that we can be certain is not the result of eyes tired with too much brightness. Whether her atmosphere is clear or cloudy, or what lies behind that dazzling light, we do not know" (E. W. Maunder, Royal Observatory, Greenwich, 1908).

And 50 years later in 1959 and 1961, just prior to the inauguration of the space age: "As opposed to the volume of material known about Mars, there is little known about Venus. Its diameter is estimated at 0.95 that of Earth, but this figure is far from exact. There is no apparent flattening of the sphere. No surface features have ever been discerned, its period of rotation is indeterminate, and little is known of its atmosphere. Its polar caps are ill-defined, and no other permanent markings have been seen. Its surface temperature has been estimated at 110 degrees F, and surface pressure at two Earth atmospheres, but these are no more than educated guesses" (W. E. Straly, Lunar and Planetary Exploration Colloquium, March 1959). "The rate of rotation of Venus is still a problem. On the basis of the doppler measurements, JPL claims a period of about 225 days. However, a recent article in Izvestia stated a period of 10 or 11 days was calculated from the Russian doppler measurements" (C. E. Anderson, Lunar and Planetary Exploration Colloquium, November 1961).

Not until the second decade of the space age did the veils of mystery surrounding Venus begin to be lifted. Results of the scientific experiments on the Pioneer Probes and Orbiter, coupled with measurements made by earlier flyby spacecraft and many Soviet probes and orbiters, showed the planet's true characteristics for the first time.

The Planet in General

Radar data returned from Pioneer Venus provided a first global elevation survey of the surface of Venus from which about 90% of the planet was mapped topographically. Before the mission, the surface of Venus was the least known surface of all the terrestrial planets. Optical telescopes cannot penetrate the clouds and there are limitations to the radar image coverage available from Earth-based radar. Because Venus rotates in such a manner that it turns almost the same hemisphere toward Earth when it is closest to us, Earth-based radar can only look in detail at less than half of the planet's surface and only on a narrow equatorial swath with reasonable resolution. The Orbiter spacecraft travels in a highly eccentric orbit with a 24-hr period. The altimeter mapping sequences were made over a time span of about 1 hr each orbit at altitudes below 4,700 km. The Pioneer Venus radar data show features that are larger than about 75 km diam. (The smallest cell size is about 25 km, and 2 or 3 such cells are needed to define a feature other than a long narrow feature such as a rift.) As the orbit precessed around the planet, the radar view gradually covered nearly all the surface but with lower resolution at high latitudes.

Pioneer made important discoveries about this surface. It found that at scales of about 100 km or larger Venus is generally smoother than the other terrestrial planets but has surface topography with about as much maximum positive relief as on Earth. However, the distribution of elevations is markedly different from that on Earth, with only one mode rather than two. Both the topography and the gravity suggest that even though the interior of Venus is probably dynamic like the Earth, its tectonic evolution has not been like that of the Earth.

Pioneer obtained altimetric observations of more than 90% of the surface of Venus, extending from 73° north to 63° south latitude (fig. 6-1). To map Venus, the distance from the spacecraft to the surface below was measured by the radar altimeter. The orbit of the spacecraft is accurately known

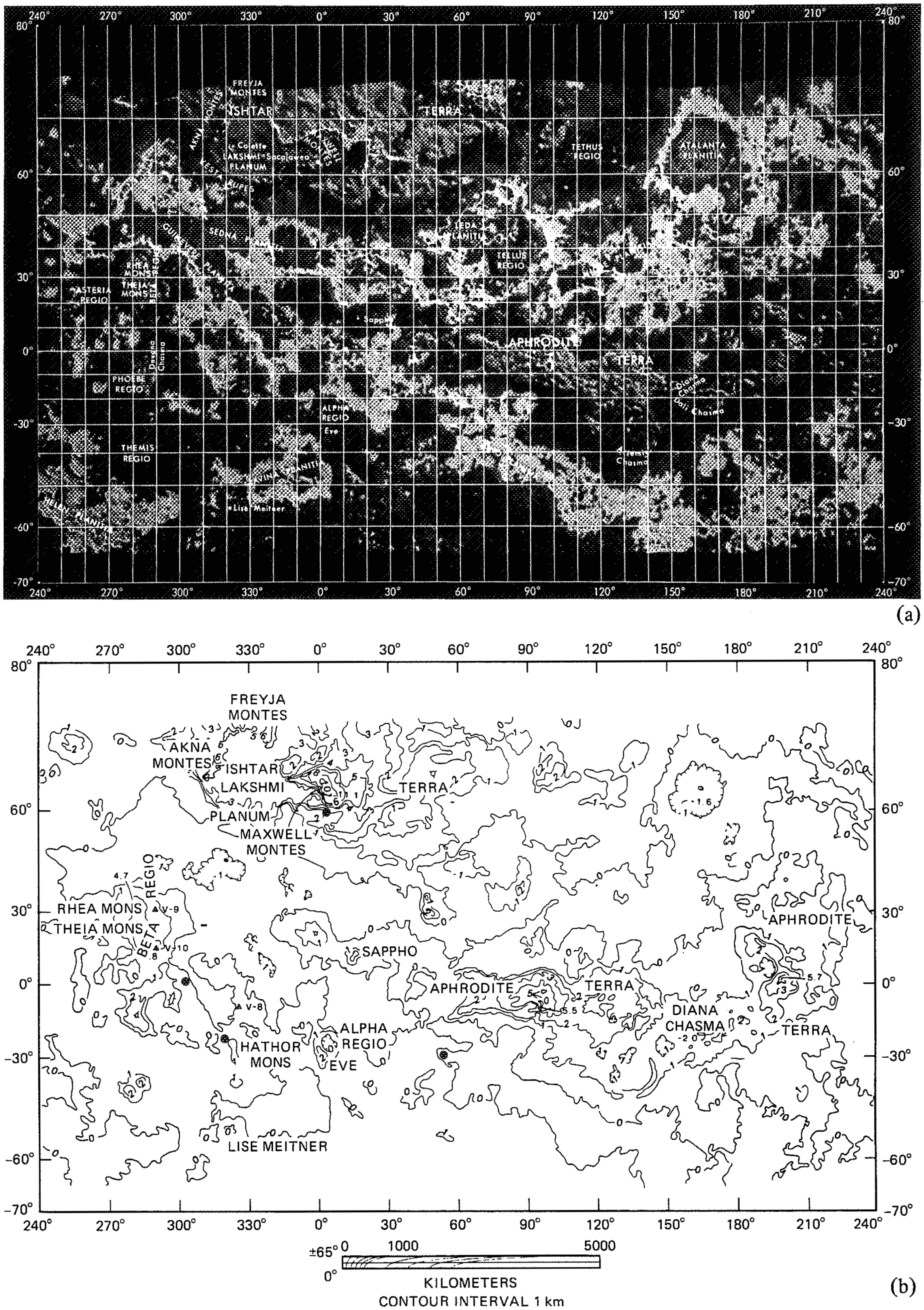


Figure 6-1. Topography of Venus as revealed by Pioneer. (a) Topographic map of the surface derived from the radar data returned from Pioneer Orbiter; dark grey is low, light grey is high. (b) Contour map of the surface with contour intervals of 1.0 km. The highest point is the summit of Maxwell Montes, the lowest is a point in the rift valley, Diana Chasma. V-8, V-9, and V-10 show where the Venera spacecraft landed. ⊛ Shows entry point for each of the four Pioneer probes.

from ground tracking. This permitted altitude measurements to be converted to radius measurements at discrete positions on the surface.

Venus is quite round, very different from the other planets and from the Moon. Earth, for example, is flattened at the poles and bulges 21 km at the equator. The Moon has a bulge toward the Earth. Mars bulges, too, but Venus has neither polar flattening nor an equatorial bulge. Earth has major variations between continents and ocean basins, which cover 30% and 70% of the surface, respectively. The mean levels of the terrestrial continents and the ocean floors are separated by 4.5 km. Mars also has major variations and the colossal uplift of the Tharsis region. By contrast, Venus has a very narrow distribution of surface elevations: 20% of the planet lies within 125 m of the mean radius, and 60% lies within 500 m of it. The planet is mostly a very monotonous world with only a few large continent-sized areas and smaller island areas rising above a global plain.

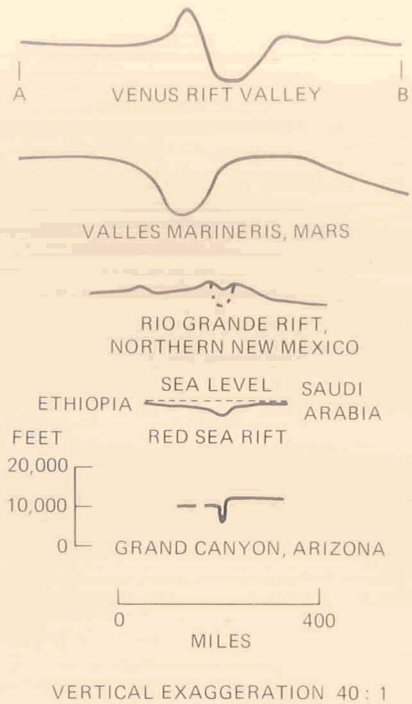


Figure 6-2. Comparison of a Venus rift valley with the Valles Marineris on Mars and some terrestrial valleys (vertical scale exaggerated).

The highest point on Venus is a summit in Maxwell Montes, 10.8 km above the mean level. The lowest point is 2.9 km below the mean level, in a rift valley located at 156° east longitude and 14° south latitude. This depth is similar to that of the Vallis Marineris on Mars (fig. 6-2), and only one-fifth the greatest depth on Earth in the Marianas Trench.

Comparisons between Earth-based radar observations of Venus and the Moon show that on a small scale Venus is significantly smoother than the Moon at all radar wavelengths. However, one part of Venus is rougher than the roughest area on the Moon.

Estimates of the harmonic coefficients of the gravity field of Venus were obtained by processing long periodic variations of the mean orbital elements of the Orbiter. The oblateness of the planet is exceedingly small as expected from its slow rate of rotation. Detailed gravity measurements have been made over a significant area of Venus and many anomalies were detected (fig. 6-3). But unlike gravity

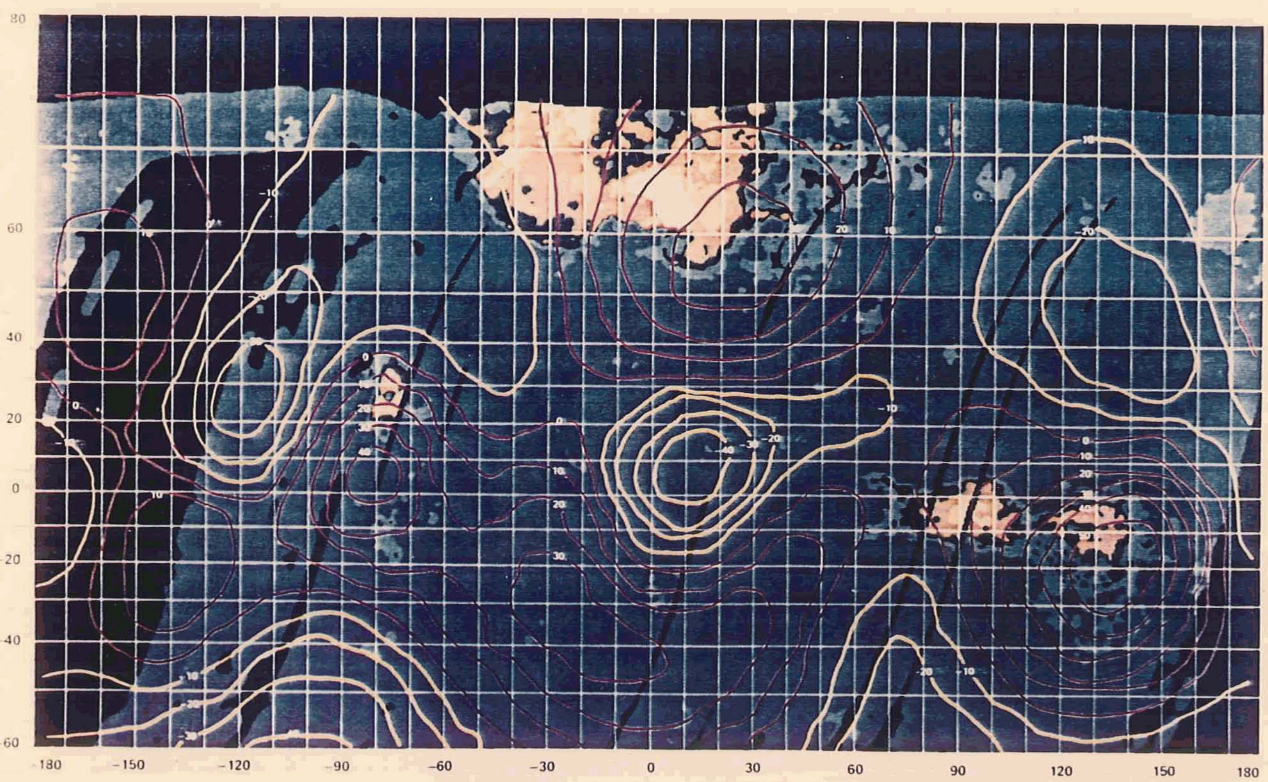
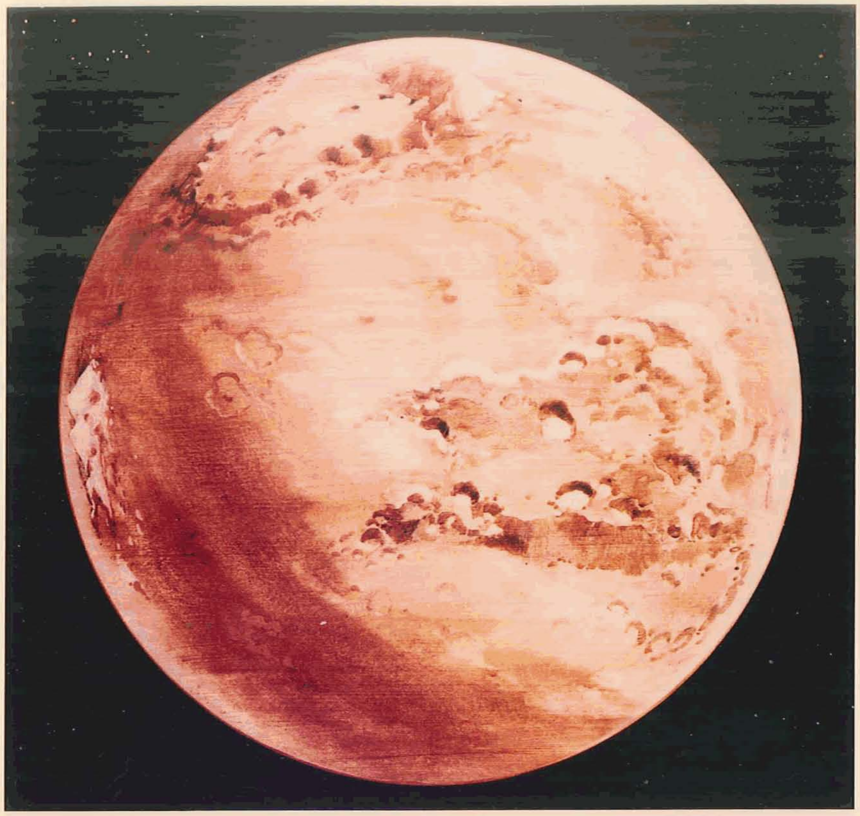


Figure 6-3. Gravity field of Venus showing sixth degree and lower-order harmonic coefficients evaluated at 100 km above the mean surface, in milligals.



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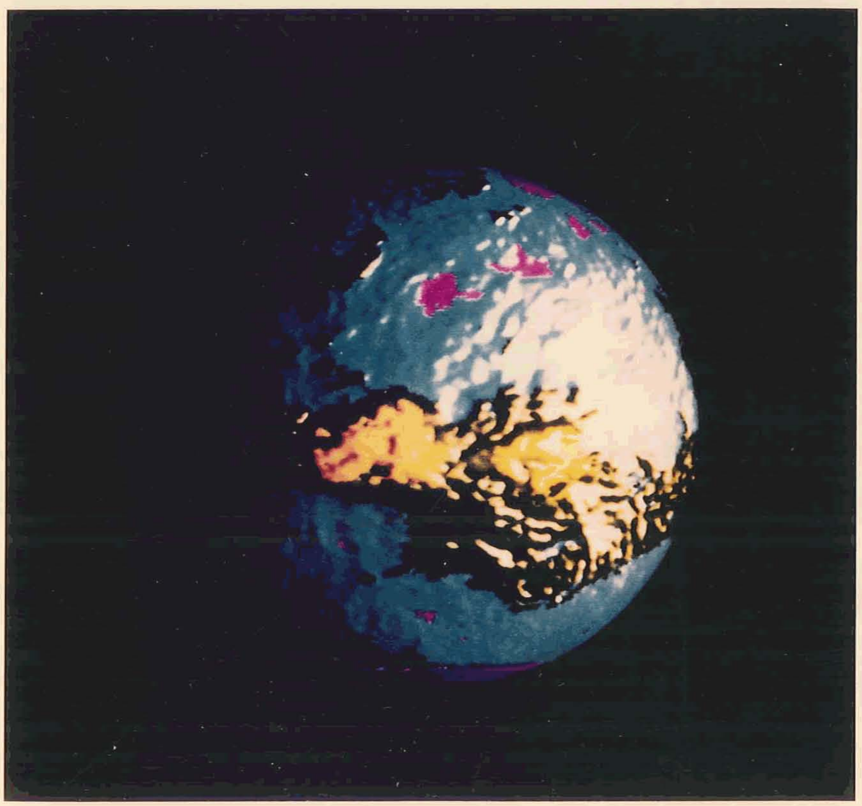


(b)

anomalies on the Moon and Mars, their amplitudes are relatively mild and similar to those of Earth. This magnitude of the Venusian gravity field is the one aspect in which it was consistent with inferences made on the basis of observations from the Earth, in the sense of stress implication; both Mars and the Moon are much different from Venus. Analysis of the spectrum of the harmonic model derived from these observations suggests that topographic consequences of the anomalies of Venus' interior density are different from those of Earth. On Venus the anomalies correlate with topography, on Earth most do not.

The conclusion is that significant adjustment to the crust of Venus has taken place to reduce topographic effects, and that partial isostasy or general equilibrium of crustal masses now prevails.

The Surface

The Orbiter's lifting of the veils of Venus (fig. 6-4) has revealed a world of great mountains, expansive plateaus, enormous rift valleys, and shallow basins. Some of the types of features revealed by Pioneer on the surface of Venus had been deduced from Earth-based radar. The wide range of the Pioneer data about the surface confirmed the existence of these features seen from Earth and considerably expanded the coverage of the planet. However, from the new data many of the earlier interpretations had to be revised.

A preliminary interpretation of the history of the crust of Venus results

Figure 6-4. Venus without its veil of clouds. (a) Artist's concept of the surface of Venus showing the major continents of Ishtar (top) and Aphrodite. Far to the left is the mass of Beta Regio. The vertical scale has been exaggerated. (b) Computer-generated globe of Venus developed from the radar data.

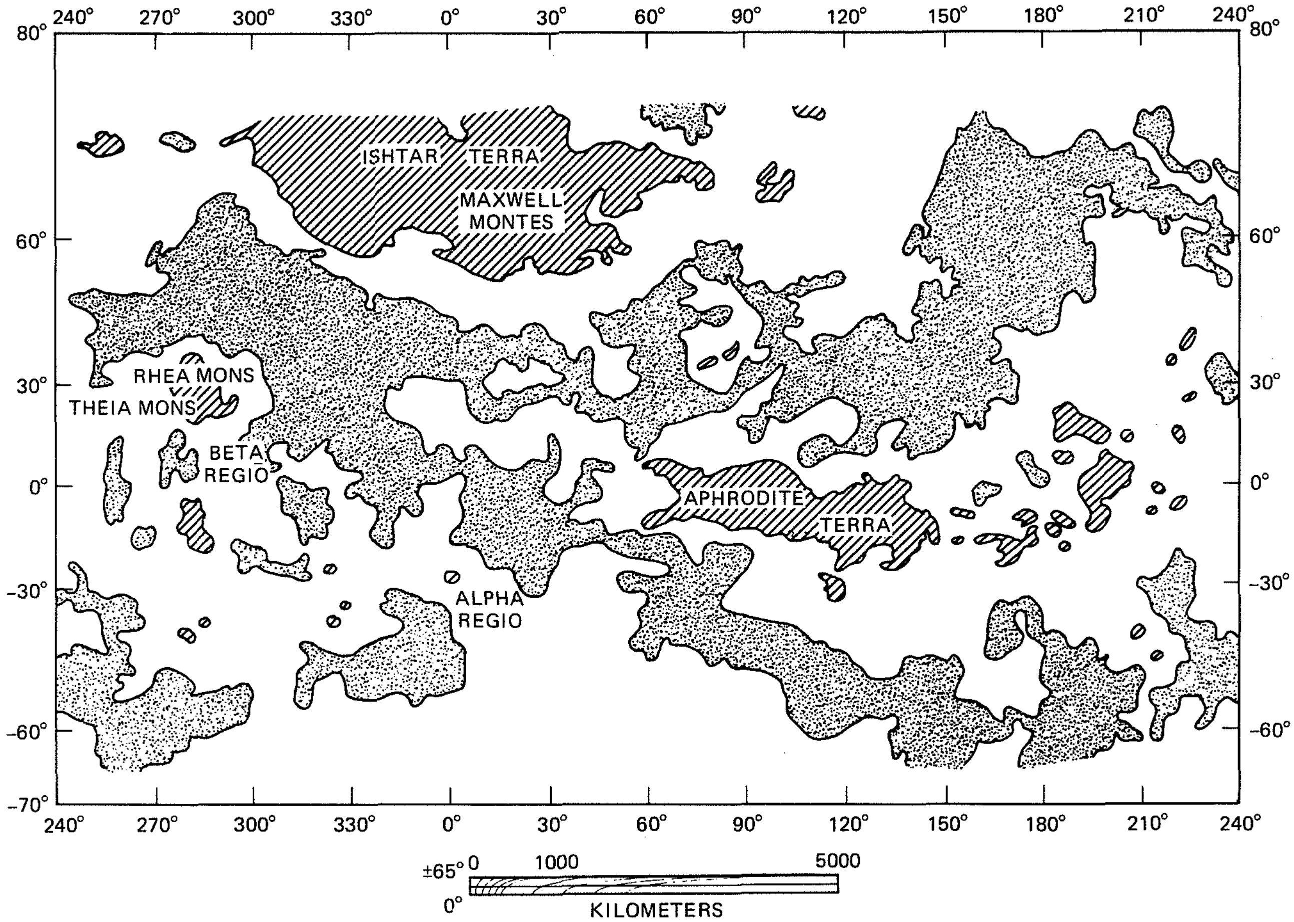


Figure 6-5. Map showing distribution of topographic provinces of Venus. The white areas are the rolling plains; the highlands are hatched, and the lowlands are the dotted areas.

from the Pioneer Venus altimetry and images coupled with Earth-based radar data. Three quite different regions are apparent – ancient crust at intermediate elevations, relatively smooth lowland plains, and highlands. Most of the ancient crust of the planet, those parts of the planet between 0 and 2 km above the mean radius, may be preserved in the upland plains of Venus. Venera 8 landed in these regions and its gamma-ray experiment showed that the rocks there have uranium, thorium, and radioactive potassium contents that are consistent with a granitic composition. Later data indicate that these rocks may have a different composition.

Most of Venus (65% to 70%) consists of these upland rolling plains (fig. 6-5) on which circular dark features may possibly be remains of large impact craters. If so, these plains are the remaining parts of ancient crust. The circular features are about 500 to 800 km diam but very shallow – only 200 to 700 m deep. Their shallowness may be caused by erosion or by flooding with lava or wind-blown deposits. Bright spots in the radar images of the craters may indicate that they have central peaks. Earth-based radar mapping reveals other smaller circular features with narrow rims and dark, deeper floors. There are also small circular features which look much like young impact craters, the ejected material from the impact having produced a surrounding rough area which appears bright on the radar images.

If a full population of craters down to smaller sizes is revealed when these plains are further investigated at higher resolution by a Venus Orbiter, which would be the next desirable step in the exploration of Venus, then Venus may be shown to have preserved ancient crustal material. Counts of the numbers of craterlike features now revealed produce a crater density curve that aligns with those derived from counts of craters on other terrestrial planets. This supports the viewpoint that a heavily cratered ancient crust may be preserved on Venus as it is on the Moon, Mercury, and Mars.

The lowlands of Venus cover about 25% of the surface compared with the terrestrial lowlands which cover 70% of Earth. They also differ markedly from the lowlands of Earth which are the floors of the terrestrial oceans. Plateaus and mountains on Venus are as high as or higher than those of the Earth but the lowlands are only one fifth the greatest depth of Earth's lowlands. To the Earth-based radar they appear dark, so they must be

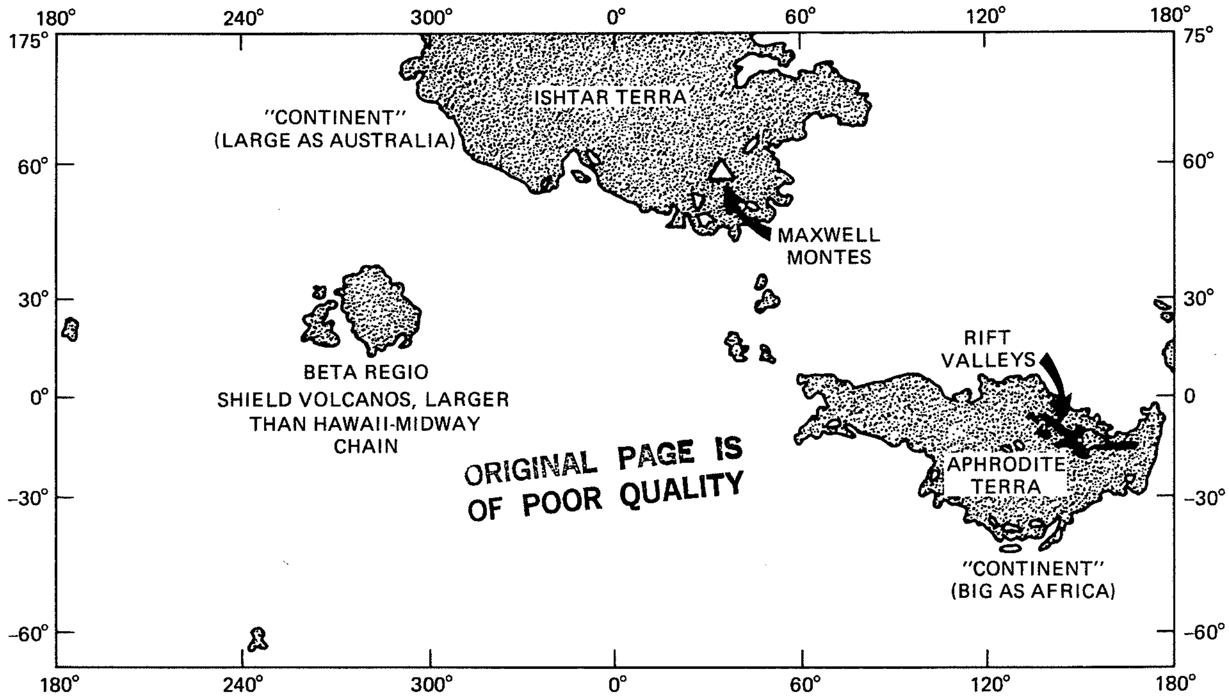


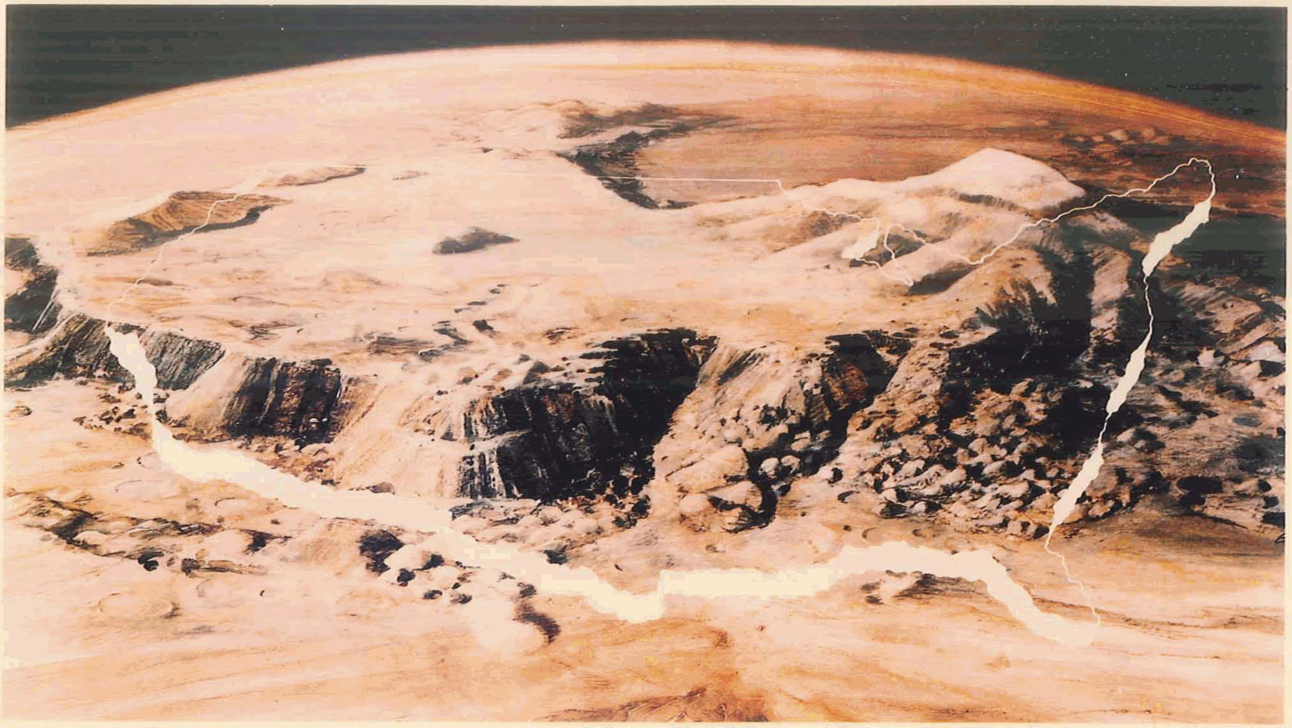
Fig. 6-6. Major continental masses of Venus. The size of Ishtar Terra is exaggerated compared with Aphrodite Terra on the Mercator projection.

smooth or else consist of radar absorbing material.

An extensive lowland basin, Atalanta Planitia, centered at 170° longitude and 65° latitude, is about the size of the Earth's North Atlantic Ocean basin. (Except for some features with names that have become established from Earth-based observations, the features on Venus are now being given female names following the tradition of the name of the planet itself, the only planet of the Solar System with a female name (see appendix B). The smooth surface of Atalanta Planitia, about 2 km below the mean elevation, resembles the mare basins of the Moon. Because there are no circular bright features that could be impact craters on the lowland areas, the surface may be young. The basin forms part of a large belt of irregular unconnected lowlands – possibly lava-flooded areas – encircling the planet. Precise observations of the orbit of Pioneer around Venus allowed the gravity field to be mapped in detail. One non-unique interpretation of gravity anomalies is that these plains have a thin crust below them of lower density than that below the upland plains. This is similar to conditions on the Moon and Mars. Some geologists have suggested that these low areas are depressions that were later filled with basaltic lavas, like the mare surfaces of the Moon and some of the plains of Mars. Others suggest that they may be filled with now consolidated wind-blown sediments.

There are only two highland or continental masses on Venus: Ishtar Terra and Aphrodite Terra. (Ishtar was the mythological Babylonian goddess of love, and Aphrodite the Greek goddess of love.) Ishtar Terra is located between 30° east and 60° west longitude and 60° and 75° north latitude, and Aphrodite Terra, between 80° and 140° east longitude and 5° north and 15° south latitude. A much smaller elevated region, Beta Regio, located between 40° and 50° west longitude and 10° and 40° north latitude, appears to be a volcanic area associated with a major rift valley system. Beta Regio is probably the youngest region, and its mountains are possibly still forming. Ishtar Terra may be next in age, and the oldest region may be Aphrodite Terra (fig. 6-6). But Atla Regio (the "Scorpion's Tail") at the east end of Aphrodite may also be young.

Points on Ishtar rise to about 11 km and on Aphrodite to about 5 km above the mean radius of the planet. But only 5% or 6% of the surface in these "continental" regions is more than 1600 m above the mean level, compared with 30% on terrestrial continents. The mass of these regions is about 80% compensated. Three possible causes are mantle convection underplating the highland masses with silicic rocks, mantle plumes of upwelling magma producing local differentiation to balance the thickness of the crust, or plate tectonic processes causing continental growth. Continental growth by tectonics does not have supporting evidence of deep subduction troughs or midbasin ridges which are characteristic of terrestrial plate tectonics. However, the presence of some complex forms of troughs and ridges in many



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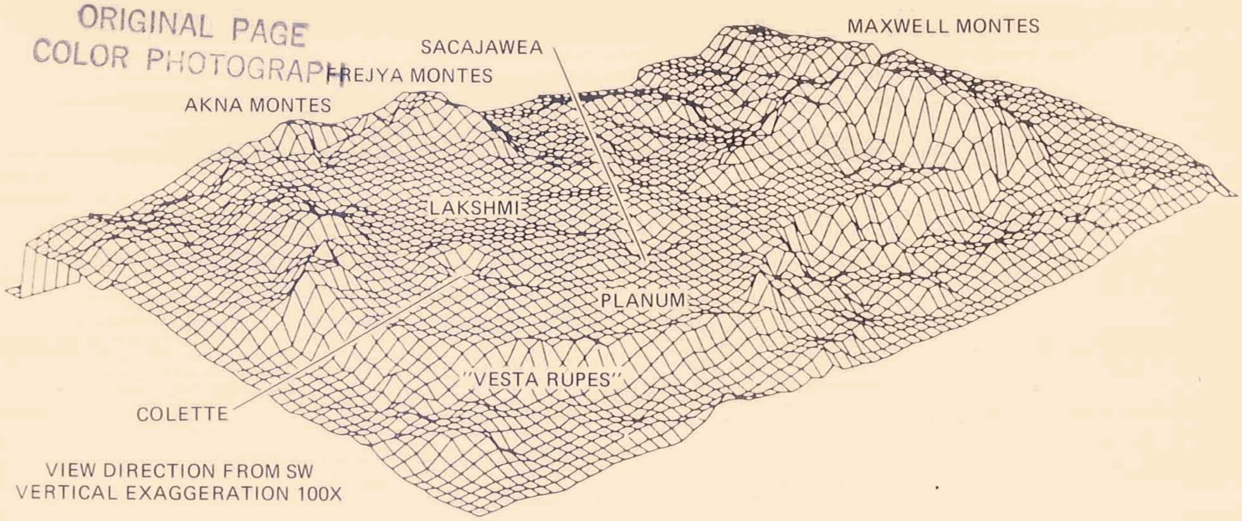

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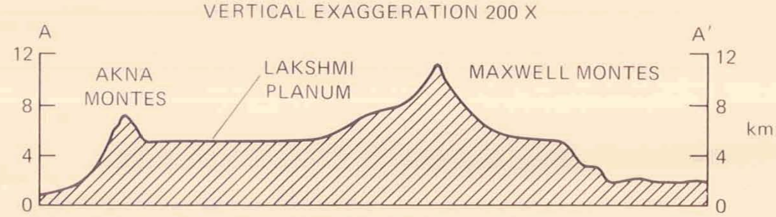


(c)

Figure 6-7. Ishtar Terra, the northern continental mass. (a) Artist's concept of Ishtar Terra with the outline of the US overlaid to show the relative sizes. (b) Computer-generated three-dimensional plot of Ishtar Terra showing its main features. (c) Section across Ishtar Terra showing the relative heights of the mountains, the central plain, and the surrounding territory.

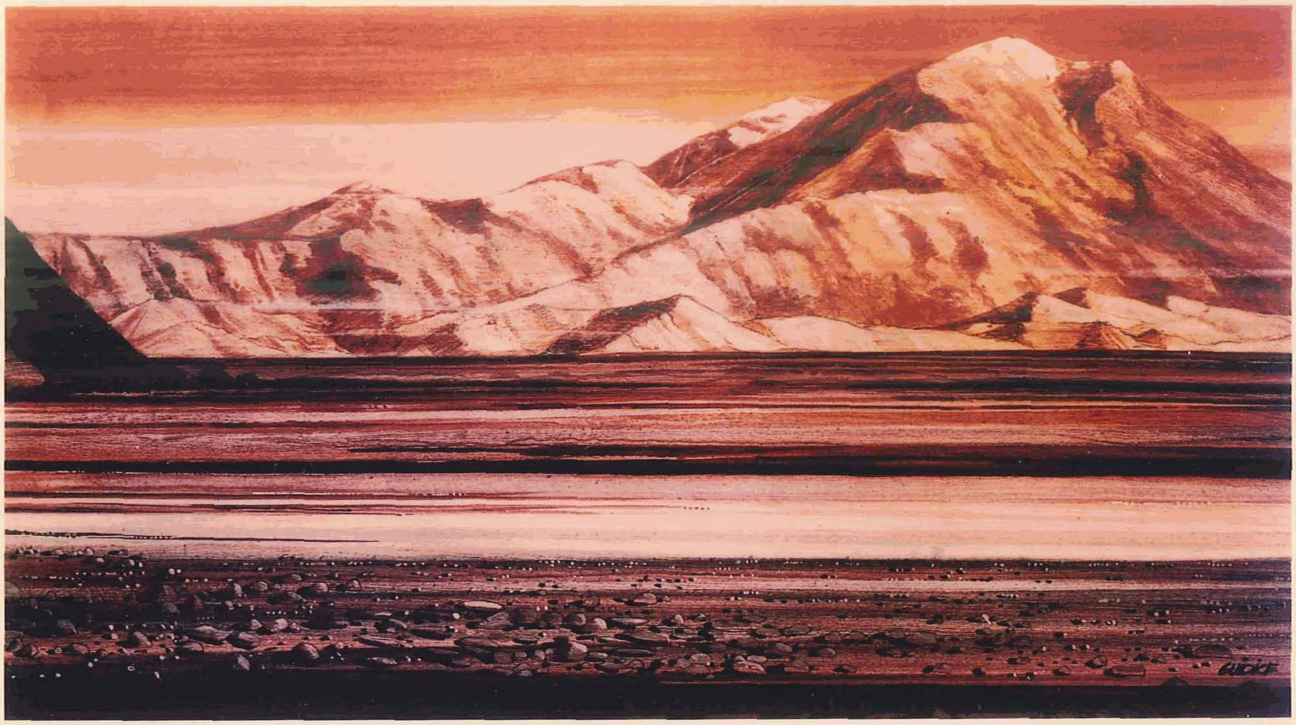


Figure 6-8. Imaginary view of Maxwell Montes as seen across the plains of Venus.

areas may indicate that large-scale motions of the crust have occurred.

Ishtar Terra is about the size of Australia or the continental United States (fig. 6-7), has the highest peaks on Venus, and consists of three geographic units – Maxwell Montes, Lakshmi Planum (named after a Hindu goddess) with mountain ranges of Akna Montes (named after the Mayan goddess of birth), and Freyja Montes (after a Norse goddess) on its northern and northwestern margins, and an extension of the Lakshmi Planum. Lakshmi is about 4 to 5 km above the mean level of Venus, about the same general elevation as the terrestrial Tibetan plateau is above Earth's mean sea level. But it has twice the area of the largest terrestrial plateau. A bright scarp on the southern boundary may consist of talus slopes of eroded debris along a fault zone. Such a rough surface could account for the strong radar reflection.

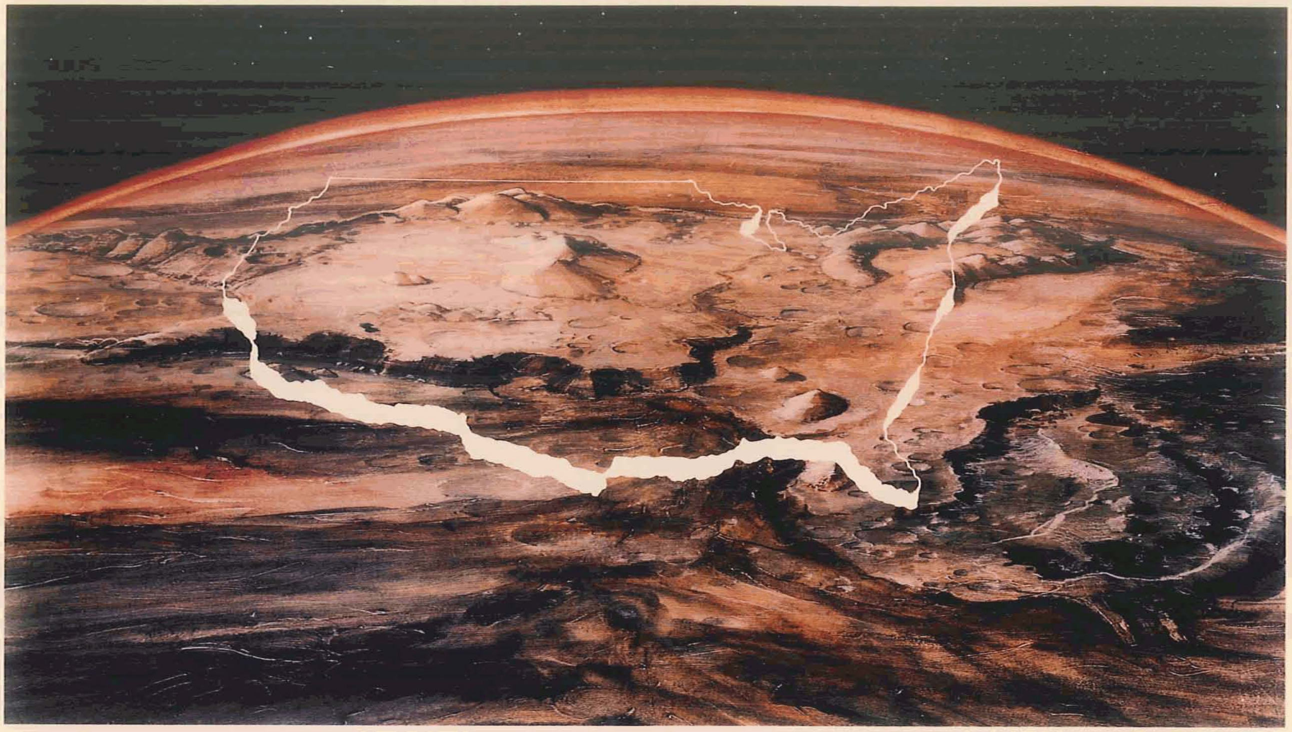
If Ishtar consists of basaltic lava flows a large gravity anomaly would be expected. But the data from Orbiter show a relatively mild positive anomaly. This suggests that Lakshmi Planum consists of thin lavas overlying an uplifted segment of ancient crust, similar to the Tharsis region of Mars.

On the eastern side of Ishtar the huge Maxwell Montes thrust their peaks high into the Venusian sky (fig. 6-8). Maxwell was discovered by Earth-based radar. On it is a great circular feature which may be a caldera about 100 km across and 1 km deep which is offset toward the east flank of the mountain some 2 km below the summit. No bright flows radiate from this caldera. The implication is that erosion has smoothed any lava flows. If so, the volcano must be much older than those in Beta Regio. Much of the slopes of Maxwell are, however, bright in the radar images, indicating that they are covered with rocks that scatter the radar signal, probably because the slopes of the mountains are covered with debris. Polarization data indicate that these slopes are rougher than the very rough floor of the fresh lunar-impact crater Tycho, which is the roughest area of the Moon.

Scorpion-shaped Aphrodite Terra (fig. 6-9) is about the size of Africa. It has two mountainous areas – on the east, mountains rise 5.7 km above the mean radius of Venus; on the west, claw-shaped mountains are about 4 km high. Between them are rolling uplands with a topographically complex mountain rising about 3 km above it. The mountains have very rough surfaces like those of the Ishtar continent. South of Aphrodite is a large arcuate feature (fig. 6-10) called Artemis Chasma.

The highland areas of Venus do not appear to have any circular features that could be interpretated as craters, because craters are difficult to detect on rough terrain. The existence of these highlands may imply that there is very little water in the crust of Venus, because at the high surface temperatures water-rich crustal rocks would deform more readily and the highland areas might not persist.

The bright radar area of Beta Regio is also an interesting region dominated by a large complex shield volcano, and a large trough (fig. 6-11). The trough is part of a fault zone that may extend far to the south where two additional small highland areas (Phoebe Regio



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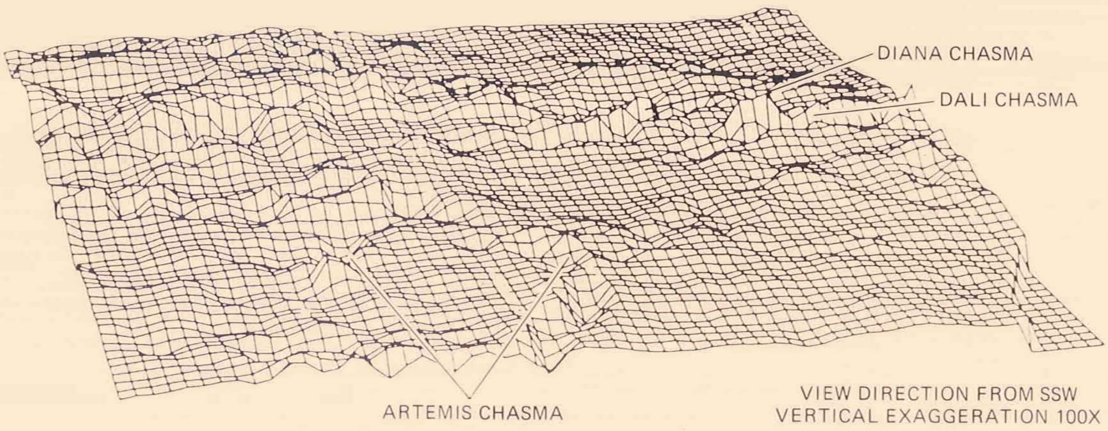

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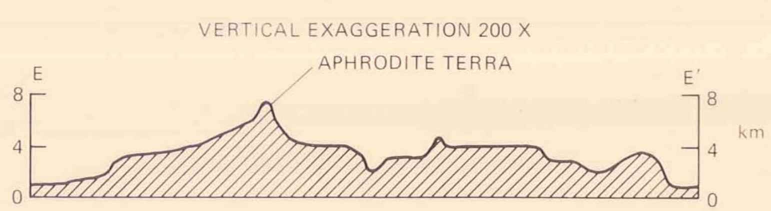


(c)

Figure 6-9. Aphrodite Terra, a large continental-type region on Venus. (a) Aphrodite Terra compared with the continental United States. (b) Computer-generated three-dimensional plot showing the great chasms in Aphrodite Terra. (c) Section across Aphrodite showing the relative heights of the features compared with the surrounding plain.

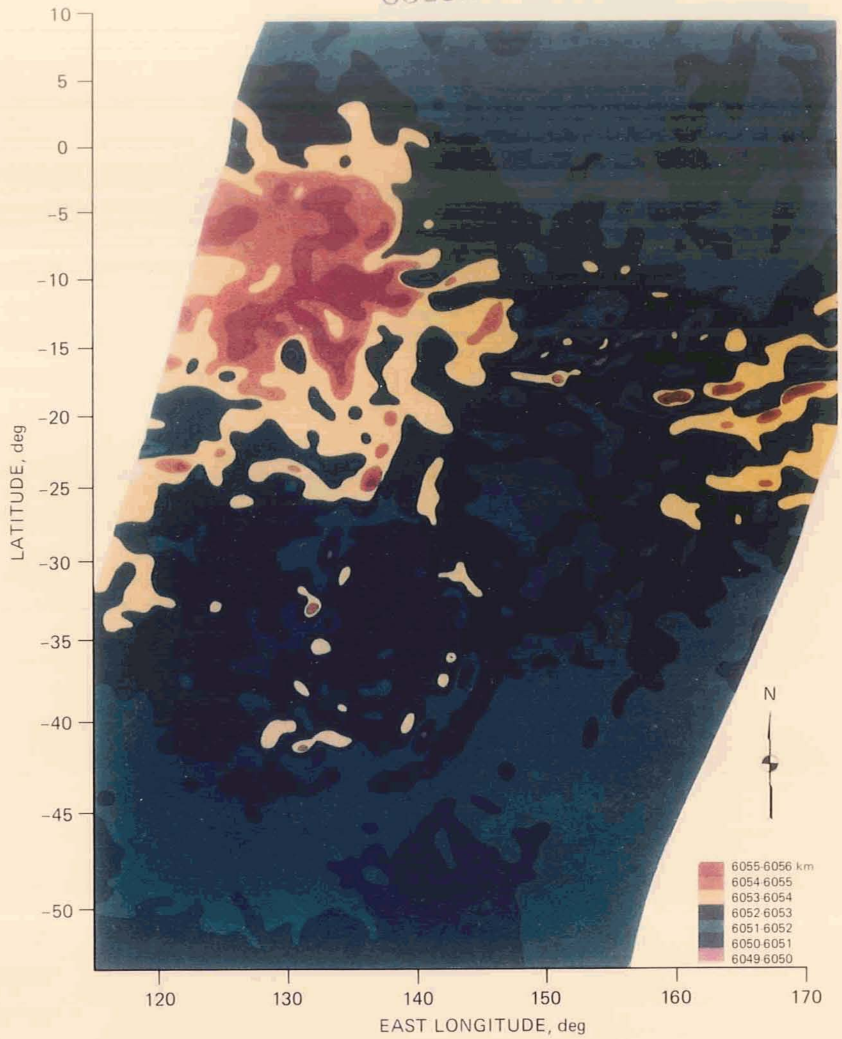


Figure 6-10. Arcuate feature on borders of Aphrodite Terra. This enlarged radar image shows the circular form of this feature, but we do not know if it is a volcanic or impact feature.

and Themis Regio) are aligned. Other small highlands, including Asteria Regio, located west of Beta Regio have a north-south trend. Lava flows extend radially from the volcanic centers, and two Soviet spacecraft landed directly east of Beta and found "basalts" there based on gamma-ray emanations from the surface. The highest mountainous features on Beta Regio are Theia Mons and Rhea Mons, both of which are 4 km high and have volcanoes on them. (Theia and Rhea are two of the six female Titans, daughters of Gaea in Greek mythology.) A large southward trending ridge has elevations up to 2 km. West of Beta Regio is flat terrain with a linear tectonic feature extending 4500 km to the SSW.

The new information about this region proves to be of great geological interest. At first, from Earth-based radar data, Beta seemed to be a shield volcano with a central caldera, but additional information from Pioneer Venus indicates that it is, in fact, part of an upland area of volcanics – Beta Regio – split by a great rift valley with high shoulders whose nearest terrestrial analogue is the Great African rift valley system. Bright radial streaks radiating from these shield volcanoes are suggestive of lava flows which lead to the suggestion that this is a comparatively young geologic feature.

Alpha Regio (fig. 6-12), a plateau within the rolling plains of Venus, is located at 25° south latitude and 5° east longitude. It is one of the brightest features on Venus and is elevated about 0.5 km above the mean level with a 2 km high rim. Its surface is cut by many fractures.

Many rift valleys on Venus (fig. 6-13) are revealed by the radar data from the Orbiter. They appear to be straight, or gently curved, tectonic features, some of which are 5000 km long. In various regions they form striking patterns and there is a great concentration of them east of Aphrodite and also east of Ishtar. They probably are caused by regional distortions resulting in the formation of tectonic valleys.

Geophysics points to a somewhat different story from that derived from the geological interpretation of the radar images. The gravity field of Venus as mapped by the Orbiter matches closely the topography, much more than for Earth where, for example, in the Pacific Ocean there are large gravity anomalies that may be the result of dynamic processes. But the anomalies of Venus seem to be closely associated with the topography. East of Ishtar there is a large region extending from 40° to 14° longitude and from 50° to 75° north latitude consisting of complex ridges and troughs, probably disrupted by extensive faulting. It appears to be the most tectonically disturbed region of Venus. There have been speculations that this region is possibly one where plate tectonics started or where a plume of hot magma rose through the mantle to produce a thickened low density crust.

Other features also suggest tectonic activity on Venus; vertical uplift at Lakshmi Planum, and the northern and western mountainous ridges marginal to Ishtar. These ridges on the Ishtar Terra may be due to plate motion, but there is no evidence for

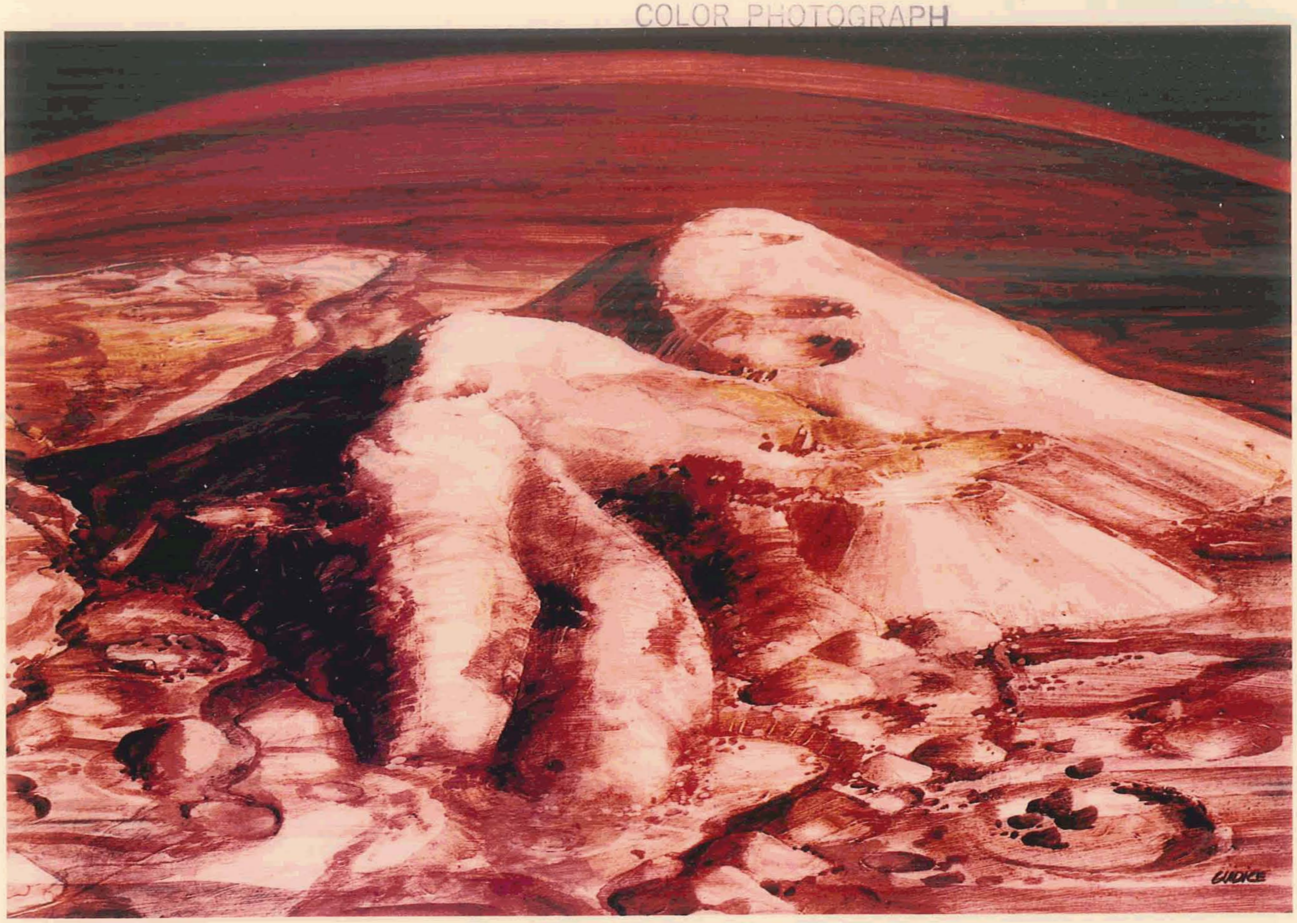


Figure 6-11. The great volcanic area of Beta Regio with many calderas, is probably the youngest continental mass on Venus.

