TEN YEARS OF DISCOVERY

August 1989
PIONEER VENUS ORBITER — TEN YEARS OF DISCOVERY

A Report of the
Pioneer Venus Science Steering Group

Edited by
Lawrence Colin
Pioneer Venus Project Scientist

August 1989
ABSTRACT

The Pioneer Venus Orbiter has completed an unprecedented ten years in orbit about Venus. Ten of the twelve scientific experiments onboard are fully operational and continue to collect valuable data about the Venus environment. Expectations are for continuation into 1992.

In this paper, we describe the totality of scientific accomplishments for the ten-year period and the expectations for the remaining four years. The accomplishments cover practically all aspects of the environment: surface geology and electrical properties; planetary gravity field properties; intrinsic magnetic field strength; neutral atmosphere composition and temperature structure; cloud structure and microphysics; atmospheric electrical discharges; ionospheric composition and temperature structure; and the physics of the interaction of the solar wind with the ionosphere. Continuous operation over a complete solar cycle in a spacecraft orbit that has changed significantly over that period has produced unique temporal and spatial knowledge.

A large number of space scientists have participated and contributed to the mission, and have produced a sizeable archive of published scientific results. Over 1000 scientific papers in the ten year interval discussed in this report have been published by more than 160 participating scientists. These scientists represent institutions in academia (45% of the scientists), federal laboratories (47%), and industrial laboratories (8%). Thirty-four colleges and universities, 14 federal laboratories and 15 industrial laboratories employ the participating scientists. Ten countries outside the US are represented, as are 19 of the US states.
Project management and spacecraft operations have been conducted in an extremely efficient and cost-effective manner. A very small number of management and spacecraft operations personnel support the Pioneer Venus Orbiter mission, relative to the large number of benefiting scientists. The total cost of the mission (including hardware) is currently $125,000,000 (in actual dollars) amortized over 17 years. Average annual funding since orbit insertion (1978) is $5,000,000; of which 60% is spent for science and 40% for management and operations. The Pioneer Venus Orbiter mission has been one of the most scientifically beneficial-low cost programs conducted by NASA, and will continue to support that assertion for the remaining four years of its life.
ACKNOWLEDGMENTS

A mission the size and duration of Pioneer Venus depends for its success on the expertise and dedication of many individuals working as a coordinated team for many years. A sampling of these individuals is mentioned throughout this report; unfortunately, there will be inevitable, unavoidable, and unintended omissions. I apologize for such oversights and assure you they are not deliberate.

I would like to take this opportunity to acknowledge a few individuals who have made substantial contributions to the preparation of this report who are not otherwise mentioned herein. Richard O. Fimmel has served as Project Manager of the Pioneer Project Office at Ames Research Center for the past eight years of operation of the Pioneer Venus Orbiter. His leadership and management skills have been crucial to the success of the Orbiter and to this report. He has been blessed with the extraordinary skills and dedication of his staff: Roger Craig, Bob Jackson, Larry Lasher, Dave Lozier, Jim Phillips, Marcie Smith, and Fred Wirth.

Joel Sperans and Jack Dyer, Chief and Deputy Chief, respectively, of the Space Explorations Project Office have not only been supportive of the Pioneer Project Office but also have made many personal contributions to the project. Jack Dyer has, in fact, made important editorial comments and suggestions on several drafts of this report.

Eric Burgess is responsible for the integration of the inputs from a disparate set of individuals into the hopefully coherent document you are about to read. Janelle Washington, Secretary of the Space Exploration Projects Office, has applied her skills and her Macintosh to the production of the report.

Our heartfelt thanks to all these individuals for making it possible to achieve and document the extraordinary scientific results of the Pioneer Venus Orbiter.

Lawrence Colin, Editor
# PIONEER VENUS ORBITER — TEN YEARS OF DISCOVERY

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1.0 INTRODUCTION

The Pioneer Venus Orbiter (PVO) celebrated its tenth anniversary in orbit on December 4, 1988. PVO was launched on May 20, 1978 and was inserted into orbit around Venus on December 4, 1978. Pioneer Venus is a program which yields high scientific return for a relatively low cost. This report summarizes the extraordinary scientific results achieved by the spacecraft experiments over the 10 years of operation. PVO is expected to continue producing valuable scientific data through mid-1992, and some expectations of the scientific benefits from the data to be gathered during this period are briefly described.

In addition to describing the scientific accomplishments and future expectations, this report lists the manpower and funding resources devoted to the Pioneer Venus program.
2.0 PVO SCIENCE EXPERIMENTS

Twelve science experiments are integrated into the PVO spacecraft. In addition, six radioscience experiments make use of the S- and X-band transmissions from the spacecraft to the Deep Space Network. These experiments are listed in Table 2.0.1, along with the names of the responsible investigators.

In addition to the Principal Investigators (PIs) and Radioscience Investigators (RIs), several other categories of scientists are formally included in the program: Co-Investigators (COIs), Associate Investigators (graduate students or post-doctoral fellows who are clearly identified as associated with PIs or COIs), Interdisciplinary Scientists (IDs), and Guest Investigators (GIs). Participating PVO Interdisciplinary Scientists are listed in Table 2.0.2, and Guest Investigators are listed in Table 2.0.3.

Pioneer Venus was the first NASA program to formally select Interdisciplinary Scientists for participation from the beginning of the program. The objective was to include senior scientists with a broad perspective that cuts across the disciplines represented by individual experiments. The science payload of PVO was viewed as an integrated set of instruments addressing more global scientific questions than could be addressed by any individual experiment. The Interdisciplinary Scientists have played major roles in producing the scientific results of the missions. In addition, they have assumed key science management and advisory roles to the Project and Program Offices and to the Pioneer Venus Science Steering Group.

The Guest Investigator program was introduced to Pioneer Venus in 1981. Again, the purpose was to involve new scientists in the program who would bring a fresh perspective to data analyses and interpretations. The Guest Investigators have fulfilled this expectation in splendid fashion.