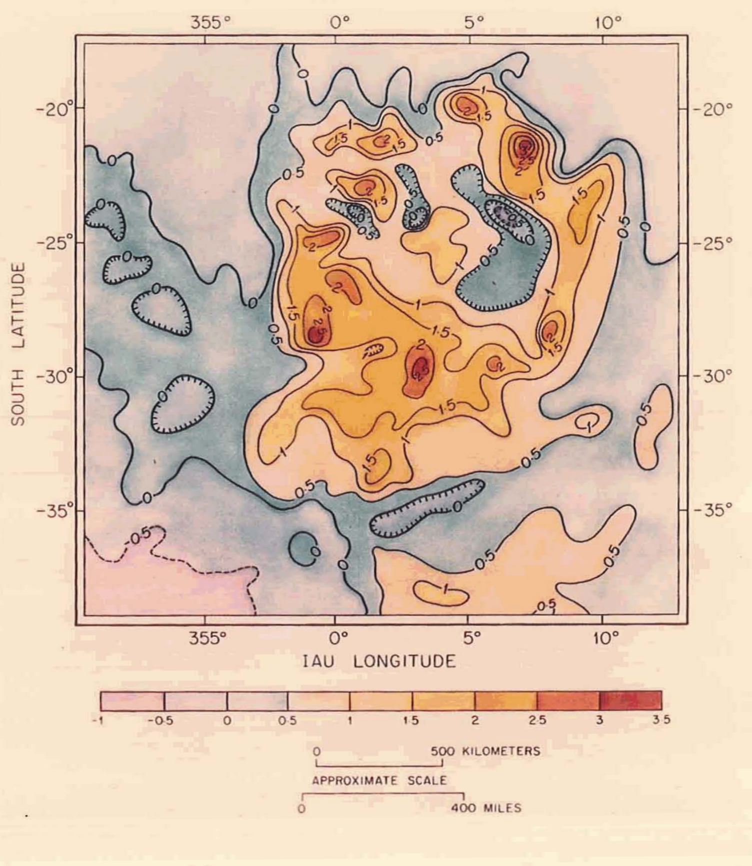
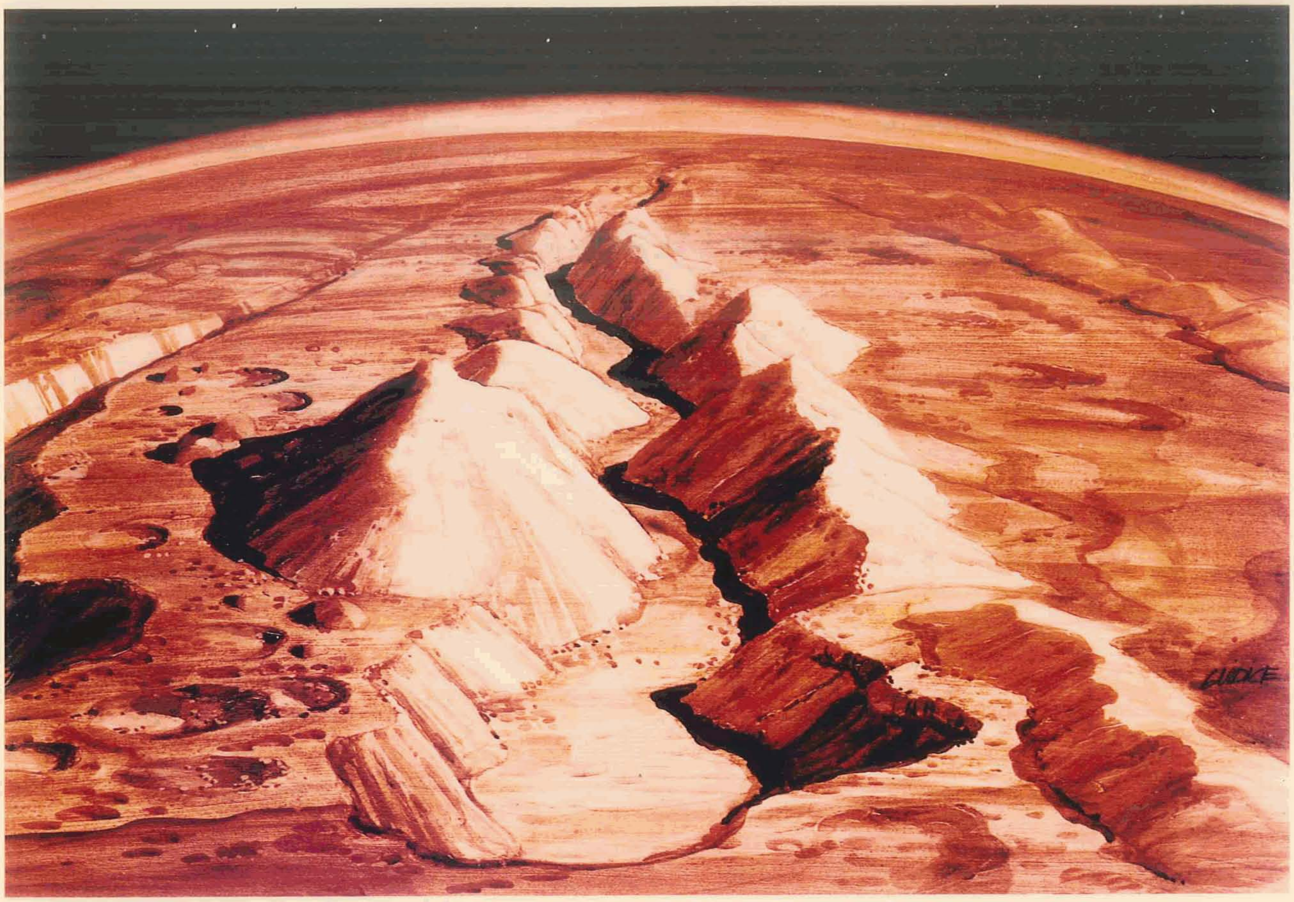


Figure 6-12. Alpha Regio is a bright area in radar; it is a high plateau surrounded by mountains. Elevations are kilometers above and below the median radius.

integrated plate tectonics on Venus. The development on Venus of what may be interpreted as thin crusted lowlands and thick crusted highlands suggests that Venus experienced a period of widespread mantle convection early in its history. The resolution of the Earth-based radar and the Pioneer Venus images are, however, sufficient to show that if plate tectonics do exist on Venus, they are grossly different in character from the plate tectonics of the Earth.

Venus seems to be different from any of the other terrestrial planets. It seems to have signs of regional displacements which may be evidence of incipient, or rudimentary, or past plate tectonics. Development of plate tectonics may have been stopped because Venus lacks water, but there is no



(a)

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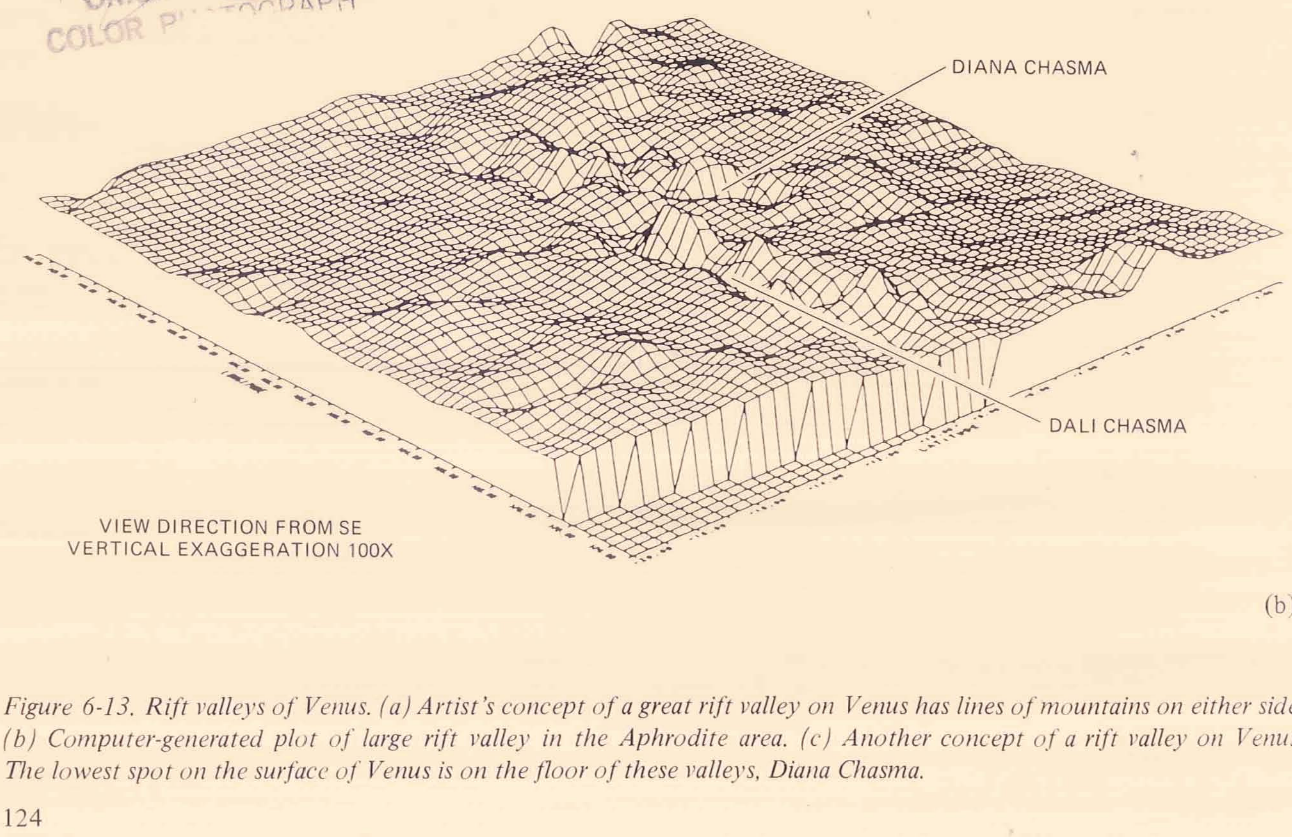

(b)

Figure 6-13. Rift valleys of Venus. (a) Artist's concept of a great rift valley on Venus has lines of mountains on either side. (b) Computer-generated plot of large rift valley in the Aphrodite area. (c) Another concept of a rift valley on Venus. The lowest spot on the surface of Venus is on the floor of these valleys, Diana Chasma.

(c)

proof that the presence of much water has anything to do with plate tectonics. Speculating why Venus should be so different from Earth when so similar in many respects, geophysicists have suggested that the higher surface temperatures have led to domination of the tectonics by a thick layer of basaltic material which cannot be subducted. Computer enhanced surface relief images are shown in figure 6-29.

The Atmosphere

Pioneer Venus Orbiter significantly extended observations of the ultraviolet patterns in the clouds of Venus. While Mariner 10 obtained 8 days of pictures, Pioneer Venus obtained hundreds of days of pictures to provide a greatly improved record of the bulk motions of the cloud tops. A question arising from the Mariner 10 observations was whether the features that move around in a 4-day period were bulk movement of masses of atmosphere or wave motions in the atmosphere. The Pioneer probe results indicate that the air is actually moving at the indicated speed of about 100 m/sec. Below the clouds, probe data show that the velocity starts to decrease to a very small value at the surface. The large features, especially the Y and C markings, can be regarded as waves of a special kind that move around the planet at the same speed as the air. All four probes, and some Soviet probes as well, showed the same westward motion with little or no north-south motion.

Additionally, the atmosphere was probed by many instruments from the Orbiter and sampled by others carried by the four probes and the Bus. Regions of the atmosphere are generally classified according to the behavior of the temperature, as shown in figure 6-14. On this figure, the solid lines in the thermosphere and cryosphere represent data gathered by the Probe Bus and the Orbiter; limited data from the small probes gave the dashed lines. Direct probe measurements (solid lines) cover the range from the mesosphere to the surface. The Orbiter infrared radiometer has given almost global information for the stratosphere, and additional results are obtained by the radio occultation experiment. These data from the surface to the ionosphere fit together to provide a rather complete picture of the temperature, pressure, and density structure of Venus' atmosphere.

Concerning the temperature structure, probably the most exciting discovery was of the enormous change in temperature between day and night in the upper atmosphere. Even on the dayside of Venus, the temperature of the upper atmosphere is not nearly as hot as Earth's upper atmosphere where temperatures are 700 to 1000 K at sunspot minimum. The heating is a byproduct of the formation of the ionosphere by very short wavelength ultraviolet radiation from the Sun. Venus somehow manages to keep a

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cooler temperature than Earth's upper atmosphere even with twice the flux of incoming solar radiation. But the real surprise is the low temperature of the upper atmosphere on the nightside. This region cannot be called "thermosphere" (hot sphere) like the equivalent region in the terrestrial atmosphere. (The thermosphere is the region of the atmosphere where the incoming solar photons are being absorbed and solar heat is transferred into the atmosphere.) The name "cryosphere" (cold sphere) has been coined to describe this cold region of the upper atmosphere of Venus. Even though the Sun is not directly heating the nightside, heat must be flowing to the nightside from the dayside, and also upward on the nightside from the warmer mesosphere. The gradient between day and night is rather sharp, occupying little more than the twilight zones, 20° to 30° of longitude. Although theories have been developed to describe and fit the behavior of Earth's thermosphere, they do not work for Venus. Most of these temperature features of the Venus atmosphere are unexplained. Improvements in the theory are clearly needed.

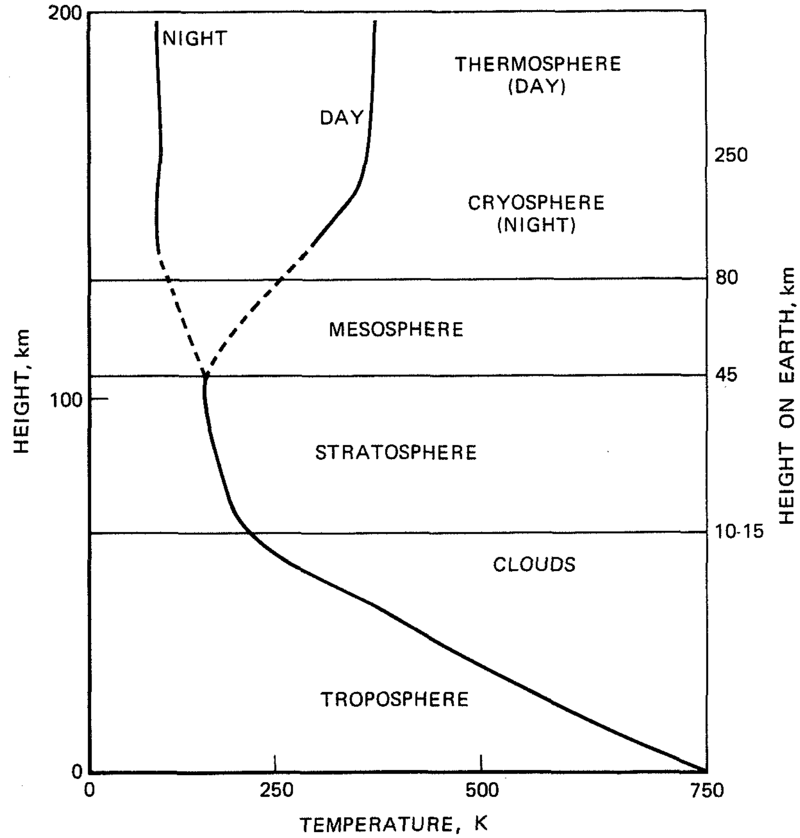


Figure 6-14. Typical temperatures for the Venus atmosphere and the corresponding regions. Heights for Earth are also shown for comparison.

Because the nightside is so cold, the atmospheric pressure falls very rapidly with increasing height and becomes much less than it is on the dayside at the same atmospheric levels. This large difference was observed directly by the Orbiter, and must cause very strong winds to blow from day to night. Unfortunately, there was no instrument that could have directly observed such winds, but there are some indirect confirmations of their presence.

The bottom 65 km of the Venus atmosphere is the troposphere. The boundary of this region, the tropopause, coincides approximately with the cloud tops. Pressures at the tropopauses of Earth and of Venus are similar, but the heights are quite different because of the different surface pressures. Above the tropopause is the region of the middle atmosphere. On Earth the middle atmosphere is divided into stratosphere and mesosphere; the boundary between these two regions is a temperature maximum caused by the presence of ozone which absorbs solar ultraviolet radiation. Venus has no detectable ozone and no temperature maximum to divide the two regions. No single name has yet been agreed upon for this combined region in the atmosphere of Venus, and both regions are shown in figure 6-14. This region is believed to be one in which there is a great deal of chemical activity driven by solar ultraviolet radiation. Very scarce atoms, such as chlorine, are thought to suppress the amount of oxygen and ozone to the very low levels that make detection of these gases impossible, even though they are certainly being released into the atmosphere by the breakdown of carbon dioxide. In important ways, the situation is like that of a highly polluted stratosphere of Earth.

In the lower atmosphere a major finding is that below the clouds there is really very little thermal contrast between night and day and from the equator to 60° latitude. Thus, variations of temperature at and near the surface of Venus are very small. Thermal contrasts provide the driving mechanism for the general circulation since they set up the pressure differences to drive the flow. The absence of large thermal contrasts in the atmosphere of Venus means that there is a very effective transport of heat from equator to poles and from the subsolar to the antisolar points by means of the atmospheric circulation; the atmosphere must be able to transport heat from the region below the Sun to the rest of the planet. Only slow winds are required to do this because the atmosphere is so dense. For the same reason, the rate at which temperature can rise or fall due to varying inputs of solar heat is very small, and the observed situation is easily explained.

A surprising discovery is that much of the deep atmosphere is stably stratified, like the Earth's stratosphere, or like the air in the Los Angeles basin on a smoggy day. From the clouds down to 30 km altitude (a layer 23 km deep) and in a lower layer between 15 and 20 km altitude, the atmosphere is stratified and free of convective activity. It does not rise and overturn in the way that air does over hot farm or desert lands on Earth, or in cumulus clouds. This was unexpected because the high temperatures in the deep atmosphere were thought to be a source of hot, rising gas which would lead to deep convective cells and turbulence. Also, before Pioneer Venus, theoretical studies had indicated that at radiative equilibrium much of the lower atmosphere would be unstable and would be overturning. The Pioneer Venus data have already led to needed revisions to these models.

The external sensors on all four probes (temperature and net flux instruments) started returning anomalous data at altitudes between 12 and 14 km. Although the explanation of the failure is unknown, high temperature combined with the chemical environment may be the cause. Some of the missing data have been pieced together by combining related measurements, but the net fluxes cannot be ascertained from the data.

The high surface temperatures measured by all four probes, and also by several Soviet probes, are equal within their uncertainties of a degree or so, once they are corrected to a constant "height" (really, distance from the center of Venus). Surface temperatures have also been sensed from Earth at radio wavelengths, with comparable results. The one thing that prominently sets Venus apart from Mars and Earth is this very high surface temperature. One of the primary objectives of the Pioneer Venus Multiprobe mission was to test thoroughly the belief that the "greenhouse effect" is responsible for the high surface temperature. This effect requires that only a few percent of the solar energy can reach the surface, be converted into heat, and be redistributed globally. Further, the atmosphere and clouds must form an insulating blanket through which heat (infrared or thermal) radiation penetrates only with difficulty.

The results leave no doubt that the greenhouse mechanism is operative. The greenhouse mechanism describes the state of the atmosphere above about 35 to 50 km altitude. Below that, dynamics control the temperature structure, while radiative heating associated with the greenhouse mechanism drives the dynamics. About half the heating of the atmosphere by incoming solar radiation occurs near the top of the clouds, while the rest of the energy is distributed at lower altitudes and the surface. The measured infrared fluxes show several anomalies the origin of which is still being debated. Taken at face value, the anomalies suggest that parts of the atmosphere are transmitting about twice the energy upwards that is available from solar radiation at the same level. Possible instrumental errors in this difficult measurement may be responsible. A possibility is that two of the probes entered regions that are unusually transparent to thermal radiation, but this is rather unlikely because much of the absorption is due to ubiquitous carbon dioxide which makes up nearly all the atmospheric gas. The suggestion has been made that the heat balance oscillates around its average state, and that the anomalous measurements were made during the cooling phase. In spite of these difficulties in interpreting some of the observations, the greenhouse effect, coupled with global dynamics, is now well established as the basic explanation of the high surface temperature.

The Atmosphere – Clouds

When viewed from the Earth in visible light the disk of Venus appears to be completely covered with a bright veil of unchanging, featureless, yellowish clouds. Before the Pioneer Venus mission these clouds had been intensely explored by Earth-based observations. Some *in situ* data through the cloud depths were available from the Soviet Venera missions to Venus, especially Veneras 9 and 10. Earlier, Mariners 5 and 10 flyby spacecraft experiments had also yielded some information, primarily about regions near the cloud tops. A principal objective of the Pioneer mission to Venus was to determine the nature and composition of the planet-enshrouding clouds.

The Earth-based observations first revealed the planetary nature of the clouds, showing them to be generally featureless, not only at visible wavelengths but also, with the resolution available to early investigators, at infrared wavelengths. However, at near ultraviolet wavelengths some features were discernible over the planet, hinting at some form of horizontal cloud structure. Further, these features appeared to circulate around the planet approximately every 4 days, as compared with the surface rotation period of 243 days measured by Earth-based radars. Mariner 10 obtained sufficiently detailed imaging of Venus to confirm this 4-day rotation period and to obtain detailed measurements of the circulation near the cloud tops. The images showed that the motions observed are generally zonal; that is, in general directions parallel to the equator.

Earth-based observations had also been instrumental in providing first-hand evidence about the detailed properties of the particles of which the uppermost clouds are composed. Measurements of scattered sunlight that had interacted with the uppermost layers were obtained on Earth. Particularly useful were measurements of the changes in polarization of the scattered sunlight as the angles of observation of the clouds relative to the solar illumination varied. From such measurements and from comparisons with calculations based on models that considered particles with various properties, the best agreement was found when the particles were all assumed to be spherical and of about the same size with an effective radius of about 1.05 μm and an index of refraction of 1.44 for visible light.

These conclusions and the results of attempting to fit additional spectroscopic data obtained from Earth strongly suggested that the upper cloud particles were composed principally of concentrated sulfuric acid.

Optical experiments aboard the Veneras 9 and 10 probes as they fell through the atmosphere obtained data consistent with these conclusions. Analyses of the data from the nephelometer (light scattering) experiments aboard these probes yielded information showing that the vertical cloud structure consists of three main layers and other regions, and also yielded information about the variations of effective particle sizes and indices of refraction in each of these layers and regions.

At lower altitudes the data from these experiments suggested that larger particles with large indices of refraction were present, and these were tentatively identified as large sulfur droplets. Furthermore, since sulfur seemed a likely candidate, sulfur crystals were also proposed as the high-altitude absorbers responsible for the ultraviolet contrasts.

Additionally, although invisible from Earth, a very tenuous haze was revealed on the Mariner 10 images. The haze layers were above the cloud tops at altitudes of 70 to 80 km. Bright transitory polar caps or bands, lasting from weeks to months, were observed from Earth.

Based on the above background, experiments for Pioneer were chosen to investigate, in detail, cloud properties at depth and temporal "weather-related" features at the cloud tops. For example, experiments on the probes were selected to detail the vertical cloud structure at each of the four entry sites, and experiments on the Orbiter have now provided several years of cloud-top observations. As described in a previous chapter, primary cloud experiments selected specifically to examine the clouds included large- and small-probe nephelometers, large probe cloud-particle size spectrometer, and Orbiter cloud photopolarimeter/imager. Cloud-related experiments to provide information from which cloud properties could be inferred included the large probe solar net flux radiometer, the large probe neutral mass spectrometer, the large probe gas chromatograph, Orbiter infrared radiometer, and Orbiter ultraviolet spectrometer. Further supporting information was obtained from the large probe infrared radiometer, the small probe net flux radiometer, and the large and small probe atmospheric structure experiments.

The combination of the data provided by the in-depth measurements from the four probe locations and the Orbiter's planetwide observations have led to a much more complete general understanding of the clouds, of their morphology, of the microphysical description of the particles of which they are composed, of their physical and chemical composition, of their optical properties and role in planetary energy processes, and of their interaction with atmospheric motions.

Cloud Morphology

We now know of several particle-bearing regions that have been identified in the Venus atmosphere from the Pioneer measurements. These include:

a) An upper haze region, extending from about 70 to 90 km, composed of very small particles observed by the Orbiter cloud photopolarimeter, ultraviolet spectrometer, and infrared radiometer experiments.

b) The main cloud deck consisting of three more-or-less distinctively differentiated regions: an upper cloud region (56.5 to 70 km), a middle cloud region (50.5 to 56.5 km), and a lower cloud region (47.5 to 50.5 km), each with varying microphysical properties observed by the probe nephelometer and cloud-particle size spectrometer experiments.

c) A lower haze, extending from 47.5 km to about 31 km, observed by the probe cloud-particle size spectrometer, with evidence of matter suspended in the atmosphere at lower altitudes provided by some of the probe nephelometers.

d) Additional thin-layered structures, identified as precloud layers, existing as transitory clouds in the upper part of the lower haze region.

Figure 6-15 shows the results of the nephelometer measurements of the vertical structure of the clouds at four Pioneer Venus sites and one Venera

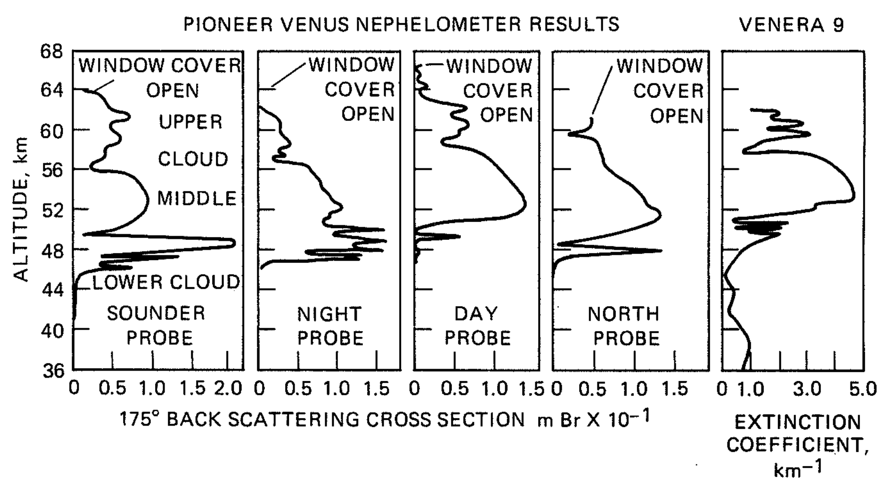


Figure 6-15. Comparison of results from the Pioneer Venus probes and Venera 9. A remarkable similarity in the profiles suggests that the cloud system is planetary, even though similarities in features of the vertical structure suggest changes in large-scale dynamics.

TABLE 6-1.– SUMMARY OF CHARACTERISTICS OF VENUS CLOUDS

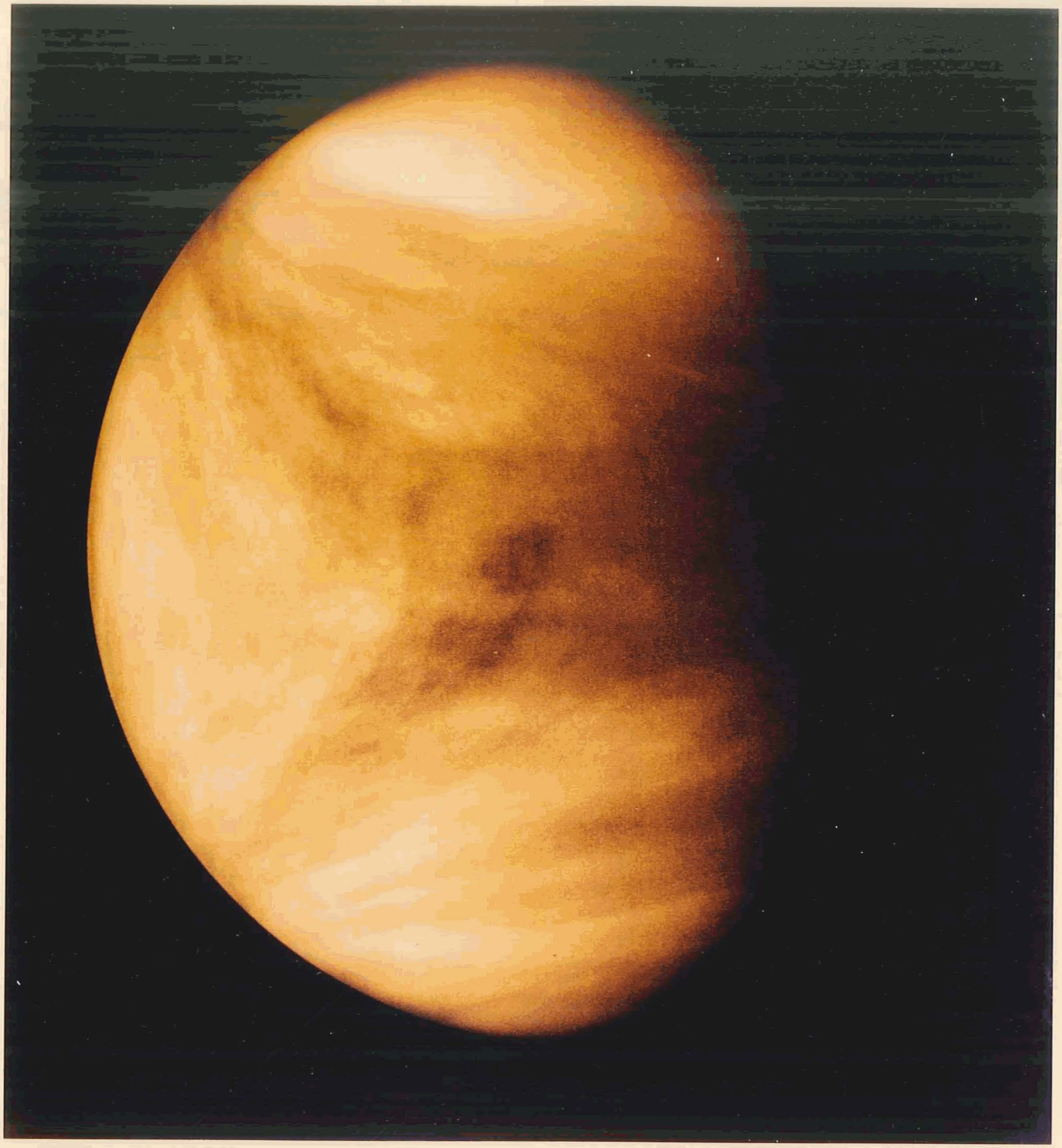
Region	Altitude, km	Temperature, °C	Refraction index	Composition	Diameter, μm
Upper haze	90.0-70.0	-83 to -48	1.45	sulfuric acid + contaminants	0.4
Upper cloud	70.0-56.5	-48 to 13	1.44	sulfuric acid + contaminants	0.4, 2.0 (bimodal)
Middle cloud	56.5-50.5	13 to 72	1.42 1.38	sulfuric acid + contaminants + crystals	0.3, 2.5, 7.0 (trimodal)
Lower cloud	50.5-47.5	72 to 94	1.32	sulfuric acid + contaminants + crystals	0.4, 2.0, 8.0 (trimodal)
Layers	47.5-46.0	94 to 105	1.46 1.50	sulfuric acid + contaminants	0.3, 2.0 (bimodal)
Lower haze	47.5-31.0	94 to 209	---	sulfuric acid + contaminants	0.2

site, and table 6-1 summarizes properties of the hazes and main clouds assembled from Pioneer Venus experiments.

The upper and lower cloud regions are much more variable in structure than the middle cloud region. By analogy with Earth clouds, all the clouds observed could be classified as stratiform, consisting of fairly large scale, uniformly layered structures. With the possible exception of the middle cloud, the cloud regions are remarkably stable against vertical overturning. For such cloud structures there may be a possibility of light mist or drizzle, but not, in general, for the heavy precipitation identified with cumulus-scale convection in an unstable atmosphere. Furthermore, the similarities in main cloud deck profiles and in stability properties (measures of the atmosphere's tendency to overturn by convection) at each of the four sites of the probes strongly suggest that the major features of the cloud system are planetary and are not very dependent on local longitude or latitude except perhaps at high latitudes and at the equator.

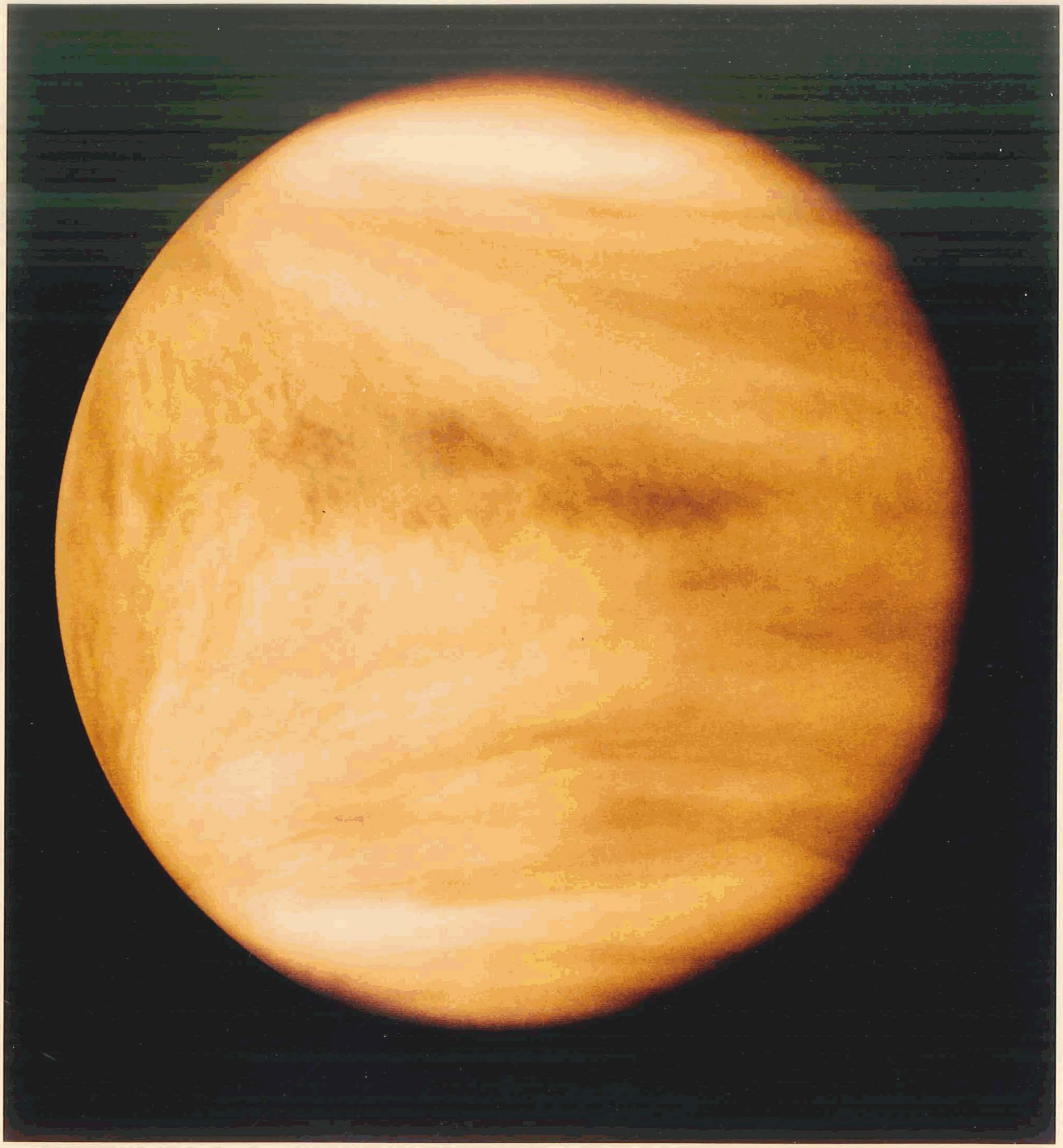
The features observed at ultraviolet wavelengths are thought to be principally identified with the motion of an ultraviolet absorber in the atmosphere, because changes in the concentration of sulfuric acid particles cannot account for these patterns and the haze is not sufficiently dense to provide the observed contrasts. Although the ultraviolet absorbing species, other than sulfur dioxide (which has been identified as one of the absorbing species), has not been identified, and since it is known that solar energy absorption takes place principally in and above the upper levels of the main cloud deck, it is reasonable to assume that vertical motions of this unknown species from below the haze may be responsible for the observed dark regions. Note, however, that such an assumption would imply a dark region of upwelling ultraviolet radiation absorber at the subsolar point on the planet. In fact, the subsolar point is a bright region. Nonetheless, it is thought that the absorber tends to mask motions in the atmosphere by indicating regions of horizontal variation or of vertical displacement of the absorber (presumably from below the cloud tops) to higher altitudes where regions of ultraviolet absorption would appear darker. The ultraviolet absorber not only acts as a marker of motion but also, since it absorbs appreciable amounts of energy, it may play a role in the dynamics of the cloud layers. Figure 6-16 shows some examples selected from the hundreds of images of near ultraviolet cloud features obtained by the Pioneer Venus cloud photopolarimeter/imager. Additional images of Venus cloud features are shown in figure 6-30.

General features observed at ultraviolet wavelengths may be categorized into those associated with three distinct regions of the planet. There is a polar zone above 50° latitude, a mid-latitude zone between 20° and 50°, and an equatorial zone extending about 20° north and south of the equator. A ubiquitous small-particle haze covers the planet, varying in density with latitude such that a polar haze collar (bright in ultraviolet light) encircles the polar regions at about 55° latitude. However, even at lower latitudes there are significant amounts of haze present above the cloud tops, and there is evidence of increased amounts of haze at the morning and evening terminators. The haze even covers the polar regions where it obscures in the ultraviolet images features which are discernible in the infrared images. Changes in the general haze features appear to occur within a time scale ranging between months and years.



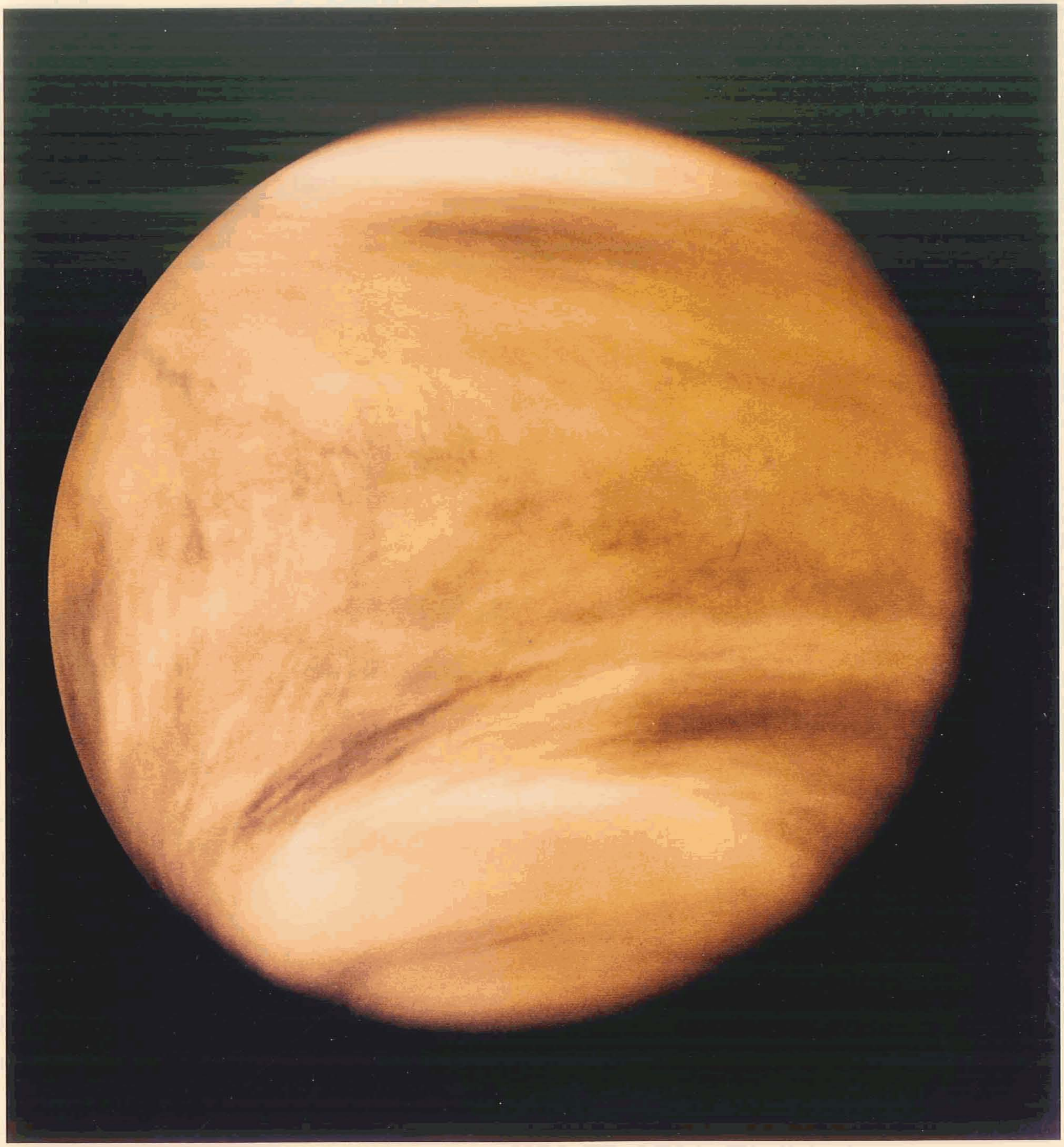
Venus 00078 10 Jan 79 (DOY 10) 12 : 10 - 15 : 26 UT
Altitude: 50,000 km Orbit: 37 Phase Angle: 55°
Subspacecraft Latitude: 0°

Figure 6-16. Selection of UV images from Pioneer Orbiter.



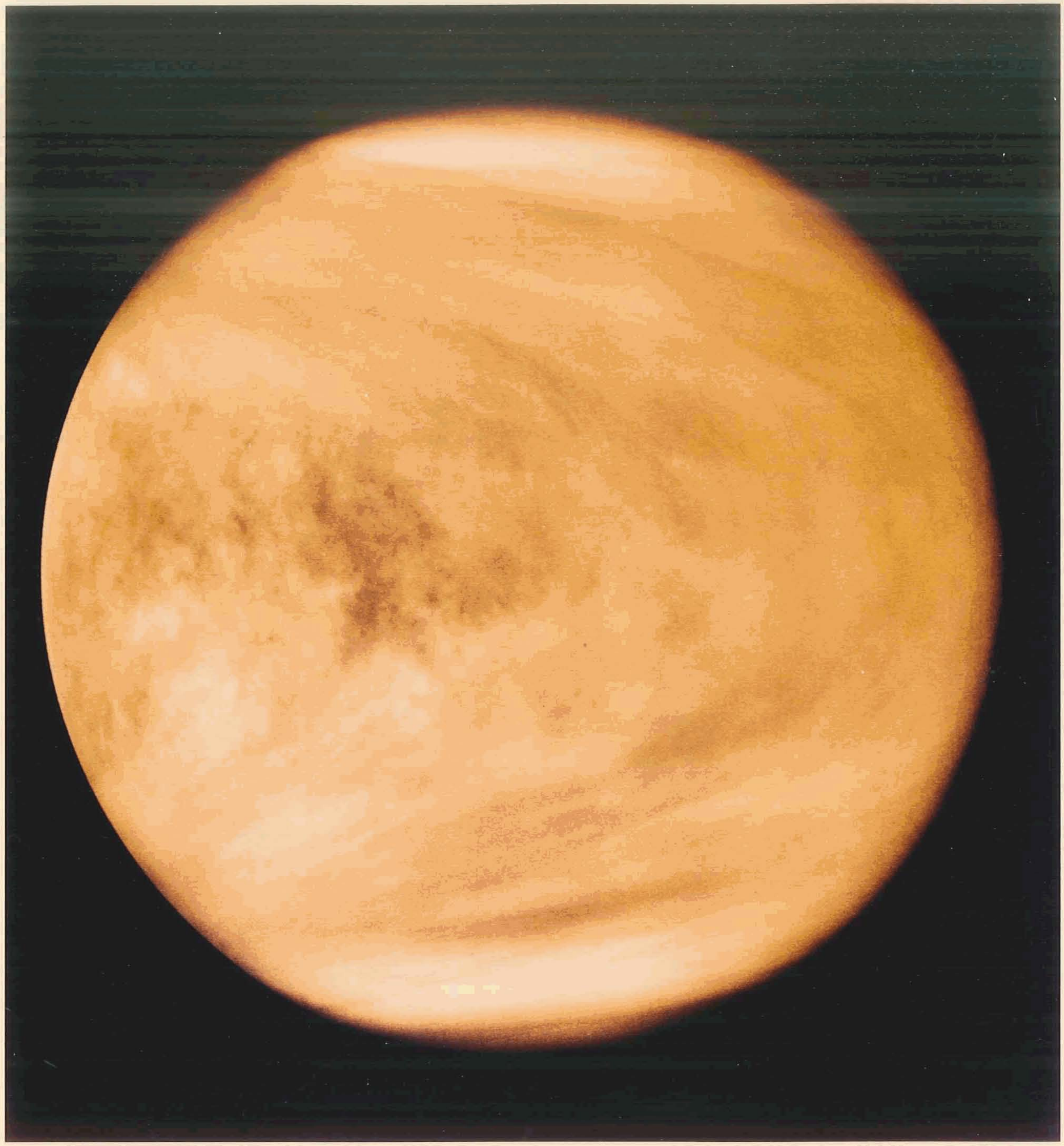
Venus 00156 31 Jan 79 (DOY 31) 10 : 58 - 14 : 45 UT
Altitude: 58,000 km Orbit: 58 Phase Angle: 23°
Subspacecraft Latitude: 8° S

Figure 6-16. Continued.



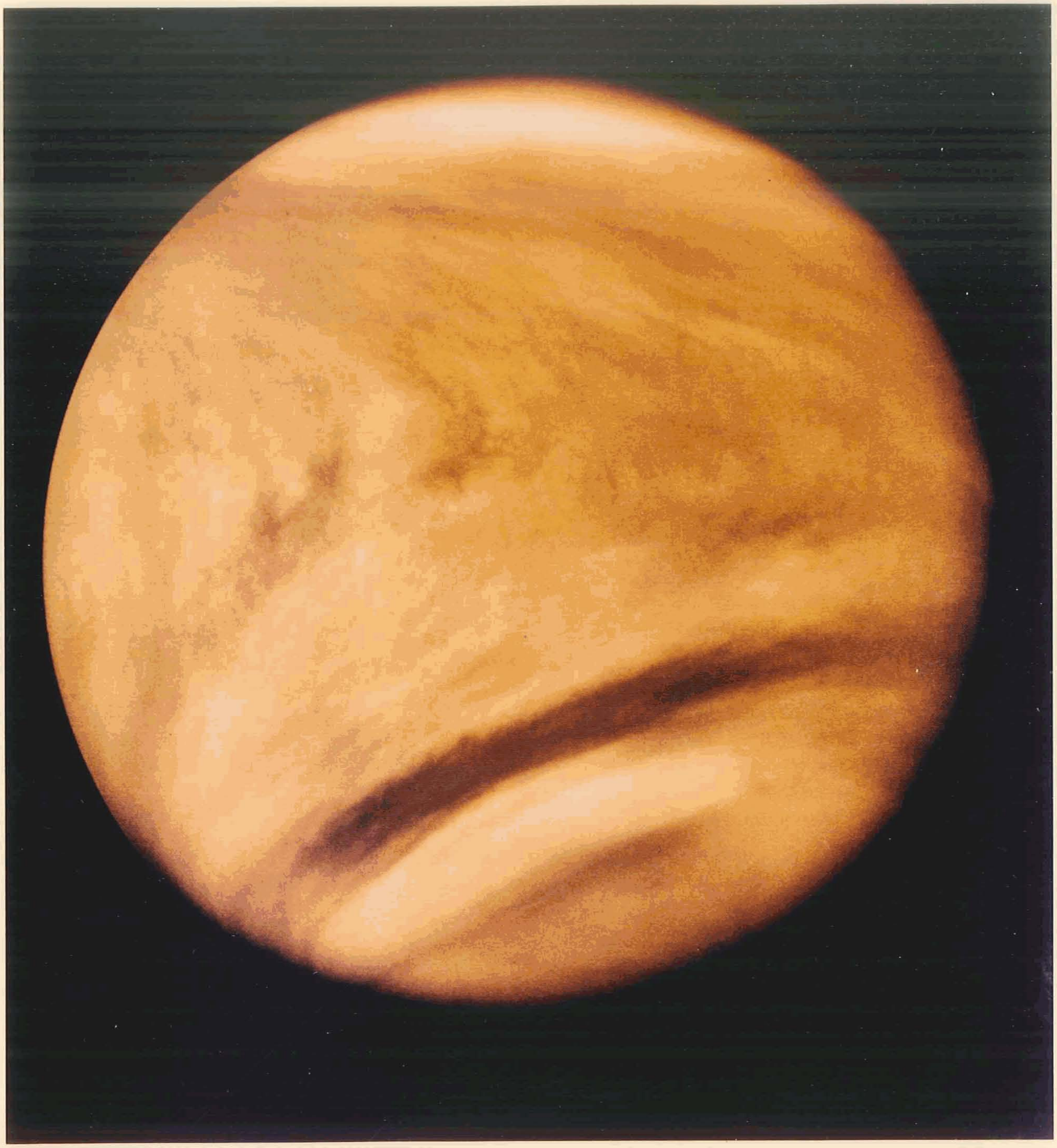
Venus: 00174 5 Feb 79 (DOY 36) 07 : 23 - 11 : 38 UT
Altitude: 65,000 km Orbit: 62/63 Phase Angle: 22°
Subspacecraft Latitude: 15° S

Figure 6-16. Continued.



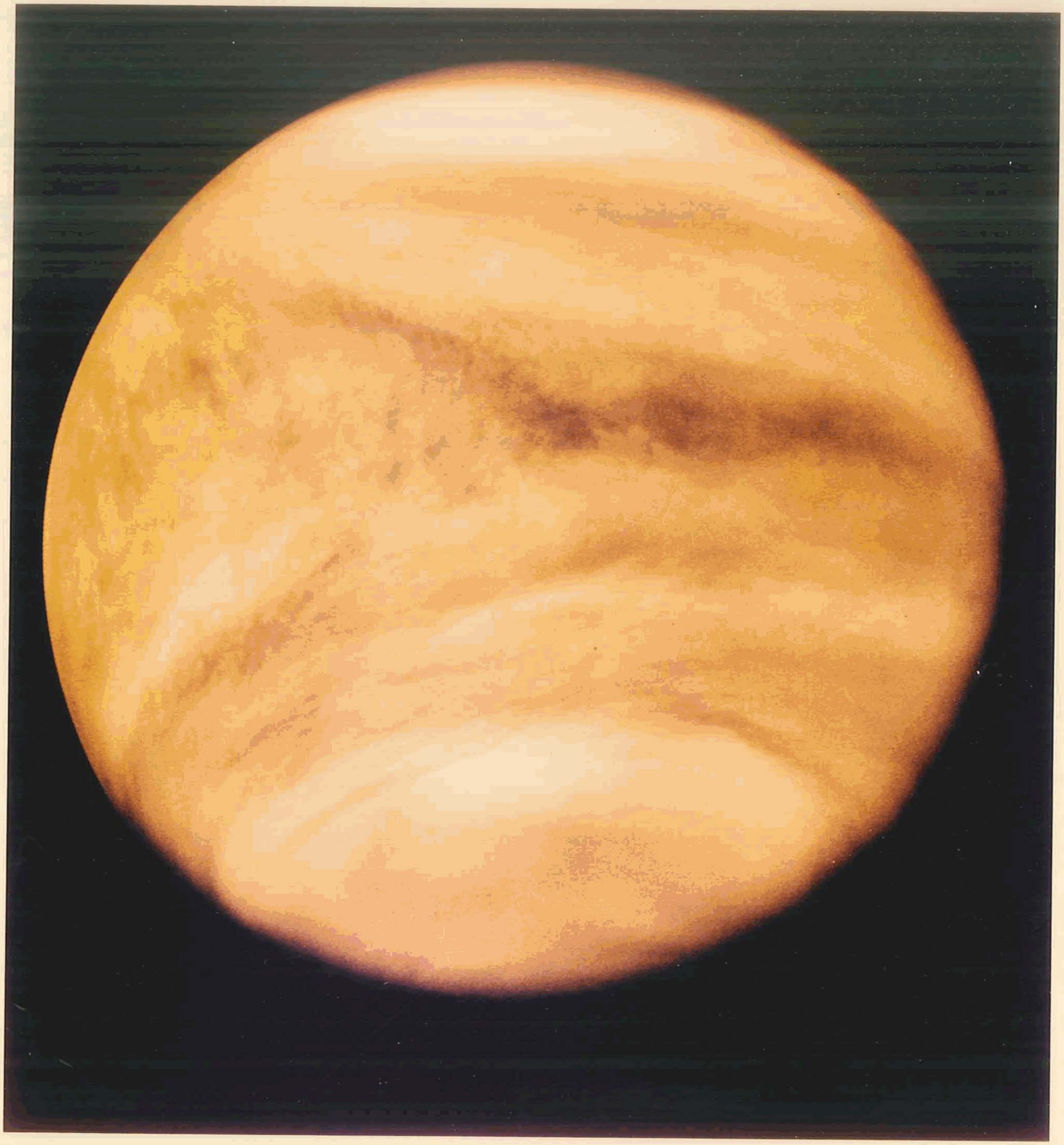
Venus 00183 8 Feb 79 (DOY 39) 12 : 39 - 16 : 10 UT
Altitude: 50,000 km Orbit: 66 Phase Angle: 8°
Subspacecraft Latitude: 2° S

Figure 6-16. Continued.