Scientific experiments are generally of two types, in-situ and remote sensing. Table 2.0.1 groups the experiments according to the appropriate category. In-situ experiments measure quantities at the spacecraft's location, either by ingesting particles into the instruments or by measuring local, non-propagating fields. Remote sensing experiments measure electromagnetic fields (optical, infrared, ultraviolet, X-ray, and radio) propagating from a reflecting or emitting source on the planet or within its atmosphere. Thus, the ability of each type of experiment to make measurements is a function of where the spacecraft is in its orbit and, therefore, the actual orbital parameters selected. Clearly, some of the
Table 2.0.1

PIioneer venus orbiter — ten years of discovery

Science experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>ID</th>
<th>Principal Investigator/Institution</th>
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<td><strong>In-Situ</strong></td>
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<tr>
<td>Neutral Mass Spectrometer</td>
<td>ONMS</td>
<td>H.B. Niemann/GSFC</td>
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<tr>
<td>Ion Mass Spectrometer</td>
<td>OIMS</td>
<td>P.A. Cloutier/Rice (1)</td>
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<td>Electron Temperature Probe</td>
<td>OETP</td>
<td>L.H. Brace/GSFC</td>
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<tr>
<td>Retarding Potential Analyzer</td>
<td>ORPA</td>
<td>W.C. Knudsen/Knudsen Res. (2)</td>
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<tr>
<td>Magnetometer</td>
<td>OMAG</td>
<td>C.T. Russell/UCLA</td>
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<tr>
<td>Electric Field Detector</td>
<td>OEFD</td>
<td>R.J. Strangeway/UCLA (3)</td>
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<tr>
<td>Plasma Analyzer</td>
<td>OPA</td>
<td>A. Barnes/ARC</td>
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<td><strong>Remote Sensing</strong></td>
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<td>Radar Mapper</td>
<td>ORAD</td>
<td>G.H. Pettengill/MIT</td>
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<tr>
<td>Infrared Radiometer</td>
<td>OIR</td>
<td>F.W. Taylor/JPL/Oxford</td>
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<tr>
<td>Ultraviolet Spectrometer</td>
<td>OUVS</td>
<td>A.I.F. Stewart/Colorado</td>
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<td>Cloud Photopolarimeter</td>
<td>OCPP</td>
<td>L.D. Travis/GISS (4)</td>
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<td>Gamma Ray Burst Detector</td>
<td>OGBD</td>
<td>R.W. Klebesadel/LASL (5)</td>
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<td><strong>Radiosoncence</strong></td>
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<td>Gravity Experiment</td>
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<td>Internal Density Dist. Exp.</td>
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<td>Radio Occultation Exp.</td>
<td>ORO</td>
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<tr>
<td>Radio Propagation Exp.</td>
<td>OGPE</td>
<td>T.A. Croft/SRI</td>
</tr>
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</table>

(1) H. A. Taylor, Jr./GSFC 1974 — 1988
(2) Formerly at LMSC
(3) F.L. Scarf/TRW-UCLA 1974 — 1988
(5) W.D. Evans/LASL 1974 — 1982
(6) Formerly at MIT
### Table 2.0.2

**PIONEER VENUS ORBITER — TEN YEARS OF DISCOVERY**

**INTERDISCIPLINARY SCIENTISTS**

<table>
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<td>T.M. Donahue</td>
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<tr>
<td>D.M. Hunten</td>
<td>University of Arizona</td>
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<tr>
<td>H. Masursky</td>
<td>US Geological Survey, Flagstaff</td>
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<tr>
<td>G.E. McGill</td>
<td>University of Massachusetts</td>
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<tr>
<td>A.F. Nagy</td>
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<tr>
<td>J.B. Pollack</td>
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<tr>
<td>G. Schubert</td>
<td>University of California, Los Angeles</td>
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<tr>
<td>N.W. Spencer</td>
<td>University of Maryland (1)</td>
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(1) Formerly of Goddard Space Flight Center
### Table 2.0.3

**PIioneer Venus Orbiter — Ten Years of Discovery**

**Guest Investigators**

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<thead>
<tr>
<th>Name</th>
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<th>Period</th>
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<tr>
<td>J.M. Ajello</td>
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<td>J. Anderson</td>
<td>Jet Propulsion Laboratory</td>
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<tr>
<td>K.A. Anderson</td>
<td>University of California at Berkeley</td>
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<td>J. Appleby</td>
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<td>G. Balmino</td>
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<td>C. Bowin</td>
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<td>S.H. Brecht</td>
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<td>D.L. Carpenter</td>
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<td>R.T. Clancy</td>
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<td>P.E. Clark</td>
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<td>R.E. Daniell</td>
<td>Beers Associates</td>
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<td>M. Dryer</td>
<td>National Oceanic and Atmospheric Admin.</td>
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<td>L. Elson</td>
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<td>E.G. Fontheim</td>
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<td>J.L. Fox</td>
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<td>J.C. Gerard</td>
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<td>E.W. Greenstadt</td>
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<td>W. Hoegy</td>
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<td>S. Kumar</td>
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<td>S.S. Limaye</td>
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<td>P. Morgan</td>
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<td>P. Mougins-Mark</td>
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<td>L.J. Paxton</td>
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<td>P. Rodriguez</td>
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<td>J.A. Slavin</td>
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**Guest Investigators**

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<td>D. Smith</td>
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<td>W.T. Vestrand</td>
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<td>D.R. Williams</td>
<td>Arizona State University</td>
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<td>D. Winske</td>
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<td>R. Wolff</td>
<td>Apple Computer (2)</td>
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<td>R. Woo</td>
<td>Jet Propulsion Laboratory</td>
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<tr>
<td>A. Young</td>
<td>California State University at San Diego</td>
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<tr>
<td>Y. Yung</td>
<td>California Institute of Technology</td>
<td>84,85</td>
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(1) Formerly University of Illinois, Smithsonian Astrophysical Institution
(2) Formerly JPL
(3) Formerly Phoenix Corporation
(4) Formerly University of Arizona
(5) Formerly JPL
in-situ measurements are possible only when the spacecraft dips into a sensible atmospheric or ionospheric environment. This restriction does not apply to the magnetic field and the solar wind measurements or to the remote sensing; however, sampling and viewing geometry are critical, so orbital position is important for them too.

Hence, to appreciate fully the scientific results, it is important for the reader to understand the mission background of the PVO which is described in the following section.
3.0 PVO MISSION BACKGROUND

3.1 DYNAMICS OF VENUS AND EARTH

Key features of Venus' orbit and rotation, along with corresponding values for Earth, are listed in Table 3.1.1. Venus revolves around the Sun in a nearly circular orbit with a period of 224.701 days; the sidereal period. The planet's mean distance from the Sun is 0.7234 astronomical units (AU), but its elliptical orbit causes the planet to approach or recede by 0.05 AU from this mean distance. Earth revolves on its orbit in the same direction, in a somewhat more elliptical orbit, with a period of 365.26 days. The orbits of the two planets are nearly co-planar, inclined to each other by only 3.39 degrees.

Venus rotates slowly on its spin axis in a retrograde sense (i.e. in a direction opposite to that of its orbital motion) with a period of 243.01 days, while Earth rotates much more rapidly in a prograde sense with a period of 23 hours, 56 minutes, 4 seconds. Venus' spin axis is oriented only 2.6 degrees from a perpendicular to its orbit plane, while Earth's axis is inclined by 23.45 degrees. Venus' sidereal period of 224.7 days, and its axial rotation period of 243.01 days retrograde, combine to produce a solar day on the planet's surface lasting 116.75 Earth days. Days and nights on Venus each last half this time, and the Sun rises in the west and sets in the east to a local "observer."

The orbit periods of Venus and Earth combine to produce a synodic period for Venus of 583.92 days, i.e. 1.6 years or about 19 months. This synodic period is the time between successive inferior conjunctions, i.e. closest approaches of the two planets, and also the time between superior conjunctions, or largest separation between the two planets. The actual distances are approximately 41.9 million kilometers and 257.3 million kilometers, respectively. The Venus-Earth geometry is not precisely the same at each inferior conjunction, because the orbits of the two planets are not quite circular and not quite co-planar. In fact, nearly identical geometrical relationships are repeated every eight years, or five synodic periods. The PVO has operated through six synodic periods through 1988. Venus' rotation period and the synodic period are almost synchronized such that the face of Venus presented to an Earth-based observer at inferior conjunction does not change much between two inferior conjunctions.
in-situ measurements are possible only when the spacecraft dips into a sensible atmospheric or ionospheric environment. This restriction does not apply to the magnetic field and the solar wind measurements or to the remote sensing; however, sampling and viewing geometry are critical, so orbital position is important for them too.

Hence, to appreciate fully the scientific results, it is important for the reader to understand the mission background of the PVO which is described in the following section.
3.0 PVO MISSION BACKGROUND

3.1 DYNAMICS OF VENUS AND EARTH

Key features of Venus' orbit and rotation, along with corresponding values for Earth, are listed in Table 3.1.1. Venus revolves around the Sun in a nearly circular orbit with a period of 224.701 days; the sidereal period. The planet's mean distance from the Sun is 0.7234 astronomical units (AU), but its elliptical orbit causes the planet to approach or recede by 0.05 AU from this mean distance. Earth revolves on its orbit in the same direction, in a somewhat more elliptical orbit, with a period of 365.26 days. The orbits of the two planets are nearly co-planar, inclined to each other by only 3.39 degrees.

Venus rotates slowly on its spin axis in a retrograde sense (i.e. in a direction opposite to that of its orbital motion) with a period of 243.01 days, while Earth rotates much more rapidly in a prograde sense with a period of 23 hours, 56 minutes, 4 seconds. Venus' spin axis is oriented only 2.6 degrees from a perpendicular to its orbit plane, while Earth's axis is inclined by 23.45 degrees. Venus' sidereal period of 224.7 days, and its axial rotation period of 243.01 days retrograde, combine to produce a solar day on the planet's surface lasting 116.75 Earth days. Days and nights on Venus each last half this time, and the Sun rises in the west and sets in the east to a local "observer."

The orbit periods of Venus and Earth combine to produce a synodic period for Venus of 583.92 days, i.e. 1.6 years or about 19 months. This synodic period is the time between successive inferior conjunctions, i.e. closest approaches of the two planets, and also the time between superior conjunctions, or largest separation between the two planets. The actual distances are approximately 41.9 million kilometers and 257.3 million kilometers, respectively. The Venus-Earth geometry is not precisely the same at each inferior conjunction, because the orbits of the two planets are not quite circular and not quite co-planar. In fact, nearly identical geometrical relationships are repeated every eight years, or five synodic periods. The PVO has operated through six synodic periods through 1988. Venus' rotation period and the synodic period are almost synchronized such that the face of Venus presented to an Earth-based observer at inferior conjunction does not change much between two inferior conjunctions.
Table 3.1.1

PIONEER VENUS ORBITER — TEN YEARS OF DISCOVERY

PLANETARY DYNAMICS

<table>
<thead>
<tr>
<th></th>
<th>Venus</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Orbital Elements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semimajor axis, AU</td>
<td>0.723</td>
<td>1.000</td>
</tr>
<tr>
<td>Perihelion distance, AU</td>
<td>0.718</td>
<td>0.983</td>
</tr>
<tr>
<td>Aphelion distance, AU</td>
<td>0.728</td>
<td>1.017</td>
</tr>
<tr>
<td>Orbit eccentricity</td>
<td>0.0068</td>
<td>0.0167</td>
</tr>
<tr>
<td>Mean orbital velocity, km/sec</td>
<td>35.03</td>
<td>29.79</td>
</tr>
<tr>
<td>Inclination of orbit to ecliptic, deg.</td>
<td>3.39</td>
<td>0.00</td>
</tr>
<tr>
<td>Sidereal orbital period, Earth days</td>
<td>224.701</td>
<td>365.256</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rotation Properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclination of rotation axis, degrees</td>
<td>177.4</td>
<td>23.45</td>
</tr>
<tr>
<td>Axial rotation period, Earth days</td>
<td>243.01 (Retrograde)</td>
<td>0.997</td>
</tr>
<tr>
<td>Period of solar day, Earth days</td>
<td>116.75</td>
<td>1.00275</td>
</tr>
<tr>
<td><strong>Venus-Earth Relations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synodic period, Earth days</td>
<td>583.92</td>
<td>-------</td>
</tr>
<tr>
<td>Inferior conjunction distance, 10^6 km</td>
<td>41.9</td>
<td>-------</td>
</tr>
<tr>
<td>Superior conjunction distance, 10^6 km</td>
<td>257.3</td>
<td>-------</td>
</tr>
</tbody>
</table>
3.2 THE PVO ORBIT

The orbit of PVO around Venus is a very eccentric ellipse inclined 74.4 degrees to Venus' equatorial plane. The eccentricity and inclination of the orbit were chosen to accomplish a variety of scientific goals and to meet a number of engineering requirements.

The closest approach of the spacecraft to Venus (orbit periapsis) was selected to be nominally 150 kilometers above the surface. This low altitude allowed the study of the surface by the remote-sounding Radar Mapper (ORAD) and of the upper atmosphere and ionosphere by the in-situ experiments; Electron Temperature Probe (OETP), Ion Mass Spectrometer (OIMS), Neutral Mass Spectrometer (ONMS), and Retarding Potential Analyzer (ORPA). Also, it provided excellent viewing geometry for the remote-sensing atmospheric experiments; Infrared Radiometer (OIR), Ultraviolet Spectrometer (OUVS), and Radio Occultation experiment (ORO).

The furthest excursion from Venus (apoapsis) was chosen to produce an orbit with a period of nearly 24 hours, requiring an apoapsis altitude of about 67,000 kilometers. This proved very beneficial for scheduling and executing tracking and ground operations and it could be produced with a reasonably proportioned retrorocket. It provided excellent viewing geometry for obtaining images of clouds with the Cloud Photopolarimeter (OCPP), and produced a wide sampling region for the solar wind interaction experiments; Magnetometer (OMAG), Electric Field Detector (OEFD), and Plasma Analyzer (OPA). Finally, this choice of a 24-hour period produced a nearly one-to-one correspondence of sequential orbit numbers with days into the mission. This brought the spacecraft data readout intervals into synchronism with the operating schedules of the Pioneer Mission Operations Center at Ames Research Center and the best viewing intervals at the Goldstone Tracking Station.