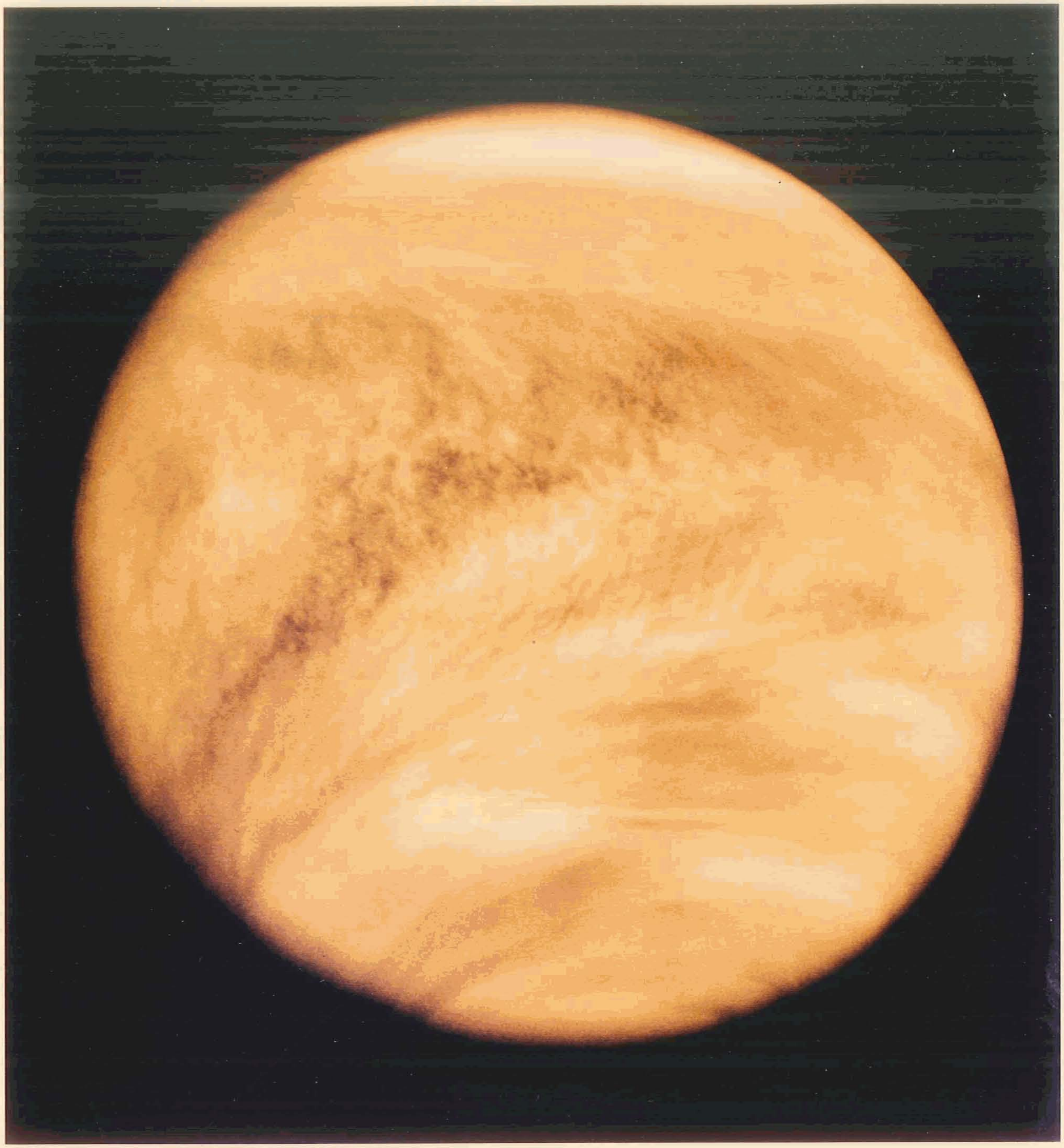
Venus 00190 10 Feb 79 (DOY 41) 07 : 20 - 11 : 33 UT
Altitude: 65,000 km Orbit: 67/68 Phase Angle: 15°
Subspacecraft Latitude: 15° S

Figure 6-16. Continued.



Venus 00194 11 Feb 79 (DOY 42) 06 : 38 - 10 : 52 UT
Altitude: 65,000 km Orbit: 68/69 Phase Angle: 16°
Subspacecraft Latitude: 17° S

Figure 6-16. Continued.



Venus 00237 26 Feb 79 (DOY 57) 06 : 00 - 10 : 15 UT
Altitude: 65,000 km Orbit: 83/84 Phase Angle: 22°
Subspacecraft Latitude: 17° S

Figure 6-16. Concluded.

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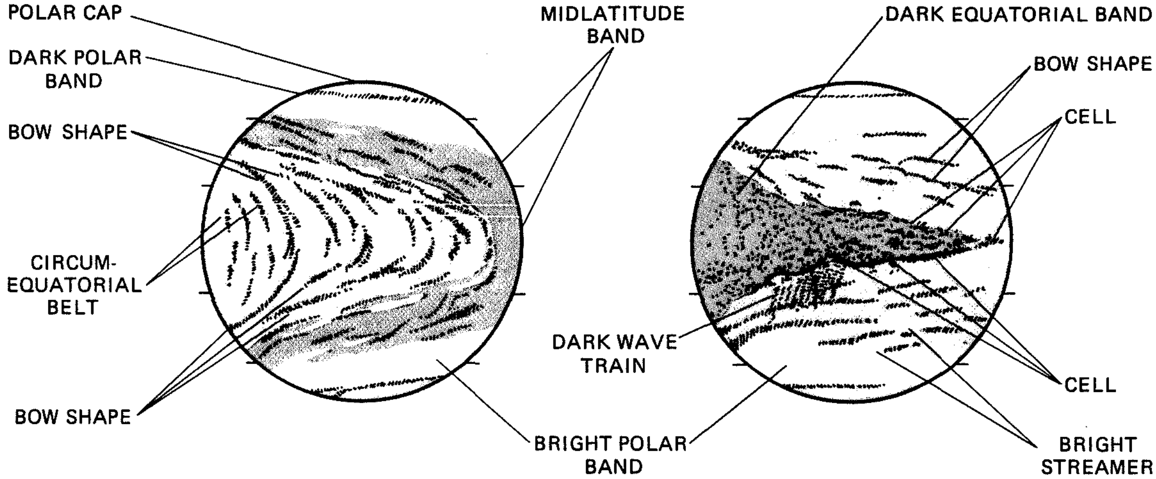

Figure 6-17. Basic types of cloud features observed in the UV images of Venus. The two views typically occur 2 days apart.

The large variety of dark features seen in the ultraviolet images of midlatitudes and equatorial regions are composed of three types of features – bow shapes, dark midlatitude bands, and a dark equatorial band (see fig. 6-17). The dark equatorial band forms a tail which together with a bow feature produces the characteristic Y-feature which has been observed from Earth and appears clearly in the images returned from Mariner 10 and Pioneer Venus. At times this Y-feature retains its structure as it moves around the planet, exhibiting a 4- or 5-day periodicity. At other times the Y-feature is absent from the ultraviolet cloud patterns. Even when it is present, many of its detailed characteristics are undoubtedly changing. The variability of the Y-feature indicates that the features of which it consists change independently.

Cellular features with either dark or bright surroundings are common at low latitudes. Most have dark centers. They are, on the average, about 200 to 300 km diam and are present in bright and dark regions, although they are more numerous in the dark equatorial region and during the afternoon on Venus.

The ultraviolet images from Pioneer Venus also show some wave-like features about 1000 km long and separated by 200 km. They make large angles with the equator and cut across other features, thereby showing that they are at different altitudes from these other features.

The Orbiter's infrared radiometer data have shown that there is a dark polar band at about 65°–75° latitude. This broad cold feature forms a collar around the pole and is most likely an unusually cold region near the base of a temperature inversion. Its coldest part seems to follow the anti-solar point around the planet. Earth-based observations indicate that polar collars usually persist for weeks or months, and are most pronounced near only one pole throughout an apparition (period when the planet is positioned suitable for observation from Earth). A localized polar brightening at very high latitudes is generally associated with collars in ground-based observations, and Pioneer Venus infrared images have, in fact, resolved this phenomenon into a pair of "hot spots" which straddle the pole. These hot spots are seen at about 85° latitude and their morphology gives the appearance of a dramatic "dipole" structure in images and maps.

Infrared images (fig. 6-18) have the capability of revealing structure on the nightside as well as near the pole. Near the pole, thin hazes and an unfavorable angle of solar illumination make observations at other wavelengths difficult. The hot spots of the polar dipole are probably clearings in the polar cloud deck. This feature has also been seen to rotate about the pole with a period of about 2.7 days (see fig. 6-18). Brightness temperatures within the hot spots approach 260 K at 11.5 μm, but the temperature may be found to be as high as 280 K if the region could be viewed from directly above. Bright filamentary streaks emanating from one eye of the dipole and dividing the collar are visible in several images. The dipole is about 2000 km long and about 1000 km across (see figs. 6-19a and 6-19b). As discussed later, the presence of the polar hot spots may be evidence of atmospheric subsidence at the center of the polar vortex. Because descending motions are not observed elsewhere in the northern hemisphere of Venus, the evidence points to a single large circulation cell filling the hemisphere at the level of the cloud tops.

Particle Microphysics

The particles in the main cloud decks of the upper, middle, and lower cloud regions are characterized by size groupings that have more than one maximum, and so are multimodal. Haze particles appear to group around one maximum value and are unimodal.

Figure 6-18. Eight consecutive polar stereographs of Venus' northern hemisphere taken at 11.5 µm. These images were taken one each day on orbits 32 through 39 (January 5 through 12, 1979). The north pole is at the center of each image and the equator is the outer boundary with the noon point at the bottom. Note that the polar dipole returns to approximately the same position in a period of three days.

In the lower and middle cloud regions the size distribution is trimodal, with modal diameters of 0.1 to 0.5, 1.8 to 2.8, and 6 to 9 µm. The upper cloud region is bimodal, consisting of particles of the first two ranges of modal diameters.

The smallest-size mode is a ubiquitous aerosol population extending throughout the main cloud deck and 15 to 20 km above and below it. Its number density varies greatly with height but is sufficient for the particles to act as centers for the growth of larger particles by heterogeneous nucleation from parent vapors in the atmosphere. The second-size mode consists of droplets of sulfuric acid with primary growth taking place in the upper cloud region and a gradual increase in number density descending through the main cloud deck. Its size distribution is extremely narrow at any one altitude, and it is the dominant planetary size mode. Best agreement with all of the Pioneer Venus and Venera data is obtained by considering particles of the largest size mode to be thin plate-like crystals with an aspect ratio (ratio of maximum to minimum projected area) high enough to preclude accurate mass determination.

Figure 6-20 shows the modal partitioning of each mode in terms of number density versus altitude. Figure 6-21 shows the average size distribution in each cloud region, as measured by the cloud-particle size spectrometer of the large probe.

The particle-size distributions are not unusual except for the second size mode, which appears to be monodisperse. Such narrow distributions may be explained by assuming competitive diffusional growth, but the uniformity of the distribution width over the planet, as hinted from the probe and Orbiter data, is mysterious. It is highly unlikely that droplets will grow by coalescing because there is low probability of their colliding with each other.

Particle Composition

Multimodal size distributions are usually indicative of several different chemical constituents of a population of particles. The second size mode particles, mode 2, have been easily identified as sulfuric-acid droplets, primarily from their optical properties, and are traced throughout the main cloud deck. The concentration of sulfuric acid in the droplets may decrease from 90% at 60 km to 80% at 50 km, but there is little effect on drop size.

The mode 1 aerosol is of variable composition as inferred from its optical properties and from considerations of particle growth, but the aerosol is mainly sulfuric acid in the upper and lower cloud layers, the precloud layers, and the upper haze regions. Sulfuric acid is formed in the region above the boundary between the upper and middle clouds. The mode 1 aerosol apparently contains other chemical species or direct condensates as scavenged contaminants that could largely account for all the particle mass remaining in the lower haze and perhaps the middle cloud regions.

Composition of the mode 3 particles is uncertain. They may well be chlorides, but if so the cation has yet to be identified. Except for any particulate matter in the lower atmosphere, essentially all particle mass is volatile at temperatures above 200° C.

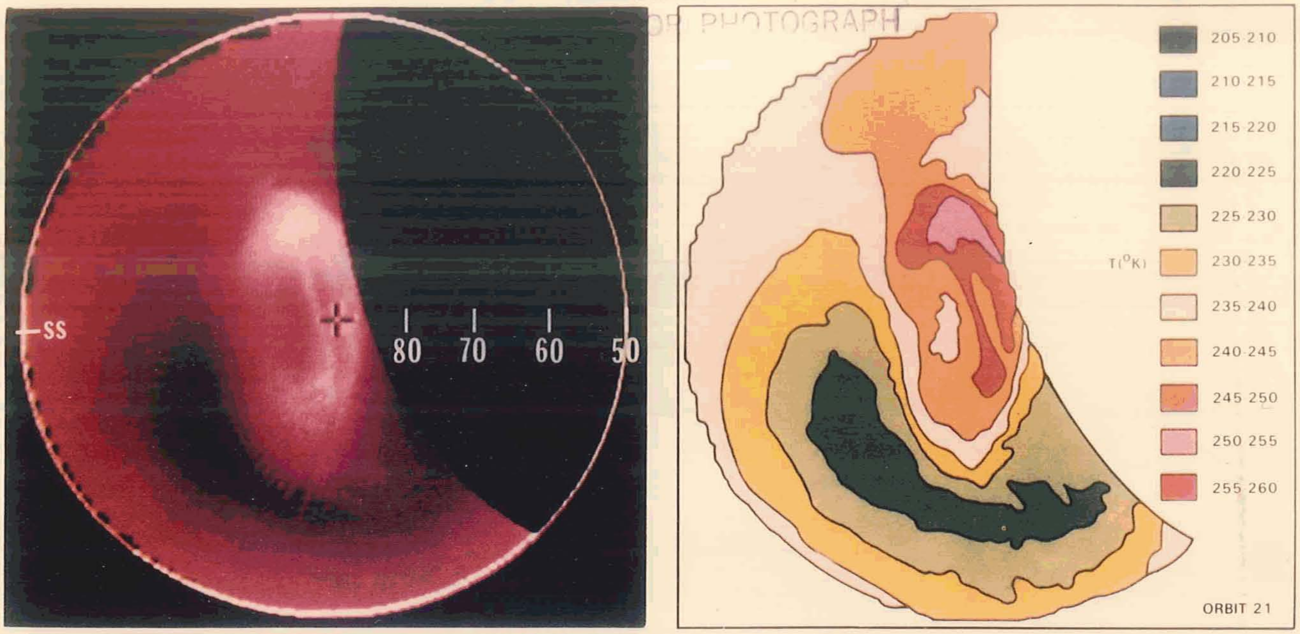

Figure 6-19(a). North polar infrared image and plot showing the temperatures. The north pole is in the center, the outer boundary is 50° north latitude, the noon point at SS at the left. The blacked out area is the region from which no data were obtained because of the geometry of the spacecraft's orbit. This image was obtained on December 26, 1978 during orbit 21.

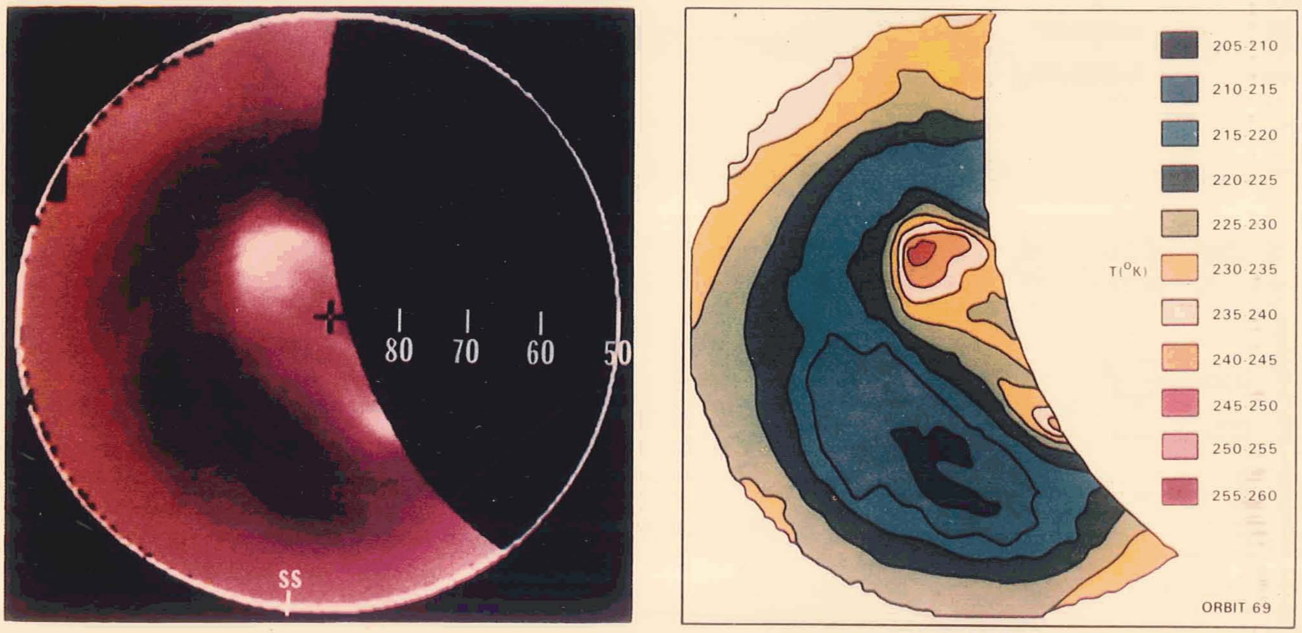

Figure 6-19(b). A similar image to (a) obtained February 11, 1979 on orbit 69.

Chlorine was detected in large amounts by Venera 11 instruments. Its role in the cloud chemistry is uncertain.

Optical Properties

The major absorption of solar energy in the atmosphere of Venus takes place at high altitudes corresponding to the locations of the high hazes down through the upper cloud regions. The actual role of the cloud particles in the absorption process itself is not clear, but they certainly play an important part in redirecting the incident solar energy by scattering processes, in increasing the actual absorption of incident photons in a horizontal layer of the atmosphere, and in redirecting most of the incident light into space.

Much of the observed absorption at far ultraviolet wavelengths has been attributed to sulfur-dioxide vapor. Infrared absorption is also attributed primarily to other gaseous constituents such as carbon dioxide and sulfuric acid. However, the absorber of an

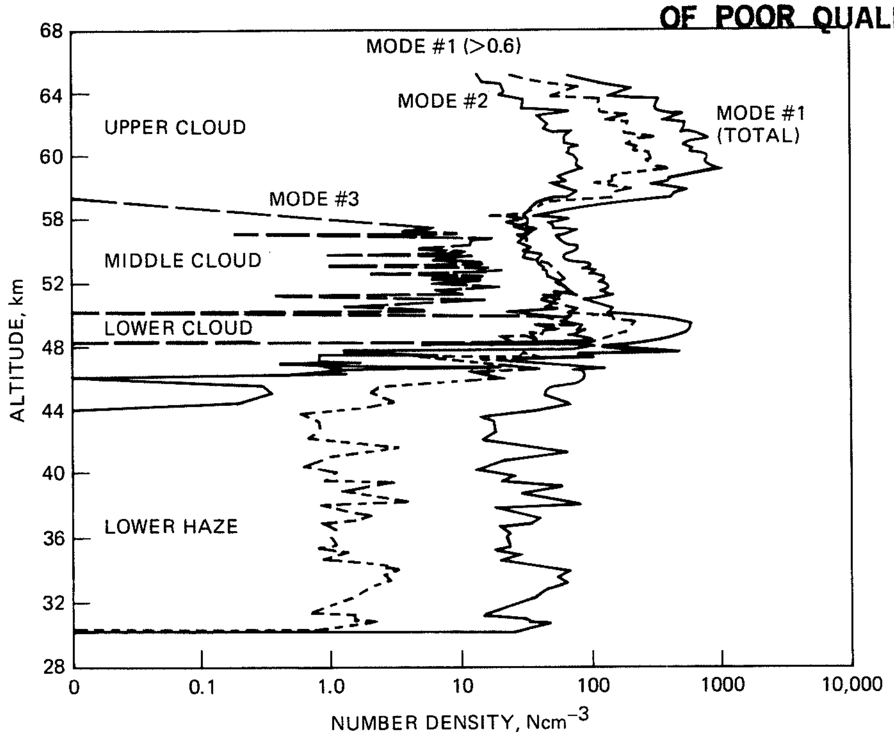

Figure 6-20. Modes of particles in the clouds of Venus. The diagram shows number density compared with altitude.

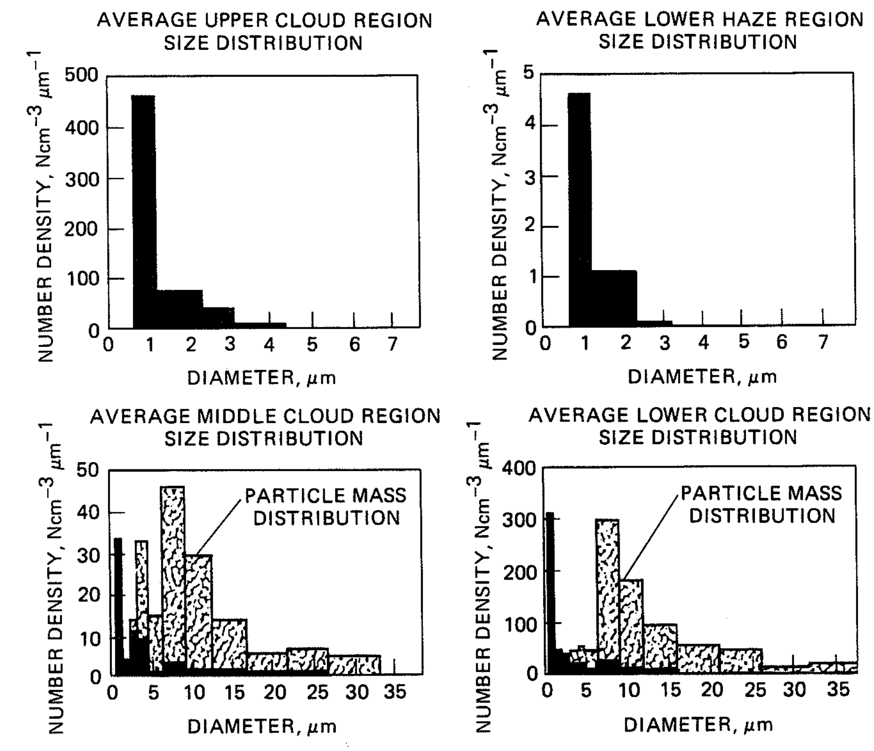

Figure 6-21. Average size distributions measured by the large probe cloud particle size instrument. The multimodal size distribution is evident even for vertical averaging over several kilometers, especially in the middle and lower cloud regions. It is still apparent in the upper cloud and in the lower haze. The pre-cloud regions, incorporated in the lower haze account for nearly all the particles larger than 1.2 µm. The mass relative distributions assume all particles are spherical.

important part of the solar spectrum, extending from about 3200 Å into the visible, which is also in large part responsible for the presence of the ultraviolet markings observed remotely, has yet to be identified.

Particles of pure sulfuric acid do not qualify as candidates for this absorption since they are transparent at the wavelengths involved. Therefore, if the missing absorber is indeed in the particulate matter it must be in the form of a contaminant or aerosol core to the sulfuric-acid particles. Furthermore, since the contrast of the ultraviolet features as observed by the Orbiter cloud photopolarimeter decreases as the phase angle of observation increases, and the greatest contrasts are observed when viewing normal to the clouds, the ultraviolet absorber must lie considerably deeper than the overlying haze.

Data from the solar net flux radiometer of the large probe, however, indicate that absorption of solar energy takes place at altitudes above optical depths of 6 or 7; that is, most absorption is in or above the upper cloud region, with little absorption in the middle or lower clouds. In addition, Orbiter ultraviolet spectrometer measurements indicate that the location of the unknown absorber is connected with the location of the sulfur-dioxide absorber.

Although fits of models to the data from the solar flux radiometer experiment of the large probe suggest that the imaginary index of refraction (the absorption portion of the index of refraction) could reach 0.05 for the mode 1 aerosol, the correlation of bright polar regions with large amounts of cloud above the sulfuric-acid main cloud at high latitudes argues for a small amount of absorption. Single scattering albedos (the ratio of the probability of scattering to the sum of the probabilities of scattering and absorption for a single particle) range from low values of 0.95 (high absorption) in the upper cloud region to 0.999 (low absorption) in the lower cloud region. Thus the larger mode 3 particles are essentially non-

TABLE 6-2.– RADIATIVE PROPERTIES OF CLOUD LAYERS AT SOUNDER PROBE LOCATION

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Cloud layer and range, km	Pressure, atm		Optical depth	Fractional contribution to optical depth			
	Top	Bottom		Mode 1	Mode 2	Mode 3	Mode 4
Upper haze above 75	0	0.015	0.04				1.0
Upper cloud 75-56.2	0.015	0.025	0.425	0.2	0.8		
	.025	.035	.5	.2	.8		
	.035	.050	.65	.55	.45		
	.050	.067	.8	.55	.45		
	.067	.083	.8	.55	.45		
	.083	.1	.8	.55	.45		
	.1	.132	2.49	.7	.3		
	.132	.187	3.01	.72	.28		
	.187	.25	2.96	.63	.37		
	.25	.402	2.49	.56	.44		
Middle cloud 56.2–50	0.402	0.661	3.82	0.14	0.5	0.36	
	.661	.77	1.41	.17	.48	.35	
	.77	.991	2.42	.24	.5	.26	
Lower cloud 50–48.3	0.991	1.102	2.5	0.21	0.25	0.54	
	1.102	1.225	2.5	.2	.29	.51	
Sub-cloud 48.3–46.8	1.225	1.501	0.8	0.43	0.43	0.14	
Lower haze 46.8-31	1.501	8.56	0.21	1.0			

From Pollack, Knollenberg, Hunten, Tomasko, and Kawabata

absorbing, but some absorption appears to be generated by unknown mechanisms at about the boundary between the upper and middle clouds.

The entire Venus cloud system has an optical depth of 25 to 35 at visible wavelengths; that is, the probability of a single normally incident photon passing through the cloud system without experiencing a single interaction with a cloud particle is e^{-25} to e^{-35}. The relative contributions of each cloud region to the total optical depth are tabulated in table 6-2.

The radiometric albedo, essentially the reflection coefficient weighted over the solar spectrum, is 0.77 to 0.82, increasing from equator to poles. The particle real refractive indices at visible wavelengths for modes 1 and 2 are approximately 1.40 to 1.46, consistent with sulfuric acid, but permitting the presence of many other species. The real refractive index of the mode 3 particles is unknown but probably ranges from 1.5 to 1.7. The imaginary index for these particles must be less than 10^{-3}.

Table 6-2 summarizes the contributions of each cloud layer and of each mode in each cloud layer to the optical depth, and figure 6-22 shows a plot of the measured optical properties of the clouds.

Dynamical Processes

The cloud system is embedded in the general circulation of the atmosphere at altitudes of greatest wind velocity and vertical wind shear. As discussed in other sections of this chapter, the atmospheric motions have been found to consist predominantly of a zonal, that is, latitudinal, circulation, moving from east to west with velocities increasing from very small values of a few meters per second at the surface to 150 m/sec at the cloud tops, corresponding roughly to the observed 4-day circulation.

In addition, a major, although much slower north-south circulation at several meters per second is suggested by the data. It occurs at altitudes corresponding to the cloud region. The data seem to indicate an atmospheric movement from equator to poles at altitudes corresponding to the tops of the clouds, subsiding at the poles, with return flow toward the equator at altitudes corresponding to the lower part of the main cloud region, and rising again near the equatorial region. Such north-south cellular motions are called Hadley cells. The combination of east-west and north-south motions gives rise to vortices in the polar region

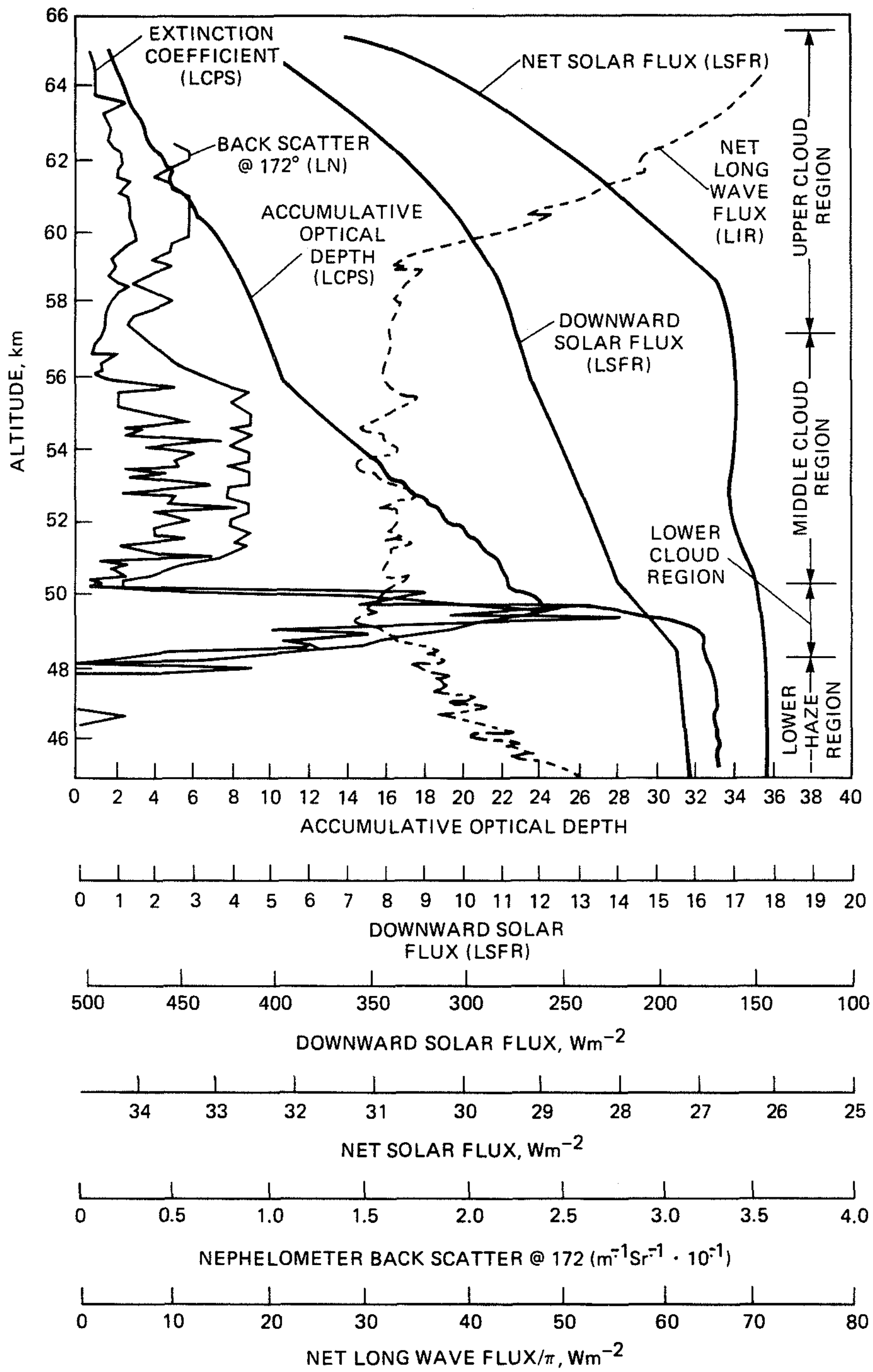

Figure 6-22. Optical properties of the cloud systems of Venus.

affecting the haze layer and producing an apparent cloud top depression in the vortices. These vortices might also be responsible for more complicated cloud features in each vortex, and for the "pileup" of high latitude hazes and the even higher latitude "cold ring" observed by the Orbiter's instruments. Figure 6-23 is a schematic drawing of the suggested pattern of circulation.

The detailed ultraviolet and infrared features observed from Earth, and from flyby and orbiting vehicles may thus be shown to be in accord with the general behavior predicted from the *in situ* probe measurements. Features involving the 4-day zonal rotation are evident in the ultraviolet imagery, and most of the other features may be shown to be the result of wave motion and convection cells tending to disturb the level of the upper-altitude ultraviolet absorber. Thus, some features, such as the large-scale Y-shaped structures, prominent at lower altitudes, may propagate slowly with respect to the atmosphere and may appear and disappear as the wave motion dictates, their major features being moved around the planet by the east-west wind. Smaller convection-type features, indicating rising atmospheric motion, are also evident. Finally, as noted earlier, the bright polar collar, the cold ring, polar hot spots, and infrared holes are plausibly described by the suggested circulation pattern.

For the most part the growth of cloud particles is not strongly influenced by the large-scale planetary circulation. The acid particles go along for the ride, simply adjusting their acid concentration to each new equilibrium offered by the circulation. The rapid circulation together with particle volatility produces the planetary cloud structures.

Growth of sulfuric-acid droplets appears to be a very slow process except in the lowest cloud regions where recondensation of sulfuric acid might be quite rapid. There is a large range of particle lifetimes between years in the upper hazes to hours in the lower cloud region. Mode 3 particle growth appears to start near the top of the middle cloud, and the particles evaporate at the bottom of the lower cloud, providing much of the middle and lower cloud structure.

Electrical signals attributed to lightning on Venus were observed by instruments carried by Veneras 11 and 12, and signals suggestive of lightning were also observed by the Pioneer Venus orbiting electric-field detector that recorded signals on its 100 Hz channel (fig. 6-24). These whistler-mode electromagnetic noise bursts were first recorded in December 1978 when the Orbiter's periapsis moved from sunlight into darkness.

The signals are believed to originate from lightning because (1) they are intense and highly impulsive, (2) they are detected near periapsis, (3) their

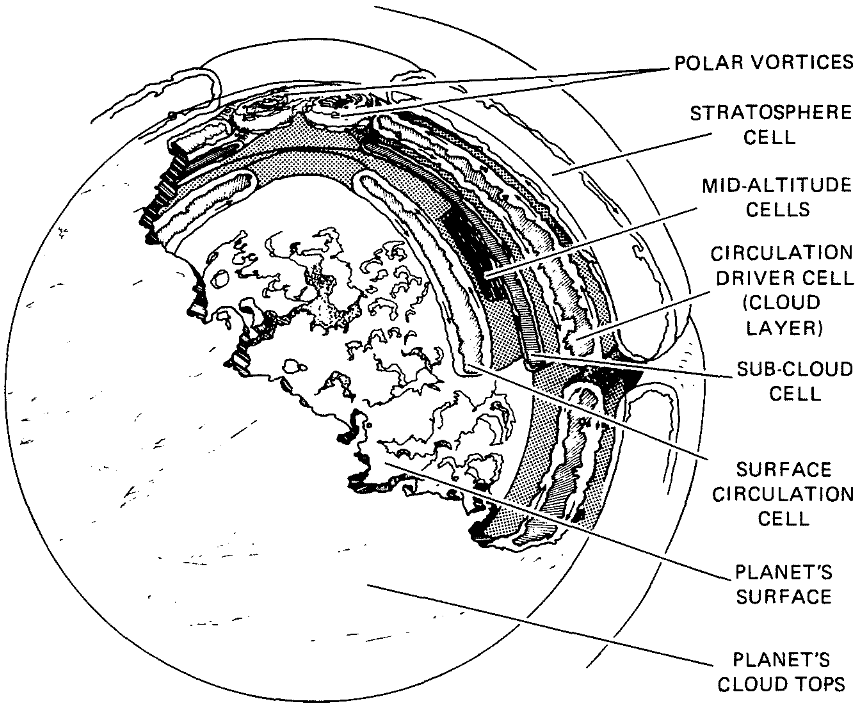

Figure 6-23. A possible pattern for the meridional circulation in the atmosphere of Venus.

spectral characteristics are consistent with whistler-mode propagation, and (4) they are often observed when low and variable electron densities are present.

Known processes for the formation of lightning require large particles and strong updrafts in cloud regions. The potential latent instability, that is, the difference between the rate at which the temperature would vary with altitude in an idealized atmosphere and the measured lapse rate, is a measure of the tendency of the atmosphere to overturn and undergo convective motion. As already described, there is evidence of planet-wide instability in the middle cloud region on Venus. Therefore, updrafts exist over a limited altitude range from 50 to 56 km. However, we have no direct evidence for large precipitative-type particles. Thus, if cloud processes generate the observed lightning then large undetected particles may exist in the Venus atmosphere. The lightning activity could also be the result of local large-scale situations such as volcanic eruptions or strong and still undetected convective motions at the subsolar point. Also, because of the high altitude of the cloud base, approximately 45 to 50 km above the surface, the lightning flashes on Venus would most likely be from cloud to cloud rather than from clouds to the ground.

Experiments attempting to observe lightning optically using the Pioneer Venus Orbiter's star sensor showed no statistically significant difference in signals received from the dark hemisphere of the planet compared with control signals derived from pointing the star sensor into deep space. These experiments thus implied that the lightning may be confined to the dayside of the planet and be relatively rare on the nightside. The results also would indicate that the lightning activity on Venus is much less intense than that required to produce significant changes in concentrations of atmospheric species.

Although our knowledge about the clouds of Venus has been enormously increased by the successful missions to the planet, there are still a number of questions remaining unanswered. The identity of the remaining ultraviolet absorber is still eluding us. Our knowing the absorber is of utmost importance to achieving fuller understanding of upper-atmosphere motions and cloud details, as well as the energetics and atmospheric chemistry of the planet. The composition of mode 3 particles and the nature of contaminants in other cloud particles are still not determined. The role of chlorine in cloud chemistry is unknown. More information concerning lightning on Venus is necessary before we can speak with certainty about its origin and any atmospheric composition changes it may cause. There are also questions about precipitation within the atmosphere. Finally, we know little of the nature of the particles suspended in the atmosphere at low altitudes, as hinted by the data from several probe instruments.

Composition

One of the most important sources of information relating to the way the terrestrial planets – Mercury, Venus, Earth, and Mars – were formed is an analysis of gases in their atmospheres. The composition of the gases that formed the primitive atmospheres of these planets is generally accepted as resembling that of the Sun and the giant planets. These gases were lost during the early stages of formation of the Solar System because of the high temperatures prevailing at that time. The present atmospheres are believed to be made up of volatile material that was originally incorporated in the solids that combined to form the planets. Subsequent to planetary formation, probably during the first few million years of the lives of these planets, these volatiles were driven out of the crusts and mantles of the planets because of high internal temperature and tectonic activity. Some of the volatiles constitute the present atmospheric gases. Others, such as water vapor, have condensed or otherwise been transformed. On Earth the water constitutes the oceans. On Mars the water may now be hidden below the surface in some form such as permafrost. On Earth, carbon dioxide has been converted chemically to carbonate rocks such as limestone.

A simple consequence of this scenario is that the amount of each kind of gas in the atmosphere of a terrestrial planet should depend mostly on the mass of that planet. Studies of Mars carried out by Mariner and Viking probes showed this is not true. Even allowing for its smaller size Mars seems to be deficient in volatiles such as carbon, oxygen, nitrogen, and the noble gases neon, krypton, and argon, compared with Earth. Deficiency factors are as large as 100 to 200. After the Viking mission, an interpretation of these results was that the material out of which Mars was formed was deficient in volatiles compared with Earth and that a smaller percentage of volatiles had been released from the Martian interior. The reason for the deficiencies was not known. Nevertheless, because Earth and Venus are so similar in size, mass, and distance from the Sun the volatile inventories of these two planets were expected to be very similar. An exception was known to be necessary regarding water because Venus was known to have no ocean. Hence, the stage was set for a crucial test of models of planetary formation by the Pioneer Venus mission.

Before the Pioneer Venus mission scientists generally agreed that the atmosphere of Venus was mostly carbon-dioxide gas. Estimates of the fraction varied between about 95% and 98%. Most of the rest of the atmosphere was believed to be nitrogen. Atmospheric pressure on Earth is about 1% of that of Venus, and carbon dioxide makes up about 0.03% of the Earth's atmosphere (table 6-3). The atmosphere of Venus contains about 300,000 times as much carbon dioxide as the atmosphere of Earth. This does not necessarily mean that more carbon dioxide has been vented into the atmosphere of Venus from its interior. The supply of carbon in limestone rocks and elsewhere in the Earth's crust indicates that most of the carbon dioxide that has been produced on Earth has been converted to carbonates. In fact, a rough comparison shows that Venus has produced no more than about twice as much carbon dioxide as the Earth. The reason that the carbon dioxide has remained in the atmosphere of Venus and has been incorporated in rocks on Earth is that there

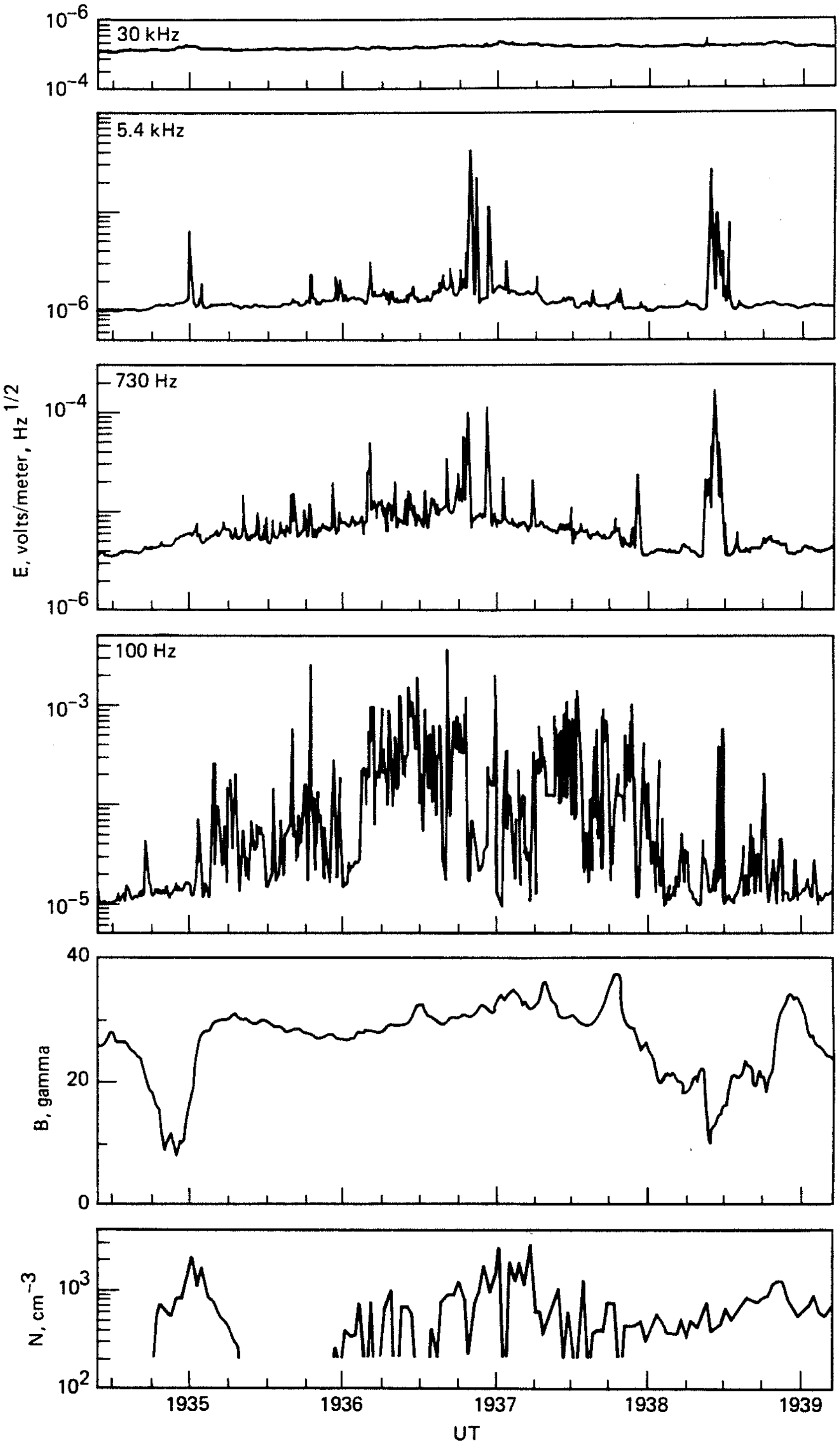

Figure 6-24. Lightning on Venus? (a) Signals received from the electric-field detector of Pioneer Orbiter that are interpreted as originating from lightning in the clouds of Venus. (b) Concept of lightning in the Venus atmosphere as observed by Venera and the Pioneer Orbiter.

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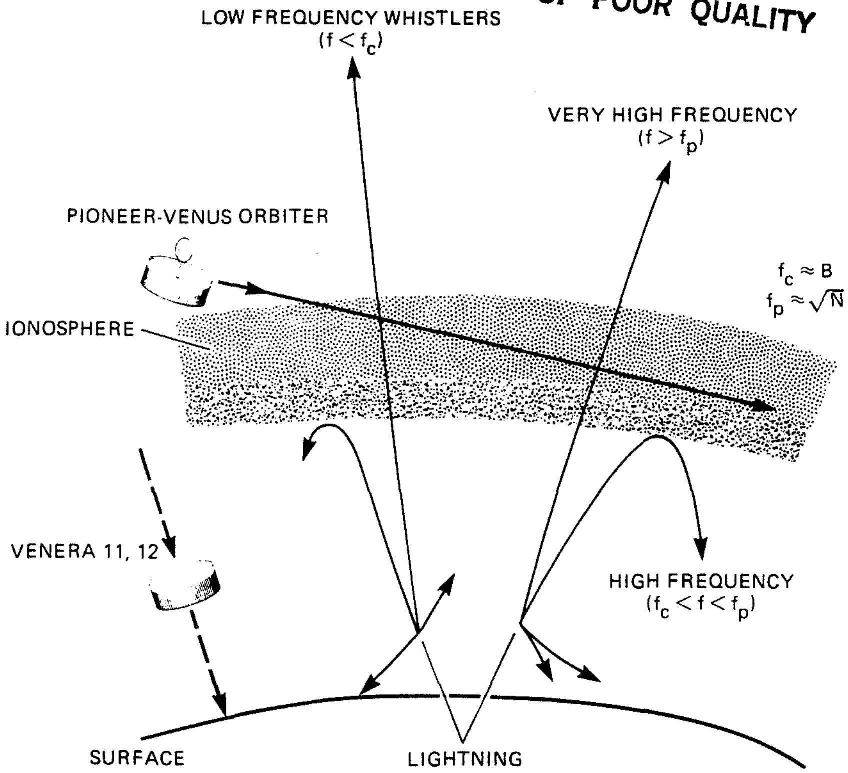


(b)

Figure 6-24. Concluded.

TABLE 6-3.– COMPARISON OF ATMOSPHERES OF VENUS AND EARTH

Gas	Venus at surface, % or ppm[a]	Earth at sea level, % or ppm[a]
Argon	70 +50 −30	0.93%
36	20 +20 −10	31
38	6[b]	6
40	31[b]	0.93%
Carbon dioxide	96%	0.02–0.04%
Carbonyl sulfide	<3	0.5
Chlorine	<10	
Hydrogen	<=500	
Krypton	0.05	0.5
Neon	10	18
20	9	16
22	1	2
Nitrogen	4%	78%
Oxygen	<30	21%
Sulfur dioxide[c]		

[a]1 ppm = 0.0001%
[b]Derived from ^{36}Ar
[c]<10 in clouds; <300 near surface

is no ocean on Venus to mediate the transformation. One of the major problems for understanding the divergent evolutionary paths followed by the two planets is to account for the present-day absence of water on Venus. Was it never present? Or were large quantities of water evolved from the interior at an early stage only to be lost later – the hydrogen to space and oxygen to the crust and interior?

Another basic question is whether some climatic change on Earth, man-made or natural, can cause an increase in the amount of carbon dioxide and water in the atmosphere to the extent that a runaway greenhouse might occur. Because carbon dioxide and water inhibit the escape of heat radiation, an increase in their concentration would probably lead to a rise in atmospheric temperature. This in turn would lead to the release of more carbon dioxide and water into the atmosphere, and the temperature would rise further, and so on. The consequence could be an atmosphere like that of Venus. All available carbon dioxide might be in the atmosphere and the temperature near the ground would approach 700 K as on Venus.

One of the major tasks of the instruments carried on the large probe, the Orbiter, and the Multiprobe Bus was to verify that carbon dioxide and nitrogen were, indeed, the principal atmospheric constituents of Venus, and also to determine their precise concentrations. But these instruments were also assigned other essential tasks. They were asked to identify other atmospheric constituents even if they represented only one part in one billion of the atmospheric molecules (1 ppb). On the large probe the instruments to which these tasks were assigned were the neutral mass spectrometer covering the range of altitudes from 62 km to the surface, and the gas chromatograph which sampled the atmosphere at 52, 42, and 22 km. On the Bus, a mass spectrometer was assigned to obtain data above 130 km, and on the Orbiter another mass spectrometer was expected to sample the atmosphere above 145 km. Additional important information concerning atmospheric composition above the clouds was to be provided by the ultraviolet spectrometer carried by the Orbiter.

The consensus concerning measurements carried out by the Pioneer instruments and those on Venera 11 and Venera 12 landers is that 96% of the atmosphere of Venus is carbon dioxide and 4% is nitrogen. Since the surface pressure of Venus is 94.5 times that of Earth and the temperature 732 K, these results mean that Venus has outgassed 1.8 times as much carbon dioxide as the Earth and 2.3 to 4 times as much nitrogen, depending on how much nitrogen is still in the Earth's crust. Thus, the expectation of a rough equality in the volatiles of Earth and Venus was confirmed for carbon dioxide and nitrogen.

However, a rude shock was delivered to the planetary science community when an assay of the rest of the volatiles of the Venus atmosphere was made. The case of argon illustrates the point. There are two types of argon isotopes of interest to scientists studying planetary atmospheres. Radiogenic ^{40}Ar, the most abundant kind of argon in the Earth's atmosphere, is produced by radioactive decay of potassium. Its abundance tells us about the primitive concentration of potassium and outgassing conditions throughout the 4.5-billion-year history of the planet. On the other hand, ^{36}Ar and ^{38}Ar are primordial gases and they tell us about the early volatile content of planetary interiors and the early outgassing scenario. On the basis of carbon and nitrogen results, scientists expected that there would be about as much ^{36}Ar and ^{38}Ar in the atmosphere of Venus as in the atmosphere of Earth. Instead, the mass spectrometers on the Pioneer and Venera landers found the concentrations of radiogenic ^{40}Ar and nonradiogenic argon to be about equal. About 30 atoms in every million atmospheric molecules (or 30 parts per million (ppm)) were ^{36}Ar. The gas chromatographs which could not distinguish among the various isotopes of argon supported the mass spectrometer results (table 6-4). Data from them showed the total concentration as being between 50 and 70 ppm. Since the atmosphere of Venus contains about 75 times as many molecules as that of Earth this means that it contains 75 times as much ^{36}Ar as the atmosphere of the Earth. And yet the ratio of ^{38}Ar to ^{36}Ar is almost identical to the terrestrial ratio.

One discordant note has been sounded by the neutral mass spectrometer on the Bus. It could not detect argon at 130 km. By extrapolation to the lower atmosphere this result would seem to mean that there is less than 10 ppm of ^{36}Ar in the atmosphere of Venus. Even this upper limit, however, does not exclude the possibility that there is 25 times as much ^{36}Ar in the atmosphere of Venus as in that of the Earth.

Examination of the case of neon, another "primordial" rare gas, confirms the argon story. The Pioneer instruments and the Venera neutral mass spectrometer place the abundance of neon between about 4 and 13 ppm – compared with 18.2 ppm for Earth. This puts the excess of neon on Venus at about 45. The ratio of ^{22}Ne to ^{20}Ne was measured as 0.07. In contrast with the argon isotopes, this ratio is lower than the value found on Earth (about 0.1), but is close to the solar ratio.

Early analysis of data from the large probe's neutral mass spectrometer did not produce any publishable values for other rare gases – krypton and xenon. Nevertheless, it was clear that the notion that Venus, Earth, and Mars were made up of materials containing the same endowment of volatiles, already shaken by the Viking results, had been completely destroyed by the data from Pioneer Venus. Why should Venus have been provided with only about twice as much carbon dioxide and nitrogen as Earth and about 50 to 100 times as much neon

TABLE 6-4.– MIXING RATIOS IN THE LOWER ATMOSPHERE

Gas	Amount, ppm
Argon	40–120
40/36	1.03–1.19
38/36	0.18
Carbon dioxide	96%
Carbon monoxide	20–28
Krypton	0.05–0.5
Neon	4.3–15
Nitrogen	3.41% (at 24 km)[a]; 4%[b]
(percentages)	3.54% (at 44 km)[a]
	4.60% (at 54 km)[a]
Oxygen	16 (at 44 km)[a]; <30[b]
	43 (at 55 km)[a]
Sulfur dioxide	185 (at 24 km)
	<10 (at 55 km)
Water	20 (at surface)
	60–1350 (at 24 km)
	150–5200 (at 44 km)
	200–<600 (at 54 km)

[a]LGC
[b]LNMS

After J. H. Hoffman; based on six different instruments – four mass spectrometers and two gas chromatographs.

and nonradiogenic argon?

One possibility suggested after the early data from the Pioneer and Venera missions were revealed was that the planets were formed from dust grains in the solar nebula which were surrounded by gas at a pressure which diminished rapidly with increasing distance from the center of the nebula. Since reactive volatiles such as carbon, nitrogen, and oxygen are chemically combined within the grains, while the rare gases are adsorbed from the surrounding gas in amounts depending on the pressure, the result would be that the grains forming the three planets would have about the same reactive volatile content but the rare gas concentration would decrease rapidly with increasing distance from the Sun. This model also required that the nebula's gas temperature should be fairly constant and that for some reason, early outgassing from Mars should be less efficient by a factor of 20 than from the other two planets.

Analysis of the large probe's neutral mass spectrometer data has recently produced another surprise. Although the atmosphere of Venus contains a large excess of neon and primordial argon, this is not so with two other rare gases. The absolute abundance of krypton is only about 3 times larger in the atmosphere of Venus than in that of Earth. There is much less than 30 times more xenon. In the grain accretion model there is no reason to expect the enrichment of one rare gas to be greater than another. In fact, a close look at the Mars data shows that from Mars to Earth the enrichment decreases from a factor of about 220 for neon through 165 for argon, 110 for krypton, to 30 for xenon.

Another way of looking at these results is to compare the ratio of "primordial" argon to krypton on the terrestrial planets with the ratio on the Sun. In the solar atmosphere this ratio is 4000, on Venus it is 1000, on Earth 50, and on Mars 40. Thus, the ratio gets more solar-like the closer the planet is to the Sun. This fact has suggested that perhaps the material which accreted to form the planets was exposed to a strong irradiation by gas of solar composition flowing away from the Sun when the Solar System was being formed. If this were true the grains and small bodies that formed the planets would have a contribution of volatiles from the Sun in addition to the contribution from the nebular gas in their neighborhood. The material forming Venus may have received a much larger share of solar gases than the other planets because in intercepting most of the solar gas it would have shielded the outer regions of the Solar System from this gas.

Another possibility is that Mars was formed much earlier than the Earth, and the Earth much earlier than Venus, which would explain why Mars lost most of its volatiles. Mars may have originated early enough to have retained such highly radioactive substances as ^{26}Al left over from a nearby supernova explosion believed to have triggered the formation of the solar nebula. The heat produced by decay of this radioactive aluminum might have driven off many of the Martian volatiles at a very early time.

Two important noble gases are produced by radioactive processes; one is ^{40}Ar, the other is ^{4}He produced in the decay of heavy elements such as uranium. The consensus regarding Pioneer Venus and Venera measurements is that ^{40}Ar and ^{36}Ar are about equal in abundance on Venus. On Earth ^{40}Ar is about 400 times as abundant as ^{36}Ar. Since there is 75 times as much ^{36}Ar on Venus as on Earth, this means there is only about one-fourth as much ^{40}Ar on Venus as on Earth. Venus either started with considerably less potassium than Earth or is yielding up its argon from the interior more slowly than is Earth. The lack of widespread tectonism, the thicker and relatively plastic unfractured lithosphere, and the absence of surface erosion on Venus may be responsible for a slow escape of gases during the 4.5 billion years lifetime of the planet.

A measurement of helium in the upper atmosphere by the Bus neutral mass spectrometer is consistent with this picture. Extrapolation to the lower atmosphere suggests that there are about 12 helium atoms per million molecules in the atmosphere of Venus. Although this works out to an absolute abundance of helium on Venus 250 times greater than on Earth, it is not proper to conclude that Venus has vented that much more ^{4}He. We know that the present atmospheric amount of helium would be produced by radioactivity in the Earth's interior in about one million years. Earth's atmosphere is losing helium at a prodigious rate. The amount actually produced, vented, and lost is at least 10,000 times what now remains. The best estimate is that 5 to 10 times as much helium has been produced and has escaped from the atmosphere of Earth compared with Venus. Hence, inefficient present release of gas from the interior of Venus may account for the difference between the radiogenic gas inventories of the two planets. This is so if they contain equivalent amounts of potassium and uranium.

The amount of water vapor present in an atmosphere has important implications for the temperature structure of that atmosphere. Water vapor plays an important role in the greenhouse mechanism invoked to account for the very high temperature of Venus' atmosphere near the surface. It also has an important bearing on the chemical composition of the atmosphere.

Unfortunately, measuring accurately the amount of water vapor in an atmosphere is very difficult. Even in connection with the Earth there persists much uncertainty about the amount of water in the stratosphere. After the Venus mission of 1979 a similar state of confusion has developed concerning the amount of water vapor in the atmosphere of Venus. The neutral mass spectrometer of the large probe gave data that says there is less than 0.1% water in the atmosphere. A special optical device on the Venera probes found a small amount, too. Its measurements indicate that water decreases from 200 ppm at 50 km to 20 ppm at the surface. On the other hand, the probe gas chromatograph data show 0.52% at 42 km and 0.13% at 22 km – very much greater amounts.

The quantity of carbon monoxide gas in the atmosphere of Venus is very small. Concentration is about 20 ppm at 22 km according to data from the gas chromatograph. At the cloud tops it is about 50 ppm as deduced from Earth-based observations. If carbon monoxide is produced above the clouds by photodissociation of carbon dioxide, and it subsequently diffuses downward, this kind of distribution would result. However, the amount of carbon monoxide expected to accompany carbon dioxide as it is vented from the interior of a planet is far greater than the amount observed on Venus. At least a thousand times as much carbon monoxide should have been produced. It is conceivable that carbon monoxide may have reacted with water to form hydrogen and carbon dioxide early in the history of the planet, and this could account for the absence of water on Venus. The hydrogen might have escaped into space. However, it is most unlikely that the initial amounts of water and carbon monoxide were so nearly equal that they would have mutually reduced each other to such minor quantities as are now present on the planet.

Oxygen is one of the other constituents found by various instruments. This gas increases from 16 ppm to 43 ppm between 42 and 52 km, according to data gathered by the probe gas chromatograph. The neutral mass spectrometer of the large probe produced data that show the amount of oxygen as less than 30 ppm, and Earth-based measurements find less than 1 ppm at the cloud tops. The coexistence of carbon monoxide and molecular oxygen in the atmosphere is difficult to understand thermodynamically. Although photolysis of carbon dioxide above the clouds would call for oxygen to be formed along with carbon monoxide and decrease in abundance downward, the amounts found below 52 km are quite inconsistent with the small amount observed above the clouds. Thus the oxygen measurements present an enigma.

Among sulfur compounds, the measurements would allow no more than 3 ppm of the interesting molecule carbonyl sulfide. However, sulfur dioxide appears to be present near 22 km in fairly large amounts – 130 to 185 ppm. Above the clouds the amount is reduced to 0.1 ppm. Finally, the neutral mass spectrometer has detected hydrogen sulfide gas with a mixing ratio decreasing from about 3 ppm at the surface to 1 ppm in the clouds. These results have an important bearing on the question of how the clouds of Venus are formed. We know the clouds contain large amounts of sulfuric acid. Before Pioneer Venus, a cycle of chemical reactions similar to one responsible for formation of sulphate aerosol layers on Earth had been proposed for Venus. In this cycle, carbonyl sulfide played a key role. The failure to find carbonyl sulfide in the atmosphere of Venus was a major surprise for the Pioneer mission. Now mechanisms that utilize a sulfur dioxide and water source to produce the sulfuric acid are being proposed.

Upper limits for other important species have been set by data from the gas chromatograph. These are 10 ppm for hydrogen, 1 ppm for methane, and 1 ppm for ethylene. So far, no values for these constituents have been reported from analysis of data gathered by the probe mass spectrometer, although it is known that the instrument detected them along with helium. Difficulties in interpreting the data have delayed the analysis. It will be interesting to see when the values are derived whether they agree with these upper limits and the helium abundance implied by the measurements made by the Bus mass spectrometer.

The water-vapor measurements present major theoretical problems. Use of the high value obtained from the Pioneer Venus gas chromatograph in a thermodynamic calculation predicts hydrogen sulfide and carbonyl sulfide concentrations somewhat larger than the gas chromatograph itself would allow, but consistent with the mass spectrometer measurements. The smaller concentration seen by the Venera photometer would not allow nearly so much hydrogen sulfide as the mass spectrometer found. On the other hand, an elementary conservation law states that the ratio of hydrogen atoms to the total number of gas molecules of all kinds must remain constant in the atmosphere below the clouds.

Therefore, whether the gas chromatograph measurement of 0.52% water at 52 km or the photometer value of 200 ppm is correct, compounds containing equivalent amounts of hydrogen atoms must exist at the surface. Their concentrations must vary so as to keep the so-called hydrogen mixing ratio constant. No such hydrogen compounds have as yet been reported. Thus, hydrogen presents us with a continuing dilemma as it so often seems to do in planetary atmospheres generally.

An important question for many purposes is whether the atmosphere is reducing or oxidizing. We are sure that it is very close to the dividing line between these two states, but we are still unsure as to which side it is on. The amount of carbon monoxide detected seems to be slightly greater than the amount of molecular oxygen, and the presence of the latter is doubted by some scientists. Thus, a case can be made that the state of the Venus atmosphere is a reducing state.

The Ionosphere

Data from Pioneer Venus dramatically improved our understanding of the ionosphere of Venus. The ionosphere of a planet is a region of the upper atmosphere characterized by a high density of electrically charged particles of electrons and ions. These charged particles are usually produced by solar radiation in the extreme ultraviolet region of the spectrum interacting with the neutral molecules and atoms of the upper atmosphere. The types and densities of ions found in an ionosphere depend on the neutral composition, on the chemical reactions that occur, and on how the ions are transported from place to place within the ionosphere. The behavior of a gas consisting of charged particles (known as a plasma) is affected by magnetic fields.

Measurement of the delay time in the arrival of a radio wave passing from a spacecraft to receiving stations on Earth provides information on the electron densities encountered along the way. By arranging for the radio waves to pass through the atmosphere of Venus on their way to Earth as the spacecraft went into and emerged from occultation by Venus, experimenters obtained information concerning the ionosphere. On earlier flyby and Orbiter missions before the Pioneer mission to Venus this radio occultation technique was used to obtain some limited information on the total electron densities. The Pioneer Venus Orbiter not only employed this technique but also made the first *in situ* measurements of the ionosphere of Venus using the following instruments: an ion mass spectrometer, a Langmuir probe, a retarding potential analyzer, and a fluxgate magnetometer. A picture of the global composition and dynamics is now being developed using the information gathered by these instruments.

On Venus the ionospheric electron density reaches a maximum at altitudes near 140 km on both the dayside and the nightside of the planet. Although this level was not directly accessible to the Orbiter because it is a few kilometers below the periapsis altitude, this density maximum has been investigated by using the radio occultation technique. Above this density peak the electron density decreases gradually with increasing height. In the regions directly accessible to the Orbiter's instruments, the high time resolution measurements of both the electron density and temperature made by the Langmuir probe on the spacecraft revealed many unusual ionospheric phenomena such as ionospheric density depletions ("holes") and detached plasma clouds. Also, the composition of the plasma in addition to the total density is being measured, for the first time, by the ion mass spectrometer on the Orbiter. Further information on composition of the plasma is being obtained by the retarding potential analyzer as well as measurements of ion temperature, photoelectron fluxes, and plasma drifts.

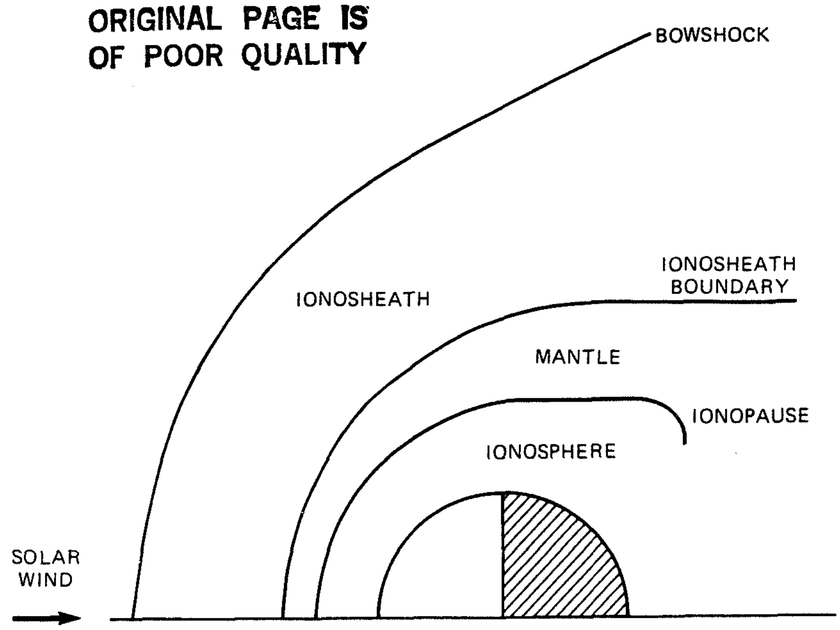


Figure 6-25. Regions of the magnetosphere of Venus from the bow shock to the ionosphere.

The Earth's ionosphere extends to heights of many thousand kilometers, gradually tapering off with increasing altitude. This extension to very high altitudes is possible because the Earth's ionosphere is shielded from the solar wind by the strong intrinsic dipole magnetic field of our planet. By contrast, the intrinsic magnetic field of Venus is negligible so that the solar wind can interact directly with the ionosphere. The ionosphere of Venus acts as an obstacle to the solar wind and deflects it around the planet. As a consequence of this interaction the Venusian ionosphere ends rather abruptly at an altitude which is typically only a few hundred kilometers, although this boundary altitude is very variable. This boundary where the ionosphere ends and the region of decelerated solar wind (ionosheath) begins is called the ionopause (fig. 6-25).

Just outside the ionopause there is a region of large horizontal magnetic field that contains some ionosheath plasma and some rapidly moving "superthermal" plasma of ionospheric origin. This large magnetic field, induced by the interaction of the solar wind with the ionosphere, acts as a medium that transmits the solar wind pressure and acts as a "piston" on the ionosphere. When the solar wind pressure is high the magnetic field is enhanced. The "piston" moves in and the ionopause is pushed to a lower altitude. When the solar-wind pressure is lower, the ionopause moves up. As a result the ionopause height is quite variable, ranging from 200 km to over 1000 km on the dayside. On the nightside there is no direct interaction of the solar wind with the ionosphere because the solar wind is deflected around the planet. However, there must be indirect interactions that are not yet understood, because even on the nightside the height of the ionopause is usually less than 1000 km.

Unlike the magnetic field just outside the ionosphere, the field within the ionosphere of Venus is very small for the most part. However, unique magnetic structures were detected by the magnetometer on the Orbiter. These structures, called flux ropes, are long, narrow, rope-like regions of strong magnetic field in which the field lines are twisted (fig. 6-26). One suggestion is that these flux ropes are formed from the large magnetic field piled up just outside the ionopause and are drawn down into and through the ionosphere by the solar wind "pulling" on the "ends" of the ropes. Another possibility is that the magnetic flux ropes are generated in a region of large ionospheric magnetic field which has been discovered near the subsolar point.

On the nightside the magnetic field in the ionosphere is generally larger and more regular than on the dayside. The average magnetic field exhibits the type of global symmetry that would be expected from a "draping" of the solar-wind field lines around the planet.

Heat conduction and transport of electrically charged particles is constrained to be along, rather than at right angles to, magnetic field lines. Therefore, the flux ropes may play a role in affecting the temperatures of electrons and ions in the ionosphere of Venus. The electron temperature is a few thousand degrees Kelvin on both the dayside and nightside of Venus. This is much hotter than the neutral gas in the thermosphere which has a temperature of only a few hundred degrees Kelvin. Another reason for high temperatures is that heat from the solar wind is being "pumped" into the ionospheric electrons at the ionopause. The temperature of the ions is also very high; about 2000 K on the dayside and more than 4000 K on the nightside. Interactions such as friction between the neutral gas and the ions generate heat that helps to keep the ions hotter than the neutrals. On the nightside some of the energy from rapid motions or horizontal drifts of the ions is converted into heat and makes the nightside ions hotter than the dayside ions.

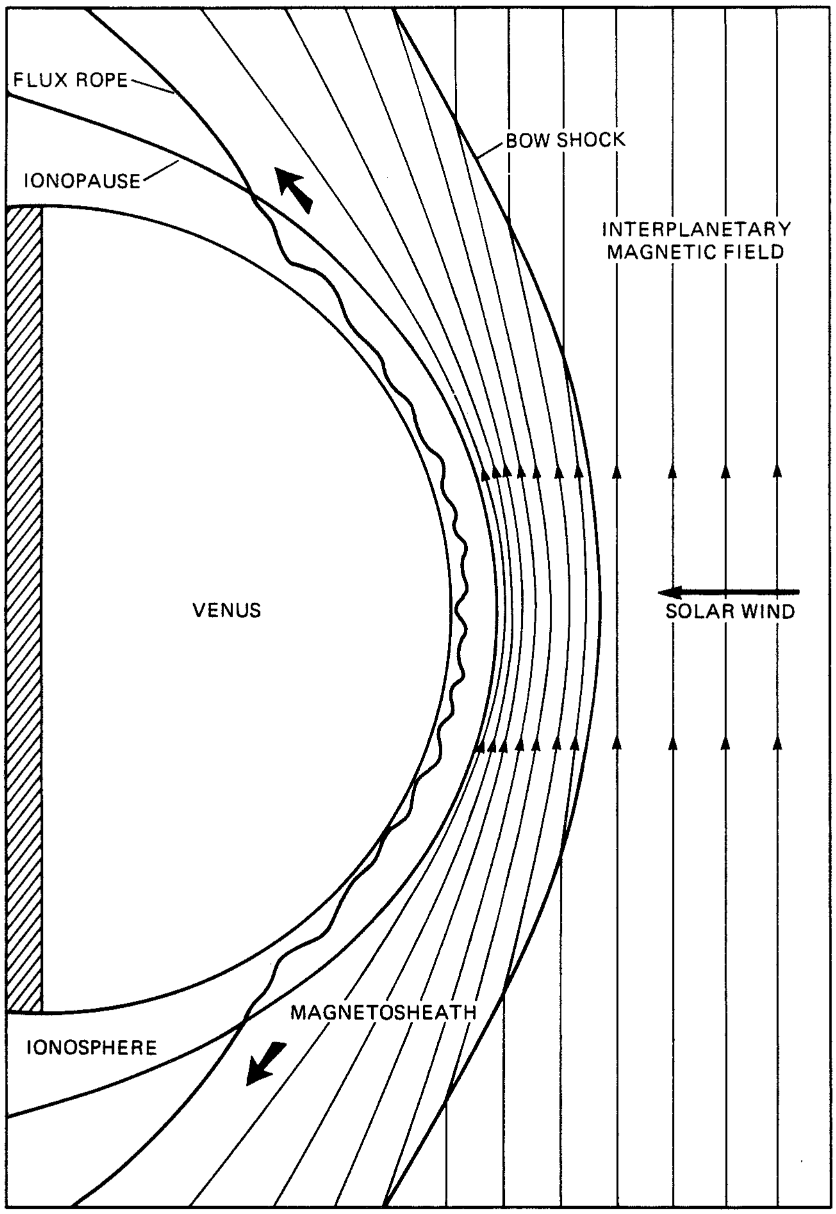


Figure 6-26. Magnetic field of the solar wind producing a flux rope through the high atmosphere of Venus.

The ion mass spectrometer on the Orbiter has established the presence of many different ions. Some ions, such as O_2^+, O^+, CO_2^+, He^+, and H^+, were expected to be present in the ionosphere of Venus from theoretical studies, but other ions found there were unexpected; namely, C^+, N^+, NO^+, O^{++}, H_2^+, and N_2^+. Molecular oxygen is the most abundant ion below 200 km on the dayside and below 160 km on the nightside. Above an altitude of about 160-200 km, atomic oxygen becomes the predominant ion, although in the predawn region of the nightside atomic hydrogen ions are just as abundant as atomic oxygen ions.

There is a strong day/night asymmetry, or local time variation, in the total plasma density. In fact, each ion species has its own day/night asymmetry; that is, the composition as well as the total plasma density depends on the local time (see fig. 6-27). At 200 km the atomic oxygen ion concentration falls off gradually by a factor of ten from the dayside to the nightside of the planet. The molecular oxygen ion density decreases rapidly at the terminator and is almost one thousand times less on the nightside than on the dayside. Atomic hydrogen and helium ions behave quite differently from the oxygen ions and are greater on the nightside than on the dayside. But the nightside distributions are not uniform; there are far more hydrogen than helium ions in the predawn region, no doubt a reflection of the predawn bulges in neutral hydrogen and helium.

The Pioneer Venus Orbiter has led to great progress being made in understanding the mechanisms responsible for maintaining the nightside ionosphere. The problem of maintaining a nightside ionosphere is that the Venus night is so very long (about 58 Earth days), much longer than the lifetime of the ions. Therefore a significant ionosphere of the type found by Pioneer Venus would not be expected on the nightside. Two sources of ionization have been identified for the nightside, largely with the help of the data gathered by the Orbiter's instruments. One of these sources, which was first supported by data from the Soviet Venera spacecraft, is the bombardment of the nightside atmosphere by fast electrons (much like the electron flux responsible for the terrestrial auroras) which are energetic enough to ionize the neutral gas. These electrons originate in the wake of the planet outside the ionopause. This mechanism can account for a significant fraction of the ionization in the lower part of the nightside ionosphere, but another source of ions is required to account for conditions at higher altitudes and to supplement the "auroral" source at lower altitudes.

Instruments on the Orbiter detected large horizontal flows or drifts of plasma from day to night hemispheres. The drift velocities were very large at high altitudes and near the terminator; up to 10 km/sec (23,000 mph). Plasma motions like these are more than sufficient to maintain the observed nighttime ionosphere at higher altitudes. In fact, a significant contribution can also be made to maintaining the lower ionosphere since as ions flow to the nightside they also sink to lower altitudes. The mechanism responsible for the plasma drifts themselves are not yet entirely understood. At lower altitudes day to night neutral winds help drag the ions along to the nightside. At very high altitudes near the ionopause, the antisunward flow of plasma on the high side of the ionopause can induce ionosphere flow below it. At intermediate altitudes the day to night gradients in the ion densities seen by the Orbiter can generate ion drifts.

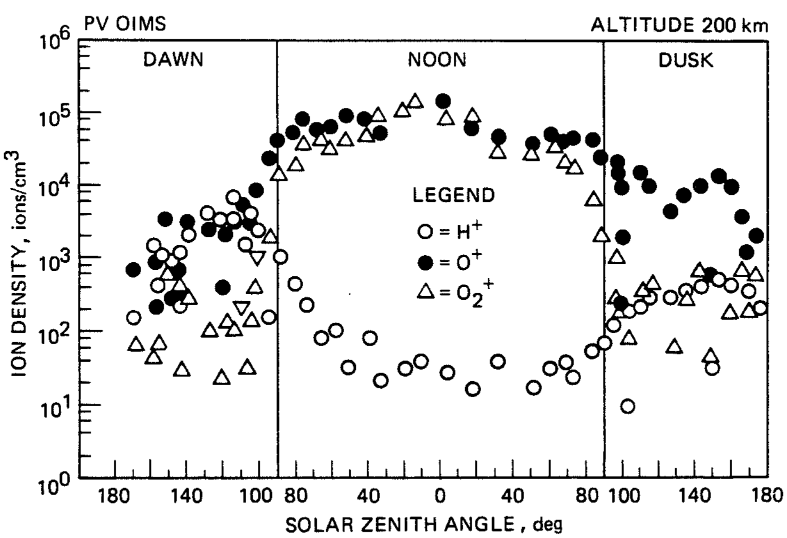


Figure 6-27. Ion densities for H^+, O^+, and O_2^+ showing the dramatic changes between dayside and nightside of the planet.

Concentrations of all ions show pronounced fluctuations from orbit to orbit on the nightside as well as near the terminators. Usually there is an ordinary nightside ionosphere as discussed, but sometimes the ionosphere on the nightside disappears entirely or, perhaps, is swept away downstream of Venus by the solar wind on occasions of very large solar wind pressure. The nightside magnetic field certainly plays an important role in this. At other times, the nightside ionosphere looks normal except for localized "holes" in the plasma where the electron density is very low and the electron temperature is very high. The magnetic field in these holes tends to be vertical, indicating that perhaps these holes are associated with the large-scale structure of the field on the nightside. Another phenomenon which is frequently observed on night and day hemispheres, mostly near the terminators, is the presence of detached layers of "clouds" of ionospheric plasma which lie outside the ionosphere, beyond the ionopause. It is likely that the solar wind (or ionosheath flow) is removing chunks of plasma from the ionopause region of the ionosphere and is carrying this plasma downstream (fig. 6-28).

Solar Wind Interaction

The upper atmosphere of the Sun, the solar corona, is so hot that it is essentially completely ionized. Even heavy atoms, such as those of iron, have lost many of their electrons. This ion-electron gas expands rapidly from the Sun, reaching speeds of over 400 km/sec (about one million mph), and forms the solar wind. At such speeds, nevertheless, the solar wind requires three days to reach Venus and four days to reach Earth. When Venus is positioned between the Sun and the Earth, the solar-wind data from Pioneer Venus can be, and have been, used to warn of impending solar-wind disturbances on their way to Earth.

The interaction of the solar wind with a planet is analogous to the inter-

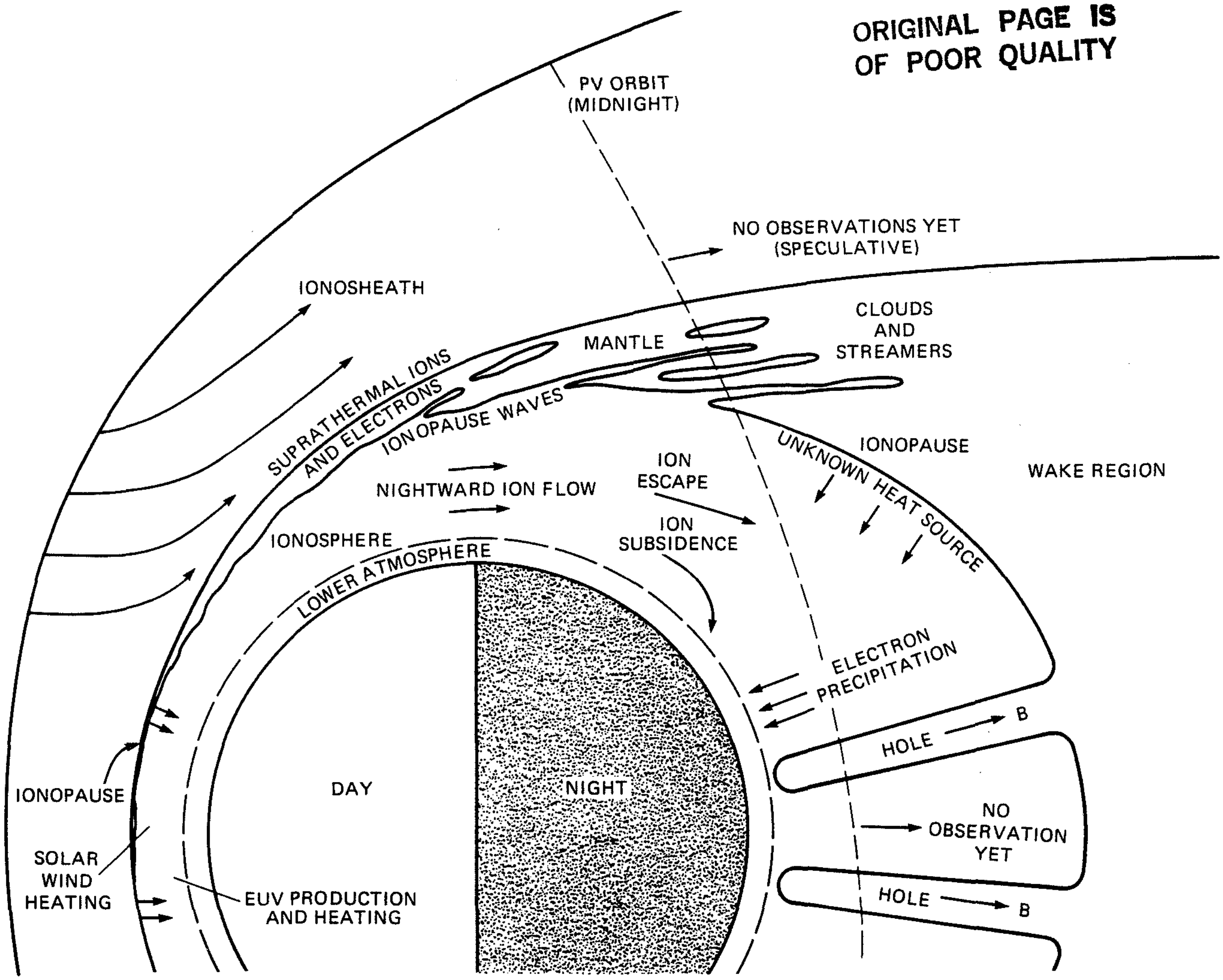


Figure 6-28. Interaction of the solar wind with the atmosphere of Venus as determined from Pioneer Venus experiments and observations.

action of an atmosphere with a supersonic aircraft. As an aircraft travels through air, pressure waves are propagated ahead of the plane at the speed of sound and warn of the plane's approach, diverting air molecules out of its path. However, when an aircraft travels at supersonic speeds the warning cannot be transmitted ahead and a shock wave forms in front of the plane and diverts the air around it. The solar wind travels faster than the speed of pressure waves which could divert solar-wind flow around a planet. As a consequence, a shock wave, or bow shock, forms in the solar wind in front of each planet analogous to the shock wave in front of a supersonic aircraft.

The bow shock of Venus is in many respects similar to the bow shock of Earth. This might be expected because the properties of the solar wind are similar at Earth and at Venus. However, there are also reasons for expecting differences. At Venus the ionosphere, which extends only a few hundred kilometers above the surface, deflects the solar wind. At the Earth the strong terrestrial magnetic field deflects the solar wind at a distance of over 10 Earth radii above the planet's surface. This results in a much larger bow shock at Earth. According to present models this could affect the energies of particles reflected back into the solar wind by the shock. However, the wave phenomena seen at Venus in association with the beams seem equal to the terrestrial wave phenomena in amplitude, in frequency of occurrence, and in other properties.

Another way in which Venus could be different from the Earth in its solar-wind interaction arises because the solar wind can reach the neutral atmosphere of Venus. As a result, processes that are thought to be important for comets could occur at Venus. In comets, the neutral atmosphere becomes ionized by either solar ultraviolet radiation or by exchanging an electron between a heavy neutral cometary ion and a light solar-wind ion (usually a proton). This process adds mass to ("mass-loads") the solar wind, and slows it down. Since the solar wind has a magnetic field which connects the slowed down solar-wind plasma to the freely flowing plasma far from the comet, a long magnetic tail is formed behind a comet joining the slow and fast ionized gas.

The neutral atmosphere of Venus is bound to the planet by gravity far in excess of that of a comet. While the gravity of Venus can hold an atmosphere, that of the comet cannot. However, some of the neutral atoms of the Venus atmosphere do reach the solar wind and can be lost through photoionization and charge-exchange processes. There is both direct and indirect evidence that Venus acts very much like a comet in its interaction with the solar wind. First, the Venusian bow shock is slightly weaker than the terrestrial shock. This could occur if charge-exchange behind the shock led to absorption by the Venusian atmosphere. Second, Venus has a comet-like magnetic tail. This would occur if the magnetic field, draped across the dayside of the planet, became mass-loaded. Third, direct observations have been made of ions from Venus flowing beside and behind the planet with a velocity almost equal to that of the solar wind.

The location of the bow shock as observed by Pioneer Venus was somewhat surprising. Before the Pioneer mission, a common belief was that any planetary magnetic field of Venus would be too weak to hold off the solar wind. Hence, the size of the bow shock would be determined by the size of the planet itself, and should be relatively unchanging. However, Pioneer Venus observed a shock that is 35% larger than the shock observed by the Soviet Venera 9 and Venera 10 spacecraft. Why should the size of the shock change? Since the Soviet measurements were made at solar minimum whereas those by Pioneer Venus were at solar maximum, a speculation was that the change in the solar cycle, in particular in the flux of ultraviolet radiation, causes changes in the upper atmosphere of Venus which alter the rate of processes such as photoionization and hence the solar wind interaction. This speculation will be investigated further during the extended mission of Pioneer Venus, when solar activity begins to decline.

One of the instruments carried to Venus for the first time by the Pioneer Orbiter was a plasma-wave analyzer which measured the electric field associated with the oscillations of ions and electrons. This instrument provided evidence for a plasma-wave mechanism which couples the energy of the magnetosheath to the ionospheric plasma via so-called whistler waves. It also provided the basis for some interesting and important comparisons among the planetary bow shocks. When the plasma emissions seen at Venus, Earth, Jupiter, and Saturn are compared, an evolution in properties is observed. The waves at Saturn are quite unlike those at Venus. The major change in the solar wind with distance is that the ratio of solar-wind velocity to the pressure-wave velocity, or Mach number, which determines the strength of the bow shock, increases with distance from the Sun. This provides experimental verification that the processes in the shock change with the shock strength. As described earlier, this instrument also provided evidence for lightning on the planet, which confirms similar Soviet observations below the cloud tops. While Pioneer Venus is not equipped with instruments that can search visually for lightning, it can detect the electromagnetic waves generated by lightning. On almost every low altitude nightside pass of the Pioneer Orbiter signals were observed which have the characteristics expected of waves generated by lightning discharges.

The Intrinsic Magnetic Field

Except for Venus and the Moon, and possibly Mars, every planet that has been visited by spacecraft is thought to have an internally driven magnetic field. There was some expectation before Pioneer reached Venus that perhaps an internal magnetic field of Venus did exist and that it was too weak to be detected by earlier missions to the planet. However, the Pioneer Venus Orbiter has probed thoroughly with highly sensitive instruments for such a field and has found none. One of the principal unsolved problems of geophysics is the nature of the source of the terrestrial dynamo that generates the magnetic field of Earth. Scientists hoped that a measure of a magnetic field of Venus, a planet which appears in many respects to be a twin of Earth, would help clarify the effect of spin rate on the dynamo process. Venus spins on its axis much more slowly than does Earth. A Venus day is 243 Earth days. Dynamo theories predict that a planetary dynamo, such as the one generating the field of Earth, should depend on spin rate. If a Venus dynamo were identical to Earth's, but weaker in proportion to the spin rate, the planet would have a magnetic field that would easily be detectable. But it does not. Other factors must be at work.

A planetary magnetic dynamo requires a highly electrical conducting fluid core. The absence of a conducting core may explain why Earth's satellite, Moon, does not have a magnetic field, but it does not explain the absence of a field of Venus. Under the temperatures and pressures present in the core of Venus there should be a highly conducting fluid. However, the composition and electrical conductivity of the fluid may be different from that of Earth. Although Venus appears to be Earth's twin in size, it may not be a twin in chemical composition since it was formed at a different place in the solar nebula and presumably at a different temperature.

Another possible difference is the weakness of any energy source which would drive the dynamo of Venus. Present thinking about the terrestrial dynamo is that a solid inner core is growing at the center of the Earth. As this core grows it releases its latent heat of fusion into the surrounding fluid. Calculations indicate that this energy source is stronger than the once popular radioactive heating mechanism. The pressure and temperature at the core of Venus are only slightly less that at Earth's core. However, this difference may be sufficient to prevent solidification of an inner core of Venus even if the internal composition of the two planets were the same.

The situation is perhaps best described by planetary theorist David Stevenson who says: "While planetary dynamo theorists have yet to be able to predict accurately anything about planetary magnetism, they have been able to rationalize all the observations."

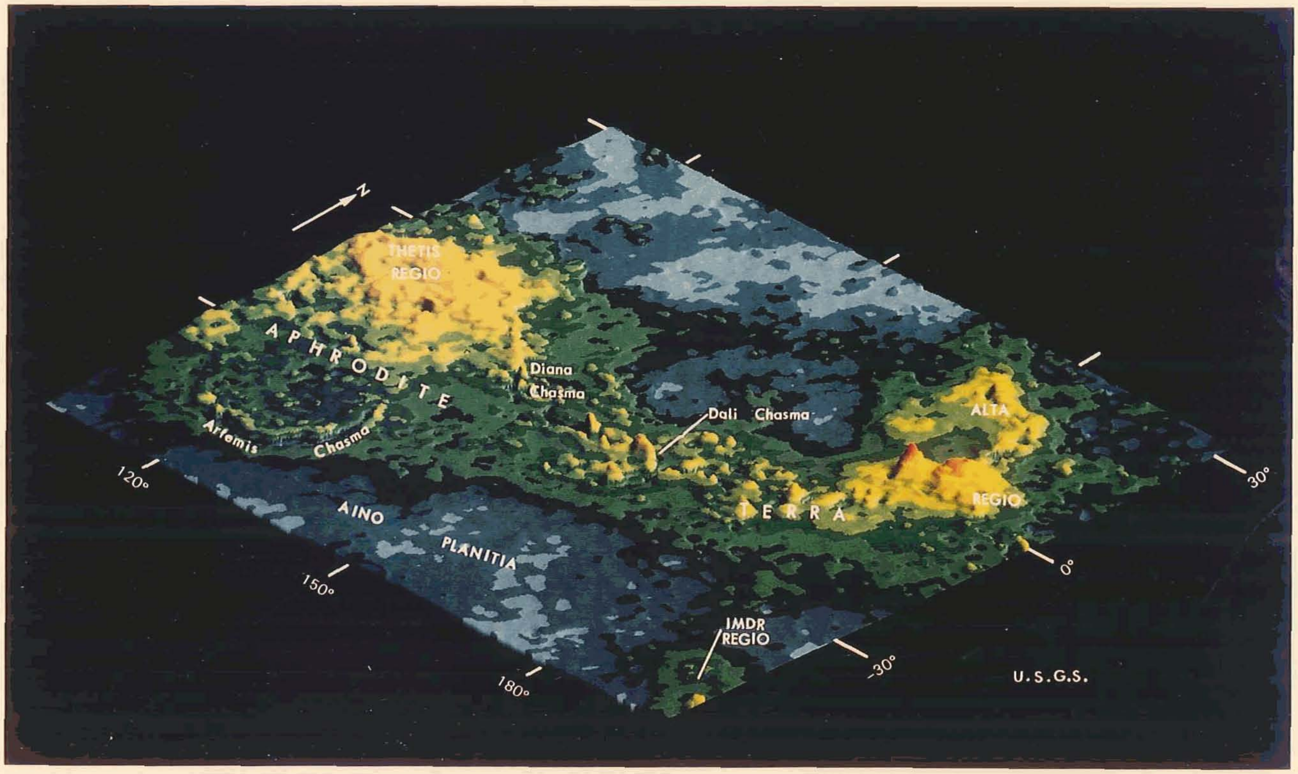
If the terrestrial dynamo process later becomes better understood, we may be able to use this understanding to infer some of the internal properties of the planet. Alternatively, if some of these internal properties become known through other means we may be able to use the absence of a magnetic field at Venus to help us understand the dynamo process. In short, all that can be unambiguously stated is that Venus at present does not have an operating magnetic dynamo. The nature of the source of planetary magnetic fields still remains one of the principal unsolved problems of geophysics.

Processed Radar Images

The following illustrations are representative of the most recent processing of radar data on Venus (figs. 6-29(a-f)). The United States Geological Survey (USGS) processed some of the data to create a three-dimensional effect which graphically reveals depressions and mountains. The areas shown are (a) Aphrodite Terra, (b) Ishta Terra (looking toward the east), and (c) Beta Regio.

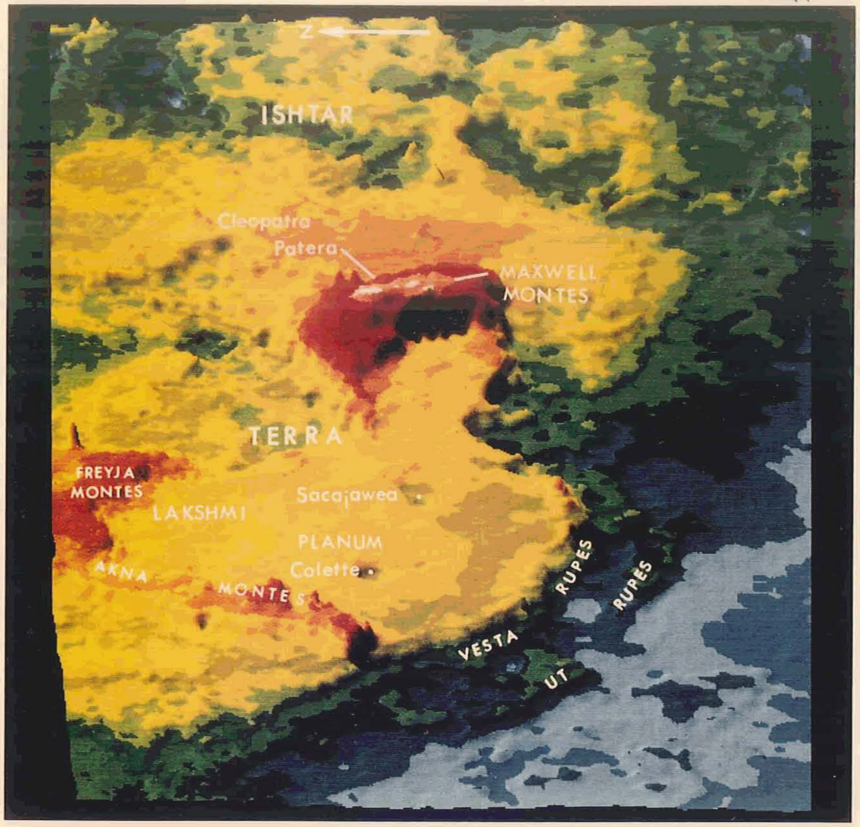
Additionally, two Mercator projections provide (d) the most up-to-date contour map of the surface of Venus and (e) an annotated map identifying the major topographical features. On both maps the color scale is identified by the chart to the right of the map indicating height in terms of the planet's radius together with a kilometer scale above and below the mean radius.

The final illustration in this group (f) shows a detailed strip of the equatorial region of the planet identified in terms of radar brightness given by the scale on the right.



(a)

Figure 6-29. Recent computer enhanced surface relief images of Venus.



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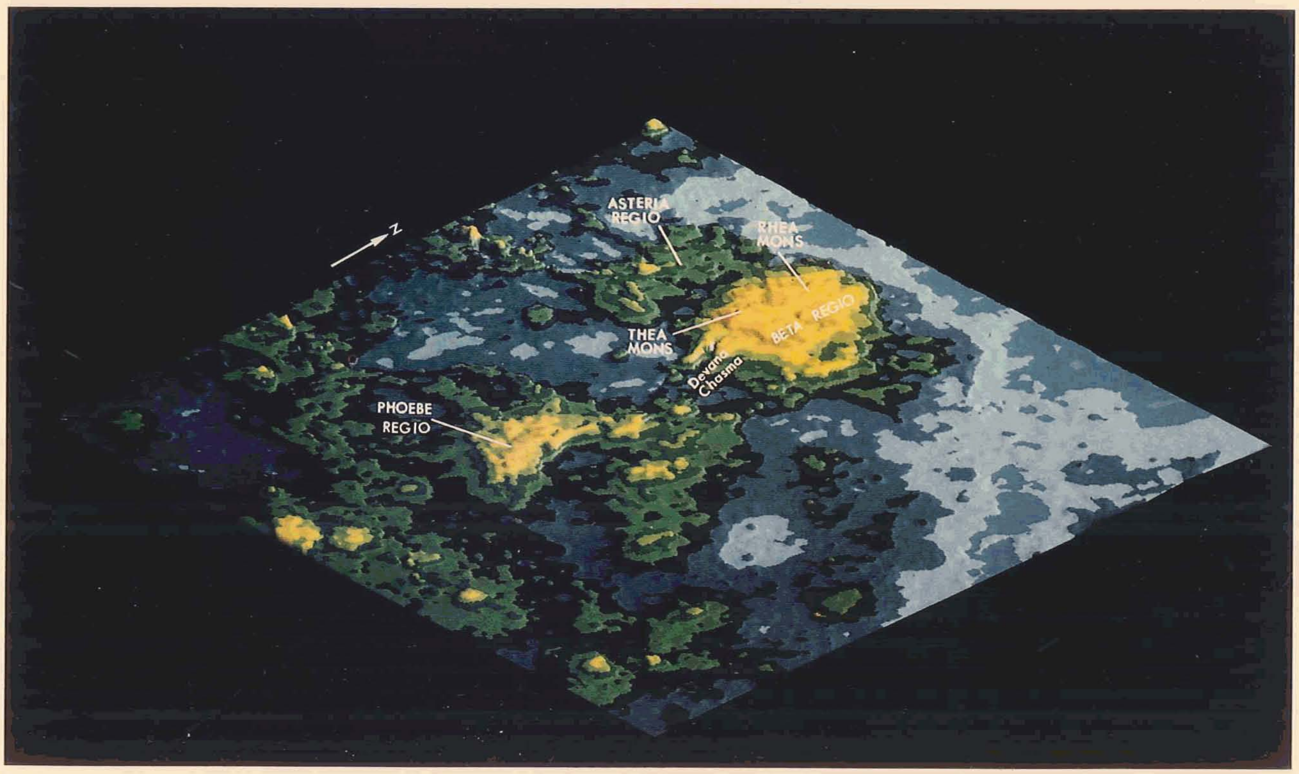
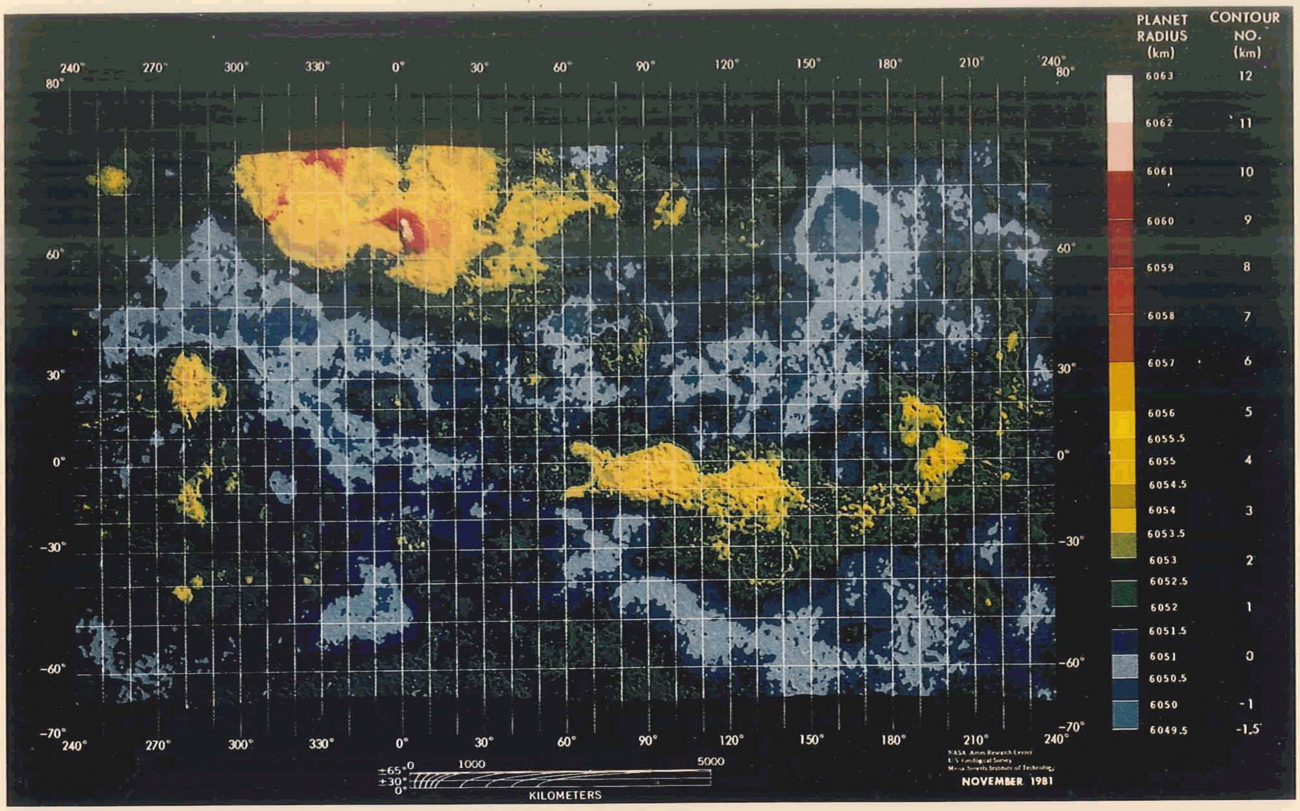


(c)

Figure 6-29. Continued.



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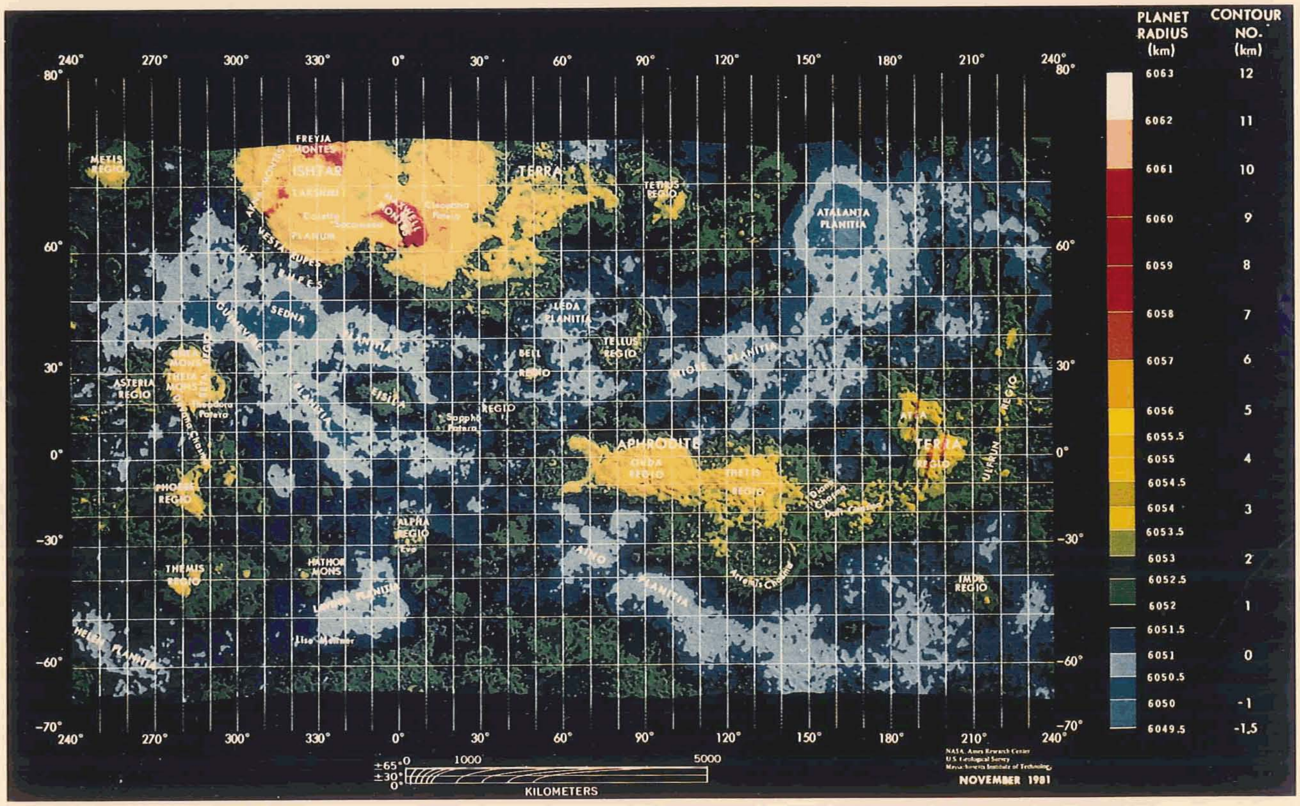
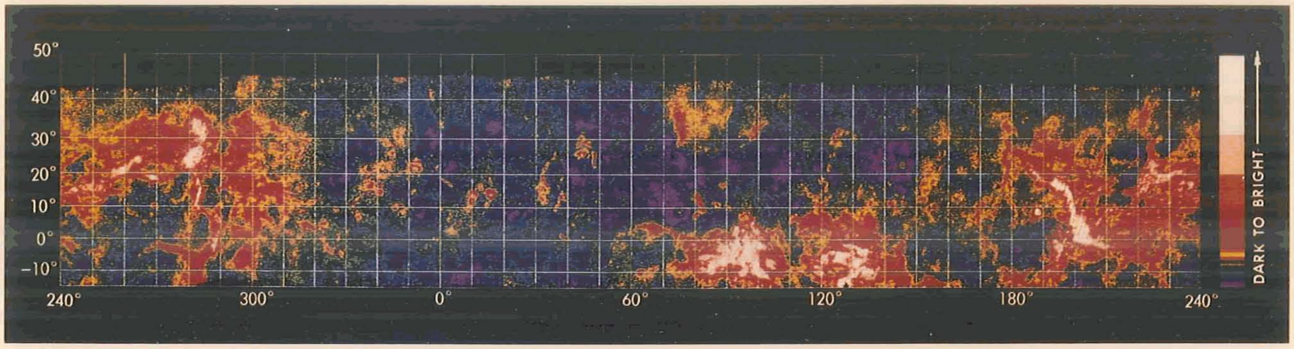


(e)

Figure 6-29. Continued.



(f)

Figure 6-29. Concluded.

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Imaging and Polarimetry from Pioneer Venus Orbiter

The Cloud Photopolarimeter experiment on the Pioneer Venus Orbiter acquired 350 images of Venus in ultraviolet light and 250 4-color polarization maps during the Pioneer Venus primary mission from December 1978 through August 1979. The Cloud Photopolarimeter is a 1½-in. diam telescope which acquires its images by spin-scan mapping of the planet as the Pioneer Venus spacecraft orbits Venus once every 24 hr. The images are acquired in the portion of the orbit farthest from the planet (25,000 to 40,000 miles away) when the spacecraft is moving slowly. (During the opposite portion of the orbit the spacecraft dives at high speed through the tenuous upper atmosphere of Venus within about 100 miles of the surface, permitting other instruments to sample the atmospheric composition.) As Venus moves around the Sun once every 225 days the Cloud Photopolarimeter is able to view Venus at all phases from crescent phase to full phase and back to crescent phase.

Figures 6-30 are images that illustrate phenomena observed during the primary mission. Significant findings from the imaging and polarimetry data include:

High altitude haze. Both polar regions of Venus were unusually bright during the primary mission. The polarimetry data show that the bright polar caps are caused by an extensive haze of submicron particles, $\sim$0.25 μm in radius. A substantial amount of this high altitude haze is also found at lower latitudes, particularly in the morning sky. The haze extends vertically over at least 25 km reaching down into the main visible cloud layer where it co-exists with the larger ($\sim$1 μm radius) sulfuric-acid cloud droplets which had been identified by earlier Earth-based polarimetry studies. The refractive index of the haze is found to be 1.45 ± 0.04, suggesting that its chemical composition could be the same as that of the main cloud deck. The amount of haze above and within the main cloud deck in the polar regions decreased by more than one-half during the primary mission, indicating that there are chemical and aerosol processes at work on time scales of several months and longer.

Global atmospheric dynamics. The images are being used to study the atmospheric circulation and its relationship to regional cloud patterns. Wind speeds near the cloud tops are inferred by tracking small cloud features. These measurements reveal nearly constant high speed zonal winds, about 100 m/sec (220 miles/hr) at the equator. The winds decrease toward the poles such that the atmosphere at cloud-top level rotates almost like a solid body. This zonal circulation is different from that observed by the Mariner 10 flyby in 1974, which found strong midlatitude jet streams. The planetary scale patterns of the clouds have evolved during the Pioneer Venus primary mission, such that the dark horizontal Y-shaped feature, previously recognized by Earth-based observers, disappears for periods of a few weeks.

The Cloud Photopolarimeter continues to function perfectly during the extended mission of Pioneer Venus. Observations of the evolution of the aerosols and atmospheric circulation for several years will contribute valuable knowledge about processes that are important components in the climate system of the Earth.

The Cloud Photopolarimeter experiment team is at the NASA Goddard Institute for Space Studies (GISS, in New York City), a division of the Goddard Space Flight Center in Greenbelt, Maryland. The Cloud Photopolarimeter was constructed by Santa Barbara Research Center, a subsidiary of Hughes Aircraft Company, under cognizance of the Engineering Directorate of Goddard Space Flight Center.

Wind speeds in the Venus atmosphere can be inferred by measuring the displacement of clouds such as in Image 190. The wind speed, more than 200 mph near the equator, corresponds to a rotation period between 4 and 5 days at most latitudes, as shown in the diagram. The diagram also illustrates that the distinct midlatitude "jet stream" obtained from

Mariner 10 images in 1974 is not present in the Pioneer Venus observations. One theory for the existence of the rapid easterly winds on Venus suggests that the nature of the general circulation could vacillate between wind profiles of the types observed by Mariner 10 and Pioneer Venus. Such vacillations might be related to long term variations of the clouds and aerosols, such as the appearance and disappearance of polar caps. Continued observations during the extended Pioneer Venus mission are needed to resolve these questions.