The high inclination of the orbit was favored to achieve a near-polar orientation for wide latitude coverage of the planet for most of the experiments.

Figure 3.2.1 shows the orbit drawn to scale, and as viewed if looking perpendicular to the orbit. Time tics are shown for each hour before and after closest approach to Venus, and direction of travel of the spacecraft is shown by the arrow. Figure 3.2.2 is a view of the orbit seen from above the north pole. It shows the latitude coverage achieved by the near-polar inclination.
Because Venus is so close to the Sun, the orbit of PVO is noticeably affected by the solar gravitational pull. The significant changes are in the altitude and latitude of periapsis. For the first 20 months of the mission the spacecraft's thrusters were used to counteract this normal altitude drift to maintain scientific observations in the low altitude regions. Ultimately, periapsis was allowed to continue its normal upward drift.

To understand the scientific management of operations, it is convenient to divide the mission into three phases, as shown in Table 3.2.1. Phase I covers the first 20 months of the mission when the thrusters were used to maintain periapsis altitude in the range 150-250 kilometers. Phase II represents the interval after control of periapsis altitude was abandoned. During Phase II, periapsis rose to a maximum of 2310 kilometers on July 4, 1986, before it began descending again naturally. Over the same interval, the latitude of periapsis descended from 17 degrees north to the equator. Hence, measurements made at periapsis were continually penetrating new regions of the Venus environment. Today, after 10 years, the PVO is at the late stages of this second phase.

Phase III will begin late in 1991 as periapsis again reaches the lower thermosphere and ionosphere. Early in 1992 the remaining hydrazine propellant will be used to keep periapsis within the altitude range from 140 to 160 kilometers. Periapsis latitude will have decreased to about 10 degrees south by this time. Note that the transition from Phase II to Phase III is arbitrarily defined to take place when periapsis altitude reaches 1000 kilometers. During Phase III deeper atmospheric sampling will be attempted than was acceptable during Phase I. When all propellant is expended, in September 1992, the spacecraft will descend into the Venus atmosphere and will be incinerated.

Figures 3.2.3, 3.2.4, and 3.2.5 show the variation of periapsis altitude with date and orbit number for Phases I, II, and III, respectively. Figure 3.2.6 shows the variation of periapsis latitude with date and orbit number. Actual values to date are shown with solid lines; predictions for the future are shown as dashed lines. The sharp changes in Figures 3.2.3 and 3.2.5 represent thruster firings. The "wiggles" in Figures 3.2.4 and 3.2.6 are caused by solar gravitational effect. The figures are annotated with times of occurrence of eclipses (when PVO is repeatedly shadowed by Venus near periapsis), inferior (inverted delta) and superior (delta) conjunctions, and occultations (when PVO passes behind Venus as viewed from Earth.) Single lines indicate seasons of periapsis occultations or eclipses. Double lines indicate apoapsis events. The occultations permit studies of Venus'
Table 3.2.1

PIONEER VENUS ORBITER — TEN YEARS OF DISCOVERY

PVO ORBITAL PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>Phase I Low Altitude</th>
<th>Phase II High Altitude</th>
<th>Phase III Entry</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orbit Numbers</strong></td>
<td>0-600</td>
<td>600-4500</td>
<td>4500-?</td>
</tr>
<tr>
<td><strong>Periapsis Alt.</strong></td>
<td>142-250 km</td>
<td>250-2300-1000 km</td>
<td>1000-140 km</td>
</tr>
<tr>
<td><strong>Apoapsis Alt.</strong></td>
<td>66,900 km</td>
<td>66,900 km</td>
<td>66,900 km</td>
</tr>
<tr>
<td><strong>Average Period</strong></td>
<td>24.03 hrs.</td>
<td>24.03 hrs.</td>
<td>24.03 hrs.</td>
</tr>
<tr>
<td><strong>Inclination</strong></td>
<td>105.6 deg</td>
<td>105.6 deg</td>
<td>105.6 deg</td>
</tr>
<tr>
<td><strong>Periapsis Lat.</strong></td>
<td>17 deg N</td>
<td>17 deg N-10 deg S</td>
<td>10 deg S</td>
</tr>
</tbody>
</table>
atmosphere and ionosphere. Superior conjunctions tend to diminish or eliminate data collection for up to two or three weeks. "Apoapsis eclipses" are experienced in a series of about five orbits each Venus year, when the spacecraft is shadowed for several hours near apoapsis.

Figure 3.2.7 illustrates the drag (in units of velocity) experienced by the spacecraft at periapsis as it dipped into the upper atmosphere of Venus during Phase I. Larger values of drag are associated with the lower periapsis altitudes achieved (Figure 3.2.3); but the relationship is strongly influenced by daylight/darkness differences and by large waves in the density of the upper atmosphere. These data were used by the Atmospheric Drag (OAD) experiment to determine atmospheric density, and to provide a parameter for modeling molecular composition or temperature. Similar effects will be measured during Phase III.

Figure 3.2.8 illustrates the changing geometry among the Earth, Venus and the orbit of PVO for a typical Venus year. The corresponding positions of the Earth and Venus are shown every seven days during the 224 days it takes Venus to travel once around the Sun. Simultaneous Earth-Venus positions for selected dates are identified by a connecting dashed line. The position of Venus is also marked when an eclipse and/or occultation of the spacecraft occurs on a specific date.

The orbit of PVO is represented by its line of apsides, the line between periapsis and apoapsis. Note that the orbit is fixed in inertial space as it accompanies Venus in its solar orbit. As the year progresses, Venus rotates slowly under the orbit of PVO, and the sub-spacecraft point thus "sees" the entire planet only after 243 days, or one rotation on its spin axis. This is important to the radar mapper (ORAD) and local gravity experiments. On the other hand, the spacecraft "samples" all local times on Venus (longitudes relative to the Sun) in the 224 Earth days of a Venus year.

Although the orbit of PVO remains fixed inertially in space, its orientation with respect to the Earth and Sun changes with time as Venus and Earth move around the Sun. This combined motion results in the seasons of eclipses and occultations previously discussed. The perspectives from Earth and Sun are illustrated in Figure 3.2.9 for one synodic period, or the time it takes Venus and the Earth to return to the same celestial longitude. In this plot, the Earth-Sun line is fixed in space and the positions of Venus are shown for every seven days during the 584-day synodic period. The orbit of PVO is rotated to reflect its ever changing orientation with respect to the Sun and Earth. The position of Venus is again marked to identify an eclipse and/or occultation situation which occurs on the specific date.
Seasons of periapsis eclipses (short duration, but a large number of continuous days) can be seen when the orbit is oriented such that the apoapsis region points roughly towards the Sun. Likewise, periapsis occultations occur when apoapsis points roughly towards the Earth. Conversely, the seasons of apoapsis eclipses and apoapsis occultations (long duration, but a small number of continuous days) occur when the apoapsis region of the orbit points roughly away from the Sun and Earth, respectively.
Figure Captions

3.2.1 The Orbit of PVO as viewed perpendicular to the orbit plane. Periapsis - solid dot, apoapsis - solid square. X's are at 1 hour intervals before and after periapsis. The arrow denotes direction of spacecraft motion.