Winds on Venus

Wind speeds in the Venus atmosphere can be inferred by measuring the displacement of clouds such as in figure 6-30(a). The wind speed, more than 200 mph near the equator, corresponds to a rotation period between 4 and 5 days at most latitudes, as shown in figure 6-30(b). The diagram also illustrates that the distinct mid-latitude "jet stream" obtained from Mariner 10 images in 1974 is not present in the Pioneer Venus observations. One theory for the existence of the rapid easterly winds on Venus suggests that the nature of the general circulation could vacillate between wind profiles of the types observed by Mariner 10 and Pioneer Venus. Such vacillations might be related to long term variations of the clouds and aerosols, such as the appearance and disappearance of polar caps. Continued observations during the extended Pioneer Venus mission are needed to resolve these questions.

The Phases of Venus

Figure 6-30(c) is the first image obtained by Pioneer Venus. Low contrast is due to the oblique viewing conditions at crescent phase, in combination with high altitude haze in the atmosphere.

Figure 6-30(d) was obtained at the time the Soviet entry probe Venera 11 arrived. Venera descended at the equator near the bright limb (left edge) of this image.

Figure 6-30(e) shows Venus at full phase. Both poles have bright caps caused by an optically thick haze of small particles (radius ~0.25 μm) above the main cloud layer.

Four-Day Cycle of the Venus Clouds

A 4-day rotation period for the Venus atmosphere was first determined from the reappearance at 4-day intervals of a faint horizontal Y feature in ground-based ultraviolet images. These Pioneer Venus images, taken at 24-hr intervals, show the planet's appearance in detail as the Y feature rotates around the planet.

The dark horizontal Y is prominent in figure 6-30(f).

One day later the high zonal winds have carried the clouds from right to left by about 90° in longitude, leaving only the tail of the Y visible (fig. 6-30(g)).

The side of the planet opposite the Y is visible, revealing a pattern of linear features nearly parallel to latitude circles (fig. 6-30(h)).

Curvilinear features presage the reappearance of the Y feature, which was recorded in figure 6-30(i) on February 19.

Venus at Full Phase

Figure 6-30(j) was obtained by the Cloud Photopolarimeter on the Pioneer Venus Spacecraft on February 19, 1979 when the Sun illuminated almost the entire hemisphere visible from the spacecraft. The large-scale cloud patterns are arranged such that a horizontal Y pattern can be discerned. Such a pattern had previously been identified in much lower resolution telescopic observations from Earth. The mottled small-scale features in the center and left of center in the image are believed to represent convection cells driven by the Sun's heat.

Polar Region of Venus

When Pioneer arrived at Venus it found both poles covered by bright cloud caps, a phenomenon observed on one or both poles several times during Earth-based observations in the last two decades. The Cloud Photopolarimeter had identified the "cloud" caps as being a thick blanket of small haze particles, about 0.25 μm in radius. Views of the polar cap haze are shown.

The equatorward edge of the bright polar cap is broken by a series of parallel dark bands (fig. 6-30(k)).

Bright streamers of haze particles extend from the polar cap toward lower latitudes (fig. 6-30(ℓ)).

Polar Caps Identified by Polarimetry

Sunlight becomes polarized when it is reflected by clouds. The nature of the polarization can be used to obtain information about the physical properties of the cloud particles. Studies of ground-based polarization measurements of Venus previously revealed that the main cloud deck is composed of spherical sulfuric acid droplets 1 μm (10^{-4} cm) in radius.

The droplets in the main sulfuric-acid cloud deck produce positive polarization at ultraviolet wavelengths, as observed in the center of the disk in the Pioneer Venus polarization map (fig. 6-30(m)). This map also indicates anomalous regions of negative polarization near both poles, with the location corresponding to the bright polar caps in figure 6-30(n), which was acquired just 5 hr before the polarization map. The polarization of the polar caps indicates the presence there of a thick haze of very small particles (0.25 μm in radius) overlying the main clous layer. Except for effects of their small size, the polar properties similar to those of the droplets in the main cloud, suggesting that the haze may also be composed of sulfuric acid.

The polar haze began to partially disappear in mid-1979. The number of haze particles above each square centimeter of the main cloud deck, which was about 3×10^8 (300 million) in January and February, decreased to less than half of that over a period of several months. Continued observations during the extended Pioneer Venus mission will be used to study the cloud and haze variations, and their possible relationship with long term changes of the atmospheric dynamics.

The nature of these aerosols and their relationship with climate on Venus are of interest for studies of the Earth's climate. Similar aerosols are produced in the Earth's stratosphere after large volcanic eruptions, and it is believed that they may cause significant climate effects.

Equatorial Region of Venus

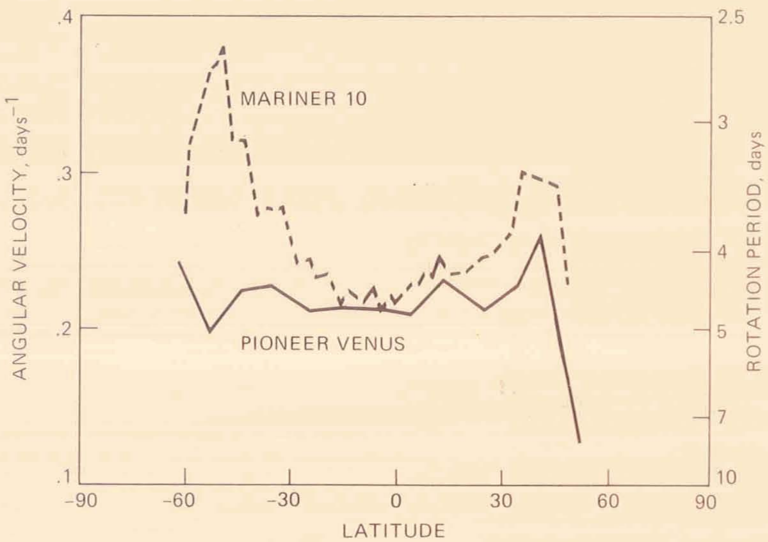
The cloudy atmosphere of Venus reveals a rich spectrum of dynamical phenomena, especially in the equatorial region. Several of the features are highlighted in these images.

(a) Bright-rimmed cells: The mottled cellular cloud patterns, particularly evident in the upper part of figure 6-30(o), are believed to be convection cells driven by the Sun's heat. These may have some analogy to tropical cumulus cloud clusters on Earth.

(b) Wave-trains: Series of short streaks cutting across background features, the almost vertical lines in the upper right of figure 6-30(p), are strongly suggestive of a wave phenomenon.

(c) Circumequatorial belts: Bright lines parallel to the equator are vaguely visible in the upper left of figure 6-30(q), where they stretch several thousand kilometers from the limb across the disk.

Image 190 – February 10, 1979 (a)



(b)

Figure 6-30. Imaging and polarimetry taken from Pioneer Venus orbiter.

Image 1 – December 5, 1978

(c)

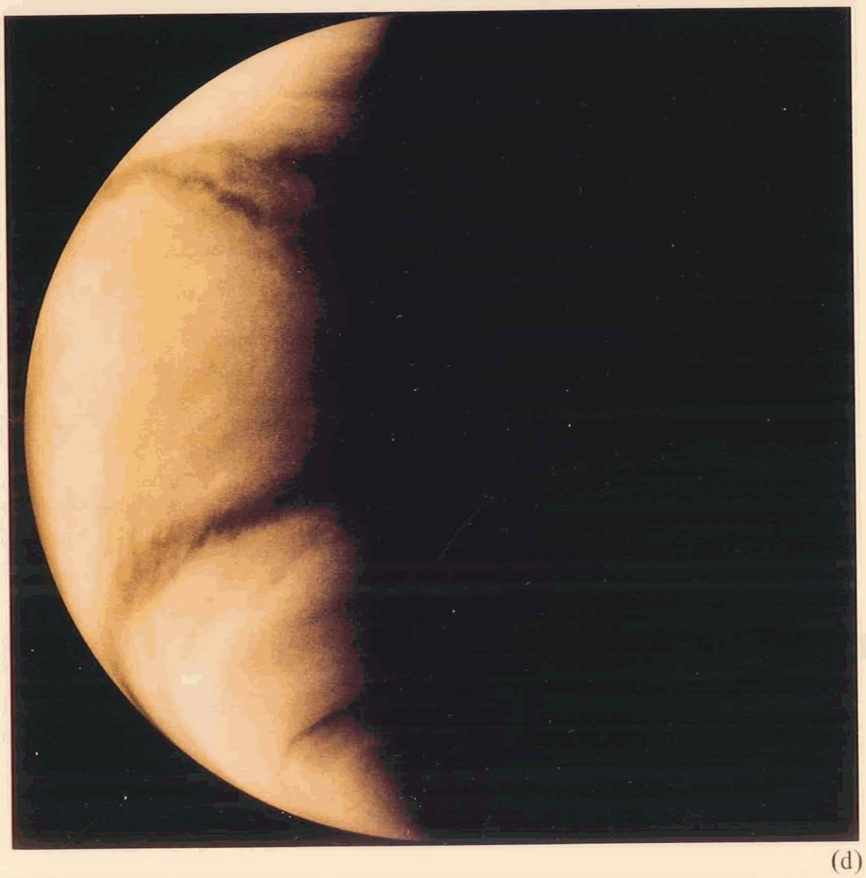


Image 38 – December 25, 1978

(d)

Figure 6-30 Continued.

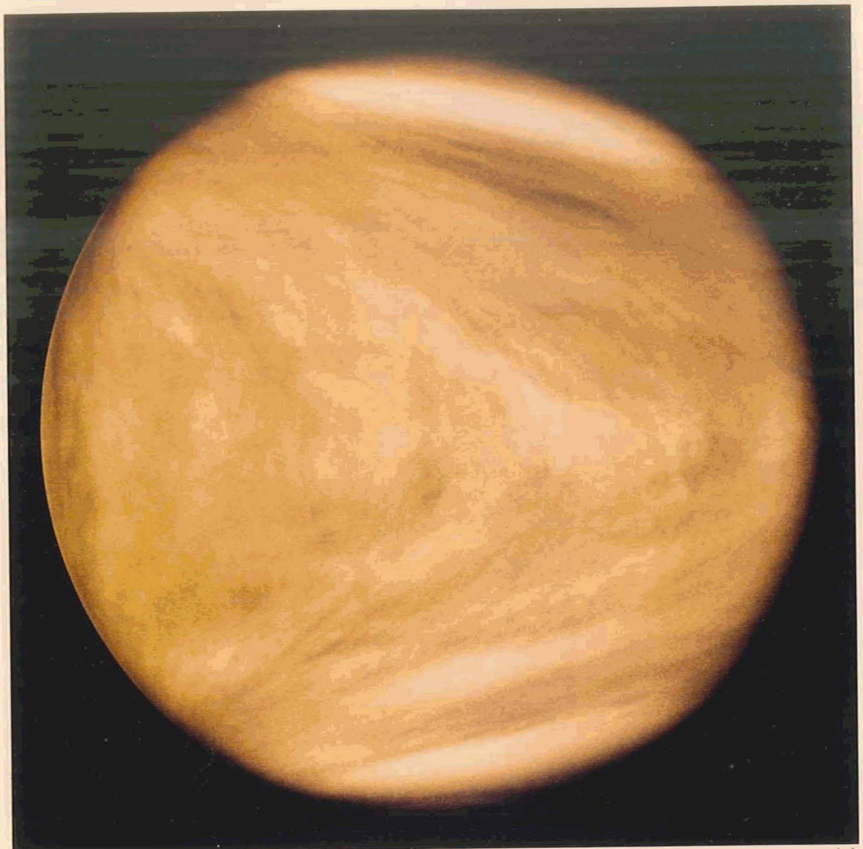


Image 187 – February 9, 1979

(e)

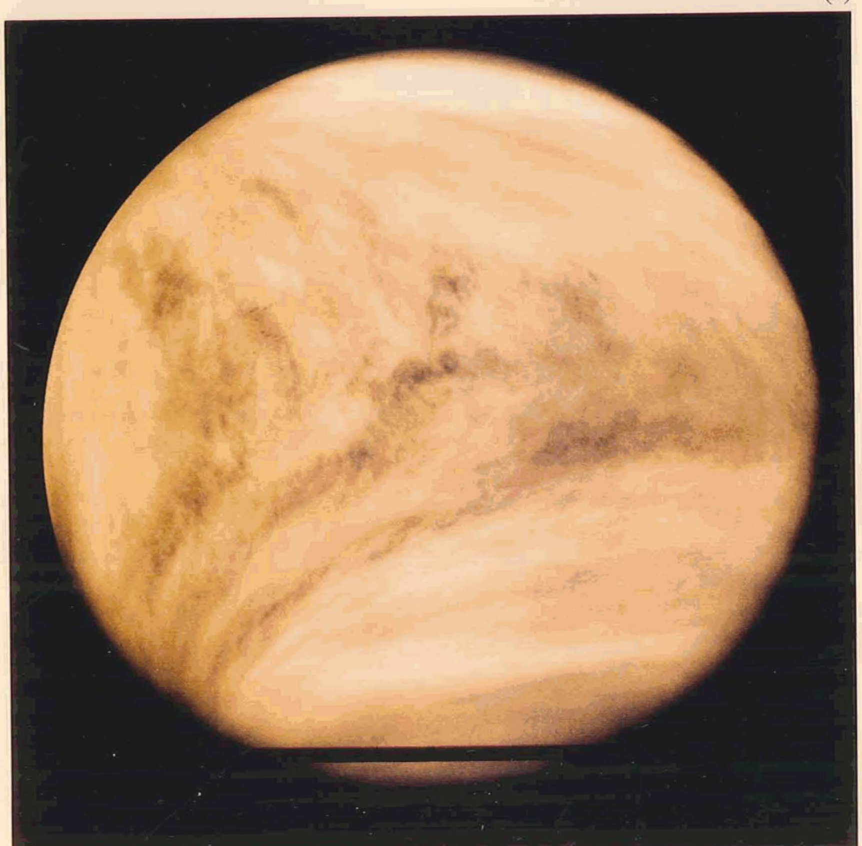
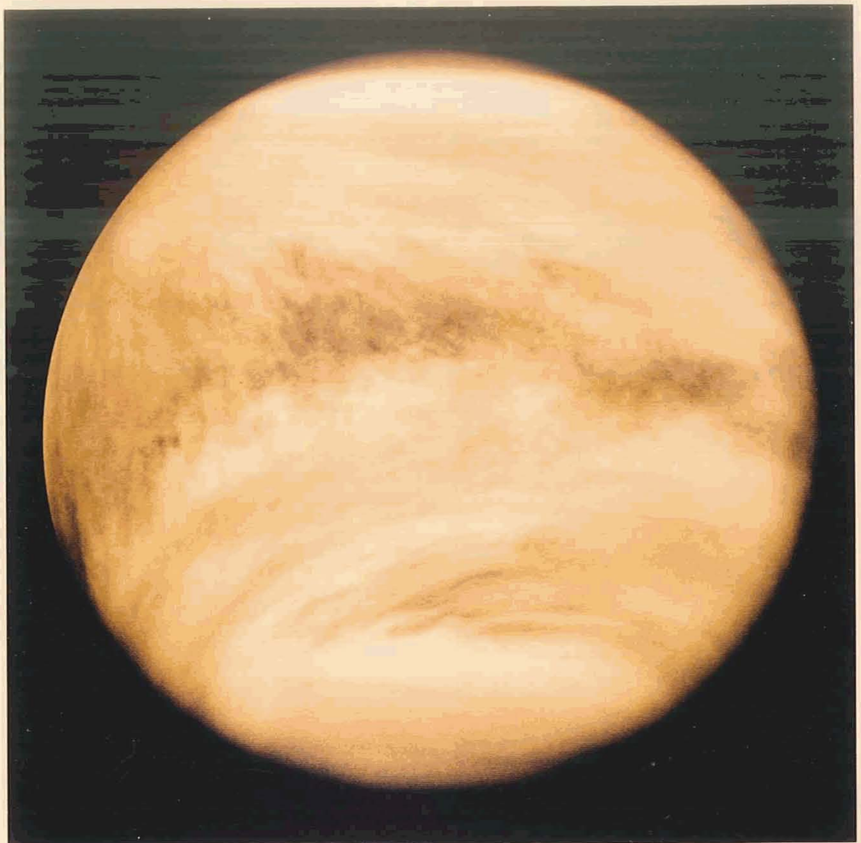


Image 202 – February 15, 1979

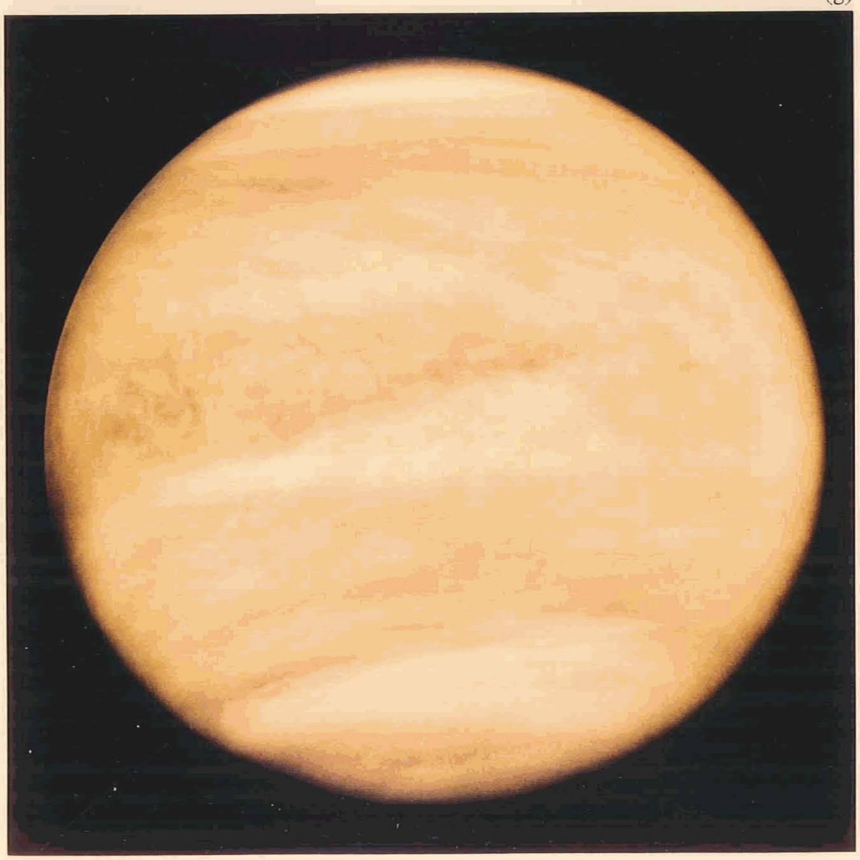
(f)

Figure 6-30. Continued.



(g)

Image 204 – February 16, 1979



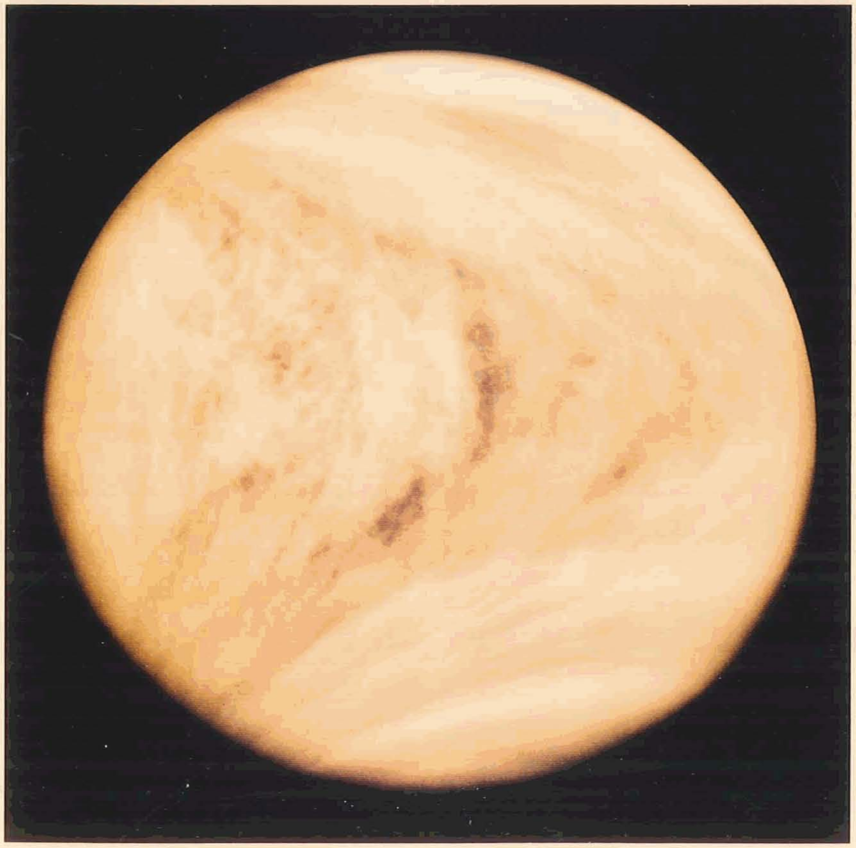
(h)

Image 208 – February 17, 1979

Figure 6-30. Continued.

(i)

Image 212 – February 18, 1979



(j)

Image 216 – February 19, 1979

Figure 6-30. Continued.

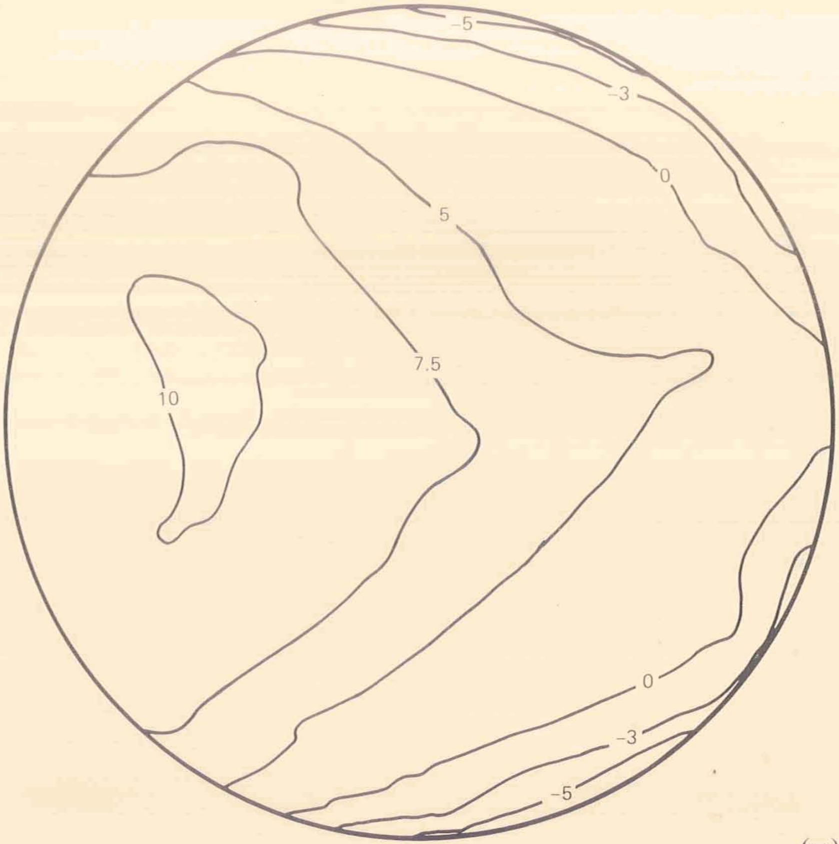
(k)

Image 117 – January 23, 1979

(ℓ)

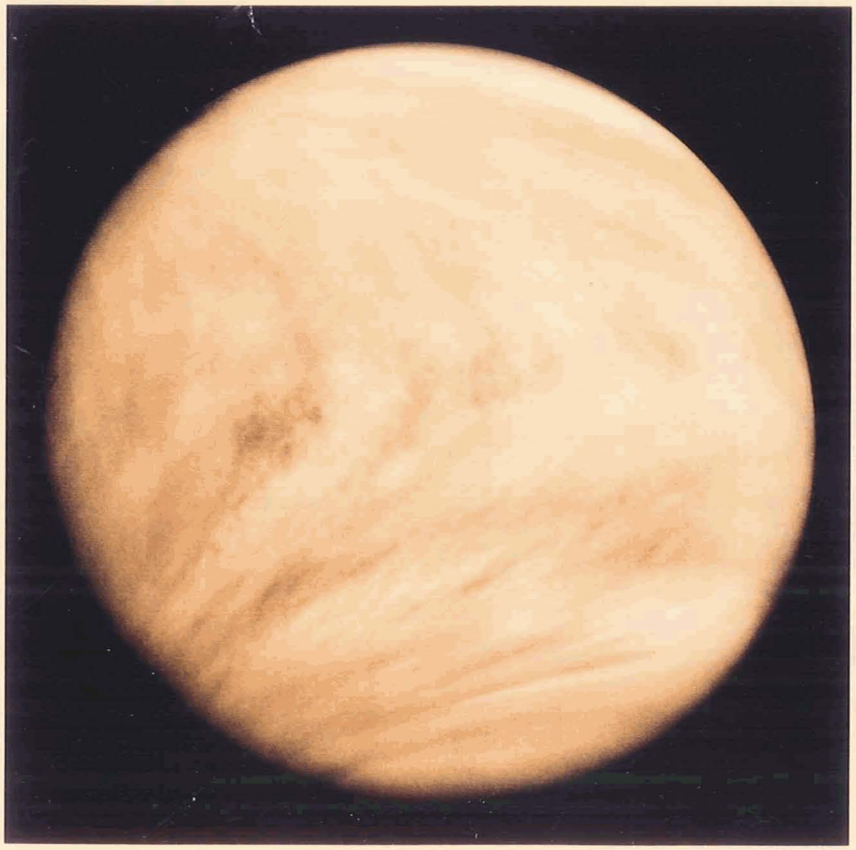
Image 204 – February 16, 1979

Figure 6-30. Concluded.



(m)

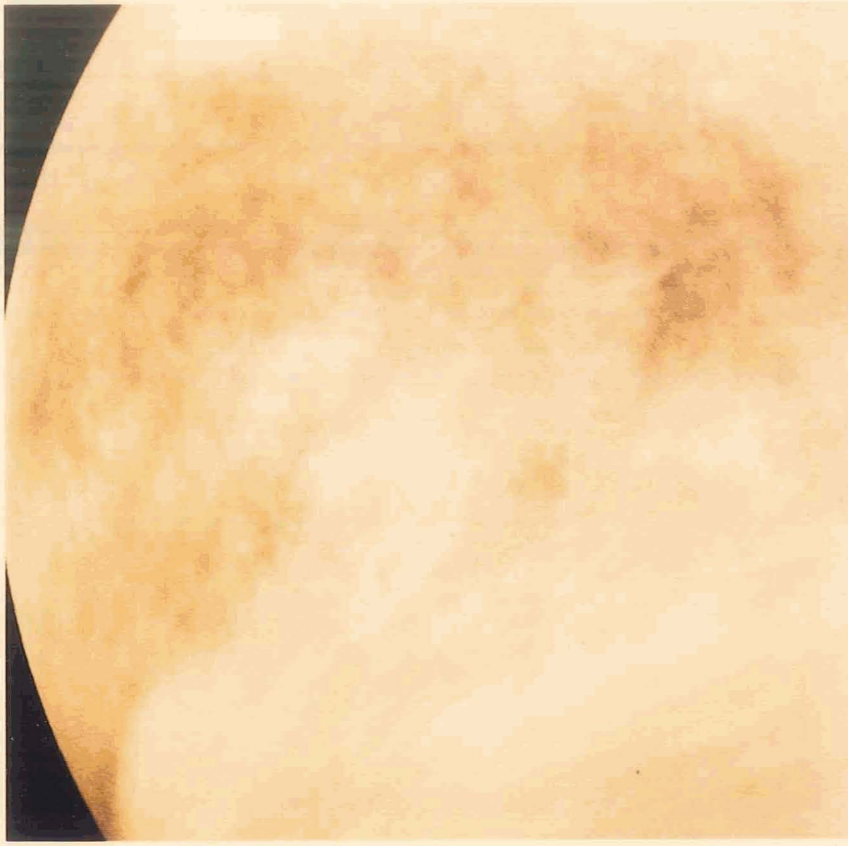
Polarimetry Map 136 – February 25, 1979



(n)

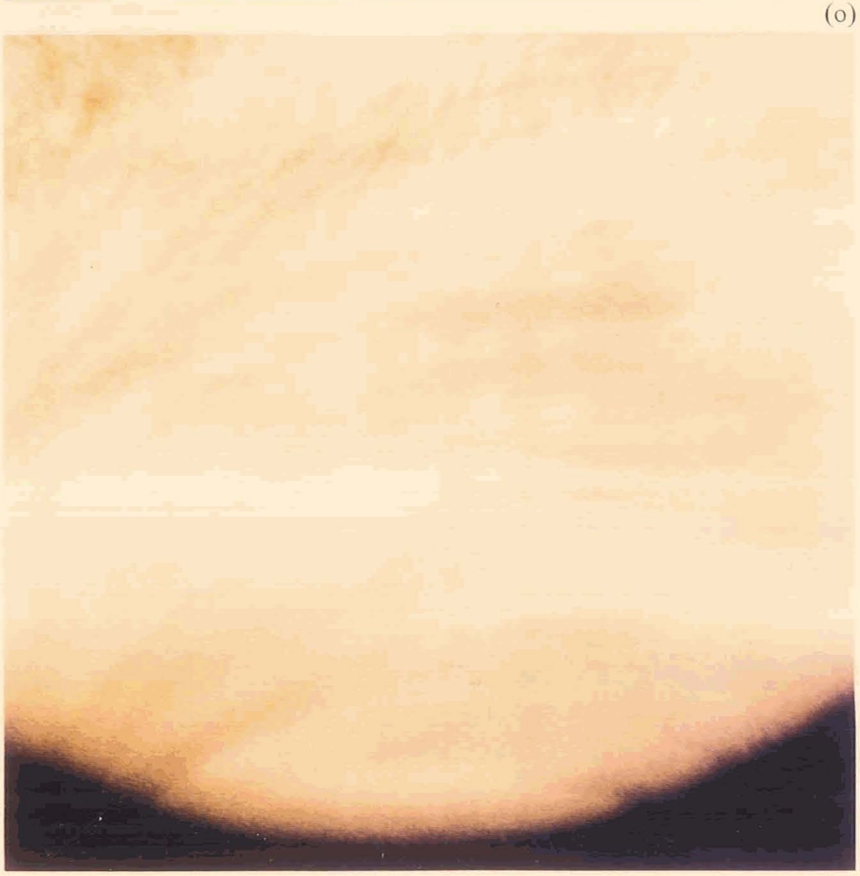
Image 235 – February 25, 1979

Figure 6-30. Continued.



(o)

Image 182 – February 8, 1979



(p)

Image 237 – February 26, 1979

Figure 6-30. Continued.

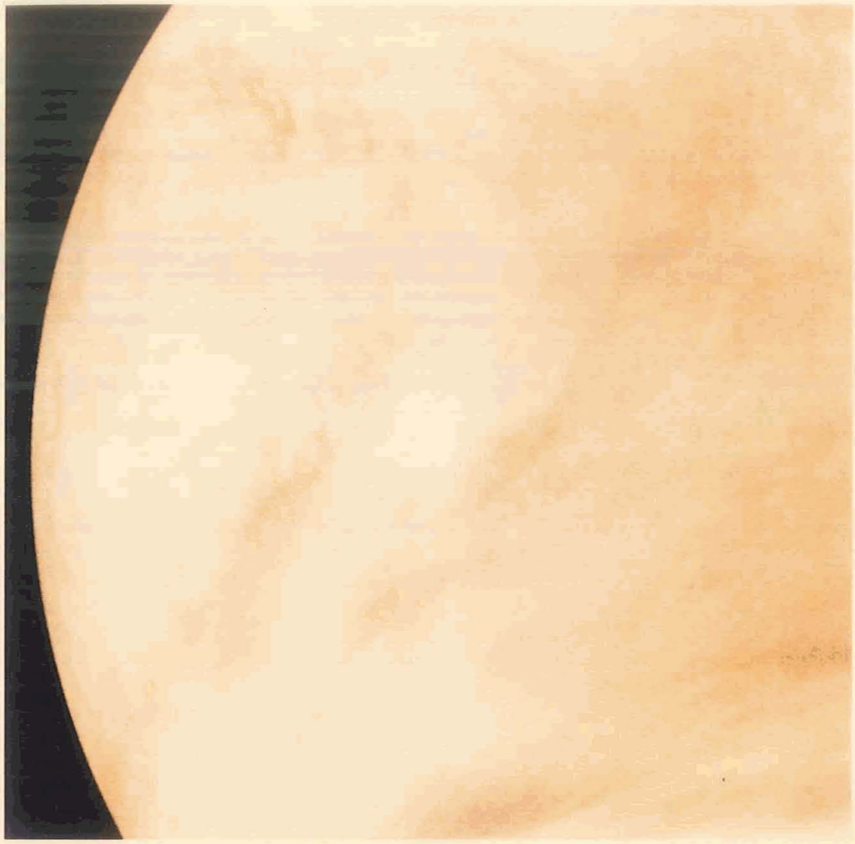


Image 98 – January 18, 1979

(q)

Figure 6-30. Concluded.

Summary of Major Results from Pioneer Venus

Highlights of the new Pioneer findings about Venus or confirmations of earlier observations include:

• Obtained radar altimetry for nearly all the surface of the planet, and many radar images; discovered volcanic and tectonic features such as rift valleys, mountains, continents, and volcanoes. Pioneer found that there is a unimodal distribution of topography (quite unlike the bimodal distribution on Earth) and a dearth of elevated regions of continental size. Confirmed the existence of great troughs ("rift valleys"); however, no evidence was found for continuous ridge systems which are characteristic of the terrestrial plate tectonics system.

• Obtained measurements of the gravity field that, when combined with the radar altimetry results, showed that the interior behavior of Venus is more Earth-like than Mars or the Moon. However, there is a great difference between Venus and Earth in that on Venus there is a strong positive correlation of gravity with topography at all wavelengths.

• Determined the structure of the clouds globally and vertically – their layers, distribution of particles of different sizes, composition, and optical properties – confirming results from earlier Soviet probes.

• Made refined measurements of composition and abundances of major, minor, and noble gas species in the lower, mixed atmosphere, and in the upper, diffusively separated atmosphere.

• Discovered much structure in the polar regions of the atmosphere, thereby clarifying our understanding of the circulation pattern in those regions.

• Discovered that sulfur dioxide is an important absorber of ultraviolet radiation at wavelengths below 3200 Å, but that another absorber must be present to account for absorption at longer wavelengths.

• Detected radio signals that are thought to originate from lightning discharges in the clouds of Venus, thereby confirming some observations made by Venera probes.

• Obtained much new data concerning the atmospheric state properties (temperature, pressure, density) globally and vertically from the surface through the clouds and into the upper atmosphere.

• Obtained measurements of vertical profiles of wind velocities at four probe locations, and global wind measurements at the cloud tops.

• Determined the sinks for solar radiation and the sources and sinks of infrared radiation in the lower atmosphere and clouds at four locations characterizing daytime, nighttime, low latitude, and high latitude conditions.

• Discovered that the high atmosphere well above the cloud tops is much colder at night than in the daytime.

• Integrated these observations into a conceptual general meteorological model for comparative meteorological studies.

• Mapped the airglow on the dark side of Venus.

• Provided strong support for a greenhouse effect which, coupled with global dynamics, explains the high surface temperature.

• Determined the global characteristics of the ionosphere – its ion composition, temperature, flows, electron concentration and temperature, modification of ionospheric characteristics by input from the solar wind, and the production and maintenance of a nightside ionosphere.

• Determined the nature of the solar-wind interaction with the planet, including temporal and spatial studies of the location of the bow shock and ionopause, and particle and energy input to the atmosphere.

• Confirmed that Venus has little if any intrinsic magnetic field, and set a very low upper limit on a magnetic moment of the planet.

7
Results of Soviet Studies of Venus

R. Z. Sagdeev, V. I. Moroz, and
T. Breus

VENUS, THE PLANET nearest Earth, has been of significant interest in the Soviet space program – the largest number of unmanned space probes have been sent there. This keen interest in Venus was prompted by its many features that are similar to our own planet. The mass and geometry of the two planets are indeed similar, and they receive roughly equal energy from the Sun.

Some 20 years ago, it was thought that Earth's "sister planet" was its exact replica, with but a slightly warmer surface, a hydrosphere, and, possibly, a biosphere. Yet, as revealed by the first studies, there are drastic differences in climate: the temperature on the Venusian surface averages 735 K (~480°C), whereas the average temperature of the Earth's surface is 15°C. Furthermore, the entire surface of Venus, irrespective of latitude or time of day, seems to be uniformly heated, distinctly different from conditions on Earth.

All these unique features of the Venusian atmosphere, however, have been established only in the era of space exploration.

Soviet Spacecraft

In the second half of the 1950s, radio telescopes yielded data about the high temperature of the Venusian surface; so unexpected was this information that not all scientists believed it. Hence, the first Soviet interplanetary automatic stations sent to Venus had "surface phase state" sensors onboard to determine whether the vehicle had landed on a solid surface or was being rocked by ocean waves.

On October 18, 1967, Venera 4, the first spacecraft to descend into the Venusian atmosphere by use of a parachute, had no such sensor onboard. However, for this mission, the spacecraft had to be protected against the extremely high temperatures encountered. The true quantitative characteristics of these conditions, however, were determined only from measurements made by Venera 4 and subsequent Venera spacecraft – Venera 5 and Venera 6 (1969) and Venera 7 and Venera 8 (1972) (see table 7-1). These probes yielded detailed information about variations in temperature, pressure, and density of the Venusian atmosphere with altitude. Venera 7 and Venera 8 accomplished soft landings and transmitted signals directly from the planet's hot surface. Instruments aboard Venera 8 took the first scattered solar radiation measurements and furnished some information about the composition of the soil (e.g., uranium, potassium, and thorium).

Unexpected results were also obtained in plasma and magnetic measurements by Venera 4 and Venera 6. It was found that there is a shock wave near Venus like that near Earth. The shock front of Venus, however, is much closer to the surface than Earth's shock is to its surface.

Before the spaceflight to Venus, it was hypothesized that the number density of charged particles in the ionosphere of Venus could exceed by three orders of magnitude that in the main peak of the terrestrial ionosphere. Ion number densities measured by Venera 4 during its descent on the nightside of Venus and the data about electron number densities on the nightside and dayside of the ionosphere (provided by the radio-occultation observations of Mariner 5) did not confirm that suggestion. In the ionosphere of Venus, the number density of charged particles in the maximum was about the same as on Earth. Mariner 5 observed a distinct upper boundary of the dayside ionosphere at an altitude of 500 km: the electron number density decreased by two orders of magnitude within an altitude range of only 50 to 100 km. The boundary was similar to the plasmapause – the upper bound of the thermal plasma envelope of Earth – hence the name ionopause was given to the Venus phenomenon. However, the plasmapause of Earth is much farther from the surface of the planet, at about 20,000 km.

Interestingly, although large-scale features typical of solar wind flow around Venus and Earth are similar, the magnetic field first measured near the planet by Venera 4 seemed to be insignificant, only about 10 γ (i.e., 10^{-4} gauss) at an altitude of 200 km. The surface magnetic field in the equatorial region of Earth is about 50,000 γ. Until recently, the question has been discussed of the role of the intrinsic magnetic field of Venus in forming the pattern of the solar-wind flow around the planet.

Operating an automatic interplanetary probe in such a hot and dense

TABLE 7-1.– SOVIET SPACE VEHICLES THAT STUDIED VENUS, 1967 TO 1978

Space vehicle		Date		Landing site			Measurements
Name	Type	Launch	Approach	Latitude	Longitude	Solar angle, deg	
Venera 4	Descent module + flyby vehicle	12.06.67	18.10.67	19	38	-20[a]	*Descent module:* temperature, pressure, density, wind velocity; CO_2, N_2, H_2O content at altitudes of 55 to 25 km; ion number density in the ionosphere, magnetic field. *Flyby vehicle:* H_α – and OI/1300 Å – radiation in upper atmosphere; ion flux in region of solar-wind flow around planet; magnetic field.
Venera 5	Same as above	05.01.69	16.05.69	-3	18	-27	Temperature, pressure, wind velocity, CO_2, N_2, H_2O content at altitudes of 55 to 20 km.
Venera 6	Same as above	10.01.69	17.05.69	-5	23	-25	Same plasma measurements as on Venera 4.
Venera 7	Descent module (soft landing)	17.07.70	15.12.70	-5	351	-27	Temperature
Venera 8	Descent module (soft landing)	26.03.72	22.07.72	-10	335	+5	Temperature, pressure, solar scattered radiation (from 55 km to surface), wind velocity.
Venera 9	Descent module (soft landing) + artificial satel-	08.06.75	22.10.75	32	291	+54	*Descent module:* temperature, pressure, wind velocity; CO_2, N_2, H_2O content, solar scattered radiation (several filters), clouds (nephelometer), panoramic survey of surfaces *Satellite:* TV survey of clouds, IR radiometry, spectroscopy of the day- and night-side; photopolarimetry; energy spectra of ions and electrons, electron and ion number densities and temperatures, magnetic field in region of solar-wind interaction with planet; radio occultations.
Venera 10	Same as above	14.06.75	25.10.75	16	291	+62	Same as above
Venera 11	Descent module (soft landing) + flyby vehicle	09.09.78	25.12.78	-14	299	+73	*Descent module:* temperature, pressure, wind velocity composition (mass spectrometer); solar scattered radiation spectrum; nephelometer, thunderstorm activity *Flyby vehicle:* upper-atmosphere UV spectrum.
Venera 12	Descent module (soft landing) + flyby vehicle	12.09.78	21.12.78	-7	294	+70	Same as above; gas chromatograph and measurements of particle-composition of cloud layer.

[a]Minus sign denotes night landing (the Sun below the horizon). First generation vehicles landed at night (except Venera 8, which landed near the terminator); it was necessary since information was transmitted directly to Earth. Since Venera 9 information was relayed via the artificial satellite from the lander and the landing was made during the day this was widely used to study solar radiation propagation in the atmosphere (to check the greenhouse hypothesis).

atmosphere as on Venus is very difficult technologically. Nevertheless, in the 1960s, spacecraft for Venus research were designed by the team headed by the academician S. P. Korolev and then by G. N. Babakin, Corresponding Member, U.S.S.R. Academy of Sciences. America's Pioneer Venus was launched 11 years after Venera 4, almost simultaneously with the Venera 11 and Venera 12.

As is usually the case in science, however, the solution of some problems immediately gives rise to a number of new, more complicated ones. Spaceflights to Venus showed that climatic and atmospheric conditions of the planet, so similar to Earth in some physical parameters, are quite different generally from those on Earth. What are the reasons for these differences? Many important questions naturally arise. Can the climate and composition of Earth's atmosphere experience the same changes in the foreseeable future? If so, what would cause such a change: altered external conditions, environmental pollution, or something else? These questions are one of the reasons why many scientists throughout the world still consider the exploration of Venus a top-priority task.

Venus can be a natural "cosmic laboratory" for studies in comparative planetology. The value of such research becomes more apparent because it is inconceivable to realize experiments on such a scale under Earth conditions.

The atmosphere of any planet is a complex system with many interactions and feedbacks. Its composition, for instance, is determined by how and under what conditions the planet formed and by outgassing processes from its solid body, by reactions among gases in the atmosphere and between the gaseous and solid matter, by the structure of the upper atmosphere from which light gases escape into the interplanetary space, and so on. The character and rate of many processes in the atmosphere depend on its temperature which, in turn, depends on the composition of the atmosphere. The last circumstance is most essential for Venus. The gaseous and aerosol composition of the Venusian atmosphere is such that some solar radiation penetrates down to the surface. The opacity of the atmosphere is high, however, for infrared radiation. As a result, the surface temperature is high. The phenomenon, called the greenhouse effect, is much more conspicuous on Venus than on Earth. (On Earth, the greenhouse effect adds about 35°C to the surface temperature.)

A fuller understanding of what is taking place on Venus required sophisticated chemical analyses of the atmosphere, an exact knowledge of the altitudes and spectral regions where solar radiation is absorbed, of the nature of the clouds that prevent astronomers from seeing the lower layers of the atmosphere, and much else.

After plasma and magnetic measurements by the first-generation Venera probes, scientists were faced with many new problems. With theories and concepts existing at the time, it might be possible to find solutions to some of them, in particular, to explain a weak intrinsic magnetic field near Venus. For example, in accordance with the theories of how magnetic fields originate and are maintained near planets, with the theory of planetary dynamos, the planet, if it has an intrinsic magnetic field, must rotate rapidly enough and have a liquid-conducting core. Close values of mean densities of terrestrial planets were used as a basis for building similar models of their inner structure. The absence of an intrinsic field in the case of Venus could be attributed to its slow rotation (period of rotation of about 243 terrestrial days).

The presence of shock waves near Venus and Earth and the much weaker intrinsic magnetic field of Venus (compared to Earth's), however, immediately put forward a question of the character of that planet's interaction with the solar wind. What is the obstacle – one different from that near Earth – that retards the solar wind and forms a shock near Venus?

Indeed, Earth and its atmosphere and ionosphere are protected against the direct effect of the solar wind by a strong intrinsic magnetic field. However, for Venus, the solar wind could interact directly with its atmosphere and ionosphere, bringing about ionization, compression, and heating of the ionosphere and atmosphere. The solar wind – flowing around the conducting ionosphere of the planet, together with the interplanetary magnetic field – could induce electric currents in the ionosphere and thus produce induced magnetic fields. If these induced fields are sufficiently strong, they may brake the solar wind and form an induced magnetosphere, rather than an intrinsic one, near the planet.

All these assumptions rested on the observed similarities and differences in the pattern of the solar wind flowing around Venus and Earth, and they had to be verified. Much more complex and accurate measurements were needed.

To conduct more detailed experiments in the deep layers of the atmosphere of Venus, interplanetary probes had to be equipped with heavier and more sophisticated instruments. But, more importantly, the vast amount of data gathered by the instruments had to be transmitted back to Earth. Accordingly, the first-generation probes, which had not been intended to deal with such problems, were succeeded by Venera 9 and Venera 10, and later by Venera 11 and Venera 12. Whereas the earlier probes had entered the Venusian atmosphere in their entirety, the new Venera probes separated some time before landing into an orbiter and a lander. The former, depending on the mission profile and ballistics, either became an artificial satellite of Venus (Venera 9 and Venera 10) or flew past the planet at a certain altitude and entered an orbit around the Sun (Venera 11 and Venera 12). The landers entered the atmosphere (fig. 7-1). The orbiters carried instruments to study the planet by its radiation at various wavelengths,

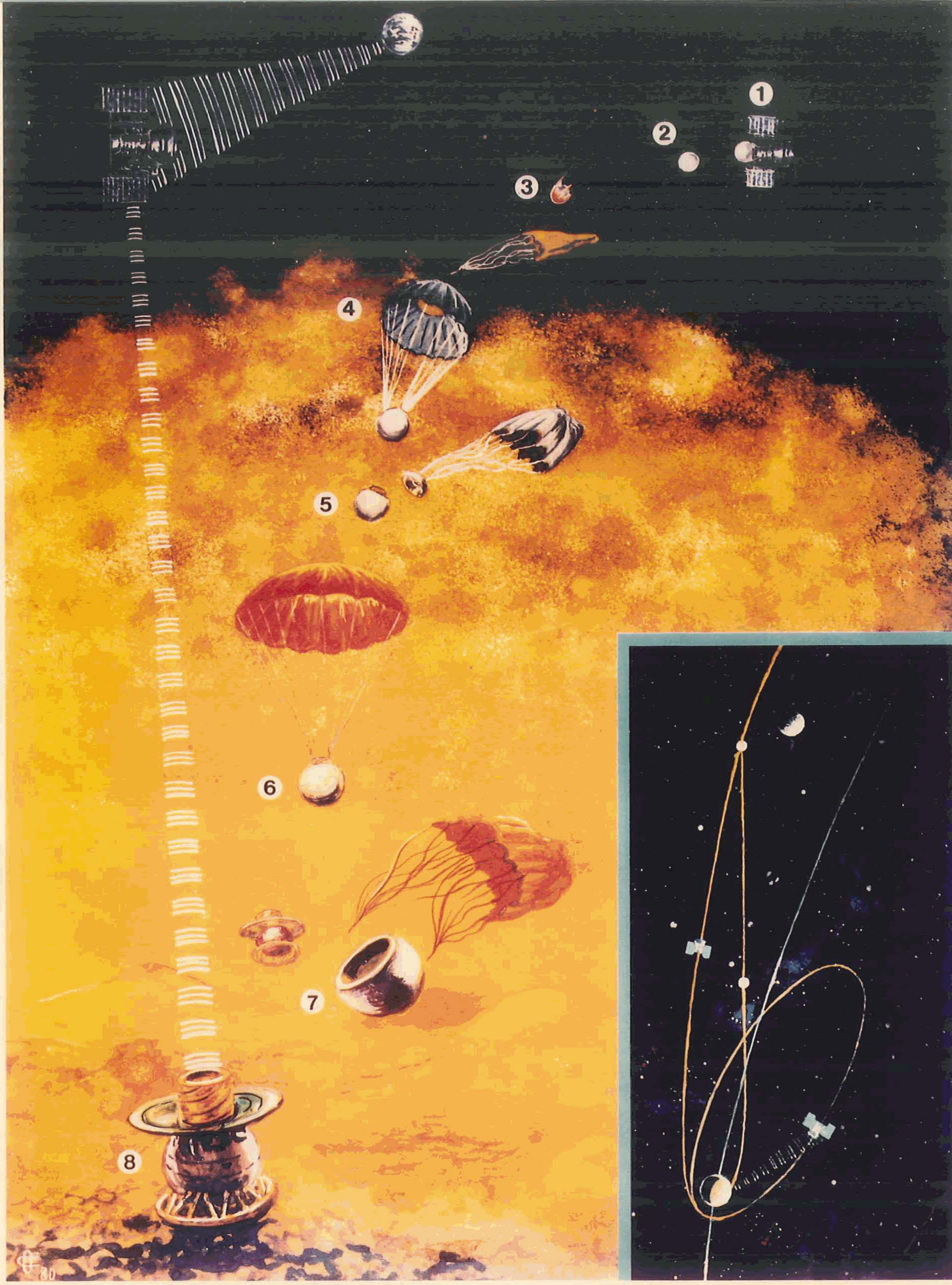


Figure 7-1. Landing scheme of the Soviet second-generation automatic spacecraft (Veneras 9, 10, 11, 12): 1 – interplanetary spacecraft on Venusian orbit; 2 – separation of descender and orbiter two days before the landing; 3 – entry into Venusian atmosphere; 4 – deployment of auxiliary and displacement parachutes; 5 – jettisoning of hatch; 6 – deployment of decelerating parachute at 66-62 km and beginning of telemetry data transmission; 7 – jettisoning of lower sector of thermal protection shell and jettisoning of decelerating parachute (height of about 48 km); 8 – landing and data transmission to Earth.

Figure 7-2. Panoramic view of the Venusian surface relayed by Venera 9 descent module. Numerous stone blocks with sharp edges are observed around Venera 9, a fact testifying to their comparatively young age. On the planet's surface at the landing site, much small-grained substance resembling dust or sand is visible. After impact, a dust cloud rose that registered on a photometer for a few minutes.

the interplanetary plasma and magnetic fields, and to conduct astronomical observations.

In 1975, Venera 9 and Venera 10 splendidly demonstrated the capabilities of a new generation of spacecraft. For the first time, a panoramic view of another planet was transmitted from its surface to Earth (fig. 7-2). A series of investigations was concerned with the optical properties of the atmosphere: the general features of the cloud structure were determined (a layer about 20 km thick, with a lower boundary at an altitude of 50 km); radiation fluxes were measured in several spectral regions, and the water vapor content was derived from the intensity of one of the absorption bands. Important results were obtained with scientific equipment onboard the orbital vehicles, the first artificial satellites of Venus.

A series of plasma and magnetic measurements and observations of radio occultations (orbiters Venera 9 and Venera 10) made it possible to study in detail the pattern of solar-wind flow around the planet, to discover a plasma-magnetic tail of the planet, to investigate the character of the magnetic field measured and the properties of the dayside and nightside ionosphere; and to determine sources of atmospheric ionization in the deep optical umbra of the planet.

The analyses of Venera 9 and Venera 10 experimental data suggested new problems. But expertise in designing sophisticated scientific equipment, capable of operating under very difficult conditions (enormous decelerations, high temperatures and pressures), allowed these problems to be solved, in many aspects, on the Venera 11 and Venera 12 probes that reached Venus late in 1978. The erection of a huge (70 m diameter) parabolic reflector at the Deep Space Communication Center greatly improved data reception from the landers.

Recent scientific results from the new generation Soviet Venera probes are discussed below. Table 7-1 summarizes the launch dates, landing coordinates of descent modules, and other data.

Chemical Composition of the Venusian Atmosphere

Until 1967, once again by virtue of the planet's similarity to Earth, it was assumed that the main chemical constituent of the atmosphere of Venus was nitrogen. Besides nitrogen, scientists expected to find a small amount (1 to 10%) of carbon dioxide, whose absorption bands had been observed as far back as the 1930s. But even the simple chemical sensors carried by the first Venera probes proved the very opposite to be the case: the most abundant gas in the atmosphere is carbon dioxide (96.5% according to the latest estimates), whereas nitrogen makes up just over 3%. It was impossible at the time to gain any reliable information about the content of many small constituents of the atmosphere – water vapor, oxygen, carbon monoxide, sulfur compounds, or noble gases. These constituents play a tremendous part in the life of the atmosphere – they absorb solar and thermal radiation (the greenhouse effect), participate in chemical reactions, condense to form cloud layer particles, etc.

The abundance of noble gases and their isotopes is of particular interest. Their isotopes may be divided into two groups: radiogenic isotopes (formed by the radioactive decay of elements) and primordial isotopes (which have survived since the formation of the Solar System's planets some 4.5 billion years ago). From the absolute and relative content of primordial isotopes, it is possible to gain some insight into the conditions in which the protoplanetary nebula at one time gave rise to the planets and into the process of their formation. This will be shown further with argon isotopes in the Venusian atmosphere as an example.

For the fine chemical analysis of the composition of atmospheric gases, the Soviet investigators used a mass spectrometer, a gas chromatograph, and an optical spectrometer. The mass spectrometer takes microscopically small samples of gases (the pressure in the instrument is the same as in an electron tube), ionizes them, and sorts ions, according to their mass, with high frequency electric field. The mass

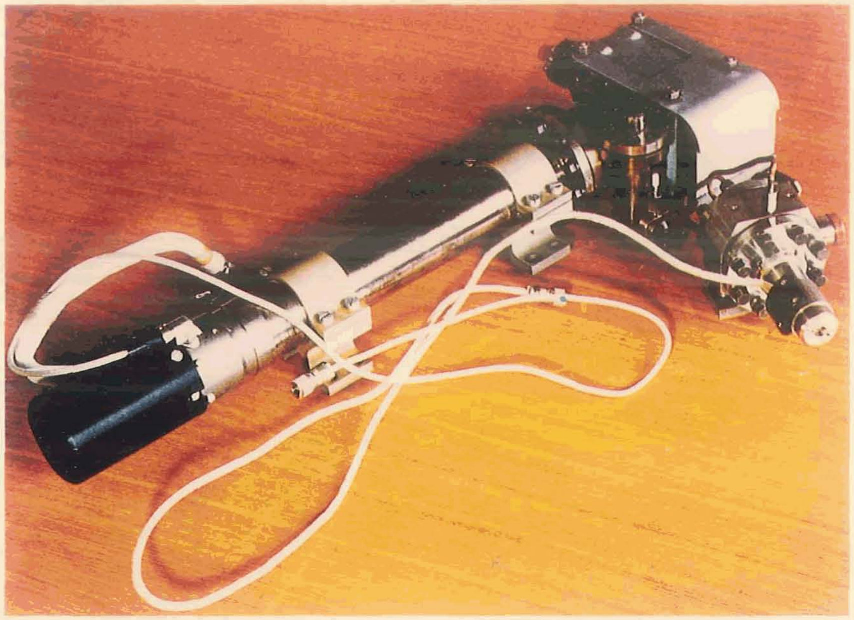


Figure 7-3. Mass spectrometer (general view).

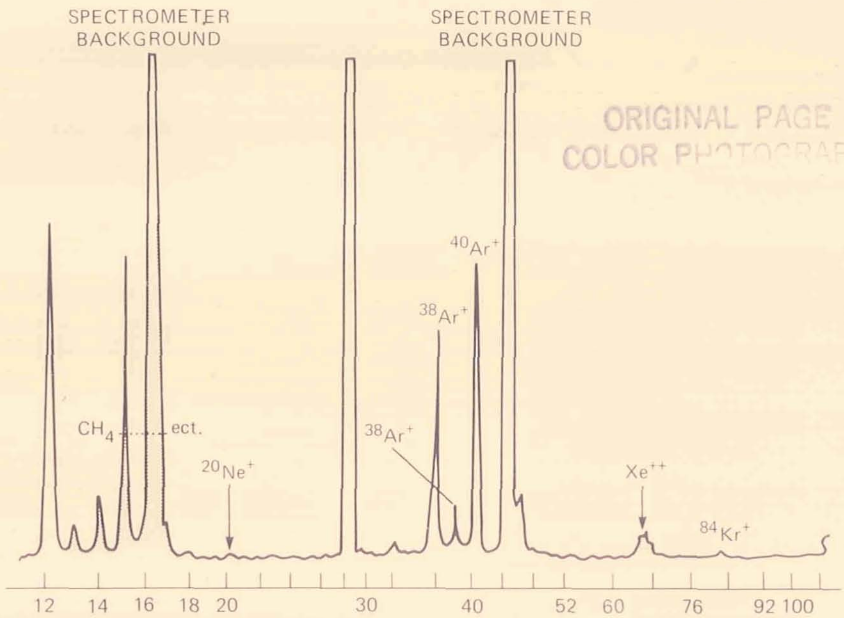


Figure 7-4. Averaged mass spectrum (the sum of seven separate spectra) obtained in the regime of noble gas analysis.

spectrometer experiment was conducted by a group of scientists headed by Vadim Istomin (Institute of Space Research, U.S.S.R. Academy of Sciences). The instruments (fig. 7-3) carried by both vehicles were switched on at an altitude of about 24 km and operated until touchdown. These instruments scanned the mass range from 10 to 105 atomic units in 7 sec; the gas sampling time was under 5×10^{-3} sec, and the sampling rate was once every 3 min. A total of 22 samples were taken, and about 200 mass spectra were transmitted to Earth. The mass spectrum shown in figure 7-4 is an average over 7 of 200 mass spectra.

The mass spectra exhibit peaks corresponding to the molecules CO_2 and N_2, the atoms ^{12}C, ^{13}C, ^{16}O, ^{18}O, and ^{14}N (produced by the decomposition of the CO_2 and N_2 molecules inside the instrument), and the three noble gases, neon, argon, and krypton. The quantitative data are shown in table 7-2. The presence of krypton (about $6.5 \times 10^{-5}\%$) is noteworthy. The instruments of the American Pioneer Venus probe detected no krypton.

In Istomin's experiment, every single record of the mass spectrum shows krypton. Estimates averaging over tens of records showed that the relative abundances of the main krypton isotopes with atomic weights 84, 86, 83, and 82 are comparable to those on Earth. The argon results were extremely surprising. The radiogenic isotope ^{40}Ar and the primordial ^{36}Ar are present in the atmosphere of Venus in equal amounts, whereas on Earth, ^{40}Ar is 300 times more abundant than ^{36}Ar.

A full explanation of this anomaly is a matter for the future, but an elegant hypothesis has been proposed by M. Izakov (Institute of Space Research). It is assumed that Venus derived the greater part of its atmosphere from the protoplanetary nebula. Earth (and Mars) captured relatively little gaseous material from it, whereas most of their atmospheres were outgassed from their interiors. According to this hypothesis, the meteorite and asteroid accumulation process, which gave rise to all the planets 4.5 billion years ago, proceeded more rapidly for Venus since it is closer to the Sun and the meteorite bodies involved were denser there. The capture of gas was also more rapid. Up to now, it has been considered that the atmospheres of the Earth-group planets (Venus, Earth, and Mars) are of secondary origin, formed by degassing from the interior. The ^{36}Ar anomaly for Venus has, however, cast doubt on this.

TABLE 7-2.– CHEMICAL COMPOSITION OF THE ATMOSPHERES OF VENUS AND EARTH

Gas	Content by volume, %	
	Venus	Earth
Carbon dioxide	96.5	3.2×10^{-2}
Nitrogen	3.5	78.1
Water vapor	2×10^{-3} [a]	0.1
Oxygen	10^{-3}	21.0
Carbon monoxide	3×10^{-3}	10^{-4}
Sulfur dioxide	1.5×10^{-2} [b]	10^{-4}
Hydrogen chloride	4×10^{-5} [c]	---
Hydrogen fluoride	5×10^{-7} [c]	---
Methane	10^{-4}	1.8×10^{-4}
Ammonia	2×10^{-4}	---
Sulfur	2×10^{-6} [d]	---
Noble gases:		
Helium	2×10^{-3}	5×10^{-4}
Neon	1.3×10	1.8×10^{-3}
Argon	1.5×10^{-2}	0.9
Krypton	6.5×10^{-5}	1.1×10^{-4}
Mean molecular weight	43.5	28.97

[a] Mixing ratio near surface. At an altitude of 50 km, it is an order of magnitude higher; at 70 km, an order of magnitude less.

[b] Mixing ratio below 20 km; at 70 km, it is four orders of magnitude less.

[c] Mixing ratio above 60 km (only the data for ground-based spectroscopy available).

[d] Gaseous sulfur is meant (molecules S_2, S_3, S_4, S_5, S_6, S_7, and S_8); estimate refers to altitudes below 40 km.

The Venusian atmosphere was also analyzed chemically by the Sigma gas chromatograph (fig. 7-5). (This experiment was supervised by Lev Mukhin of the Institute of Space Research.) Gas chromatographic analysis is based on the different degrees of adsorption of various gases by porous substances. The heart of the gas chromatograph is a chromatographic column filled with a specific sorbent through which a sample of atmospheric gas is pumped. There the mixture is separated into individual components. Various constituents of the mixture leave the column one by one and are recorded by a special ionization detector.

A chromatograph was also installed onboard the Pioneer Venus large probe (this experiment was supervised by V. Oyama at Ames Research Center). Oyama (1979) reported that no carbon monoxide was found, but the Venusian atmosphere contained a large amount of molecular oxygen (exceeding the upper limit obtained in the Soviet experiment). Oyama later reported (1980) that he had misidentified the relevant chromatographic peaks and the missing carbon monoxide was finally found. Oyama's data revealed another aspect that has not been explained: he discovered relatively large amounts of water vapor – approximately 0.5% at an altitude of 44 km and 0.1% at 24 km.

Water is known to absorb light in several spectral bands, some of which (7200, 8200, and 9500 Å) are quite distinct in the spectra obtained by means of the optical spectrophotometer (fig. 7-6) onboard the Venera 11 and Venera 12 descenders. (This experiment was supervised by V. Moroz.) From the intensity of the bands, it was possible to determine the water content in the Venusian atmosphere at different altitudes. This quantity proved very small – $2 \times 10^{-3}\%$ near the surface and $2 \times 10^{-2}\%$ at 50 km (Oyama's experiments had yielded a quantity several orders of magnitude greater).

Parallel measurements with a chromatograph and a mass spectrometer provided independent control of the results. The Venera 12 chromatograph did not detect water vapor. From this it follows that at an altitude below 24 km the water vapor content is below 0.01%. The Venera 11 and Venera 12 mass spectrometers registered a slight excess in the ^{16}O mass peak as compared with ^{18}O; if the $^{18}O/^{16}O$ ratio is assumed exactly equal to Earth's, note that ^{18}O and ^{16}O are formed in the instrument from CO_2. If this excess is attributed to the H_2O contribution (the molecular weight of water is likewise 18), the water vapor abundance correlates reasonably well with the optical measurements.

It could be assumed that this quantity varies from site to site, but there is a simple way to verify this. The height dependence of temperature obtained by the large probe of Pioneer Venus should be compared with infrared radiation fluxes measured by the same vehicle. This comparison would make it possible to calculate the mean absorption coefficient for thermal planetary radiation (into which the diffuse solar light penetrating deep in the atmosphere is transformed). This coefficient depends strongly on the concentration of water vapor in the atmosphere. The calculated water vapor concentration corresponds closely with the optical measurements.

The total amount of water vapor in the Venusian atmosphere appears to be "disastrously" small. If the planet's entire water vapor ($2 \times 10^{-3}\%$) were condensed, it would form a layer of liquid no more than 1 cm thick. Obviously, there can be no seas, oceans, and liquid water on the surface of Venus – the temperature is too great for that. All of the water on Venus is concentrated either in its crust or in its atmosphere. This is yet another anomaly, no less odd than the $^{36}Ar/^{40}Ar$ ratio.

There is nothing extraordinary about the high carbon dioxide concentration in the atmosphere. Almost all of Earth's carbon dioxide is bound up in carbonates, whereas all of the carbon dioxide on Venus – because of the high temperature and absence of liquid water – is in the atmosphere.

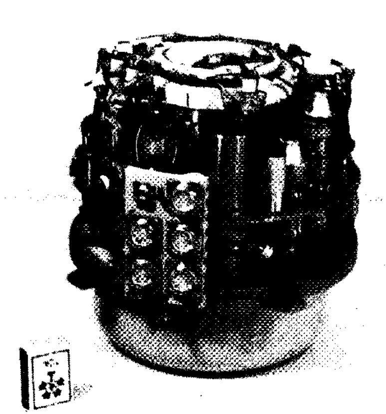


Figure 7-5. Venera 11 and Venera 12 gas chromatograph.

The total amounts of carbon dioxide on both planets are roughly equal. But the concentration of water on Venus presents a problem. Three assumptions are possible: (1) Venus was formed with less water; (2) at the early stages of evolution, the water vapor dissociated, hydrogen escaped into the interplanetary space, and oxygen vanished through chemical reactions; and (3) the water is bound up in minerals (where there are rocks that retain water very well at high temperatures).

Solar Radiation and Clouds in the Venusian Atmosphere

Both the Venera 11 and Venera 12 landers carried a spectrophotometer. From an altitude of 65 km until touchdown on Venus, it registered, for the first time, the daylight sky spectrum and the angular distribution of the brightness at 10-sec intervals. These measurements showed that a large amount of solar radiation reaches the planet's surface. Significantly, this is scattered rather than direct sunlight. An observer could not see the Sun on the surface of Venus nor at an altitude of 55 km since the cloud cover at 60 to 70 km scatters the solar radiation. But in terms of energy, it is unimportant what sort of radiation penetrates the atmosphere of Venus – direct or scattered. An evaluation of the solar energy reaching the surface (3%) and the thermal radiation of the planet confirmed the existence of a pronounced greenhouse effect, resulting in high temperatures in the deep layers of the atmosphere and at the Venusian surface. The hypothesis put forward by Carl Sagan as far back as 1962 has thus been confirmed.

According to Venera 11 and Venera 12 data, the energy distribution in the scattered sunlight spectrum changes as the probe penetrates deeper into the atmosphere. Just as on Earth, the effect results from aerosol scattering of light by cloud particles and from Rayleigh scattering by carbon dioxide and nitrogen molecules. Also, light absorption in ultraviolet which probably belongs to gaseous sulfur molecules was detected.

There are several layers of clouds in the Venusian atmosphere at altitudes from 50 to 70 km. Their boundaries are distinct in the curves showing the decrease in scattered sunlight intensity with the descent of the probe (fig. 7-7).

Ground-based observations fix approximately the position of the upper boundary of the cloud cover, while the lower boundary was first observed by the Venera 9 and Venera 10 nephelometers and photometers.

The Venera 9 and Venera 10 nephelometer experiments (M. Marov, Institute of Applied Mathematics, U.S.S.R. Academy of Sciences) had made it possible not only to determine the lower boundary of the cloud cover, but also to estimate the concentration of cloud particles, their sizes, and the refractive index of the atmosphere. To a limited extent, these observations were repeated on the

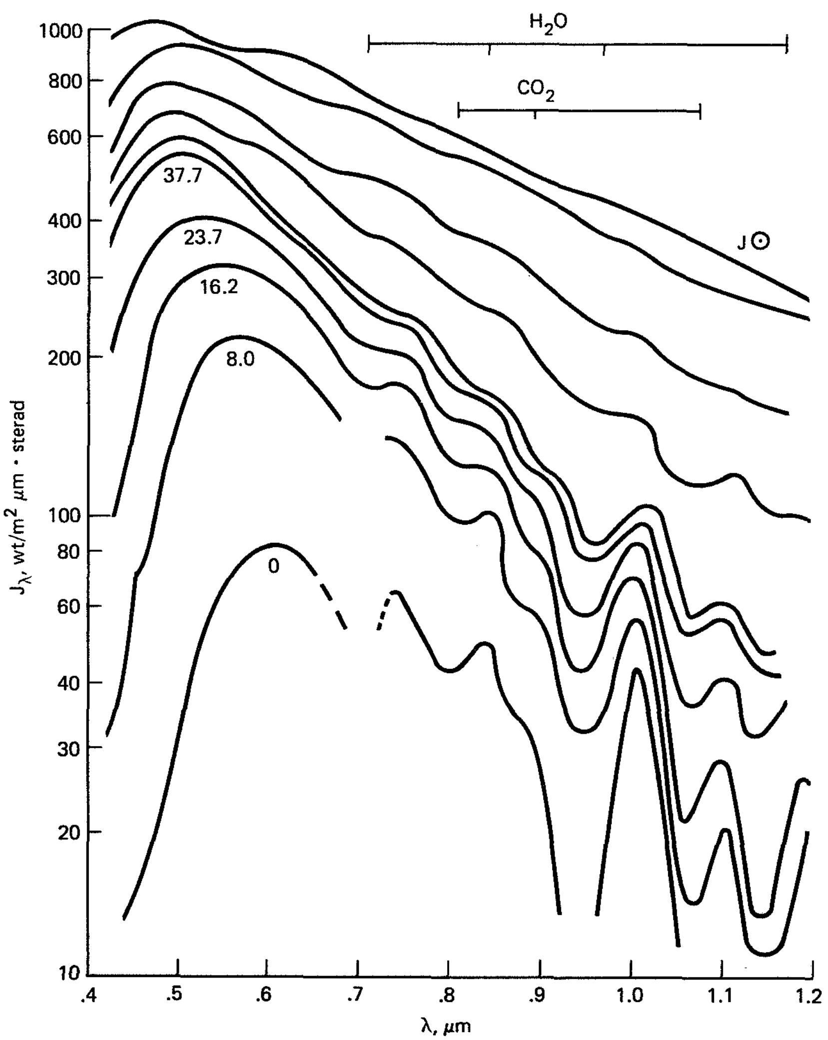


Figure 7-6. Scattered solar radiation spectrum in deep layers of the Venusian atmosphere obtained by the Venera 11 descent module. Figures along the curves indicate altitudes (in km). Note how the lines for water (H_2O) and carbon dioxide (CO_2) become more dense as the probe descends. These spectra proved to be a very good source of data on the water vapor content in the Venusian atmosphere.

Venera 11 mission. The Pioneer Venus large probe enabled R. Knollenberg and D. Hunten to study in great detail the particle-size distribution.

The clouds of Venus are relatively transparent. The meteorological visibility inside the clouds is several kilometers. There are three layers – upper (57 to 70 km), middle (52 to 57 km), and lower (49 to 52 km). Particles are of three types: large (7 μm in diameter), medium-sized (2 to 2.5 μm), and small particles (average diameter, 0.4 μm). Only small and medium-sized particles are present in the upper layer. The other two layers have particles of all three types. Large particles account for no less than 90% (in terms of mass) of the entire cloud cover.

The composition of the Venusian clouds has long baffled scientists. The simpler hypotheses, based on Earth analogies (liquid or frozen water, mineral dust) had to be discarded as soon as ground-based observations yielded data on the optical properties of the particles. Since hydrochloric acid is present in the Venusian atmosphere, scientists put forward yet another hypothesis – that the clouds consist of hydrochloric acid droplets. But a number of considerations made it necessary to abandon this assumption as well. A suitable candidate in terms of optical properties is sulfuric acid (H_2SO_4), which is present as tiny droplets in Earth's stratospheric clouds. Sulfur compounds reach the atmosphere all the time from Earth's interior, and chemical reactions produce particles that are present in the stratospheric clouds of Earth. An analogy appears quite permissible here, since both sulfur compounds (SO_2) and pure sulfur in the gaseous state occur on Venus.

Sulfuric acid is also a suitable candidate for the main component of the Venusian cloud particles in terms of refractive index and the infrared absorption coefficient. This, however, does not account for the planet's yellowish color. It has been suggested that, in addition to particles of concentrated sulfuric acid, the clouds also contain larger particles of solid sulfur.

Nephelometric experiments reveal that only the small and medium-sized particles can consist of sulfuric acid – the large particles must have a different composition. It was originally assumed that they did consist of sulfur.

The Venera 12 mission, for the first time, included an experiment on the direct chemical analysis of cloud particles (Y. Surkov, Institute of Analytical Chemistry and Geochemistry, U.S.S.R. Academy of Sciences). Particles from the cloud layer were collected on special filters and analyzed with an x-ray fluorescent spectrometer. In the instrument, a sample is subjected to hard radiation from a radioactive source. As a result, the inner electron shells of atoms (K-shells) are excited and a characteristic x-ray radiation is generated whose spectrum is recorded and used to identify the sample's composition. In fact, the composition is determined only at the element level since molecules or any types of bonds cannot be determined. At altitudes from about 61 km down to 49 km, the most abundant element in the cloud-cover particles was chlorine. Either sulfur is not present at all or there is only about 1/20 as much sulfur as chlorine. Thus, it appears that the large particles of the cloud cover consist of chlorine compounds, although it is not apparent which particular compounds these are.

Winds, Storms, and Night-Sky Glow

That Venusian winds are of an unusual character had already been established by ground-based observations. Near the upper boundary of the clouds, the speed of atmospheric streams that are fairly regular is near 100 m/sec, the atmospheric masses forming a single stream as they sweep above the slower layers of the atmosphere below and the solid body of the planet. The rotation period of the planet's solid body, it will be remembered, is very long – 243 Earth days.

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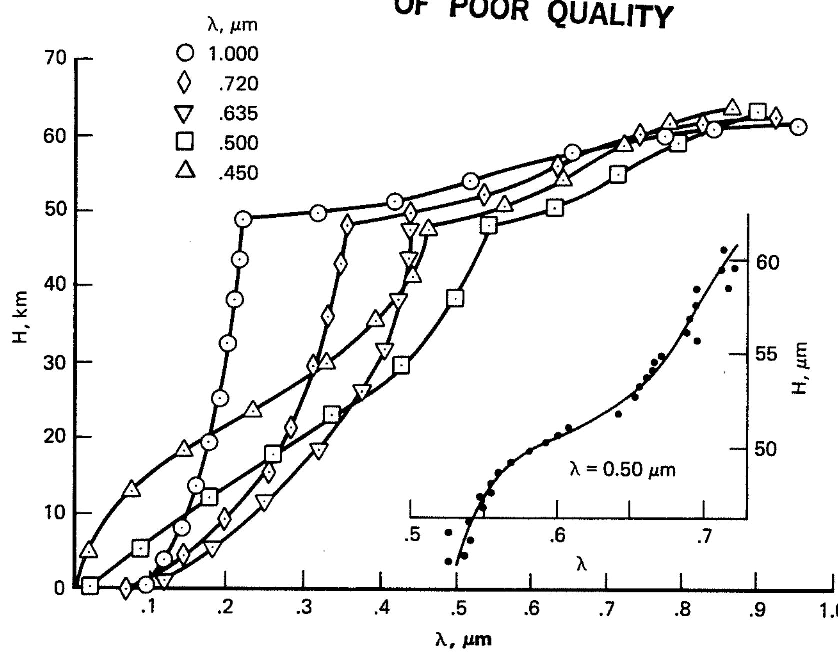

Figure 7-7. Radiation intensity from the zenith as a function of altitude for some wavelengths obtained by the Venera 11 descent module. Figures along the curves indicate wavelengths. The sharp change in the steepness of the curves at an altitude slightly less than 50 km is a result of crossing the lower boundary of the cloud layer.

Venus rotates in the retrograde direction opposite to that of Earth and other planets of the Solar System. The clouds move, together with the upper part of the atmosphere, in the same retrograde direction, completing one rotation in 4 days at an altitude of 65 to 70 km.

Measurements of the descent velocity of the lander made it possible to determine the wind profile down to the surface. As the lander approached the planet's surface, the wind gradually subsided; within the last 10-km-thick layer of the atmosphere, the wind speed is only about 1 m/sec. The Venera 9 and Venera 10 landers carried conventional wind "vanes" to measure the wind velocity when the landers were operating on the surface.

The existence of clouds in the atmosphere and the highly intensive dynamic processes that occur there make it quite probable that storm phenomena may arise. The objective of the experiments supervised by L. Ksanfomaliti (Institute of Space Research) was to find effects similar to terrestrial thunderstorms in the Venusian atmosphere. Storm discharges are known to generate low-frequency electromagnetic pulses. A low-frequency (8–100 kHz) spectrum analyzer with an external antenna was used in the experiment; pulse radiation similar to that typical of Earth's thunderstorms was, in fact, observed (fig. 7-8). After the Veneras 11 and 12 mission results, an analysis was carried out of the nightside observation data obtained earlier by the optical instruments of the Venera 9 and Venera 10 orbiters. It turned out that a short-lived glow, possibly storm-generated, had indeed been registered by Venera 9 on the nightside of Venus. Estimates suggest that the number of storms on Venus could be even greater than on Earth.

A weak nightglow (the ashen light of Venus) has been noted by many ground-based observers for a long time. It seems possible that this effect arises during periods of particularly high storm activity. Besides, another effect – a constant night airglow of Venus undetectable from Earth – results from chemical reactions in the upper atmosphere. In the visible spectrum, this is evidenced by molecular oxygen bands that are excited only in carbon dioxide-rich atmosphere such as that of Venus. The bands were first registered by the Venera 9 and Venera 10 orbiters (experiment supervised by V. Krasnopolsky, Institute of Space Research).

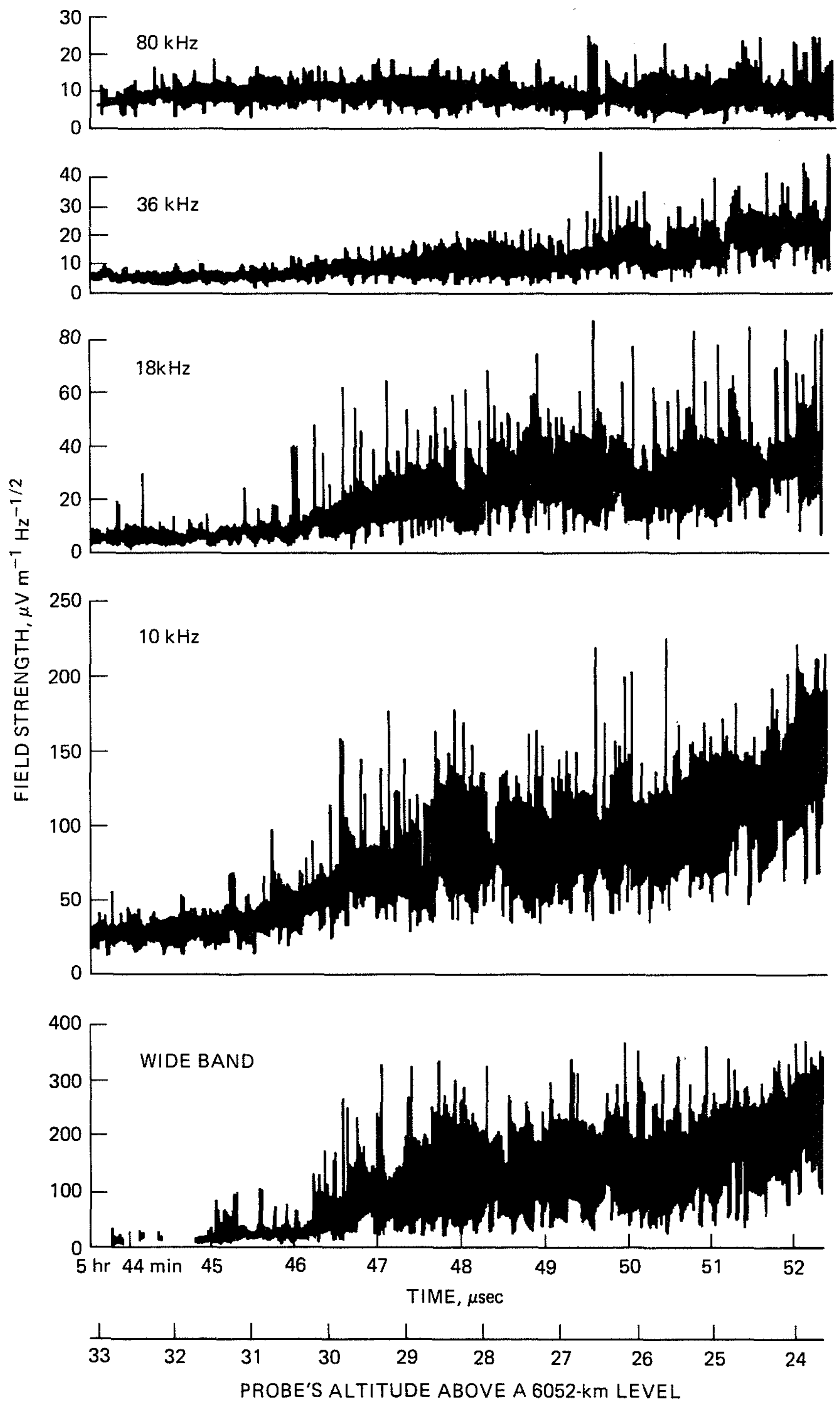

Figure 7-8. Radio noise bursts recorded by the Venera 11 descent module ("GROZA" experiment). The noise was evidently caused by lightning strokes in the Venusian atmosphere.

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The ultraviolet radiation of the Sun (in the hydrogen and helium lines) is known to be scattered by corresponding atoms in the upper atmosphere of the planets. The excited atoms re-emit ultraviolet quanta and produce line-scattered radiation. The measurements of its intensity can be converted to hydrogen and helium concentrations, and it is these lightest of elements that make up the outermost portions of the atmospheres of Earth, Mars, and Venus. The Venera 11 and Venera 12 flyby probes each carried an instrument to measure the radiation intensity in the upper atmosphere in 10 different ultraviolet intervals of the spectrum, which included the above-mentioned lines of hydrogen and helium, and of several other elements. The experiment was supervised by V. Kurt (Institute of Space Research), and also involved the French physicists, J. Blamont and J. L. Bertaux. An analysis of the high-quality spectra provided some estimates of the composition and the structure of the upper atmosphere of Venus.

The experiments conducted during the descent of Venera 11 and Venera 12 into the Venusian atmosphere were intended to study three basic problems:

a) Fine chemical analysis of atmospheric gases

b) Nature of clouds

c) Thermal balance of the atmosphere

The chemical composition studies were considered to be the most essential. All the experiments were successful. The scientific instruments on the Pioneer Venus probe were similar to those on the Venera probes – a gas chromatograph, a mass spectrometer, and some optical instruments. A comparison of the results is of great interest.

In April 1979, Soviet and American scientists who had participated in both missions met at the Institute of Space Research, U.S.S.R. Academy of Sciences, Moscow. During that meeting, data were first compared and then jointly discussed. The results of the investigations have been published and we can state that, in solving the basic problem – that is, to study the fine chemical composition of the Venusian atmosphere – the investigations of both the Venera probes and Pioneer Venus have made it possible to begin to solve the mysteries of Venus.

Plasma and magnetic field in the region of the solar wind interaction with Venus

Bow shock and intrinsic magnetic field

The first experimental observations of the bow shock of Venus were obtained from descending and flyby trajectories of Venera 4, Venera 6, Mariner 5, and Mariner 10.

The properties of the plasma were measured by Venera 4 with charged-particle traps (experiments headed by K. Gringauz, Institute of Space Research, U.S.S.R. Academy of Sciences). The magnetic field was measured by S. Dolginov and his colleagues (Institute of Earth Magnetism and Radiowave Propagation, U.S.S.R. Academy of Sciences).

The various types of charged-particle traps or wide-angle detectors are a system of electrodes – a collector and several grids. Various voltages – dc, gradually changing, or ac – are usually applied to these grids, which makes it possible to analyze the trapped particles by their energies and charge signs. The shock wave was observed as a sharp simultaneous increase in the interplanetary plasma and amplitude of the magnetic field fluctuations occuring some distance from Venus.

Systematic observations of the interactions of the solar wind with Venus were performed with plasma and magnetic instruments onboard the first Venus orbiters, Venera 9 and Venera 10. The plasma properties were measured with wide-angle analyzers – Faraday cups and retarding potential analyzers (RPA) (K. Gringauz, Space Research Institute) – as well as with narrow-angle detectors – electrostatic analyzers (O. Vaisberg, Space Research Institute). The magnetic measurements were made by S. Dolginov, Institute of Earth Magnetism and Radiowave Propagation.

An electrostatic analyzer is, in its simplest version, two curved concentric plates separated by a small gap. A potential difference is applied to the plates. Particles entering the gap pass through it only if they have a certain energy/charge unit ratio. This energy corresponds to the applied potential difference. By applying different potentials to the plates, an energy spectrum of particles can be obtained.

Figure 7-9 shows 32 crossings of the bow shock by the Veneras 9 and 10 vehicles based on the data of the wide-angle analyzers and the mean front position based on the data of 86 crossings by Pioneer Venus (Slavin *et al.*). It has been confirmed that the shock front position near Venus is near the surface – about 0.3 R_V in the frontal subsolar area (where R_V is the radius of Venus). The differences in the mean front positions revealed – from the data of both Soviet and American vehicles – are apparently associated with two circumstances. These satellites crossed the front at different latitudes and the measurements were obtained during different phases of the solar activity cycle.

As shown by Veneras 9 and 10 measurements taken with electrostatic analyzers, the asymmetry of the bow shock of Venus was found to be associated with the anisotropic nature of the solar wind. The radial distance of the bow shock in the polar direction is approximately 2000 to 3000 km greater than in the equatorial direction.

After the experiments on Venera 4 by S. Dolginov and his colleagues, the magnetic moment value of Venus was initially estimated as 5 to 8×10^{21} gauss cm^3 (10 γ on the surface). On the basis of Veneras 9 and 10 data, this estimate was lowered and the intrinsic field on the planet's surface was assumed not to exceed 5 γ.

The magnetic field measurements of Pioneer Venus at altitudes from 140 to 200 km showed that most of the

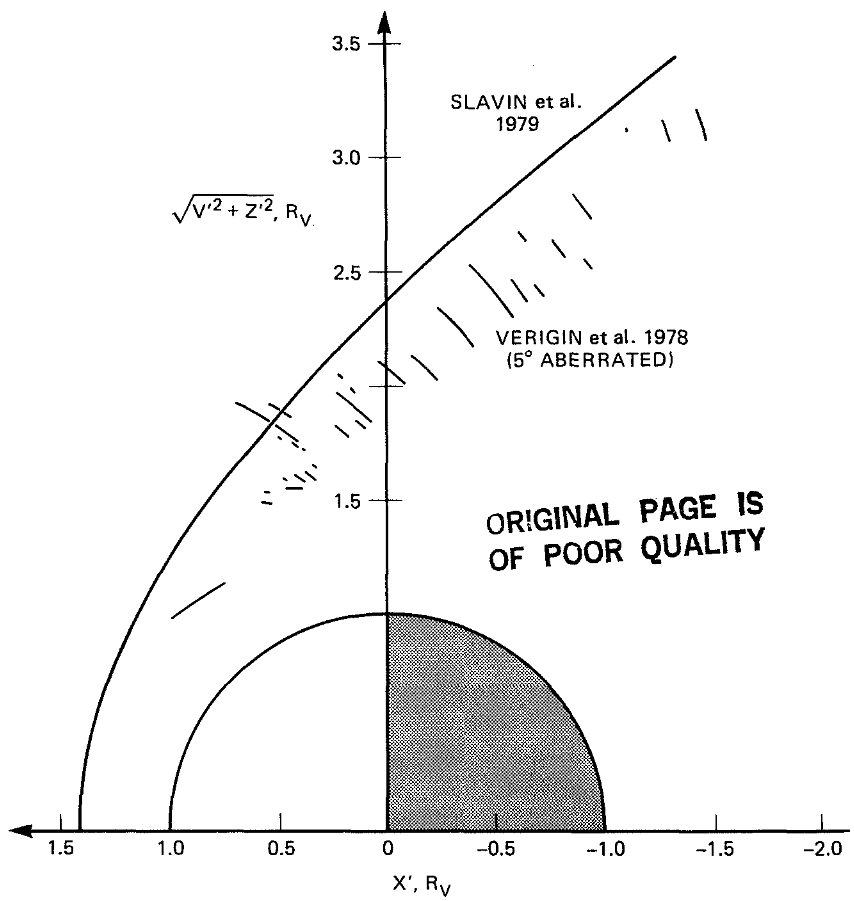

Figure 7-9. Position of the shock front near Venus measured by Veneras 9 and 10 (lengths of curves and points show the portions of the orbits where the satellites crossed the front). The solid curve shows the average position of the front from Pioneer Venus data. The cylindrical system of coordinates is used where the x'-axis is oriented to the solar wind direction.

field values did not exceed the threshold sensitivity of the instrument, that is, 2 γ. Thus it has been confirmed that the intrinsic magnetic field of Venus is all but absent.

Plasma magnetic tail– All the trajectories of the Soviet vehicles that have landed on planets and the orbits of the artificial satellites of the planets have been such that the vehicles have approached the planets from their nightside and have allowed observations of the planet's wake at altitudes greater than 1500 km. Veneras 9 and 10 entered the dayside only to latitudes above 32°. These vehicles penetrated deep into the optical umbra of the planet and allowed detailed measurements of the distribution of the plasma and magnetic field. These measurements showed that a plasma-magnetic tail with typical features exists near Venus, some of the features being similar to those of the tail of Earth's magnetosphere. In particular, as in Earth's magnetotail, the oppositely directed bundles of magnetic field lines along the Sun-planet direction were observed on Venus, that is, the magnetic field component along the Sun-planet direction was essentially higher than the others.

These field line bundles in the tails were separated by the layer where the magnetic energy density had a deep minimum as in the "neutral-sheet" of Earth's magnetosphere. The data from the wide-angle analyzers showed that the properties of the plasma and its distribution in the tail also resembled that in Earth's magnetotail: at the boundary of the tail and in the transition region, a characteristic change in differential ion spectra was observed similar to that in Earth's boundary layer, that is, the plasma mantle. The plasma features deep in the tail resembled those in Earth's plasma sheath.

Figure 7-10 shows schematically the region of the solar wind interaction with Venus: the shock wave, the *transition region* (A) behind the shock front and the plasma-magnetic tail. The B-region corresponds to the corpuscular penumbra or boundary layer. The data from the electrostatic analyzers also indicated a tail boundary that separated the plasmas with different properties. Outside this boundary, the plasma was evidently of solar wind origin, but was disturbed by its interaction with the obstacle. Inside the boundary, the plasma was cooler and had a smaller bulk velocity. The latter can be assumed to be an accelerated or heated plasma of planetary origin. Such a boundary layer could appear and its properties would resemble that at the boundary of two liquids – one of which moves and, because of viscous interaction with the lower liquid, accelerates and heats the latter. In this case, when the solar wind plasma with the frozen-in magnetic field moves relative to the ionospheric plasma, then the boundary separating these liquids can be unstable. For instance, because of the increasing solar wind pressure, the boundary begins to move or fluctuate and the bubbles of the solar wind plasma flow are pressed into the ionosphere and are torn away from the flow. This condition could also occur with the ionospheric plasma rising up in the transition region. A variety of processes cause plasma instabilities, smear the boundary, and cause dissipation of the solar wind energy and its subsequent transfer into the ionosphere.

As shown in figure 7-10, the region extending to 5 R_V (C-region), where the regular ion fluxes were absent, was

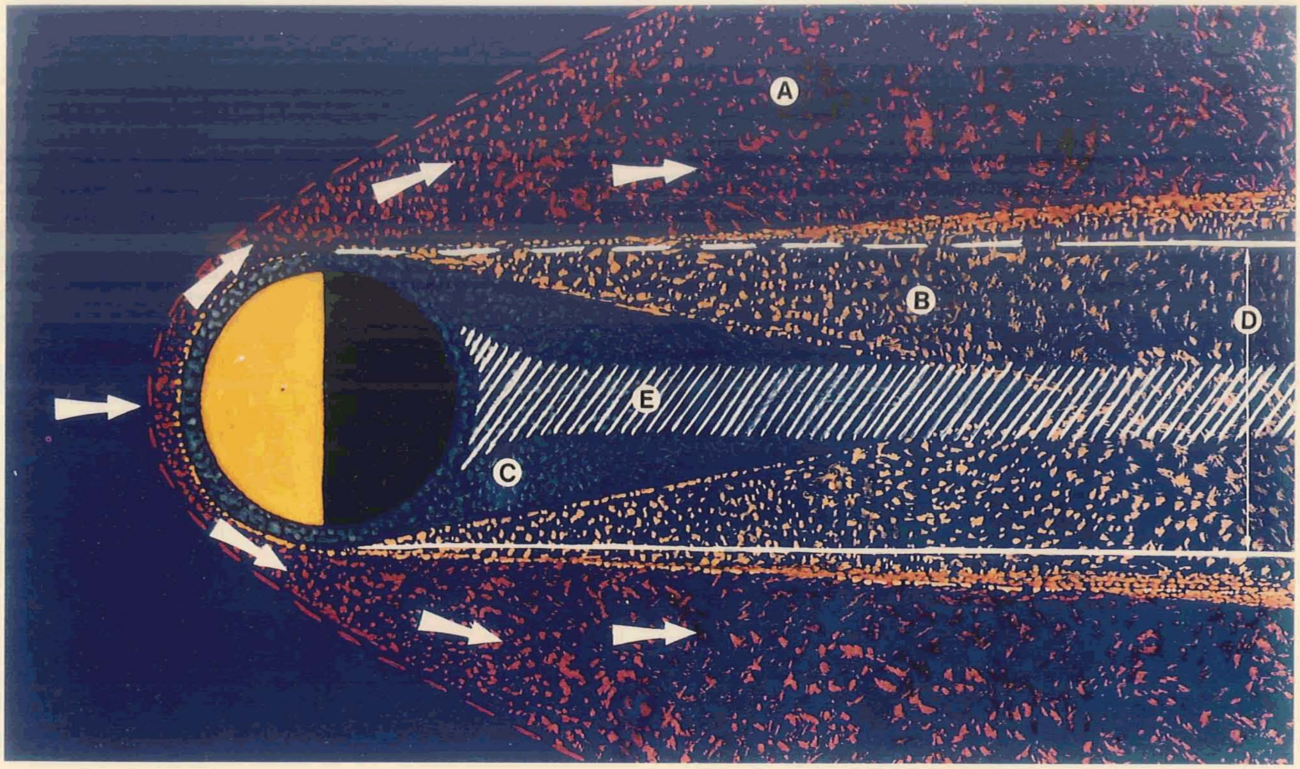

Figure 7-10. Schematic representation of the near-planet shock wave (dotted line) and the magnetosphere of Venus from Venera 9 and Venera 10 data. Arrows show the direction of the solar wind plasma flow. The A-region is the transition layer behind the shock front, the B-region is the boundary layer, the C-region is the corpuscular shadow, the D-region (solid line) is the magnetosphere boundary, and the E-region is the plasma sheath inside which there is a neutral sheet separating magnetic field lines directed toward each other.

positioned under the corpuscular penumbra, which is the corpuscular umbra region that does not coincide with the optical shadow of Venus. It should be emphasized (in fact, it is essential for consideration of the sources of the Venus nightside ionization) that the behavior of the electron fluxes was quite different from that of the measured ion fluxes. They were observed everywhere, including the corpuscular umbra. Only their intensity decreased (fig. 7-11) and the character of the spectrum changed, that is, high-energy tails appeared in the spectrum. Apparently, electrons as well as ions inside the tail were subjected to some acceleration processes.

It was likely that in the far tail regions of Venus, as for Earth, the boundary layer gradually thickened and merged with the plasma sheath. As in the plasma sheath of Earth's magnetosphere, the accelerated ion fluxes with energy >2 keV were observed (C-region in fig. 7-9) near the neutral-sheet plane when the B_X component of the magnetic field reversed its sign (x-axis was along the Venus-Sun line) (fig. 7-12). Thus, the large-scale pattern, magnetic field topology and plasma distribution in the Venusian tail showed a striking resemblance to Earth's magnetosphere.

Nature of the obstacle forming a shock wave– The existence of the extended tail near Venus with properties similar to those in Earth's magnetosphere seem rather striking. Initially, before the experiments on Pioneer Venus, it led the American specialist (C. T. Russell) to revise the magnetic field estimates previously made by Soviet specialists; he increased the estimate of the value of the intrinsic magnetic field of Venus.

More careful study and detailed revision of the data of magnetic and plasma measurements near Venus have begun. Such an analysis of the data of magnetic measurements, several sessions at a time, on the Veneras 9 and 10 vehicles showed that the magnetic field properties in the Venusian tail had one essential difference. This difference became apparent after comparing the data obtained simultaneously on two spacecraft, one of which was in the undisturbed solar wind and the other in the planet tail region.

During each measurement, the magnetic field topology – the existence of two field line bundles stretched along the tail – was preserved. However, in several instances, the plane of the neutral-sheet separating these bundles changed its orientation. Sometimes this plane was located vertically, almost parallel to the meridian plane,

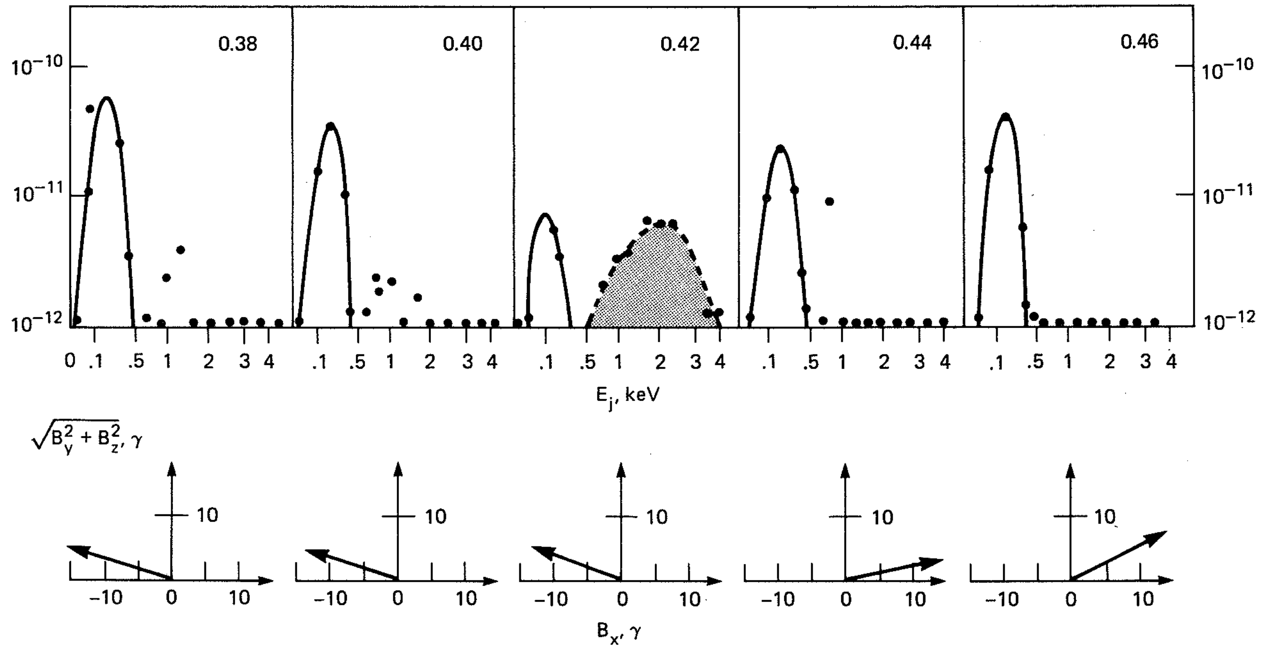

Figure 7-11. Ion energy spectra obtained by Venera 10 on April 19, 1976. The intense flows of energetic ions were measured (shaded part of 0.42 spectrum) in the region of the planet tail where the magnetic field B_x-component changed its sign (B_x-component turn is shown underneath the spectra between 0.42 and 0.44). These flows are part of the plasma sheath of the Venusian tail.

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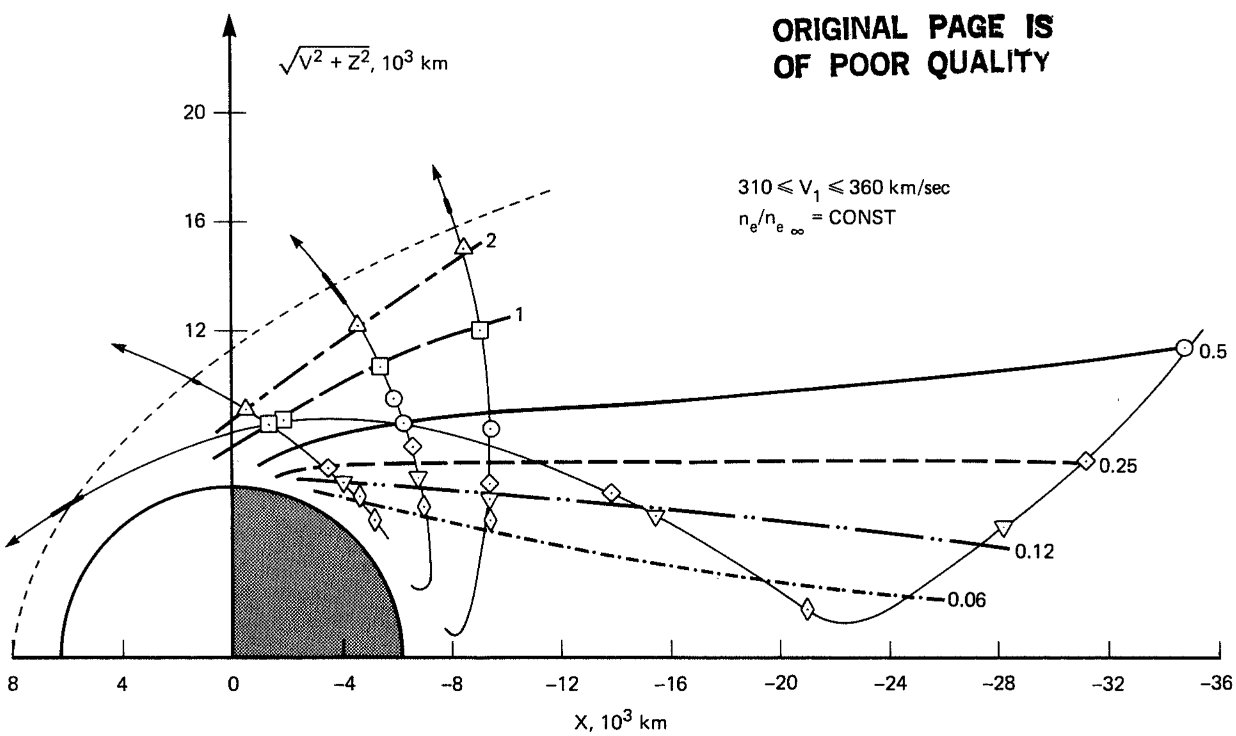

Figure 7-12. Lines of distribution of constant number densities of the electron component of the plasma near the region where the solar wind interacts with Venus (from Venera 9 and Venera 10 data). The measurements of electrons corresponding to the velocities of the solar wind v_i in the narrow interval 310 to 360 km/sec were chosen for the analysis. Figures along the lines designate the values of electron number-density h_e relative to their values in the solar wind.

but this is not typical, for example, of Earth's magnetotail. E. Eroshenko (Institute of Earth Magnetism and Radiowave Propagation) showed by comparing the magnetic data simultaneously obtained on two spacecraft that the neutral-sheet plane in the tail remained always perpendicular to the transverse component of the interplanetary magnetic field. It rotated together with the rotation of this transverse component.

The conclusion is that the measured magnetic field is not the intrinsic field of the planet, but is the field of the "magnetic barrier" induced by currents flowing in the conductive ionosphere of the planet. In other words, magnetic field tubes of the solar plasma flowing around the planet encounter an almost ideal conductor, the ionosphere. They cannot penetrate it and they deform, retarding especially strongly near the stagnation subsolar point of the ionosphere. The magnetic field accumulates at the subsolar region and forms a magnetic barrier. The solar wind still flowing around the planet carries with it the ends of the field tubes retarded at the frontal part of the planet. The tubes drape the planet and are stretched as a tail on the nightside. Thus the field line bundles are elongated in opposite directions on the two sides of the planet. The orientation of the plane separating these bundles depends on the orientation of the magnetic field in the undisturbed solar wind. For example, in the simplest case, if the interplanetary magnetic field vector lies in the ecliptic-horizontal plane, field lines of the tubes draping the planet are in opposite directions on the dawn and dusk sides. In this case, the neutral-sheet plane is parallel to the meridian plane. If the interplanetary field vector is in the meridian plane or near it, the neutral-sheet plane will either partially or completely coincide with the ecliptic plane. It is very difficult to distinguish this case from that of the intrinsic magnetosphere tail, with the dipole axis near the polar axis, that is, as for Earth.

The problem remains unsolved for currents that form the induced magnetosphere flow and how an extended induced magnetic tail can form.

After the experiments on Veneras 9 and 10 and on the basis of research by American investigators (P. Cloutier and R. Danniel), E. Eroshenko assumed that the currents are induced in the ionosphere itself and are mainly in its maximum. As a matter of fact, the region from the ionosphere maximum to its upper boundary is 200 to 300 km on the dayside.

Soviet laboratory simulation experiments (carried out at the Space Research Institute, headed by I. Podgorny) were very important in understanding the formation of the tail in the "induced" magnetosphere. In these experiments, a Venusian artificial ionosphere was formed from the vaporization products of a wax sphere, placed in the hydrogen plasma flow with a frozen-in magnetic field. On the dayside of the artificial ionosphere, a sharp boundary was formed over which the magnetic field was observed to increase with the "magnetic barrier," the field lines being parallel to the ionospheric boundary. The measurements on the nightside of the wax sphere showed that a long tail forms up to 10 R_{sph}) with the field orientation in the tail being typical of the observed Venusian magnetosphere (fig. 7-13).

The experiments on Pioneer Venus finally confirmed that Venus has practically no intrinsic magnetic field and that a magnetic barrier forms on its dayside.

If the assumption that the induced current flow inside the ionosphere is correct, then the upper ionosphere boundary should coincide with the upper boundary of the magnetic barrier. However, this did not prove to be the case. From Pioneer Venus data, as a rule, the barrier's magnetic field sharply decreases, on the upper ionosphere boundary – the ionopause – simultaneously with the growth of the concentration and the temperature of the thermal ionospheric plasma, that is, the field behaves as if there is a conductor carrying a current in the ionopause region at 50 to 100 km. It should be mentioned that sometimes Pioneer Venus detected high values of the magnetic field inside the ionosphere in the region of the main maximum.

It is evident that, in the ionosphere itself, strong currents could flow. C. T. Russell associated that phenomenon with the discovery of magnetic "flux ropes" in the Venusian dayside ionosphere. American specialists (F. Johnson and W. Hansen) and Soviet specialists (T. Breus, E. Dubinin *et al.*, Space Research Institute) gave qualitative explanations and estimated flux-rope characteristics.

In the dayside ionosphere, the magnetic field tubes from the magnetic barrier, which result from the instability of the ionopause that fluctuates because of solar wind pressure, apparently could press in the ionosphere, tear off the solar wind flow, and submerge into the ionosphere. With these tubes moving in such a manner, the field aligned current can twist the tubes into spirals and make their cross sections more compressed as they submerge deeper into the ionosphere. The Pioneer Venus data showed that the entire dayside ionosphere was often filled with these flux ropes or their pieces.

Dayside and Nightside Ionospheres of Venus

Properties of the dayside and nightside ionospheres of Venus were investigated while observing radio occultations during the flyby of Mariner 5 and Mariner 10, Venera 9 and Venera 10, and the Pioneer Venus Orbiter.

The first direct measurements of the upper limit of the ion number density in the Venusian nightside ionosphere were made by ion traps on Venera 4 in 1967. In 1978-1979, Pioneer Venus, using various mass spectrometers and plasma analyzers, made direct measurements of ion and electron number densities, temperatures, and the composition of the ionosphere down to 140 km on both the day- and nightsides of Venus.

Dayside ionosphere of Venus– As shown by the first experiments and from the observations of radio occultations during Mariner 5 and Mariner 10 flybys near Venus a sharp upper boundary exists – an ionopause – on electron number density profiles in the dayside ionosphere.

The ionopause heights of these profiles were essentially different – 500 km on Mariner 5 and 350 km on Mariner 10. Because the dynamic pressure of the undisturbed solar wind during the flyby of Mariner 10 was higher than that measured by Mariner 5, the American investigators suggested that the solar wind should compress the Venusian ionosphere (S. T. Bauer). As a result, the electron number density profile should be distorted and the significant flow of the solar wind could then penetrate to the ionosphere. According to some estimates (C. T. Russell), the value of the incoming solar wind flow could be 30% of the total solar flux. As a result, the shock wave might "settle down" on the surface of Venus and become attached rather than detached (C. T. Russell). As the data from Veneras 9 and 10 showed (N. Savich, Radioelectronics Institute) the ionopause has a distinct dependence on solar zenith angle: near the subsolar region the ionopause was observed at 250 to 280 km, and with the increase in the Sun zenith angle x, the ionopause height increased. This dependence had the following form: $1/\cos^2 x$, that is, it corresponded to variations with zenith angle of the solar wind's dynamic pressure $\rho v^2 \cos^2 x$ (ρ is density and v, velocity of the solar wind.