3.2.2 The orbit of PVO as viewed from over the north pole of Venus to show the latitude covered by the near polar inclination of 74.4 degrees. Periapsis - solid dot, apoapsis - solid square. X's are at one hour intervals before and after periapsis. The arrow denotes direction of spacecraft motion.

3.2.3 Variation in altitude of periapsis during Phase I of the mission and identifying periods of solar eclipses, Earth occultations and conjunctions.

3.2.4 Variation in altitude of periapsis during Phase II of the mission.

3.2.5 Variation in altitude of periapsis during Phase III of the mission.

3.2.6 Variation of the latitude of periapsis plotted against years and orbit numbers.

3.2.7 The drag at periapsis in units of velocity experienced by PVO during Phase I of the mission.

3.2.8 The changing geometry of Earth, Venus, and the PVO's orbit plotted in seven-day intervals from December 4, 1978 showing periods of eclipses and occultations.

3.2.9 The Pioneer Venus orbit during the first synodic period to illustrate the perspectives from Earth and Sun. The Earth-Sun line is fixed. The orientation of the PVO orbit is plotted every seven days.
DENOTES DARK SIDE
FIG. 3.2.4

SOLAR ECLIPSES
EARTH OCCULTATIONS
CONJUNCTIONS

ALTIMETRY OF PERIAPEX, KM

ORBIT NUMBER
SOLAR ECLIPSES

EARTH OCCULTATIONS

CONJUNCTIONS
SOLAR ECLIPSES
EARTH OCCULTATIONS
CONJUNCTIONS

FIG. 3.2.6
DAYSIDE PERIAPSIS ORBITS

ORBIT NUMBER

DRAG AT PERIAPSIS, M/S
FIG. 3.2.8

- ECLIPSE ONLY ■
- OCCULTATION ONLY +
- ECLIPSE AND OCCULTATION ★
- NO ECLIPSE OR OCCULTATION ○
4.0 SCIENTIFIC RESULTS

4.1 INTRODUCTION — T.M. Donahue

In this section five scientists associated with the Pioneer Venus Orbiter's mission summarize the revolution that has occurred in understanding of the planet Venus during the past ten years as a result of discoveries made by instruments on the spacecraft.

Donald Hunten, of the University of Arizona, an interdisciplinary scientist on the mission, discusses the properties of the atmosphere above the clouds, the startling scarcity of oxygen and carbon monoxide that exists despite the copious production of these species from carbon dioxide by solar ultraviolet radiation, the strong winds that carry constituents of the atmosphere across the terminator from the dayside to the nightside where they descend into the lower atmosphere, the very low nightside temperature, and the great bulges in hydrogen and helium densities that are found in the predawn sector.

Lawrence Brace of NASA-Goddard Space Flight Center, and Christopher Russell of University of California, Los Angeles, who both are experimentalists responsible for instruments carried by PVO, describe the ionosphere and the way the solar wind flows up to and around the outer regions of Venus, a planet that has no discernible magnetic field of its own. The result of this encounter of the solar wind with the planet is that the solar wind becomes draped around Venus and a long magnetospheric tail develops in the solar wind. In this tail region on the nightside of Venus, the ionosphere displays behavior quite unlike anything experienced on Earth. Deep holes of hot tenuous plasma are poked into the ionosphere in some places. Elsewhere, plasma blobs and long thin streamers appear to stretch away from the planet, some of them to distances of thousands of kilometers.

Issues regarding the ionosphere that were seriously disputed for years were settled almost immediately after the spacecraft went into orbit. The ionosphere was found to be composed mainly of molecular oxygen ions, not carbon dioxide ions as had been thought, and the temperature of the daytime atmosphere was found to be about 300 Kelvins, not 700 Kelvins.

Analysis demonstrated convincingly that a light ion of two atomic mass units was ionized deuterium (an isotope of hydrogen), not molecular hydrogen. This was a result consistent with a finding by the Pioneer Venus probes that the ratio of deuterium to hydrogen abundance on Venus is one
hundred times greater than on Earth. This result has implications for a primal ocean on Venus as Hunten discusses in Section 4-2.

Ian Stewart of the University of Colorado shows how remote sensing from the Orbiter has been used to follow the motions of the sulfuric acid clouds of Venus and to detect trace gases, such as sulfur dioxide, above the clouds. He also discusses the unique observations of Comet Halley that were made by the ultraviolet spectrometer of Pioneer Venus Orbiter in its location in orbit around Venus.

Harold Masursky of the U.S. Geological Survey, a member of the Pioneer Venus radar mapper team, discusses what radar sounding has revealed about mountains, craters, volcanoes, and other interesting features of the surface of Venus that distinguishes this planet from the others in the family of terrestrial planets.

Finally, Hunten puts the lessons learned about Venus by the PVO mission into a terrestrial context, particularly with regard to the similarities and contrasts of the effects of greenhouse gases and pollutants on these two neighbors in the Solar System.

There is one instrument carried by the PVO that has nothing to do with Venus. It is a gamma burst detector which is designed to act in concert with half a dozen other spacecraft located at large in the Solar System. The aim is to pinpoint the location of sources of mysterious large bursts of cosmic gamma rays in our galaxy. Some thirty events have been mapped, all over the galactic sphere in and out of the galactic plane. One event, on March 5, 1975, occurred near a supernova remnant in the Large Magellanic Cloud. It appeared to generate a stupendous energy yield of $10^{45}$ ergs.
4.2 NEUTRAL UPPER ATMOSPHERE/THERMOSPHERE —
D.M. Hunten

Many of the Instruments on the Pioneer Venus Orbiter were carefully chosen to form a synergistic package to explore the atmosphere and ionosphere. This is just what they did during the first three Venus years of the mission, with the consequence that the aeronomy of Venus is better understood than that of any other planet than the Earth. However, the spacecraft was operated conservatively, with the result that no in-situ measurements were made below 140 kilometers, and few below 170 kilometers. This is the reason why diagrams such as Figures 4.2.1 and 4.2.2 refer to a height of 170 kilometers. In the next section of this report, Figure 5.2.2.1 illustrates a model developed by Massie, Sowell, and Hunten in 1983 which attempted to bridge the gap between 140 and 100 kilometers by use of the best available aeronomical theory. Prospects for further improvement are discussed in Section 5.2.2. Other "models" (really elaborate curve-fits) have been provided by Seiff (1983), Hedin et al. (1983), and VIRA, the COSPAR Venus International Reference Atmosphere (Keating, et.al, 1986). Figures 4.2.1 and 4.2.2 illustrate the densities of carbon dioxide, oxygen, and helium as a function of local solar time, at the 170 kilometers altitude mentioned above. Some of these variations are due to the fact that the nightside of Venus' atmosphere is much colder than the dayside, as illustrated in Figure 4.2.3. These particular data were derived from scale heights measured by the mass spectrometer, but essentially identical results concerning temperature and composition were independently obtained from measurements of the orbital decay due to atmospheric drag at different periapsis altitudes.