In the stagnation region, where $\cos^2 x = 1$ and the dynamic pressure is maximum, the ionopause is much nearer the surface. At the flanks, with an increase in x, it moves farther away from the surface and is subjected to greater variations in height. Beginning with a zenith angle of approximately 58°-60°, a region appeared above the main ionization maximum with an almost constant electron number density of the order of 10^3 cm^{-3}, and with an extension of about 300 km or more, the so-called "ionosheet." The Pioneer Venus data showed that heights of the upper ionospheric boundary vary considerably. The

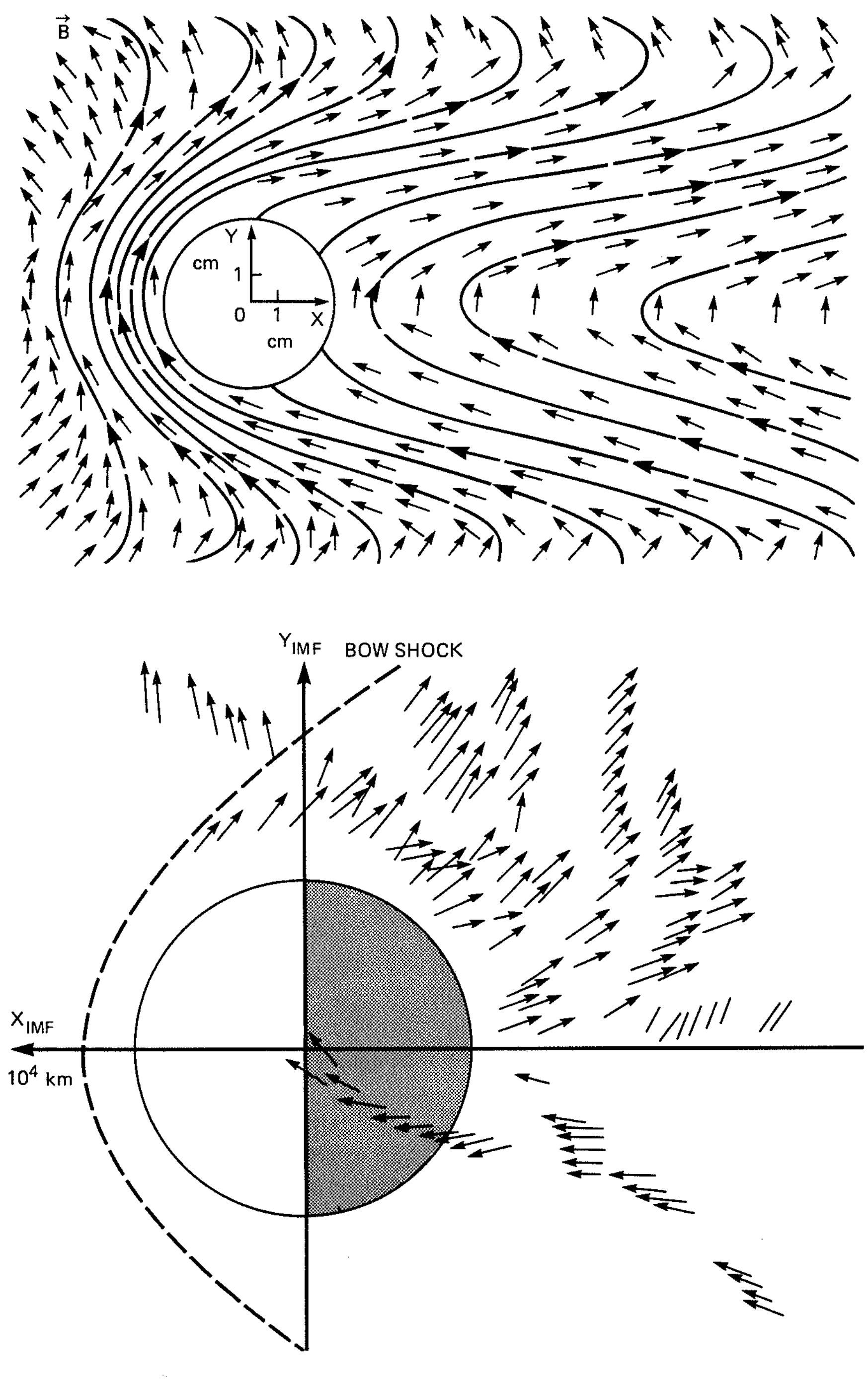

Figure 7-13. Comparison of laboratory model of induced magnetosphere (top of figure) with the field topology in the tail of the Venusian magnetosphere measured during the Veneras 9 and 10 experiments. Projection of magnetic field vectors is shown in the system of coordinates rotating together with the interplanetary magnetic field vector.

amplitude of its variations increased with zenith angle, but the character of the boundary behavior was generally the same as that shown by Veneras 9 and 10 data. The large range in heights of the ionopause measured on Pioneer Venus could be associated, to some extent, with the differences in measurement techniques. Its positions were given by the data from various sensors that were subjected to the effect of the vehicle potential, especially near the terminator. The point is that, during the transfer from the illuminated to nonilluminated portion of an orbit, the photocurrent from the vehicle decreases in the shadow, and consequently the potential of the free body in the plasma decreases, that is, the zero reference in measurements with traps.

The other reason could be that, because of a very low position of the Pioneer Venus orbit periapsis, its trajectory in the ionosphere gave a horizontal rather than vertical cross section, and the results depended on horizontal plasma variations, perhaps even greater than usually found in data from radio occultation observations.

In any case, according to radio-occultation observations on both Pioneer Venus and Venera 9 and Venera 10, these ionopause variations were less striking. However, this problem requires further analysis and correlation.

Keeping in mind that, with increasing distance from the subsolar point, the boundary between the solar wind and the ionosphere becomes unstable and, as mentioned earlier, because of the viscous interaction of two plasmas, instabilities, and dissipation of energy, the magnetohydrodynamic boundary layer is developing. Its thickness grows to the flanks. Possibly the formation of the "ionosheet" on the electron number density profile is associated in a yet unknown way with the formation of this boundary layer.

How much of the solar wind penetrates to the ionosphere of Venus? Is it 30% of the flux coming toward the planet, or less?

As shown, based on indirect data (T. Breus, Space Research Institute) and theoretical estimates (P. Cloutier and R. Danniel), the absorption should be negligibly small, not exceeding 1%, because the shock front position near Venus is sufficient to follow the law of magnetohydrodynamic flow around an impenetrable obstacle. This value was later confirmed by Pioneer Venus results and calculations from these data.

Nightside ionosphere of Venus– It became evident after radio-occultation experiments onboard Mariner 5, Mariner 10, Venera 9, and Venera 10 that the nightside ionosphere of Venus is irregular. Electron density profiles in the nightside ionosphere sometimes have two narrow maxima approximately of the same order of magnitude spaced 5 to 10 km apart. Sometimes the number density in the upper maximum exceeded that in the lower one. It was natural to associate the irregular variations of the electron density in the nightside ionosphere with the influence of solar wind flows on it. It was just such an assumption (as mentioned earlier) that Soviet specialists made after the Venera 4 experiments (1967) and American specialists made after the Mariner 5 experiments. But it was still obscure – before the Venera 9 and Venera 10 experiments had been made and the plasma magnetic tail had been discovered near Venus – how the solar wind falls to such low heights in regions far from the terminator. The assumptions and estimates for the Venusian nightside atmosphere ionization by the fluxes of solar wind electrons seemed inconclusive. Hence American specialists suggested another hypothesis. They assumed that ions of hydrogen and oxygen (in the recent models) forming in the dayside ionosphere are transported, together with the solar wind flux, to the nightside of Venus; the ions then diffuse down to the heights of the main maximum of the night ionosphere and exchange charge with neutral molecules CO_2 and O_2; as a result, ions O_2^+, O^+, and CO_2^+ form – of which the nightside ionosphere consists.

As mentioned earlier, Veneras 9 and 10 measured the fluxes of electrons at an altitude of 1500 km in the region of the optical umbra of Venus (see fig. 7-11). K Gringauz and his colleagues Verigin, Breus, and Gomboshi suggested that these fluxes can produce ionization of the atmosphere and form the upper maximum of the night ionization.

The calculations showed that, because of these fluxes of electrons, the maximum of the electron number density can really be formed, which corresponds to that measured by the radio-occultation observations of Venera 9 and Venera 10 (fig. 7-14). Variations of the electron density in the flux at altitudes of 1500 km correlated well with those in the upper maximum of the ionosphere, also the argument in favor of the assumption. The calculated and experimental profiles, however, coincided only when the neutral atmosphere density used for the calculations (that is, an initial ionizable material) was more than an order of magnitude less than for the then available models. The neutral temperature also might be lower than in these models. The Veneras 9 and 10 results of the radio-occultation measurements (N. Savich) also showed the neutral temperature to be much lower (about 100 K) than had been suggested before. Also needing an explanation was the fact that, in the experiments, glows of the night atmosphere, excited by the electron fluxes coming into it, were not observed. In addition, the question remained: how were electrons measured at 1500 km able to reach 140 km?

Some explanation should also be found for a source of ionization that produces the second maximum in the nightside ionosphere which frequently has the same order of magnitude as the upper one. A source of ionization, such as transport of ions from the dayside ionosphere, diffusion and charge-exchange of these ions with atmospheric molecules, can hardly provide

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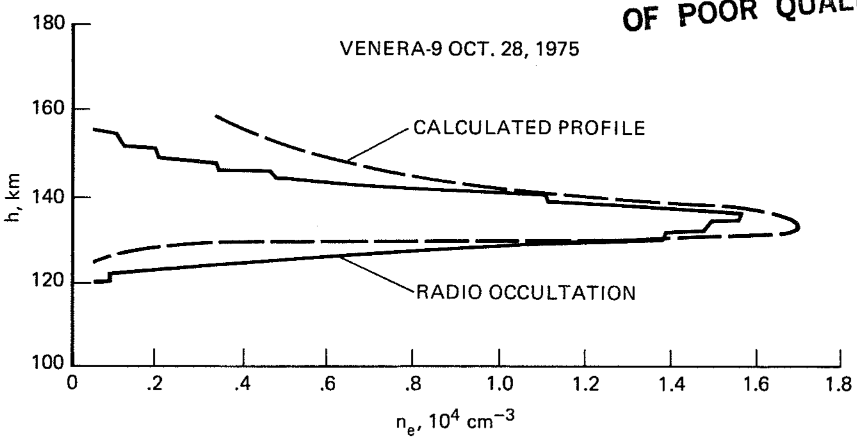

Figure 7-14. Comparison of electron number-density profile in the nightside ionosphere of Venus (from Venera 10 data that measured electrons ionizing the atmosphere) with the profile obtained by radio occultation.

the appearance of one or two very narrow maxima that have been observed during experiments. Electrons with energies of <70 eV, which Soviet specialists had used for the calculations described earlier, could not reach the lower maximum since they "died" at higher altitudes. American specialists (D. Butler and J. Chamberlain) and the Soviet specialist (V. Krasnopolsky) stated the hypothesis, in accordance with which the lower maximum forms as a result of meteor ionization appearing at the altitude level where the number density of neutrals is 10^{12} to 10^{13} cm^{-3}. This level is actually lower by about 20 km than that for 2×10^9 cm^{-3}, at which the upper ionization maximum estimated by K. Gringauz and his colleagues is formed. Meteor ionization can produce a rather narrow maximum. Nevertheless, despite the significant correction of the neutral atmosphere models available, various difficulties of interpretation, and criticism concerning the hypothesis of a source of electron ionization of the upper atmosphere, the Soviet investigators followed this hypothesis based on their own data.

After the Pioneer Venus experiments, data were obtained that confirmed the results of these calculations and such an interpretation of this hypothesis.

First of all, the number density of neutral components and plasma temperature at the height of the upper maximum of ionization was found to be several tens of times less than in the models available (fig. 7-15). The neutral temperature in the nightside Venusian atmosphere was about 100 to 140 K.

Pioneer Venus detected fluxes of electrons with energies ⩽250 eV (the upper threshold of the instruments) at an altitude of 140 km, the intensity of which was sufficient to produce ionization equal to that measured experimentally. This information was particularly conclusive and also was direct evidence that the hypothesis of the Soviet specialists concerning an electron source of ionization in the upper ionosphere of Venus is true.

Pioneer Venus measured velocities of the ion O^+ transport from the dayside to the nightside ionosphere; these velocities were sufficient to sustain the nightside ionosphere. However, the maximum of ionization so formed gradually decreases with increasing height in the region over the maximum. As the Soviet specialists showed, in this case the thickness of the ionization layer at the maximum half-width level exceeds by about two times the thickness of the experimental profile layer.

Thus it became clear that the fluxes of electrons contribute much to the formation of the narrow upper maximum of ionization in the nightside ionosphere of Venus. It is even possible that the double-component electron flux, for example, consisting of electrons with energy <70 eV and >350 eV, forms double maxima of very irregular ionization, or the accelerated fluxes of ions detected by Venera 9 and Venera 10 in the tail form the lower maximum (T. Breus, A. Volacitin, and H. Mishin). The transport of O^+ ions from the dayside ionosphere contributes mainly to the formation of the upper region of the ionosphere.

Where do the electron fluxes appearing in the optical umbra of the planet form and how do they enter the atmosphere at altitudes of 100 to 140 km?

The Venera 9 and Venera 10 detection of the plasma-magnetic tail near Venus provides at least a partial answer to these questions; at least for the present it allows appropriate assumptions to be made.

Indeed, in the plasma sheath, the acceleration of particles of the solar wind was observed, the latter flowing into the tail from its flanks. Also, accelerations of ions and electrons of the dayside ionosphere could occur and these could be transported to the tail and picked up by the solar wind flux.

The electron fluxes accelerated by different mechanisms in the tail can evidently precipitate, then be injected into the atmosphere at low altitudes, to produce an irregular source of ionization. Such a source essentially depends on the properties of the solar wind and the situation in interplanetary space.

Thus, as we have seen, the Soviet plasma and magnetic experiments conducted near Venus for the last decade were useful. At the XVII General Assembly of the International Association of Geomagnetism and Aeronomy in Canberra, Australia (December 1979), recent results of magnetic and plasma measurements

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near Venus were summarized. New basic results obtained by the Soviet (Veneras 9 and 10) and American (Pioneer Venus) investigators, as well as theoretical works and models that contributed much to the interpretation of these results are:

(1) Discovery of the plasma-magnetic tail (Venera vehicles),

(2) Identification of the induced nature of the magnetic field measured near Venus (Venera vehicles and Pioneer Venus),

(3) Determination of the shock front position (Venera vehicles),

(4) Detection of the shock front asymmetry (Venera vehicles),

(5) Hypothesis of an electron source of nightside ionosphere ionization (Venera results and calculations),

(6) Confirmation of the existence of the Venus "induced" tail in the laboratory simulation experiments (Soviet data),

(7) Evidence for the pressure balance at the ionopause, sustained by the "magnetic barrier" and the ionospheric thermal plasma pressure on one hand and by solar wind streaming pressure on the other (Pioneer Venus),

(8) Discovery of magnetic "flux ropes" in the ionosphere (Pioneer Venus),

(9) Explanation of the nature of the magnetic "flux ropes" (Soviet and American interpretation of results), and

(10) Detection of the magnetic field increase before the ionopause in laboratory and numerical experiments, confirming the existence of the "magnetic barrier" (Soviet results).

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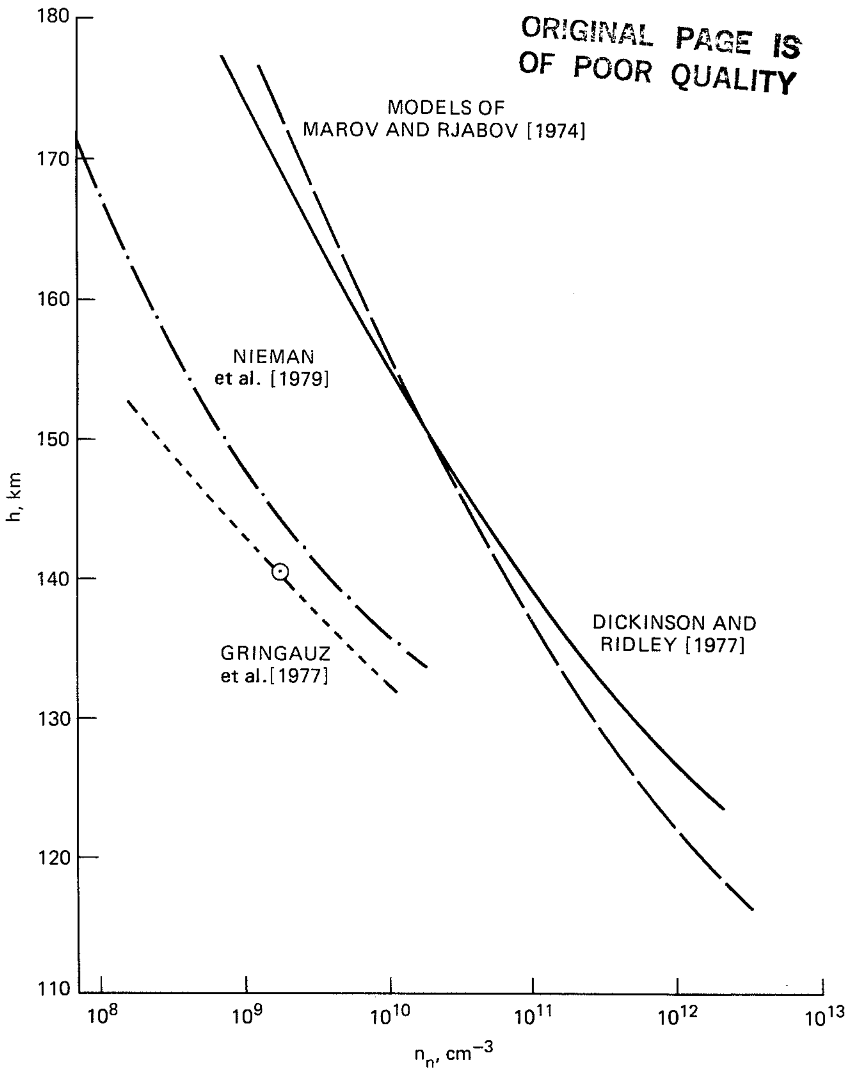


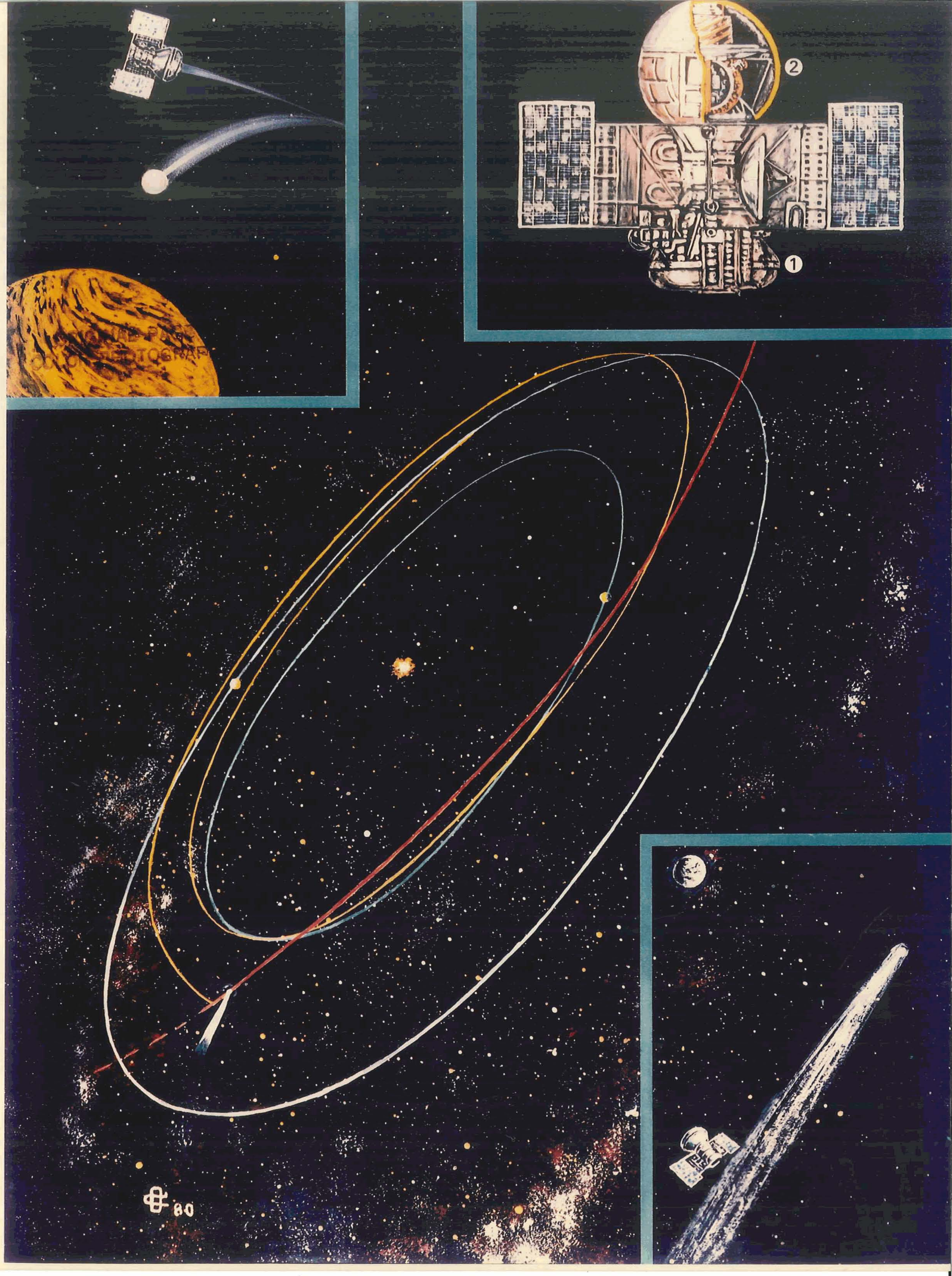
Figure 7-15. Dependence on a height h of the number density of neutral particles n_n according to the models by M. Marov and O. Rjabov (Institute of Applied Mathematics, U.S.S.R. Academy of Sciences), R. Dickinson, and E. Ridley. The dependence n_n (h) suggested by the group headed by K. Gringauz (Space Research Institute, U.S.S.R. Academy of Sciences) agrees with the results of H. Niemann et al. obtained from Pioneer Venus.

Prospects for Further Research

Not everything learned about Venus in the past 15 years has been listed here. Our knowledge of the planet has been enriched considerably. But has Venus ceased to be a mystery planet? Unfortunately (or fortunately), it remains such a planet. Many mysteries were unraveled, many problems were solved – but new mysteries arose which are much more difficult to unravel.

Some of the problems yet to be solved are given below.

- We still have no true explanation of the higher content of the primordial inert gases on Venus.
- It is entirely unclear why there is so little water in the Venusian atmosphere. Has Venus formed without water? Is water hidden in the crust, or was it lost during the planet's evolution? Why is the vertical profile of water vapor concentration so extraordinary?
- The chemical composition of the cloud cover particles has not yet been determined.
- The mechanism responsible for the motion of the atmosphere at altitudes of 40 to 70 km (the four-day rotation) is not understood.
- How active is the planet's interior? Is there volcanic or seismic activity?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• Finally, we do not know (and this is quite important) when the present temperature conditions of the Venusian atmosphere and surface set in. Did these conditions exist when Venus was formed or, during a sufficiently long initial epoch, was the climate of Venus more moderate? Many questions can also be posed, as about the plasma and magnetic phenomena observed near Venus, questions not yet explained.

How should the exploration of Venus continue? Evidently, such diverse problems can only be solved by spacecraft of different types. To study the atmosphere dynamics, balloons are indispensable. They could also be used to investigate the physical and chemical properties of the cloud cover.

The chemistry of the minor constituents of the atmosphere of Venus and its thermal budget must be studied by descenders (probes) operating along the usual descent trajectory from parachute deployment to touchdown. It is desirable that they begin to function at the highest altitude possible (at no less than 70 km).

Finally, seismic observations require that instruments remain on the planet's surface for many months – this special equipment must be designed to operate at high temperatures. In short, the technical problems are numerous, but we are hopeful that they will be solved. It is natural that, besides those that have thus far operated perfectly, other new and more sophisticated instruments will appear.

An interesting program was outlined in the Soviet-French project Venera, which includes the flyby of two spacecraft of the same type as Venera 11 and Venera 12 near the planet and the jettisoning of two landers into the Venusian atmosphere which will softly land. Each flyby spacecraft would also inject two balloons to study the atmospheric dynamics.

The chemical composition of inert gases, aerosol particles, thunderstorms, and other properties of the atmosphere will be studied by landers during their descent. It is planned that these landers will measure pressure, temperature, chemical composition of the soil on Venus, and possibly seismic activity as well.

This project, very significant in itself, was unexpectedly supplemented by a scientific goal no less fascinating. One of the brightest and most interesting comets of the Solar System – the comet Halley – approaches the Sun once per 76 years. Such an event will occur in 1986.

Comets generally are of great interest for planetary cosmogony. There is an assumption that the nuclei of comets are the initial material from which the planetary system formed. Comets have been studied to the present only by ground-based astronomy. Practically unknown are the structure of the nuclei, the ionization sources in comets, the mechanisms for the formation of plasma structures in their tails, the reasons for their various shapes, and so on.

The approach of Halley's comet in 1986 will occur for the first time in the epoch of space exploration when it can be studied directly, not from Earth's surface. It is especially urgent to study Halley's comet directly since conditions for observing the comet from Earth will be relatively unfavorable in 1986. The European Space Agency plans to launch the probe Giotto to investigate Halley's comet.

The U.S.S.R. did not plan a special mission to the comet. However, it turns out that the flyby vehicles of the future mission to Venus, which will use a gravitational maneuver near Venus, can be sent on to the comet (fig. 7-16). These vehicles will probably approach very near the comet at a distance of several thousand kilometers and will not only photograph the cometary nucleus but also will study the components of the dust and gas evaporated by the nucleus, the content and concentration of ions and many other phenomena, most important in understanding the physics of comets and the origin of our Solar System. These two projects – the European Giotto and the Soviet probe to Halley's comet – will complement each other, both in terms of scientific goals and the equipment used.

It should be emphasized that the studies of Venus and other planets and comets of our Solar System will provide the key to a better understanding of the evolution of Earth. These problems are vitally important to the future of mankind, and all efforts invested in such projects are certain to bear fruit.

Figure 7-16. Venera-Halley mission – the red line shows the flight trajectory of Halley's comet; the yellow line shows the trajectory of the flyby vehicles of the Veneras 11 and 12 type which will be sent to the comet. The green and blue lines show the orbit of Venus and Earth, respectively. In the top right, the general view of the Venera 11 interplanetary automatic station is shown – orbiter (1) and decent module (2) – the prototype of a station for the Venera-Halley mission.

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8
Epilogue

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FROM ORBIT INSERTION on December 4, 1978 to the writing of this book, Pioneer Venus Orbiter has produced a wealth of scientific data concerning all aspects of the environment of Venus. Eleven of the 12 original scientific instruments remain fully functional, although the Radar Mapper was commanded off as planned after periapsis of Orbit 834 on March 19, 1981.

The mission interval between orbit insertion and July 1980, denoted as Phase I, was marked by periodic thruster firings required to control the altitude of periapsis to remain within Venus' topside ionosphere. Since July 1980 the orbital characteristics of the Orbiter have been slowly changing due to natural causes, opening new regions in the Venus environment for exploration. This mission interval, denoted as Phase II, will continue until early 1992 when periapsis altitude will return to topside ionospheric levels. At this point thruster firings will again be used to control altitude as in Phase I.

It is estimated that sufficient fuel will remain to control periapsis altitude for several months in this last Phase III. It is the purpose of this final chapter to summarize Phases II and III scientific opportunities.

The nominal Phase I orbital parameters are listed in table 8-1, and figure 8-1 is a scale drawing in solar ecliptic coordinates of the Orbiter's orbit. Figure 8-1a is a view from the north ecliptic pole with the Sun upward. Figure 8-1b is a view from the antisolar point with the north pole upward.

Figure 8-2 illustrates the way certain orbit relationships vary during the course of the Orbiter's mission. The

TABLE 8-1.– NOMINAL ORBITAL PARAMETERS FOR PHASE I MISSION

Periapsis altitude	150-200 km
Apoapsis altitude	66,900 km
Eccentricity	0.843
Average period	24.03 h
Inclination to equator	105.6°
Periapsis latitude	17.0° N

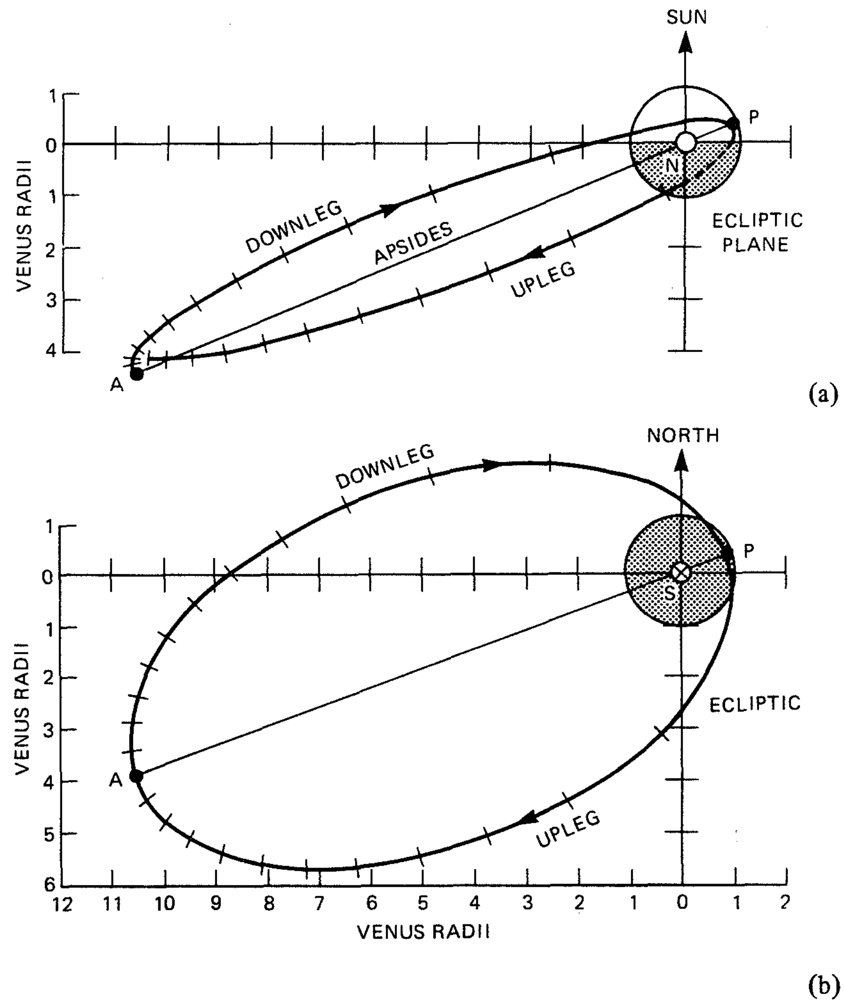

Figure 8-1. Pioneer Venus Orbiter's orbit in solar ecliptic coordinates. (a) View from the north ecliptic pole with the Sun upward. (b) View from the antisolar point with the north pole upward. Nightside hemispheres are shaded. One-hour time ties either side of periapsis, P, out to apoapsis, A, are marked. The orientation of the line of apsides with respect to the Venus-Sun line is shown for December 9, 1978 (Orbit 5) which was Pioneer Venus Multiprobe Entry Day. Periapsis occurred at 180 km altitude, 17° North latitude on the dayside about 22° longitude from the evening terminator (Venus rotates in a retrograde direction about its spin axis – clockwise looking down from the north pole).

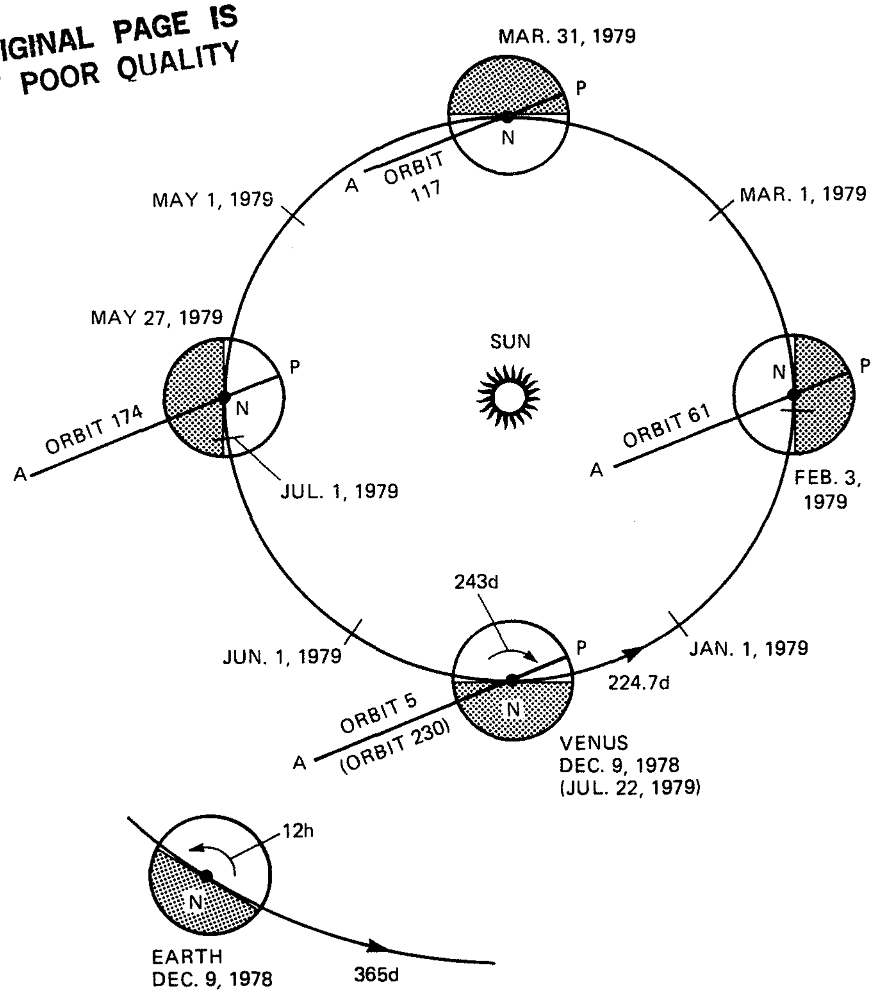

Figure 8-2. How certain orbit relationships vary during the Orbiter's Mission.

Sun-Venus-Orbiter system is depicted in increments of 1/4 sidereal year from December 9, 1978 to July 22, 1979 (224.7 days). Figure 8.1a is repeated at the bottom center of figure 8.2 (only line of apsides is shown to represent the Orbiter's orbit). Since the orbit is fixed in an inertial reference frame, the lines of apsides remain "parallel" to one another in subsequent representations. Thus, the *local time* of periapsis increases by 360°/224.7 d = 1.6°/day (or per spacecraft's orbit) and therefore first "samples" the dayside, subsequently crosses the evening terminator and samples the nightside, crosses the morning terminator and samples the dayside, and returns to the original local time after 224.7 days. Note that since Venus itself rotates with a 243 day period, the *longitude* of periapsis increases more slowly, i.e., by 360°/243 d = 1.48°/day. Thus, the full 243 days are required to "sample" all Venus longitudes.

Because Venus is close to the Sun, solar gravity induces important perturbations on the Orbiter's orbit. One major effect is to cause periapsis altitude to change with time and to cause a corresponding change in apoapsis altitude. The Orbiter's 13-1/2-year mission includes two periods when weekly maneuvers are required to counteract this effect and one period when the corrections are not made. We may thus divide the Orbiter's mission into the three phases listed in table 8-2.

The behavior of periapsis altitude is illustrated in figure 8-3. The Nominal Mission of the Orbiter ran for one Venus sidereal day (243 Earth days) and ended on August 4, 1979. A second sidereal day ending on Orbit 486, April 4, 1980, and part of the third sidereal day were completed before Phase I ended and Phase II began (Orbit 600, July 27, 1980). From the beginning of Phase II and to the time of writing, the Pioneer Venus Orbiter has completed the third, fourth, and fifth sidereal days on Orbit 729, December 3, 1980; Orbit 972, August 4, 1981; and Orbit 1215, April 14, 1982, respectively.

Maximum periapsis altitude of 2270 km will be reached on Orbit 2762, June 29, 1986, after which this altitude will decrease due to the same solar gravity effects that caused the altitude to rise, until it re-enters the ionosphere in 1992, ending Phase II and beginning Phase III.

While periapsis altitude is varying as shown in figure 8-3 during Phase II, the *latitude* of periapsis changes from 17° North during Phase I to 10° South during Phase III. The effect is illustrated in figure 8-4. The combined effects of periapsis *altitude* and *latitude* changes during Phase II are seen in the periapsis sections of the Orbiter's orbit shown in figure 8-5.

TABLE 8-2.– MISSION PHASES OF PIONEER VENUS ORBITER SPACECRAFT

Phase	Period	Orbits	Periapsis altitude
I (Low altitude)	12/4/78-7/27/80	0-600	142-250 km
II (High altitude)	7/27/80-5/22/92	600-4911	not controlled
III (Reentry)	5/22/92-8/21/92	4911-5002	150-250 km

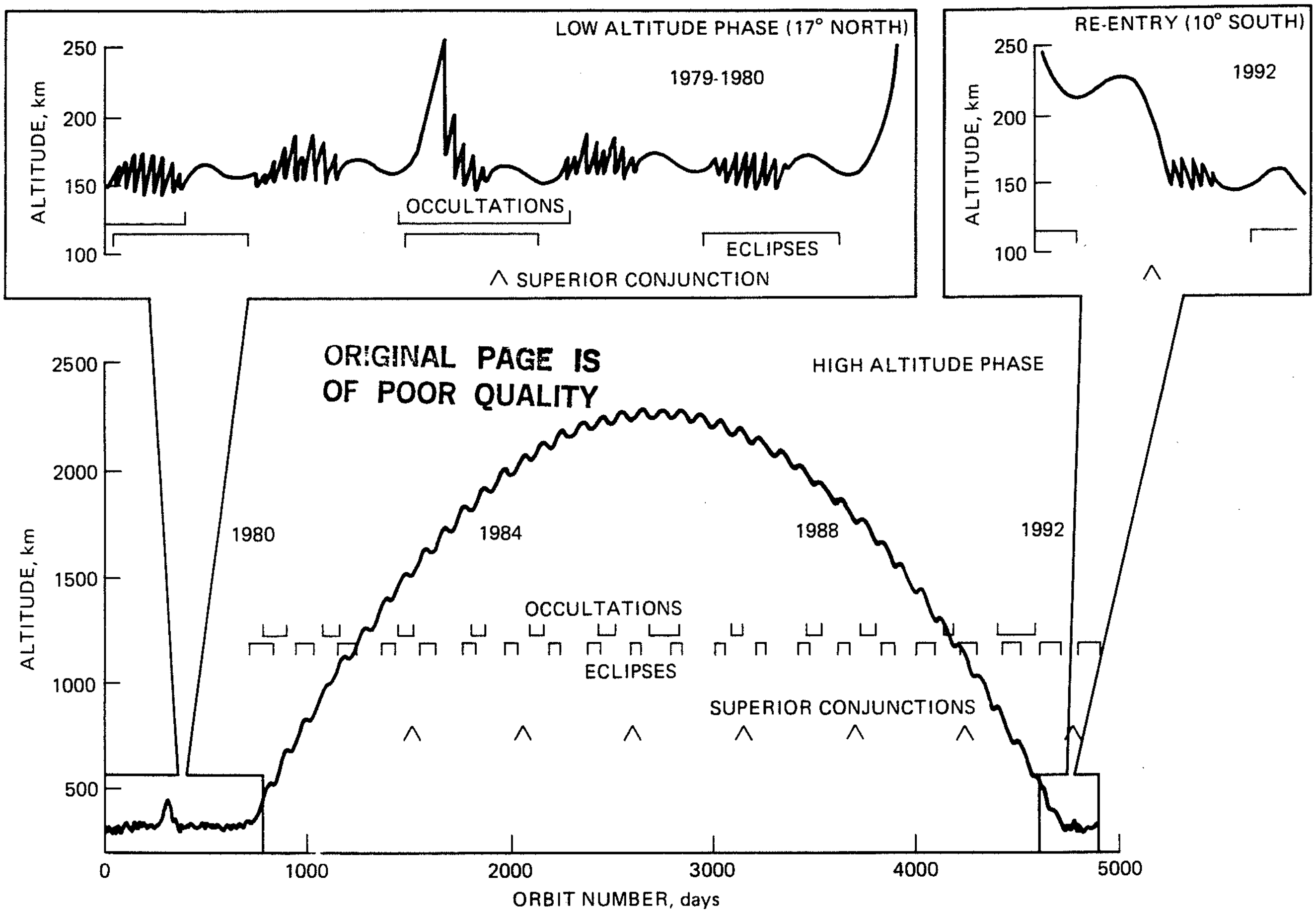

Figure 8-3. Profiles of the periapsis altitudes of Pioneer Venus Orbiter during its entire mission through 1992. Periods of occultations and eclipses are indicated and also the times of superior conjunction when Venus and the spacecraft are on the far side of the Sun from Earth.

SPACECRAFT STATUS

The spacecraft's systems are operating nominally. About 10 lb of fuel are left compared with 70 lb at launch. About 3 lb are required for attitude control through 1992 to maintain the spin period within 13.0-13.2 sec, and the spin axis within 3° of perpendicular to the ecliptic. About 4 lb are required for periapsis altitude control during a 90-day Phase III mission, and 0.8 lb to invert the spacecraft for enhanced radar mapping. Thus, sufficient propellant should be available, although it is difficult to predict thruster tank performance at low, uncalibrated levels.

Solar panel output is now 10 A compared to 13 A at encounter. There is a slow, continuous degradation with major drops coincident with solar-flare activity. The latter should become less frequent as solar minimum is reached so a leveling out in the curve is expected during the next few years. Seven amperes are required for full operations. Should the panel output fall below that level, selected spacecraft and instrument systems will need to be turned off. The Orbiter's battery and other systems are all operating nominally.

SCIENTIFIC INSTRUMENT STATUS

The Orbiter's Infrared Radiometer (OIR) failed on Orbit 71, February 13, 1979, during Phase I. The Orbiter Radar Mapper (ORAD) was operated until Orbit 834, March 19, 1981, during Phase I (except for a 20-day period when the instrument performed erratically, and then was recovered with redesigned operating procedures) and for 8 months of Phase II. When periapsis altitude had risen beyond the usefulness of ORAD it was commanded off, to be reactivated in Phase III. The Orbiter Neutral Mass Spectrometer (ONMS) finished its prime mission during Phase I and operates in an ion mode during Phase II providing supplemental data to the Orbiter Ion Mass Spectrometer (OIMS). It will be commanded to the neutral mode again during Phase III. The Orbiter Atmospheric Drag (OAD) radio science experiment also completed its prime mission during Phase I and is awaiting Phase III reactivation.

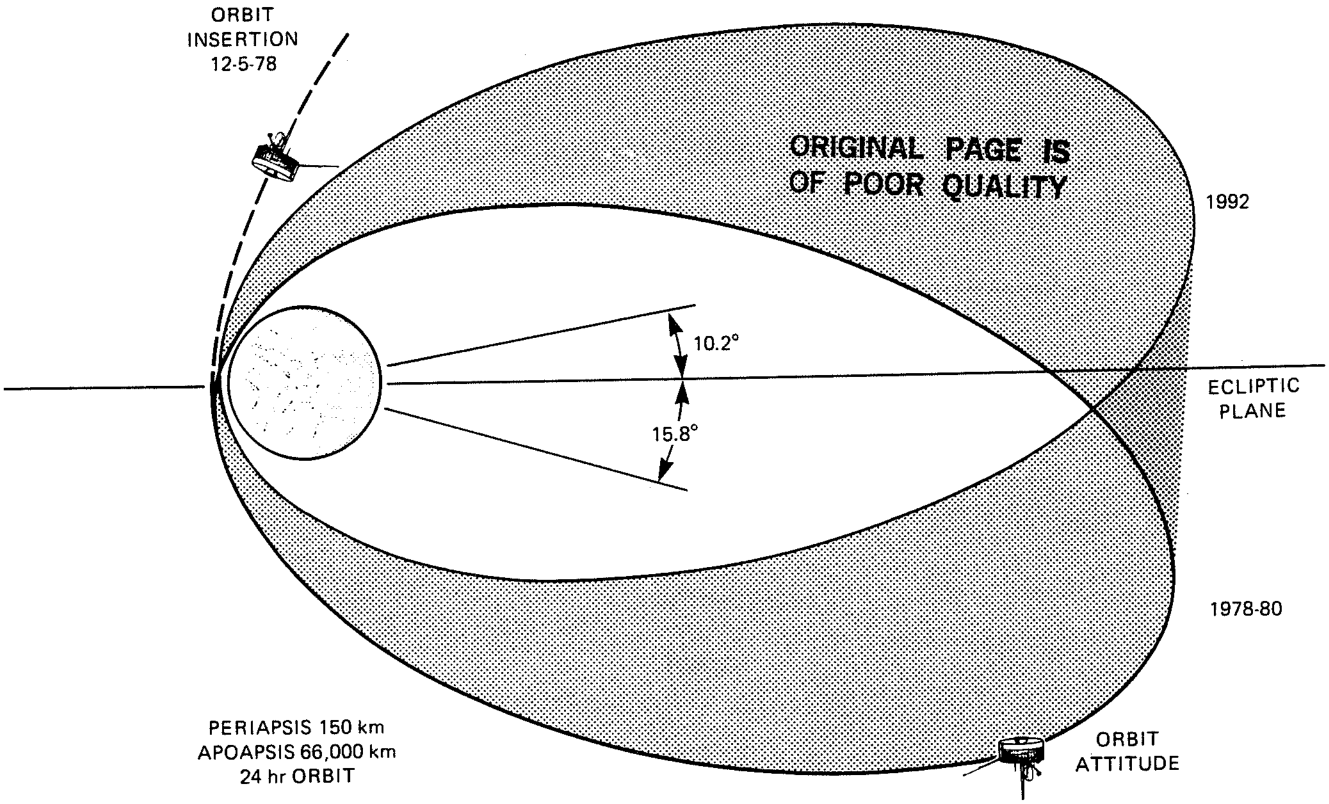

Figure 8-4. Changes in the orientation of the orbit of Pioneer Venus Orbiter during the mission moves the latitude of periapsis from northern to southern latitudes.

With the above exceptions, the remaining experiments are all operating satisfactorily and they are all primary experiments for Phases II and III of the mission.

PHASE II SCIENTIFIC OBJECTIVES

The slowly varying orbital parameters of the spacecraft, particularly periapsis altitude and latitude, occurring naturally in Phase II, opens new regions of the Venus environment for exploration. This circumstance and the accompanying time span from 1980 to 1992, permits the following scientific work:

- The solar-wind interaction region and the ionosphere will be sampled in regions inaccessible to Phase I orbits. These include the nose and near-wake regions of Venus. Combined Phase I and Phase II results, encompassing 11 years, will provide the first continuous measurements of the solar-wind interaction with a planet over an entire solar cycle. The Pioneer Venus Orbiter encountered Venus at a sunspot minimum period in 1978. Currently, there is a sunspot maximum. Another minimum is expected in 1987 and a maximum in 1991.
- Because the solar-wind interaction with the magnetic field-free planet Venus is the analog of the solar-wind interaction with a comet, the Pioneer Venus Orbiter will provide unique insight into the cometary-type of interaction.
- During Phase I, lightning bursts were observed by the OEFD when the Orbiter passed over the nightside hemisphere at periapsis. These appeared to correlate with surface features which may be volcanic in nature. Phase II observations are required to sample all Venus longitudes to verify this tentative conclusion of correlation.
- Periodic mapping of the cloud tops with ultraviolet images will permit long term studies of cloud features, including the formation and decay of major structures and the persistence of haze overlying the cloud tops. Results will be compared with Earth's global cloud system.
- Gravity measurements from the new orbits will permit accurate determination of global field characteristics in the absence of the small-scale anomalies due to local topographic perturbations.
- During 1986 unique observations of Halley's Comet are expected. The solar-wind environment will be described and closeup ultraviolet observations will be made of the comet's nucleus and coma. The observations will complement those planned for USSR, European, and Japanese spacecraft.
- Although many gamma ray bursts were detected, only three

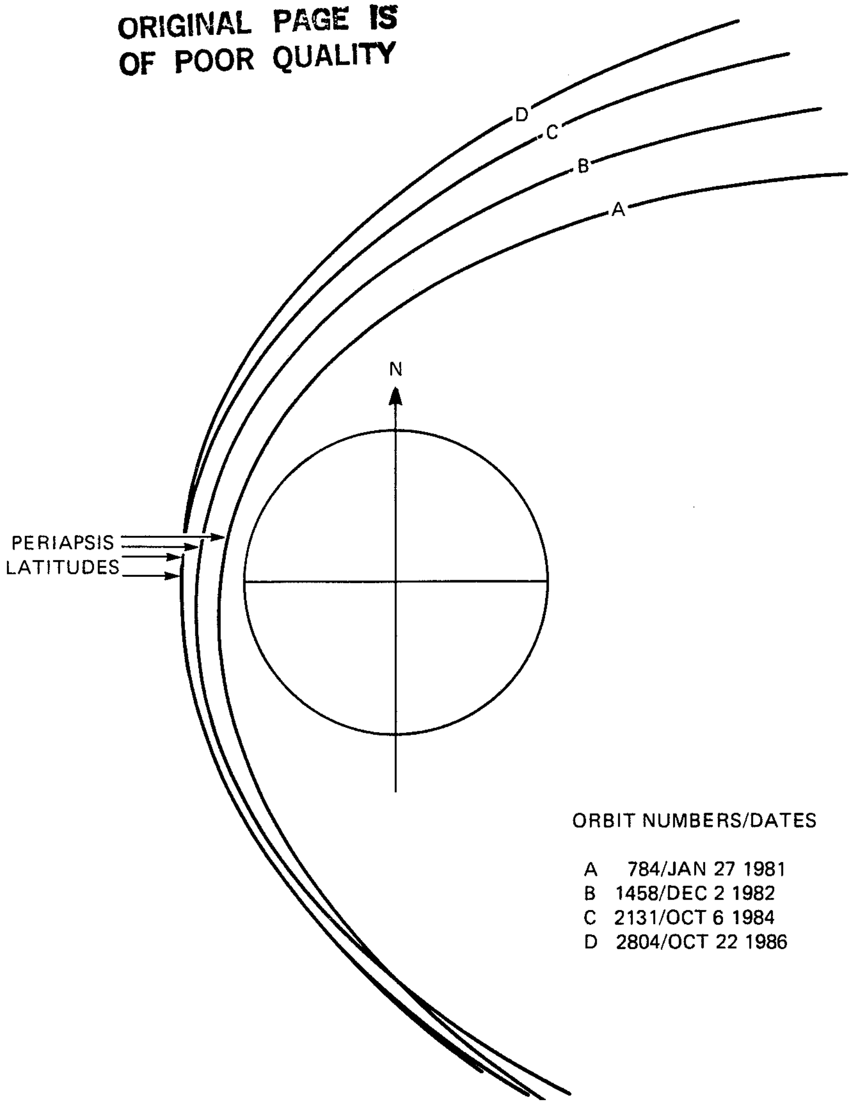

Figure 8-5. Combined effects of periapsis altitude and latitude changes are shown here for four orbit numbers, 784, 1458, 2131, and 2804 extending from 1981 to 1986.

gamma ray bursts could be uniquely located during Phase I. Gamma ray burst data will be enhanced many times through the extended observation interval. About 20 bursts are expected per year and several spacecraft simultaneously observing each burst are required to determine the precise directions in space from which each burst arrives. Spacecraft in addition to Pioneer Venus Orbiter will be operational during Phase II to make these required simultaneous observations.

• Cooperation with the USSR on Venus missions, especially Pioneer Venus and Veneras 11 and 12, has provided the most fruitful planetary cooperation to date. The USSR launched Veneras 13 and 14 to Venus and encountered the planet on March 1 and 5, 1982. Veneras 15 and 16 will encounter Venus about May 1985. Correlative measurement possibilities have been discussed and detailed plans are being formulated.

PHASE III SCIENTIFIC OBJECTIVES

The reentry Phase III of the Pioneer Venus Orbiter Mission (early 1992) will be like Phase I in that periapsis altitude will be sustained between 150 and 200 km altitude. Enough fuel has been preserved for the required maneuvers. The difference from Phase I is that periapsis latitude will be in the southern hemisphere of Venus, presenting more features for exploration. The possibilities include extension of the radar topographic map to higher southern latitudes than could be reached in Phase I. Another important set of measurements during Phase III will be the *in-situ* sampling of the ionosphere into the southern hemisphere. All the Orbiter experiments will make important additional observations. The expected results, coupled with the Phase I northern hemisphere results and the full set of Phases I, II, III solar-wind interaction results, will ensure a more complete picture of the entire Venus environment as conclusions and theories are drawn from the mission.

With the depletion of the fuel during 1992, the Orbiter will descend into the atmosphere and be destroyed by atmospheric friction.

Appendix A

CHRONOLOGY OF EXPLORATION OF VENUS FROM EARTH BEFORE THE PIONEER VENUS MISSION

Date	Event
684 BC	Ninevah (Babylon) tablets record observations of Venus made as early as 3000 BC.
361 AD	Chinese annals record occultation of Venus by the Moon.
845	Chinese annals record an observation of Venus passing through the Pleiades.
1587	Tycho Brahe records an occultation of Venus by the Moon.
1610	Using the newly invented telescope Galileo discovers that Venus exhibits phases like the Moon.
1639	Horrox and Crabtree are first to observe a transit of Venus across the face of the Sun.
1643	Fontana claims that irregularities along the terminator of Venus are mountains.
1666	Cassini observes bright and dusky spots on Venus and claims Venus rotates in a little more than 24 hr.
1716	Halley records seeing Venus in daylight.
1726	Bianchini claims that Venus rotates in 24 hr.
1761	Lomonosov interprets optical effects observed during transit of Venus across the Sun as being due to an atmosphere on the planet.
1769	Captain Cook visits Tahiti to observe transit of Venus. Solar parallax determined to within a few tenths of an arcsecond.
1788	Schroter claims that his observations of Venus show that the planet rotates on its axis in 23 hr 28 min.
1792	Schroter concludes that Venus has an atmosphere because the cusps of the crescent phase extend beyond the geometrical crescent.
1807	Wurm determines the diameter of the visible disc of Venus to be 12,293 km (7639 mi.).
1841	De Vico claims, on the basis of his observations, that Venus rotates in a period of 23 hr 21 min on an axis inclined 53° to the planet's orbit.
1887	Stroobant explains that all the claims by astronomers of discovering a satellite of Venus were merely observations of faint stars.
1890	Schiaparelli concludes from his observations that Venus rotates in 225 days.
1907	Lowell produces drawings of Venus with broad dark lines that are hazy, ill-defined, and non-uniform. He concludes from his observations that Venus rotates in the same time that it revolves around the Sun, namely, 225 days.
1920	St. John and Nicholson, unable to detect any water vapor in its atmosphere, suggest that Venus is a dry, dusty world.

1922 Lyot measures the polarization of sunlight reflected from the clouds of Venus and introduces a new method of investigating the size and nature of particles in its clouds.