The model of Hedin et al. consists of a multilayer fit, using spherical harmonics, to the entire database. Two vertical profiles obtained from this model are shown in Figure 4.2.4. again emphasizing the enormous diurnal variation. A variation of this general sort was, in fact, predicted by Dickinson and Ridley in 1977, but the observed nightside is even colder than they suggested as shown in Figure 4.2.5. Along with the temperature field goes a wind field sketched in Figure 4.2.6, blowing from day to night with speeds over the terminator approaching that of sound. Minor light species are carried along with the flow, rather like soapsuds in a draining bathtub, and similarly tend to accumulate in the region of convergence and downflow. The Dickinson-Ridley model is two-dimensional, and therefore it is symmetrical with respect to the Venus-Sun axis. The convergence region is therefore at midnight. The helium bulge in Figure 4.2.2 shows that it is actually rather close to the morning terminator. To account for this a super-rotation with a period of about 6 days must be imposed on the
predicted flow, and this is indicated in Figure 4.2.6. The reason for this rotation is entirely unknown. More recent three-dimensional models must still include it arbitrarily. Other ad hoc prescriptions have been used to slow down the winds and therefore permit a colder nightside. The result is a model that fits the data rather well, but is not fully predictive.

Among the light constituents that are carried to the nightside are oxygen and nitrogen atoms, produced by solar ultraviolet radiation on the day side. The corresponding nightside bulge of atomic oxygen is shown in Figure 4.2.1. When the atoms are carried down again, they recombine into oxygen molecules and nitric oxide, emitting detectable airglows. Mapping of the nitric oxide glow as observed from PVO again reveals a concentration, this time near 2:00 a.m. local time. Oxygen glows in the near infrared and in the visual regions. The first has been detected, but not mapped, in Earth-based telescopic observations. The second has been mapped by the Venera 15 spacecraft; its variations are more subdued than those of nitric oxide.

Observation of high altitude airglow at the limb was historically important with Mariners 5 and 10 and has also been applied from PVO. All three spacecraft observed Lyman alpha radiation, which is a tracer for hydrogen atoms, and Mariner 10's data for helium gave the first unambiguous determination of the exospheric temperature as 350 Kelvins instead of the 700 Kelvins that had previously been popular. Hydrogen shows two components: at lower altitudes the most numerous is a thermal distribution at 275 Kelvins, but this component becomes negligible above 3000 kilometers and allows a nonthermal component to be detected. Many explanations of this component have been advocated over the years, but now there is general agreement that it is produced by various reactions drawing on the energy of the ionosphere.

A closely related topic is the escape of hydrogen from Venus. Thermal atoms, even of hydrogen, are not lost into space at a significant rate; the loss rate is dominated by nonthermal processes whose rates are rather uncertain. The dominant process is currently thought to be neutralization of hot protons by charge exchange with atoms in the nightside bulge; many of the resulting hot atoms can readily escape, and others contribute to the bound, nonthermal corona. The rate is perhaps one tenth that for the Earth. It is suspected that a comparable amount may be carried away as ions in plasma "blobs" that seem to be swept up from the limb regions by the solar wind.
The low rate of escape is more remarkable because deuterium is enormously enriched on Venus, by a factor of 100 relative to Earth. This seems to be strong evidence of massive loss of hydrogen, at least in the past if not the present. Alternatively, the current reservoir of hydrogen compounds would have to be exceedingly small. Certainly the reservoir is small, but we do not know if it is small enough. Enhanced loss rates in the past seem to be a better option.

The Radio Occultation experiment (ORO) clearly shows a major change in the scale height of the ionosphere between solar maximum and minimum. It is tempting, and perhaps correct, to attribute this to a drop in exospheric temperature to perhaps 200 Kelvins at solar minimum. However, it could also be due to a reduction in thermospheric atomic oxygen, which would have the same effect of reducing the average scale height. Efforts are still under way to resolve this ambiguity, but they are frustrated by the large altitude of periapsis during the relevant period, around 1986-87.
Figure Captions

4.2.1 Measurements of carbon dioxide and atomic oxygen number densities at 170 kilometers altitude taken by the Pioneer Venus Orbiter's mass spectrometer over nearly three diurnal cycles.

4.2.2 Measurements of helium number densities obtained at 170 kilometers altitude by the Pioneer Venus Orbiter's mass spectrometer over three diurnal cycles identified by a, b, and c.

4.2.3 Diurnal variation of the exospheric temperature as derived from the number densities and scale heights measured by the Pioneer Venus Orbiter's Neutral Mass Spectrometer. The sampling of one diurnal cycle lasted 225 Earth days, the sidereal period of Venus.

4.2.4 Empirical model densities as a function of altitude at noon and midnight at the planet's equator, based on the data of the Pioneer Venus Orbiter's Neutral Mass Spectrometer. The density correction factor of 1.63 used by Hedin et al. in their 1982 model is not included.

4.2.5 Diurnal variation of upper atmospheric temperature. The theoretical Dickinson-Ridley pre-PVO model is compared with the PVO OAD empirical model.

4.2.6 Along with the temperature field goes a wind field blowing from day to night with speeds over the terminator approaching that of sound.
FIG. 4.2.1

LOCAL SOLAR TIME (hr)

CO₂

O

AMBIENT DENSITY (cm⁻³)
FIG. 4.2.2
EXOSPHERIC TEMPERATURE (°K)

DICKINSON-RIDLEY MODEL, 1977

LOCAL SOLAR TIME (HRS)

FIG. 4.2.5
4.3 DYNAMICS OF THE IONOSPHERE — L. H. Brace

4.3.1 BACKGROUND

Before the arrival at Venus of the Pioneer Venus Orbiter (PVO) on December 4, 1978, no spacecraft had entered that planet's ionosphere to study it. Three years earlier, Soviet scientists had obtained altitude profiles of its ionospheric electron density by observing the occultation of the radio frequency telemetry signals from their Venera 9 and 10 satellites as they passed behind the planet. Russian probes to the surface had only passed through the ionosphere without measuring it.