1927 Wright and Ross photograph Venus through ultraviolet filter.

1932 Adams and Dunham detect carbon dioxide in the atmosphere of Venus with a high dispersion spectrograph on the Mount Wilson 100-in. telescope.

1942 Wildt shows that the high surface temperature of Venus could arise from a greenhouse effect in an atmosphere possessing a high proportion of carbon dioxide.

1945 Kuiper begins a long series of experiments with low- to high-resolution spectrographs to study rotational temperature of carbon dioxide at the cloud tops using infrared wavelengths.

1955 Hoyle suggests that the Venus clouds are a photochemical hydrocarbon smog.

1956 Mayer, McCullough, and Slonaker detect radio waves from Venus at 3-cm wavelength, indicating that the surface temperature must be very high, about 330°C (626°F).

1956 Price makes the first radar sounding of Venus.

1957 Boyer discovers a 4-day rotation period of ultraviolet markings in Venus' clouds.

1960 Sinton and Strong establish temperature of the cloud tops as -39°C (-38.2°F), by infrared bolometry.

1960 Dollfus, using polarimetry, determines pressure at the cloud tops as 90 mbar.

1961 Opik proposes that clouds are thick dust consisting of calcium and magnesium carbonates.

1961 Sagan suggests that the high temperature of Venus' surface results from a greenhouse effect.

1961 Pettengill makes further radar observations of Venus and determines the astronomical unit with high precision.

1962 Kuz'min and Clarke show that the low radar reflectivity of Venus rules out any possibility of large bodies of water being on the surface.

1962 Carpenter and Goldstein, by radar observations of Venus, establish its rotation as being retrograde with a period of approximately 240 days.

1964 Deirmendjian proposes that the clouds are composed of water.

1966 Ash, Shapiro, and Smith analyze radar data and conclude that the diameter of Venus is 12,112 km (7526 mi.).

1966 Boyer and Guerin determine a cloud circulation of about 4 days from a study of ultraviolet photographs.

1966 Connes measures traces of HCl and HF in the atmosphere.

1967 Kuiper makes the first airborne observations of Venus.

1968 Eshleman and colleagues estimate surface temperature and pressure from radio, radar, and Venus probe data as 427°C (800°F) and 100 atm.

1970 Singer suggests that Venus lost its initial spin and obtained its present slow retrograde spin by impact of a satellite in a retrograde orbit.

1973 Young and Sill propose that the clouds of Venus consist of drops of sulfuric acid.

1973 Pollack observes Venus from a high-flying aircraft observatory and concludes that clouds are deep hazes of sulfuric-acid drops.

1973 Young describes observations of carbon-dioxide absorptions in the Venus atmosphere that show a 20% fluctuation over a 4-day period which represent upward and downward motions of the cloud deck on a planetwide scale.

1973 Goldstein's radar scans of Venus reveal huge, shallow craters on its surface.

1974 Goldstein produces high-resolution radar images of small areas of the planet's surface showing many topographic features.

1976 Carbon monoxide is detected in the upper atmosphere of Venus by Kitt Peak National Observatory. This gas had been detected earlier at lower altitudes through infrared spectroscopy.

1977 Radar images obtained at Arecibo indicate large volcanoes and craters on the planet.

1978 Barker identifies carbonyl sulfide in the Venus atmosphere.

1979 Sulfur dioxide is discovered in the atmosphere by observations from an ultraviolet satellite.

Appendix B

VENUS NOMENCLATURE AND MYTHOLOGY

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U.S. Geological Survey
Flagstaff, Arizona

Names of surface features on Venus shown on recently published maps (Masursky et al., 1980; Pettengill et al., 1980; U.S. Geological Survey, 1981) and a globe (U.S. Geological Survey and Massachusetts Institute of Technology, 1981) have been chosen and approved during the last 5 years by committees of the International Astronomical Union (IAU) (1980). This nomenclature was developed in order to facilitate discussions by planetary scientists of the surface features, physical, chemical, and mechanical surface processes, and conditions within the interior of the planet – all of which have led to its present surface configuration.

Because Venus' surface is hidden from visual observations by a dense atmosphere and clouds, no system of nomenclature like those devised for the other terrestrial planets was developed for Venus before the mid-1960s. Early in that decade, monostatic and pulsed Earth-based radar systems were developed that were able to detect echoes from the surface of Venus, by which its spin-axis orientation and period of rotation were determined. At the same time, certain areas of anomalous reflectivity or brightness were recognized. The two brightest areas in images obtained in 1964 at the Jet Propulsion Laboratory, Goldstone, California, were named by Goldstein (1965) "Alpha" and "Beta." These and other anomalously bright areas were later confirmed by workers at other facilities (Carpenter, 1966; Dyce et al., 1967; Rogers and Ingalls, 1969) during the middle and latter 1960s. At that time, each radar facility had its own informal system of nomenclature (Carpenter, 1966). In 1967, astronomers at the Arecibo facility, Puerto Rico, informally named features with high delay-Doppler frequencies for renowned physicists; one such feature that had not been recognized previously was named "Maxwell" (Jurgens, 1970). By 1969, circular areas of very low reflectivity had been recognized (Rogers et al., 1974), and in the early 1970s other circular and elongate features were discriminated on higher-resolution images.

When plans for the Pioneer Venus mission were completed, a Task Group for Venus nomenclature was established under the direction of the Working Group for Planetary System

TABLE B-1.– VENUS MYTHOLOGY

Venus – Roman goddess of love and beauty, grace, fertility
- *Vesper* – Latin, ancient Roman, evening star
- *Lucifer* – Latin, ancient Roman, morning star

Aphrodite – Greek goddess of love, beauty, fruitfulness
- *Hesperos* – Ancient Greek, evening star
- *Phosphoros* – Ancient Greek, morning star
- *Ouaiti* – Egypt, evening star
- *Tioumoutiri* – Egypt, morning star
- *Ruda* – Arab, evening star
- *Helel* – Hebrew, morning star

Ishtar (Istar) – Babylonia, Assyria, Mylitta, Chaldea, Sumeria

Astarte (Ashtarte) – Caanan, Phoenicia, Aramean, South Arabs, Egyptians

Athtar (Allat) – Arab

Ashtoreth – Biblical Israelite pagans

Anahita – Persia
- Above five names are pagan semitic goddesses of love, fertility, maternity, sexual activity, war

Tai-pe – China, beautiful white one

Freya (Freyja) – Teutonic goddess of love, beauty, fertility
- *Frija* – Old German
- *Frig (Friga)* – Anglo-Saxon; Friday – 6th day of week
- *Frigg (Freia)* – Old Norse

Chasca – Inca, goddess of love

Tlazolteotl – Mexico, goddess of love

Quetzalcoatl – Kukulcan – Post-classic Maya, lord of dawn

Noh Ek (Great Star), Chac Ek (Red Star), Sastal Ek (Bright Star), Ah Sahcab (Companion of the Aurora), Xux Ek (Wasp Star) – Mayan Venus

Cythera – Island birthplace of Venus

TABLE B-2.– VENUS NOMENCLATURE ASSIGNED

Name	Latitude	Longitude	Attribute
Chasmata (goddess of the hunt; Moon goddess); canyons			
Artemis	30–40S	125–145	Goddess of the hunt/Moon
Dali	21S	165	Goddess of the hunt
Devana	0	289	Goddess of the hunt
Diana	15S	150	Goddess of the hunt/Moon
Heng-o	348–358	50	Chinese Moon goddess
Craters (modern notable woman)			
Eve	32S	000	Symbolizes the first biblical woman
Colette	65N	322	French novelist and writer
Lise Meitner	55.5S	321.5	(1878–1968) German-Swedish physicist
Sacajawea	63N	335	(1786–1812) Shoshone Indian guide to the Lewis and Clark expedition to the Pacific Northwest
Patera (classical notable woman); irregular, possibly volcanic craters			
Cleopatra	70	65N	(69 B.C.–30 B.C.) Famous Egyptian queen; notable for her love affairs with Julius Caesar and Mark Anthony
Sappho	44N	.16E	(580–610 B.C.) Greek lyric poetess of great power
Theodra	280	23N	(508–548 B.C.) Wife of Justinian; most famous and powerful woman in Byzantine history. Influential in passing laws that first recognized the rights of woman
Linea (goddess and heroine of war); lines			
Antiope	40S	350	Amazon
Guor	20N	0	Valkyrie; Norse female warrior; means "battle"
Hariasa	19N	15	Germanic war goddess
Hippolyta	42S	345	Amazon
Kara	44S	306	Valkyrie maiden who, in Icelandic legend, sang so sweetly that the enemy could not defend themselves because of her singing
Lampedo	57N	29S	Amazon queen in Scythia
Molpadia	48S	359	Amazon
Vihansa	54N	20	War goddess
Montes; mountains			
Akna	+68N	318	Yucatan; goddess of birth
Freyja	+73N	335	Mother of Odin in Teutonic mythology
Hathor	25S	323E	Ancient Egyptian goddess of the sky
Maxwell	+65N	4	(1831–1879) James C. Maxwell; British physicist
Rhea	+32N	283E	Female titaness; Earth goddess
Theia	+25N	281E	Female titan in Greek mythology

Nomenclature of the International Astronomical Union. This group was charged with formulating a systematic plan for naming the features elucidated by the Pioneer Venus altimetric and imaging systems, as well as those features seen in a proliferating number of high-resolution Earth-based images. The Task Group chose a theme in keeping with the age-old feminine mystique associated with Venus (table B-1, researched and compiled by L. Colin): features would be named for females, both mythological and real, who were famed in the mythologies and histories of all world cultures. Circular, craterlike features would be named for notable historical women, whereas other features would bear the names of goddesses and heroines from myth and legend (IAU, 1977). The exceptions were the name "Alpha" (the first feature identified), which was retained from the informal nom-

TABLE B-2.– CONCLUDED

Name	Latitude	Longitude	Attribute
			Planum; plateaux
Lakshmi	67	330	Indian goddess of fortune and prosperity
			Plainitiae (heroines)
Aino	-45	90	Finnish heroine; Vainamoinen, one of the Kalevala heroes, wished to marry her; she became a water divinity and thus escaped him
Atalanta	+54	162	Atalanta swore she would only marry the man who could beat her at a footrace. Melanion dropped three golden apples during the race and was able to win the race when Atalanta stopped to pick them up
Guinevere	+40	310	Wife of King Arthur and beloved of Lancelot
Helen	-55	255	Wife of Menelaus; Paris, son of Priam of Troy, fell in love with her and carried her off to Troy thus precipitating the Trojan war
Lavinia	-45	350	Wife of Aeneas
Leda	+45	65	Wife of Tyndareus; Zeus, enamored of her charms, disguised himself as a beautiful swan and seduced her. She gave birth to Pollux and Helen (by Zeus) and Castor Clytemnestra (by Tyndareus)
Niobe	+38	132	Wife of Amphion of Thebes. She gave birth to 12 children, who were all killed by Artemis and Apollo
Sedna	+40	335	A beautiful Eskimo girl, who was wooed and won by a phantom bird who carried her off to a far shore. Sedna's father followed them, stole Sedna back, and started home with her. The phantom bird made a great storm come up, and the father, in fear, threw Sedna into the ocean. When she tried to climb back in the kayak, her father cut off parts of her fingers, which became seals, walruses, and whales
			Regiones (alphanumeric; female titans); regions
Alpha	20–30S	000–010E	First letter in the Greek alphabet
Asteria	18–30N	228–270	Greek titaness
Beta	20–35N	280–290E	Second letter in the Greek alphabet
Eisila	350–50	10–25N	Norse giantess
Imdr	211	42S	Norse giantess
Metis	62N	255	Greek titaness
Phoebe	+10–20	275–300	Greek titaness
Tellus	35N	80	Greek titaness
Tethus	55N	100	Greek titaness
Themis	-37–40	275–310	Greek titaness
Ulfran	220–230	108N–3S	Norse giantess
			Rupes (goddess of hearth, home); cliffs
Ut	48–53N	305–325	Turco-Tatar goddess of the hearth fire
Vesta	55–65N	295–355	Roman hearth goddess
			Terrae (goddesses of love); continents
Aphrodite	10–05N	075–130E	Greek goddess of love
Ishtar	60–75N	315–025E	Babylonian goddess of love

enclature; "Beta" (second feature identified), and "Maxwell" were also retained because these three names were by then well established in the radar literature. The Task Group compiled an extensive list of names; as the Pioneer Venus data were reduced to map format, names from the list were applied to conspicuous features shown on the maps.

The two most distinctive features on the topographic, reflectivity, and image maps of Venus are large radar-bright areas of highland terrain that are the size of terrestrial continents. These areas – Ishtar (Babylonian) and Aphrodite (Greek) Terrae – were named for goddesses of love; Ishtar Terra is also conspicuous in Earth-based images and on a mosaic compiled by the astronomers at Arecibo (Campbell et al., 1980). Linear highland regions, which usually are also radar bright, are named for other goddesses; examples are Akna and Freyja Montes (mountains). Akna was the goddess of birth worshipped in Yucatán; Freyja was the principal Norse goddess and mother of Odin (Maxwell Montes, mentioned above is an exception). A high, relatively flat, and radar-dark area is named Lakshmi Planum (plateau), to honor the Indian goddess of prosperity and fortune. Low quasi-circular or elongate lowland plains that are generally radar dark are named for mythological heroines; for example, Helen Planitia (plain) is named for the lady whose face "launched a thousand ships," while Sedna Planitia honors a beautiful Eskimo girl. Linear clefts or canyons (chasmata) in the Venusian surface are named for goddesses of the hunt or of the Moon. (Both attributes were often assigned to a single personage: Artemis was the Greek goddess of the hunt and of the Moon; Diana was her Roman counterpart.) Radar-bright linear features that coincide with an abrupt topographic change, such as a cliff (Rupes), are named for hearth goddesses; Vesta Rupes was named for the Roman goddess.

The names of notable deceased women were given to all circular features. Irregular craters at or near the summits of mountains were named for classical women; for example, Sappho Patera is named for the Greek poetess. Craters in plains areas are named for modern women, such as the physicist Lise Meitner.

The term "Regio" has been applied traditionally to any feature on a planetary surface that is not clearly defined or understood, ordinarily because attainable resolutions are insufficient. The term was applied first to the albedo features on Mars and has been used more recently for dark regions shown on Voyager images of Ganymede. On Venus, the term was originally used to describe the radar-bright features Alpha and Beta identified by Earth-based radar systems. It has now been extended to include regions of somewhat elevated terrain that are smaller than continents but do not necessarily appear as discrete features on other data sets. These features are named for titanesses and giantesses. Other features, the radar-bright linear regions known as lineae (lines), have such low topographic expression at Pioneer Venus resolutions that they are well shown only in reflectivity images; these features are named for goddesses and heroines of war, such as Hippolyta, the Greek leader of the Amazons, and Vihansa, the Teutonic war goddess. Features now designated as a linea or regio (region) may be given other generic feature designations at a later date if higher-resolution data obtained by future radar missions clarify their true geomorphic expression.

Names that have been applied to the features on Venus are listed in table B-2. Other names will unquestionably be added as the surface of Venus becomes better imaged and better understood.

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World Book Encyclopedia

Appendix C

PIONEER VENUS TEAM

A MANAGEMENT

NASA Headquarters

N. Hinners (later T. Mutch, B. I. Edelson) . . . . Associate Administrator for Space Science
V. Johnson (later A. J. Stofan) . . . . Deputy
R. S. Kraemer (later A. T. Young, A. Guastaferro, J. Moore) . . . . Director, Planetary Programs
S. I. Rasool (later G. A. Briggs) . . . . Deputy
F. D. Kochendorfer (later E. Montoya, F. Carr, G. Strobel) . . . . Pioneer Venus Program Manager
P. Tarver . . . . Deputy
R. F. Fellows (later R. E. Murphy, H. C. Brinton) . . . . Pioneer Venus Program Scientist
J. F. Yardley . . . . Associate Administrator for Space Transportation Systems
J. B. Mahon . . . . Director, Expendable Launch Vehicle Programs
F. R. Schmidt . . . . Manager, Atlas/Centaur
W. C. Schneider . . . . Associate Administrator for Space Tracking and Data Systems
A. C. Belcher . . . . Network Operations
M. E. Binkley . . . . Network Support

Ames Research Center

C. A. Syvertson . . . . Director
J. V. Foster (later D. R. Chapman, W. F. Ballhaus) . . . . Director of Astronautics
C. F. Hall (later R. O. Fimmel) . . . . Pioneer Venus Project Manager
R. R. Nunamaker . . . . Deputy Pioneer Venus Project Manager
L. Colin . . . . Pioneer Venus Project Scientist
R. W. Holtzclaw . . . . Spacecraft Systems Manager
J. Sperans . . . . Experiment Systems Manager
R. J. Hofstetter . . . . Mission Operations Manager
W. M. Hawkins . . . . Project Adviser
D. C. Sewell . . . . Project Adviser
H. LaGow . . . . Project Adviser

Jet Propulsion Laboratory

B. C. Murray . . . . Director
R. E. Ryan . . . . Operations Planning and Coordination
R. B. Miller (later A. Berman) . . . . Tracking and Data Systems Manager
E. S. Burke, Jr. . . . . Supervisor, DSN Operations Planning Group
W. Kirhoffer (later S. K. Wong) . . . . Navigation Team Chief
D. W. Johnson (later A. Bouck, J. Nash) . . . . Network Operations Project Engineer

Lewis Research Center

J. McCarthy . . . . Director
L. J. Ross . . . . Chief, Vehicles Engineering Division
C. B. Wentworth . . . . Chief, Program Integration Division
E. Muckley . . . . Mission Project Engineer

ORIGINAL PAGE IS
OF POOR QUALITY

Hughes Aircraft Company

A. D. Whelan . . . . Vice President and General Manager, Space and Communications Group
H. Palmer . . . . Manager, NASA Programs Division
S. Dorfman . . . . Pioneer Venus Program Manager

Pioneer Project Team, Ames Research Center

H. Asch
C. R. Ball
J. G. Ball
T. L. Bridges
J. H. Camp
T. Canning
B. Chin
R. A. Christiansen
R. E. Corridan
S. J. Cosgrove
J. R. Cowley, Jr.
R. A. Craig
D. M. Cusano
D. E. Davis
S. DeLoura
F. F. DeMuth
C. E. Derose
L. W. Dickerson
J. A. D'Urso
J. W. Dyer
R. L. Edens
L. Edsinger
J. A. Ferandin
A. R. Fernquist
R. O. Fimmel
J. L. Frank
W. O. Garden, Jr.
R. S. Gittelson
J. J. Givens
C. F. Hall
V. A. Henderson
W. D. Hightower
S. M. Hing
R. U. Hofstetter
R. P. Hogan
R. W. Holtzclaw
S. R. Huntley
J. J. Hurt
P. F. Intrieri
E. J. Iufer
R. W. Jackson
G. C. James
E. Jesse
M. F. Johnson
R. D. Johnson
T. Kato
J. Keeler
C. H. Keller
C. A. Leidich
J. E. Lepetich
K. Lincoln
D. W. Lozier
J. E. Maghan
A. Mandell
L. A. Manning
E. L. Z. Miller
J. R. Mulkern
J. P. Murphy
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G. J. Nothwang
V. A. Noyer
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L. M. Peckham
J. R. Phillips
R. B. Pittman
B. Podrick
J. F. Pogue
L. J. Polaski
E. G. Polk Jr.
D. L. Porter
F. Y. Prevost
R. Ramos
J. A. Rubenzer
G. F. Schimmel
G. A. Schroeder
G. L. Shillinger
R. Simin
D. B. Sinnott
G. S. Smith
E. S. Somer
S. C. Sommer
J. R. Spahr
J. Sperans
J. E. Terhune
G. W. Thorley
E. Tischler
D. A. Tristram
R. J. Twarowski
J. C. VanEss
P. W. Waller
T. T. Weber
A. J. Wilhelmi
M. E. Wilkins
M. N. Wirth
T. Wong
L. Yee

SUPPORT SERVICES CONTRACTOR

Bendix Field Engineering Corporation

P. J. Barclay
D. E. Bass
S. H. Campbell
R. A. Campo
G. R. Chavez
J. M. Coronado
P. Davisson
R. A. Davisson
J. R. Eagle
J. Garcia
T. F. Groves
F. B. Gullett
A. Gutierrez
K. W. Hartgraves
C. J. Hay
C. M. Jackson
K. C. Jednorozec
K. L. Jones
S. A. Kusalo
C. M. Larsen
C. L. McGhan
J. G. Mearns
R. D. Pak
J. O. Ragle
J. Revillar
J. E. Rork
T. L. Saunders
K. R. Schmidt
P. L. Shoals
J. L. Smith
J. L. Swiatek
R. Thompson
R. L. Weaver
C. M. West
T. E. Young
G. U. Zamora

B SCIENCE TEAMS

Orbiter Cloud Photopolarimeter

Principal Investigator
J. E. Hanson (later L. D. Travis)
Goddard Institute for Space Studies

Co-Investigators
Goddard Institute for Space Studies
D. L. Coffeen
K. Kawabata
A. A. Lacis
W. A. Lane
E. K. Rivas
P. H. Stone

Orbiter Electric Field Detector

Principal Investigator
F. L. Scarf
TRW Systems

Co-Investigator
TRW Systems
I. M. Green
W. W. L. Taylor

Orbiter Electron Temperature Probe

Principal Investigator
L. H. Brace
Goddard Space Flight Center

Co-Investigators
T. M. Donahue, University of Michigan
M. B. McElroy, Harvard University
A. F. Nagy, University of Michigan
A. Pedersen, European Space Agency

Orbiter Gamma Ray Burst Detector

Principal Investigator
W. D. Evans
Los Alamos Scientific Laboratory

Co-Investigators
Los Alamos Scientific Laboratory
J. P. Connor
P. R. Higbie
R. W. Klebesadel
R. A. Olson
I. B. Strong
Sandia
R. E. Spalding

Orbiter Ion Mass Spectrometer

Principal Investigator
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Goddard Space Flight Center

Co-Investigators
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R. E. Hartle
J. R. Herman
University of Graz, Austria
S. J. Bauer
Rice University
P. A. Cloutier
F. C. Michael
University of Michigan
T. M. Donahue

Orbiter Magnetometer

Principal Investigator
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University of California, Los Angeles

Co-Investigators
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R. C. Elphic
C. F. Kennel
J. G. Luhmann
R. L. McPherron
G. L. Siscoe

Orbiter Neutral Mass Spectrometer

Principal Investigator
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Goddard Space Flight Center

Co-Investigators
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G. E. Carignan
Goddard Space Flight Center
R. E. Hartle
N. W. Spencer
University of Arizona
D. M. Hunten

Orbiter Radar Mapper

Team Leader
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Massachusetts Institute of Technology

Team Members
Jet Propulsion Laboratory
W. E. Brown
University of California, Los Angeles
W. H. Kaula
US Geological Survey
H. Masursky
University of Massachusetts
G. E. McGill

Orbiter Retarding Potential Analyzer

Principal Investigator
W. K. Knudsen
Lockheed Missiles and Space Company

Co-Investigators
Lockheed Missiles and Space Company
K. L. Miller
IPW, Germany
K. Spenner
Stanford University
J. R. Spreiter
Ames Research Center
R. C. Whitten

Orbiter Plasma Analyzer

Principal Investigator
J. H. Wolfe (later A. Barnes)
Ames Research Center

Co-Investigators
Ames Research Center
H. R. Collard
D. D. McKibbin
J. D. Mihalov
R. C. Whitten
University of California, Los Angeles
F. V. Coroniti
Carmel Research Center
D. S. Intriligator

Orbiter Infrared Radiometer

Principal Investigator
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Oxford University, United Kingdom

Co-Investigators
Jet Propulsion Laboratory
R. Beer
M. T. Chahine
D. J. Diner
L. C. Elson
C. B. Farmer
J. V. Martonchik
National Center for Atmospheric Research
J. C. Gille
University of Oxford, United Kingdom
J. T. Houghton
G. D. Peskett
C. D. Rogers
E. J. Williamson
California Institute of Technology
A. P. Ingersoll

Orbiter Ultraviolet Spectrometer

Principal Investigator
A. I. Stewart
University of Colorado

Co-Investigators
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D. E. Anderson, Jr.
C. A. Barth
L. B. Esposito
C. W. Hord
G. E. Thomas

Orbiter and Multiprobe Radio Science

Team Leader
G. H. Pettengill
Massachusetts Institute of Technology

Team Members
Lunar and Planetary Institute
R. J. Phillips
Jet Propulsion Laboratory
A. J. Kliore
W. L. Sjogren
R. Woo
Massachusetts Institute of Technology
I. I. Shapiro
R. D. Reasenberg
SRI International
T. A. Croft
Langley Research Center
G. M. Keating

Multiprobe (Bus) Ion Mass Spectrometer

Same as Orbiter Ion Mass Spectrometer

Multiprobe (Bus) Mass Spectrometer

Principal Investigator
U. von Zahn
University of Bonn, Germany

Co-Investigators
University of Arizona
D. M. Hunten
Max-Planck Institute
D. Krankowsky
University of Minnesota
K. Mauersberger
A. O. Nier

Large/Small Probe Atmosphere Structure

Principal Investigator
A. Seiff
Ames Research Center

Co-Investigators
Langley Research Center
R. C. Blanchard
US Geological Survey
J. Derr
Ames Research Center
D. B. Kirk
S. C. Sommer
R. Young

Large Probe Cloud Particle Size Spectrometer

Principal Investigator
R. G. Knollenberg, Particle Measuring Systems, Inc.

Co-Investigator
D. M. Hunten, University of Arizona

Large Probe Gas Chromatograph

Principal Investigator
V. I. Oyama
Ames Research Center

Co-Investigators
Ames Research Center
W. Berry
G. C. Carle
J. B. Pollack
F. H. Woeller

Large Probe Infrared Radiometer

Principal Investigator
R. W. Boese
Ames Research Center

Co-Investigators
Ames Research Center
L. P. Giver
J. H. Miller
J. B. Pollack

Large Probe Mass Spectrometer

Principal Investigator
J. H. Hoffman
University of Texas, Dallas

Co-Investigators
T. M. Donahue, University of Michigan
R. R. Hodges, Jr., University of Texas, Dallas
M. A. Kolpin, TRW Systems
M. B. McElroy, Harvard University

Large/Small Probe Nephelometer

Principal Investigators
- B. Ragent, Ames Research Center
- J. Blamont, University of Paris

Large Probe Solar Flux Radiometer

Principal Investigator
- M. G. Tomasko, University of Arizona

Co-Investigator
- W. L. Wolfe, University of Arizona

Small Probe Net Flux Radiometer

Principal Investigator
- V. E. Suomi
- University of Wisconsin

Co-Investigators
- Jet Propulsion Laboratory
  - G. E. Danielson
  - A. L. Fymat
- University des Sci. Tech.
  - M. Herman
  - J. Lenoble
- University of Wisconsin
  - L. A. Sromovsky

Multiprobe Differential Long-Baseline Interferometry

Principal Investigator
- C. C. Counselman
- Massachusetts Institute of Technology

Co-Investigators
- Massachusetts Institute of Technology
  - G. H. Pettengill
  - R. Prinn
  - I. I. Shapiro

Interdisciplinary Scientists

S. Bauer, University of Graz, Austria
T. Donahue, University of Michigan
R. Goody, Harvard University
D. Hunten, University of Arizona
J. Pollack, Ames Research Center
N. Spencer, Goddard Space Flight Center
H. Masursky (Associate, E. Eliason), US Geological Survey
G. McGill, University of Massachusetts
A. Nagy (Associate, T. E. Cravens), University of Michigan
G. Schubert (Associate, C. C. Covey), University of California, Los Angeles

Guest Investigators

C. Bowin, Woods Hole Oceanographic Institute
M. Dryer, National Oceanic and Atmospheric Administration
J. Fox, Smithsonian Institution
J. Gerard, University of Liege, Belgium
S. Kumar, University of Southern California
L. Limaye, University of Wisconsin
H. Perez-de-Tejada, University of Mexico
P. Rodriguez, Naval Research Laboratory
R. Wolff, Jet Propulsion Laboratory
A. Young, San Diego State University

C CONTRACTORS

Aiken Industries, Inc., College Park, Md. .... Multiprobe Bus and Orbiter Ion Mass Spectrometers
Arcturns Manufacturing Co., Oxnard, Calif. .... Pressure Vessel Forgings
Ball Brothers Research Corp., Boulder, Colo. .... Large Probe Infrared Radiometer and Cloud Particle Size Spectrometer
Star Sensors
Bendix Field Engineering Corp., Sunnyvale, Calif. .... Mission Operations and Software Development
DCA Reliability Laboratory, Mountain View, Calif. .... Electronic Parts Procurement and Screening
Eagle-Picher Industries, Inc., Joplin, Mo. .... Silver-zinc Battery Cell
Frequency Electronics, Inc., New Hyde Park, N.Y. .... Stable Oscillators
General Dynamics, Convair Division, San Diego, Calif. .... Launch Vehicle
General Electric Co., Gainesville, Fla. .... Nickel-cadmium Battery Cell
General Electric Co., Philadelphia, Pa. .... Deceleration Modules
Hughes Aircraft Co., Data Systems Division, Culver City, Calif. .... Data Storage Unit
Hughes Aircraft Co., Space and Communications Group, El Segundo, Calif. . . Prime Contractor, Spacecraft Radar Mapper
IPW, Freiburg, W. Germany .... Orbiter Retarding Potential Analyzer
Jet Propulsion Laboratory, Pasadena, Calif. .... Orbiter Infrared Radiometer
Multiprobe and Orbiter Ground-based Radio Science Experiments
Lockheed Missiles and Space Company, Sunnyvale, Calif. .... Orbiter Retarding Potential Analyzer
Los Alamos Scientific, Los Alamos, New Mexico .... Orbiter Gamma Ray Burst Detector
Martin Marietta Corp., Denver, Colo. .... Large Probe Solar Flux Radiometer Electronics
Massachusetts Institute of Technology, Cambridge, Mass. .... Multiprobe and Orbiter Ground-based Radio Science Experiments
Motorola Inc., Phoenix, Ariz. .... Transponders
Newbrook Machine Corp., Silver Creek, N.Y. .... Pressure Vessel Machining
Northrop Corp., Los Angeles, Calif. .... Thermal Louvers
Particle Measuring Systems, Inc., Boulder, Colo. .... Large Probe Cloud Particle Size Spectrometer
Sandia Laboratories Albuquerque, New Mexico .... Orbiter Gamma Ray Burst Detector
Santa Barbara Research Center, Santa Barbara, Calif. .... Orbiter Cloud Photopolarimeter
Siliconix, Inc., Santa Clara, Calif. .... Input Buffers
Southwest Research Institute, San Antonio, Texas .... Pressure Vessel Testing
SRI International, Menlo Park, Calif. .... Multiprobe and Orbiter Ground-based Radio Science Experiments
Walter V. Staley, Inc. .... Reliability and Quality Assurance
Systron-Donner, Concord, Calif. .... Large and Small Probe Accelerometers
Thiokol Chemical Co., Elkton, Md. .... Orbit Insertion Motor
TRW Systems Group, Redondo Beach, Calif. .... Large and Small Probe Nephelometers
Orbiter Electric Field Detector
University of Arizona, Tucson, Ariz. .... Large Probe Solar Flux Radiometer Sensor
University of Bonn, Bonn, W. Germany .... Multiprobe Bus Neutral Mass Spectrometer
University of California, Los Angeles, Calif. .... Orbiter Magnetometer
University of Colorado, Boulder, Colo. .... Orbiter Ultraviolet Spectometer
University of Minnesota, Minneapolis, Minn. .... Multiprobe Bus Neutral Mass Spectrometer
University of Texas, Dallas, Texas .... Large Probe Neutral Mass Spectrometer
University of Wisconsin, Madison, Wis. .... Small Probe Net Flux Radiometer
Western Aerospace Laboratories, Gardena, Calif. .... Large and Small Probe Atmosphere Structure Instruments
Orbiter Plasma Analyzer
Westinghouse, Inc., Baltimore, Md. .... Orbiter Magnetometer

Appendix D

PIONEER VENUS AWARD RECIPIENTS

Distinguished Service Medals
- Lawrence Colin
- Charles F. Hall

Outstanding Leadership Medals
- Robert U. Hofstetter
- Ralph W. Holtzclaw
- Joel Sperans

Distinguished Public Service Medals
- John M. Bozajian
- Thomas M. Donahue
- Steve D. Dorfman
- C. Malcolm Meredith

Exceptional Service Medals
- John E. Ainsworth
- Thomas L. Bridges
- Dean R. Chapman
- John W. Dyer
- Richard O. Fimmel
- Robert S. Gittelson
- John J. Givens
- Ernest J. Iufer
- Robert W. Jackson
- Marshall S. Johnson
- Carl H. Keller
- William E. Kirhofer
- Richard B. Miller
- Edwin T. Muckley
- George J. Nothwang
- Robert R. Nunamaker
- Barry Olton
- Vance I. Oyama
- Louis J. Polaski
- Boris Regent
- Ruben Ramos
- David B. Sinnott
- Simon C. Sommer
- J. Richard Spahr
- Gary W. Thorley
- Edward Tischler
- Peter W. Waller
- Manfred N. Wirth

Exceptional Scientific Achievement Medals
- Charles C. Counselman, III
- Donald M. Hunten
- Robert G. Knollenberg
- Harold Masursky
- Hasso B. Niemann
- Gordon H. Pettengill
- James B. Pollack
- Alvin Seiff
- Nelson W. Spencer
- A. Ian Stewart
- Verner E. Suomi
- Fred W. Taylor
- Martin G. Tomasko

Group Achievement Awards
- Ames Pioneer Venus Project Team
  - Ames Research Center
- Ames Research Center Support
  - Ames Research Center
- Reliability and Quality Assurance Team
  - Ames Research Center
  - Walter V. Sterling, Inc.
- Pioneer Venus Study Team
  - Ames Research Center
- Pioneer Venus Orbiter Science Team
  - Ames Research Center
  - Goddard Institute for Space Studies
  - Goddard Space Flight Center
  - Jet Propulsion Laboratory
  - Langley Research Center
  - Los Alamos Scientific Laboratory
  - Naval Research Center
  - Office of Naval Research
  - U.S. Geological Survey
  - Massachusetts Institute of Technology
  - Rice University
  - Stanford University
  - University of California at Los Angeles
  - University of Colorado
  - University of Massachusetts
  - University of Michigan
  - University of Oxford
  - University of Southern California
  - Applied Science Associates, Inc.
  - Ball Aerospace Systems Division

Group Achievement Awards (continued)

Computer Science Corporation
Computer Science and Technicolor Associates, Inc.
Electric Construction Company
Environmental Research Institute of Michigan
Hughes Aircraft Company
Lockheed Palo Alto Research Laboratories
Norlin Industries
Sandia Laboratories
Santa Barbara Research Center
SRI International
TRW Defense and Space Systems Group
Ultramet Corporation
Westinghouse Aerospace Division
Institut fur Physikalische Weltraumforschung
Messerschmitt-Boelkow-Blohm

Pioneer Venus Multiprobe Science Team
Ames Research Center
Goddard Space Flight Center
Jet Propulsion Laboratory
Langley Research Center
Harvard University
Massachusetts Institute of Technology
Rice University
University of Arizona
University of Bonn
University of Michigan
University of Minneapolis
University of Texas at Dallas
University of Wisconsin
Analytical Mechanics Associates
Ball Aerospace Systems Division
Computer Science and Technology Associates, Inc.
Informatics, Inc.
Martin-Marietta Corporation
Norlin Industries
Particle Measuring Systems, Inc.
Systems Consultants, Inc.
Technology, Inc.
TRW Defense and Space Systems Group
Max Planck Institut fur Kernphysik

Launch Vehicle Team
Lewis Research Center
John F. Kennedy Space Center

Pioneer Venus Ground Data Systems Operations Team
Jet Propulsion Laboratory
Bendix Field Engineering Corporation

Pioneer Venus Multiprobe Data Acquisition Implementation Team
Jet Propulsion Laboratory
Spectral Dynamics Corporation
Martin-Marietta Corporation

Pioneer Venus Mission Navigation Team
Jet Propulsion Laboratory

Pioneer Venus Project Advisory Committee

Public Service Medals

Gary D. Figgins
Richard M. Goody
Thomas F. Groves
Anthony M. Lauletta, Jr.
Arnold L. Neil
Leo J. Nolte
Louis R. Pochettino
D. S. Stephenson

Public Service Group Achievement Awards

Pioneer Venus Ground Data Processing Software Team
Bendix Field Engineering Corporation

Pioneer Venus Mission Operations Support Team
Bendix Field Engineering Corporation

Pioneer Venus Parts Screening Team
DCA Reliability Laboratory

Pioneer Venus Spacecraft Team
Hughes Aircraft Company

Pioneer Venus Probe Deceleration Module Team
General Electric Company

Pioneer Venus Spacecraft Transponders and Exciters Team
Motorola, Inc.

Pioneer Venus Probe Pressure Vessel Team
Newbrook Machine Corporation

Pioneer Venus Spacecraft Star Sensor Team
Ball Aerospace Systems Division

Appendix E

SCIENCE RULES AND WORKING GROUPS

A. Rules of the Road for Pioneer Venus Investigators

The Pioneer Venus Science Steering Group developed a set of procedures and rules for themselves to assure an orderly and efficient analysis and interpretation of the mission's scientific results. These rules are listed here for historical interest and to suggest their applicability to future projects of this nature.

1) Instrument Principal Investigators, Radio and Radar Science Team members, and Interdisciplinary Scientists (among whom the project scientist is included for the purpose of these rules) will be designated PVIs; investigators (research projects involving unpublished PV data) may be sponsored only by PVIs.

2) Each instrument PVI is responsible for the analysis and interpretation of data obtained by his instrument. He and his co-investigators (Co-Is) are responsible for the initial analysis, interpretation, and publication of these data. *During the three months following the acquisition of any data by the PVI he should identify the investigations he, his Co-Is, and associates expect to pursue with these data.* (Associates are people such as graduate students or post doctoral research fellows who are clearly identified as associated with the PVI or his Co-Is. Normally the criterion would be funding for their salaries through PV data analysis contracts. They would specifically not be senior independent scientists who belong to the same institution as the PVI or Co-I.)

3) PVIs and Co-Is have free access to all data acquired during the mission (and extended mission) and publications resulting from the use of those data. The normal vehicle for data dissemination will be the Unified Abstract Data System (UADS).

4) Any PVI whose unpublished data are to be used in an investigation has the right to be included among the authors of any publication that results. During the formative stages of an investigation it is the responsibility of the sponsoring investigator to solicit the participation of the PVI whose data or results are to be used. The PVI whose cooperation is solicited may refuse coauthorship but not the use of his data. He must, however, provide information concerning the quality of the data in question and may require that suitable caveats regarding the data be included in the publications.

5) The role of an IDS (Interdisciplinary Scientist) in this mission is to enhance the scientific output of the mission by promoting investigations that involve data obtained from a multitude of instruments, i.e., more than one. It is hoped that the IDSs will be able to promote cooperation among other PVIs and also that such unusual insights as the IDSs may possess will be exploited by the other PVIs to enrich the interpretation of the data obtained from specific instruments as well as from an ensemble of instruments. Thus IDSs will normally be expected to participate in investigations that involve data from more than one instrument. *This may occur either as a result of their proposing such investigations or their being invited to participate in investigations by other PVIs.* When an investigation is to be proposed by a group of PVIs in an area in which an IDS is known to be a specialist, normal procedure will be to invite him to participate. *After the 3-month period defined in rule 2 an IDS may propose an investigation involving data produced by a single instrument;* Co-Is of the PVI responsible for that instrument also have a right to participate in that investigation and they may ask their associates to participate as well.

6) PVIs or Co-Is may not preempt major science areas for themselves. An investigation should be pursued promptly.

7) Scientific Working Groups will normally provide the forum in which investigations are discussed. *Titles and descriptions of proposed investigation should be sent to the Project Scientist. He will serve as the interface between investigators, project, and other PVIs. In particular he will inform all PVIs of proposed new investigations.* Objections or comments by other PVIs should be communicated to the Co-chairmen of the SSG for adjudication or other appropriate action.

8) PVIs may release their own data to whomever they wish but not data of other PIs without consent.

9) There is no PV mission policy with regard to paper form or publication medium, except for a possible agreement with regard to publication of initial results of the mission.

10) Independent scientists who are not mission PVIs, Co-Is, or associates may participate in an investigation provided:

a) They are sponsored by a PVI.

b) They provide suitable correlative data to be channelled to other PVIs through the sponsoring PVI.

c) The approval of the rest of the PVIs is obtained prior to the initiation of the investigation and a letter of invitation and cooperation issued by the SSG.

B. Pioneer Venus Working Groups

The Pioneer Venus Science Steering Group developed a set of six Working Groups that would address particular disciplines: Composition and Atmosphere Structure; Clouds; Dynamics; Thermal Balance; Solar Wind, Ionosphere, and Aeronomy; and Surface and Interior. These Working Groups were very successful and produced group papers synthesizing results from the various experiments.

COMPOSITION/ATMOSPHERE STRUCTURE WORKING GROUP

Primary

J. Hoffman (LNMS) – Chairman
A. Stewart (OUVS)
V. Oyama (LGC)
U. von Zahn (BNMS)
H. Niemann (ONMS)
A. Seiff (LAS/SAS)
D. Hunten (IS)
N. Spencer (IS)
T. Donahue (IS)
G. Keating (RADIO)
A. Kliore (RADIO)

Secondary

F. Taylor (OIR)
R. Knollenberg (LCPS)
H. Taylor (OIMS)
R. Goody (IS)
A. Nagy (IS)
J. Pollack (IS)
T. Croft (RADIO)

CLOUDS WORKING GROUP

Primary

R. Knollenberg (LCPS) – Chairman
R. Ragent (LN/SN)
F. Taylor (OIR)
J. Hansen (OCPP)

Secondary

A. Stewart (OUVS)
V. Oyama (LGC)
M. Tomasko (LSFR)
V. Suomi (SNFR)
D. Hunten (IS)
J. Pollack (IS)
T. Croft (RADIO)

DYNAMICS WORKING GROUP

Primary

G. Schubert (IS) – Chairman
C. Counselman (DLBI)
F. Taylor (OIR)
A. Seiff (LAS/SAS)
J. Hansen (OCPP)
R. Woo (RADIO)
T. Croft (RADIO)

Secondary

G. Pettengill (RADIO)
U. von Zahn (BNMS)
V. Suomi (SNFR)
R. Goody (IS)
J. Pollack (IS)

THERMAL BALANCE WORKING GROUP

Primary

M. Tomasko (LSFR) – Chairman
F. Taylor (OIR)
R. Boese (LIR)
A. Seiff (LAS/SAS)
J. Hansen (OCPP)
V. Suomi (SNFR)
R. Goody (IS)
J. Pollack (IS)

Secondary

A. Stewart (OUVS)
V. Oyama (LGC)
D. Hunten (IS)

SOLAR WIND/IONOSPHERE AERONOMY WORKING GROUP

Primary

S. Bauer (IS) (later A. Nagy (IS)) – Chairman
I. Stewart (OUVS)
F. Scarf (OEPD)
C. Russell (OMAG)
L. Brace (OETP)
H. Taylor (OIMS)
W. Knudsen (ORPA)
A. Barnes (OPA)
formerly J. Wolfe (OPA)
N. Spencer (IS)
T. Donahue (IS)
T. Croft (RADIO)

Secondary

U. von Zahn (BNMS)
H. Niemann (ONMS)
D. Hunten (IS)
G. Keating (RADIO)
A. Kliore (RADIO)

SURFACE/INTERIOR WORKING GROUP

Primary

H. Masursky (IS) – Chairman
C. Russell (OMAG)
G. Pettengill (ORAD)
W. Kaula (ORAD)
G. McGill (IS)
R. Phillips (RADIO)
I. Shapiro (RADIO)

Secondary

V. Oyama (LGC)
G. Schubert (IS)

C. Key Scientific Questions

Prior to launch of the Pioneer spacecraft, the six PVSSG Working Groups each developed a set of key scientific questions that their members and the associated experiments could and would address during the mission. These were as follows.

COMPOSITION AND STRUCTURE WORKING GROUP

Key Questions

- Present state of atmosphere
  - Lower atmosphere composition
    - Apart from CO_2, what does the lower atmosphere consist of, and how are these constituents distributed?
    - What are the clouds made of?
    - What does the atmosphere tell us about the planet's surface and interior?
  - Lower atmosphere structure
    - How do the state property profiles vary over the planet?
    - Why is the lower atmosphere so hot?
    - What role do phase changes play in the thermal structure?
  - Upper atmosphere composition and structure
    - What are the composition and temperature profiles of the upper atmosphere and where is the homopause?
    - What are the spatial and temporal variations in the Venusian upper atmosphere?
    - Is the stability of CO_2 due to global circulation or local turbulence?

- How does the neutral composition influence the ionosphere and the thermal structure?
- Does superrotation extend into the thermosphere?
- How does the upper atmosphere respond to changes in solar EUV and solar wind?

- Origin and evolution of the Venus atmosphere
  - Where did the atmosphere come from and where is it going?
  - Where is the water?
  - Why does the atmosphere of Venus differ so much from that of Earth?

CLOUDS WORKING GROUP

Key Questions

- What is the planetary cloud structure in altitude and horizontally?
- How deep do the H_2SO_4 clouds extend?
- Do larger particles or denser clouds (higher concentation) exist at lower levels? What is their composition?
- Is the concentration of cloud particles proportional to gas pressure so that the scale heights of the particles and gas are identical?
- What substance is responsible for the UV absorption contrasts? Is the UV absorber well-mixed vertically and not horizontally?
- What is the structure and composition of the thin haze layers above the visible cloud deck (70-90 km)? Do they correlate with the Mariner 10 radio-occultation inversions?
- What is the nature of the observed white polar caps?
- Is there aeolian transport of dust within 10 km of the surface?
- What are the couplings between the cloud microphysics and Venusian dynamics? What are the cloud optical properties?
- What are the cloud formation and dissipation mechanisms? Coalescence? Coagulation? Condensation? Evaporation? Precipitation? Why is the cloud size spectrum so narrow?

THERMAL BALANCE WORKING GROUP

Key Questions

- What is the cause of the high surface temperature? If it is the Greenhouse Effect what are the sources, other than CO_2, of the infrared opacity?
- Why are there small horizontal temperature contrasts near the cloud tops in the presence of strong apparent motions?
- Why are there small horizontal temperature gradients (both day-night and equator-pole) at the cloud tops and near the surface despite an expected strong variation in the local deposition of solar energy over the illuminated hemisphere?
- Why is the exospheric temperature so low?
- What are the roles of radiative and dynamical processes in maintaining the thermal balance of the atmosphere?
- What is the global (vertical, horizontal) temperature structure? How is it determined by dynamical heat transport?
- Where are the sources and sinks of heating by solar and thermal radiation fields?
- What are the cloud optical properties?
- Do latent heat effects on convection produce subadiabatic regions in the generally adiabatic-looking vertical temperature profiles? Is the nearly adiabatic structure due to small-scale convection or planet-wide circulation?

DYNAMICS WORKING GROUP

Key Questions

- Upper atmosphere circulation
  - Is the apparent 4-day rotation an actual zonal motion of the atmosphere or is it a wave phenomenon?
  - Do retrograde 100 ms^{-1} upper atmosphere zonal winds flow all around the planet, even in the antisolar region?
  - Is there a longitude-dependence of the speed of the zonal motion, especially with respect to the subsolar region?
  - What is the latitude-dependence of the apparent zonal wind velocities?
  - What is the altitude-dependence of the zonal wind velocities? Is there essentially a decoupling of the upper atmosphere from the lower, with the large zonal winds confined mainly to the upper atmosphere?
  - What are the magnitudes of meridional motions?
  - What mechanism drives the rapid zonal circulation of the upper atmosphere?

- Lower atmosphere circulation
  - What is the nature of the circulation of the lower atmosphere? Are the motions primarily zonal or meridional? What is the magnitude of the velocity? If the motions are meridional do they represent a Hadley cell circulation? If the motions are zonal is there an overall rotation of the lower atmosphere or is the circulation between subsolar and antisolar points? Are there unique motions (e.g., small-scale convection) near the subsolar, antisolar and polar regions in the deep atmosphere?

- Vertical flow and convection
  - Are there strong upward and downward convective motions? What are the horizontal scales of convective cells? What are the magnitudes of vertical velocities?

- Waves and instabilities
  - Are there any wave-like phenomena or instabilities that can be identified as occurring in the atmosphere?

- Distinctive features in the Mariner 10 imagery
  - What atmospheric processes are responsible for the circumequatorial belts, bow waves, spiral streaks, polar ring, and other distinctive features in the Mariner 10 pictures?

- Turbulence and eddy diffusion
  - What is the intensity of turbulence in the atmosphere? What are the altitudes of turbulent layers? What are their thicknesses? What are the turbulent eddy diffusion coefficients?

- Thermal contrast and energy deposition
  - What are the horizontal temperature contrasts which drive the atmospheric motions? What is the distribution of solar energy deposition in the atmosphere?

- Phase changes
  - Do phase changes and the associated latent heats of condensible species play an important role in the atmospheric dynamics?

- Nature of UV clouds
  - What material(s) and physical process(es) are responsible for the UV albedo variations?

IONOSHPERE AND SOLAR WIND WORKING GROUP

Key Questions

- Venus ionosphere
  - What is the ion composition and what controls the plasma distribution of the Venus ionosphere?
  - What is the plasma temperature of the Venus ionosphere and what controls its thermal structure?
  - What are the mechanisms and the significance of mass, momentum, and energy transfer from the solar wind to the upper atmosphere/ionosphere?
- Solar wind – Venus interaction
  - Is there an intrinsic magnetic field?
  - How do ionospheric currents contribute to the deflection of the solar wind?
  - How important are processes such as charge-exchange and mass-addition?
  - What is the source of the variability of the dayside ionosphere?
  - How much of the solar wind is absorbed by the ionosphere?
  - Is there a magnetotail?
  - Is there a plasma sheet?
  - Are there substorms on Venus?
  - How does the plasma close behind the planet?
  - What maintains the nightside ionosphere?
  - What produces the two peaks in the electron density profile in the nightside ionosphere? What causes their variability?
  - What is the source of the nighttime airglow and the ashen light?
  - Is there a boundary layer or rarefaction region in the flow?
  - How does the Venus bow shock and upstream region differ from that of the Earth?

SURFACE AND INTERIOR WORKING GROUP

Key Questions

- What is the extent of endogenic activity leading to tectonics, crustal differentiation, and volcanism?
- What is the extent of exogenic processes such as impact cratering, weathering, and transportation and erosion of surface materials by winds and crustal recycling?
- What is Venus' gravity-field distribution? Is there evidence of density contrasts?
- Are tectonic features evident on the surface: arcuate mountain systems, strip-like faults of large displacement, rifts, volcanic craters or chains of volcanic craters?
- Does the interior of Venus consist of an iron core and a mantle of magnesium and iron silicates (like Earth)?
- What is, and what is the cause of, the offset of the center-of-mass from the center-of-figure?
- What is the subsurface temperature gradient? What has been Venus' thermal history?
- Can the slow retrograde spin of Venus be explained by an exogenic effect such as solar tidal torque or a planetesimal impact?
- Does Venus possess an intrinsic magnetic field? How large is it?
- Is the surface in thermal and chemical equilibrium with the lower atmosphere?
- Is there a resonant lock between Venus' spin period and the relative orbital motions of Earth and Venus?
- Is Venus further along than Earth along the evolutionary path toward the end of complete compositional stratification and thermal quiescence?

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This bibliography contains a chronological listing of journal articles, conference/meeting papers, and reports on the Pioneer Venus Program that have been published through May 1982. The listing is considered to be complete in that it comprises all the various aspects of any space project: programmatics, mission information, engineering and technological studies, scientific objectives, and scientific results. The papers listed are authored only by people officially associated with the program.

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Currently Project Manager for the Pioneer Venus project and for all other Pioneer missions at Ames Research Center, NASA, Moffett Field, California, Richard Fimmel was previously responsible for encounter planning for the Pioneer missions to Jupiter and Saturn. As Science Chief for the Pioneer Project, he planned for and operated the science instruments on both spacecraft during the encounters, for which he was awarded the NASA Exceptional Service Medal. For his leadership in planning and directing the science-related activities of the Pioneer Venus Orbiter mission, he was also awarded the NASA Exceptional Service Medal. He has been an invited consultant to the German Space Agency (DFVLR) for the HELIOS and AMPTE missions.

Richard Fimmel is a research scientist at Ames Research Center with over 27 years of experience in research, design, development, and management of instrumentation, computers, and data systems. He was project manager for the MOBIDIC computer development at the Signal Corps Research and Development Laboratory, and manager of the Computer Products Department in Ampex International Operations.

He received a BSEE in 1949 from Rutgers University, New Brunswick, New Jersey, and an MSEE in 1954. A member of the Institute of Electrical and Electronics Engineers and the American Geophysical Union. Richard Fimmel is coauthor of a book on the Pioneer missions to Jupiter, Saturn, and beyond, has authored several papers on spacecraft data management systems, and has participated on panels, working groups, and committees to develop design and systems criteria for such systems.

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As Project Scientist for the Pioneer Venus program since its inception at Ames Research Center in late 1971, Larry Colin has participated in all its mission phases: design, development, data acquisition, analysis and interpretation, and data dissemination. He was awarded NASA's Distinguished Service Medal for his participation and accomplishments.

Dr. Colin has been the Deputy Chief, Ames Space Science Division since 1972, and has been the Acting Chief since 1980. He is also the Probe Project Scientist on the approved Galileo mission to Jupiter. He joined Ames as a research scientist in 1964, shortly after earning his Ph.D. degree from Stanford University. Previously, from 1952 to 1964, he was research scientist at the USAF's Rome Air Development Center where he specialized in the study of radio propagation and atmospheric physics applied to the development of radar systems. He received his BEE Degree from the Polytechnic Institute of Brooklyn in 1952, and an MEE Degree from Syracuse University in 1960.

He holds memberships in the American Institute of Aeronautics and Astronautics, Institute of Electrical and Electronics Engineers, American Geophysical Union, Division of Planetary Sciences of the American Astronomical Union, Sigma Xi, Explorer Society, and The Planetary Society. He serves as a consultant to the Delta Vee Corporation.

ERIC BURGESS

Consultant, author, lecturer, and journalist, Eric Burgess has written about the Pioneer space missions since the first Air Force lunar probes in 1957. Author of many of the earliest books and technical and popular articles on upper atmosphere physics, guided missiles, rocket propulsion, and spaceflight, Eric Burgess' by-line has appeared internationally in magazines and newspapers for over 40 years. He aided the formation of the British Interplanetary Society in the 1930s and the International Astronautical Federation in the 1950s. He wrote the first detailed technical papers on unmanned communication satellites in geosynchronous orbits (1946–49) and the first technical paper on a planetary probe spacecraft (1951). In the 1940s he researched and wrote the most comprehensive declassified survey of World War II rocket and missile development and had a Royal Air Force prize essay published on the future of large ballistic missiles.

He is a Fellow of the Royal Astronomical Society, Fellow of the British Interplanetary Society, Associate Fellow of the American Institute of Aeronautics and Astronautics, and a Member of the National Association of Science Writers. He has held management and technical positions in companies ranging from textiles to advanced computing and electronic systems and is currently a director and research scientist with Space Microwave Laboratories, Inc., of Santa Rosa, California.