Even before 1775, US scientists had obtained the first electron density profiles of the ionosphere of Venus by the same technique, using the telemetry signals from the US Mariner 5 and Mariner 10 spacecraft. These pioneering measurements presented an exciting first look at the ionosphere. But they also left many open questions; such as the kinds of ions present, the ion and electron temperatures, and the overall global configuration of the ionosphere. In addition, question of how the ionosphere changes from night to day, and how it responds to changes in solar radiation and solar wind pressure were still outstanding. Such questions could only be answered by making repeated measurements directly in the Venus ionosphere, and over a very long period. Only a spacecraft moving in a satellite orbit around Venus could provide such measurements.

This section reviews the basic questions about the ionosphere that were posed before Pioneer Venus was launched in 1978. Next, it describes how the orbit of PVO has evolved over the years to permit the necessary measurements to be made. Finally its summarizes what has been learned thus far about the Venusian ionosphere.

4.3.2 THE QUESTIONS BEFORE PVO

The discoveries about Venus by early US and Soviet missions prepared us to ask only the simplest kinds of questions about the Venus ionosphere. These questions were listed in review article published in Space Science Reviews in June, 1977. A few of them are listed below:

- 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?
- How does the composition of the neutral atmosphere affect the ionosphere?
- How are mass, momentum, and energy transferred from the solar wind to the upper atmosphere and ionosphere?
- What is the source of variability of the ionosphere?
- How does the upper atmosphere respond to changes in the solar extreme ultraviolet radiation and the solar wind?
- How much of the solar wind is absorbed by the ionosphere?
- Why is there a nightside ionosphere when the Venus night is more than three months long?

4.3.3 THE EVOLVING PVO ORBIT

The above questions could be addressed only by placing the satellite in an eccentric orbit that comes very close to the planet, and then makes in situ observations over a period of several years as the orbit sweeps through all local times and a wide range of altitudes. Figure 4.3.1 shows how the PVO orbit, viewed against the night sky, has evolved throughout the mission to permit a much broader sampling of the Venus environment than a fixed orbit could provide. The red lines show periapsis rising between 1979 and 1985. The yellow lines represent the years 1985-1987 when periapsis reached its maximum altitude. The green lines are the orbits predicted for 1987-1992 when periapsis will be returning slowly to the ionosphere. The blue points indicate where crossings of the Venus bowShock occurred, while the green points show the ionopause crossings, i.e., the points of entry and exit from the ionosphere.

The rise and fall of periapsis is shown more clearly in Figure 4.3.2, which covers the entire 13-year period from orbit injection to reentry. Onboard propulsion was used in 1979-80 to hold periapsis deep in the ionosphere against the perturbing force of solar gravitation, and it will be used again prior to reentry in 1992 to prolong the spacecraft life and obtain additional lower ionosphere measurements.
4.3.4 IONOSPHERE DISCOVERIES

The measurements obtained by Pioneer Venus have answered most of the simple questions of 1977, at least to a large degree. The answers are described in detail in the publications given in the PV bibliography (see Section 8.0), and an overview of the Venus outer environment is shown in Figure 4.3.3. The scale of the ionosphere (shown in yellow) is exaggerated by a factor of 2 to permit annotation. Some of these features are discussed in the following sections.

Low Periapsis Period (1978-1980)

A rapid fire series of discoveries were made during the first year or two of the Pioneer Venus mission while periapsis was maintained deep in the ionosphere. These discoveries have revolutionized our thinking about Venus in ways that we could not have imagined before its arrival in December of 1978. We found an ionosphere that was infinitely more complex and variable than we could have anticipated. The sketch in Figure 4.3.3 was an attempt to illustrate some of this complexity. The major results from the period of low altitude periapsis are outlined below.

The ionosphere is produced by extreme ultraviolet radiation from the Sun, and it is composed primarily of positively charged atoms of oxygen at high altitudes, and of ions of molecular oxygen and carbon dioxide at low altitudes. Hydrogen becomes a major ion at high altitudes in the nightside ionosphere. Photochemical calculations based on well known ionization and recombination rates are able to reproduce the PVO ion composition measurements in the dayside ionosphere. This agreement between measurement and theory is shown in Figure 4.3.4.

The ionosphere is heated internally by photoelectrons, and it is heated from above by solar wind interactions at its upper boundary, the ionopause. The electron and ion thermal balance of the dayside ionosphere is consistent with these two heat sources, balanced by the combined effects of electron and ion cooling to the neutrals, and heat conduction within the ionosphere. Figure 4.3.5 illustrates the agreement that has been achieved between the electron and ion temperature measurements and the theoretical profiles. The processes which couple the solar wind energy to the ionosphere are not understood, but they are believed to involve the absorption of plasma waves that are produced by the interaction of the solar wind with Venus.

A large bulge of hydrogen and helium ions and neutrals was found in the predawn ionosphere. This dawn-dusk asymmetry in $\text{H}^+$, shown in Figure
4.3.6, suggests that the thermosphere of Venus must be rotating faster than the planet itself, perhaps with a period of four to eight days. This discovery tended to confirm recent theory on atmospheric superrotation that calls for all atmospheres to rotate faster than their planet. Earth, Jupiter, Saturn, and now Venus, are consistent with that theory, although they have quite different rotation rates, masses and distances from the Sun.

Strong solar EUV control of the ionospheric density was discovered, but there was no detectable effect upon the temperature of the ionosphere. Figure 4.3.7 illustrates this behavior. These results confirmed earlier photochemical theory that the ionosphere is produced by solar EUV, but it reenforced the view that solar wind interactions, not the solar radiation, controls the ionospheric temperature.

A clear and direct relationship was observed between the dynamic pressure of the solar wind and the height of the ionopause. Figure 4.3.8 shows how the ionopause altitude decreases as the solar wind pressure increases. This discovery confirmed earlier suggestions that the thermal pressure of the ionosphere diverts the solar wind around Venus with little absorption. This diversion is caused by the build up of a magnetic field above the ionopause which limits the access of the solar wind to the ionosphere. When the solar wind pressure become comparable to the maximum plasma pressure in the ionosphere, the magnetic field penetrates the ionosphere and magnetizes it. As the solar wind flows around the planet, it induces surface waves in the ionopause and generates superthermal ions and electrons which form a boundary region called the mantle, as shown in Figure 4.3.3. The ionopause waves become unstable at the flanks of the planet. The waves appear to break in this region to form plasma clouds and streamers that extend far downstream. Much of this plasma is lost to space.

The ionosphere of Venus has a much higher concentration of deuterium ions (an isotope of hydrogen) than does the Earth's ionosphere. This is evident in the ion mass spectrometer measurements of H+ and O+ shown in Figure 4.3.9. These observations suggest that Venus originally may have had a deep ocean that is no longer present. This conclusion is based on the idea that the ionospheric escape of hydrogen, which would have originated in such an ocean, would leave behind the observed excess of deuterium atoms which are too heavy to escape the gravity of Venus.

A surprisingly large nightside ionosphere was found by Pioneer Venus, as illustrated by the radio occultation results shown in Figure 4.3.10. The ionosphere was expected to all but disappear during the very long night of Venus. This discovery showed that ions either were being produced locally
by energetic electron bombardment, or that ions from the dayside were being transported into the nightside. The absence of a planetary magnetic field permits the nightward flow of ions to be very large at Venus. Both nightward flow and local production seem to be important, but their relative importance varies with solar activity. Larger flows occur at solar maximum when the dayside density is high. Local production may be more important at solar minimum when the nightward flow is low.

The nightside ionosphere is very hot and has highly complex structures such as the holes illustrated in Figure 4.3.3. These holes are deep depressions in the otherwise dense nightside ionosphere, with strongly coupled magnetic field structures inside. Figure 4.3.11 shows the measurements of electron density, temperature and magnetic fields in one Pioneer Venus passage through the nightside ionosphere. The cause of these holes is not yet fully understood, but their dynamic behavior suggests that solar wind interactions with Venus may be involved. Another such dynamic feature of the nightside is the wavelike structures in the plasma and the magnetic field in the lower ionosphere just nightward of the dawn and dusk terminators. Figure 4.3.12 shows the unique phase relationship between these structures which are believed to be related to the observed supersonic nightward flow of ions through this region.

Superthermal ions and electrons are also found in the nightside ionosphere, particularly at higher altitudes and at the boundaries of the ionospheric holes. These superthermals reveal the presence of unknown plasma acceleration processes in the nightside ionosphere.

In summary, the PVO discoveries of the low periapsis period have revolutionized our thinking about the ionosphere of Venus. We found it to be infinitely more complex and variable than we could have anticipated.

Additional Discoveries Since Periapsis Began Rising (1981-1988)

As periapsis began to rise, ionospheric structure at much higher altitudes was revealed. Long ionospheric tail rays were discovered extending more than 3000 km downstream, as illustrate in Figure 4.3.3. This region has been called the ionotail. The tail rays of Venus are reminiscent of the tail of a comet, flowing to and fro like a candle in the wind. This behavior reinforces the view that solar wind interactions of the type which control comet tails may also shape the ionospheric tail of Venus. Figure 4.3.13 shows a series of electron density measurements through the night side ionosphere at high altitudes, a region known as the ionotail. These and other PVO observations suggest that the tail rays are composed of
ionospheric hydrogen and oxygen ions that has been accelerated to velocities high enough to cause them to escape from the planet. This discovery has implications for the loss of the supposed primordial Venusian ocean by solar wind scavenging from the ionosphere over geological time.

The solar cycle variations of the lower ionosphere have been measured by the radio occultation technique. Figure 4.3.14 shows the difference in the electron density in the dayside ionosphere at solar maximum (1980) and solar minimum (1986). The ionopause declined markedly at solar minimum, and the density of the ionosphere is generally much lower. The nightside ionosphere (not shown) also has much lower densities at solar minimum, and this is consistent with the earlier conclusions that it is maintained primarily by nightward ion flow. This flow is greatly reduced at solar minimum by the drastic reduction of electron density in the dayside upper ionosphere.

4.3.5 CONCLUSIONS AND NEW QUESTIONS FOR FUTURE MISSIONS

These Pioneer Venus discoveries have to a large degree answered the simple questions about the Venus ionosphere that were posed before encounter. But, in the process of answering the simple questions, the PV investigators have become aware that Venus is much more complicated than our early questions implied. Thus 10 years later we still have many questions, and the answers to our original questions have been incomplete in many cases. They were the right initial questions, of course, but nature is always more complex than one imagines from a position of ignorance. Our direct contact with this new world has brought with it many surprises and a new set of questions; questions concerned not so much with what the Venus ionosphere is like, but what causes it to be that way. The following is a list of some the questions that PVO will not be able to answer satisfactorily because of limitations in its orbit, its lifetime and its instrument complement.

Are there important latitudinal variations in the ionosphere?

The great eccentricity of the orbit, and the nearly fixed latitude of periapsis, has permitted only the low latitude ionosphere to be sampled directly. Radio occultation measurements have permitted density profiles to be obtained over a wider latitude range, but not the plasma composition, temperature and drift velocities. A future mission should be capable of achieving a low altitude circular, near polar orbit. The onboard propulsion capability should be adequate to provide a wide selection of
orbital altitudes and a long enough lifetime to exploit the sampling advantage of each.

**How does the ionosphere change throughout the solar cycle?**

The day and night sides of the ionosphere are closely coupled by nightward ion transport and by the fact that both sides are affected by interactions with the solar wind. The highly eccentric orbit of PVO does not permit simultaneous measurements on both the dayside and nightside. Thus the correlated global response of the ionosphere to solar events, such as interplanetary shocks and solar flares, cannot be observed. Therefore, comparisons of the dayside and nightside behavior are necessarily statistical in the PVO data. A future mission would benefit by a low altitude circular orbit to allow near snapshots of both the dayside and the nightside ionosphere to be obtained every 90 minutes.

**What are the processes by which the solar wind interacts with Venus?**

The lack of a full range of fields and particle measurements on PVO limits our ability to resolve and understand the solar wind interactions which produce the ionopause, the mantle, the ionospheric holes, and the ionotail. These additional instruments would have required higher telemetry rates, payload weights, and power capabilities that were inconsistent with the overall cost constraints on the mission. Hopefully, a future mission would carry additional instruments to examine these phenomenon more closely.

**How does the ionosphere change with solar activity?**

Although PVO will be able to piece together important glimpses of solar cycle variations, using the radio occultation data, its evolving eccentric orbit does not allow the associated changes in ionosphere composition, temperature and motions to be examined. Here also, a future mission should employ a circular orbit and an extensive onboard propulsion capability to improve upon the PVO legacy.

In summary, PVO discoveries have completely revolutionized thought about the ionosphere of Venus. This region is infinitely more complex and variable than could have been anticipated. Although the data obtained thus far have answered the rather simple questions of 1977, this exposure to the real world of Venus has posed many new questions. Some of these may be answered in the next four years as PVO returns to low altitudes and eventually reenters the atmosphere in the fall of 1992. The investigations planned for that period are discussed further in Section 5.
4.3.1 A view of the noon and midnight orbit tracks against the night sky showing how the orbit evolved throughout the mission. The red lines show the orbit between 1979 and 1985 as periapsis rose rapidly. The yellow lines show the orbit position between 1985 and 1987 when periapsis hung near is maximum altitude. The green lines show the decline of periapsis that is now occurring as the spacecraft returns to the lower ionosphere. The blue dots and the green dots indicate the locations of the bowshock and ionopause crossings that have been recorded thus far.

4.3.2 The changes in periapsis altitude, showing the early phase in 1978-1980 when periapsis was maintained deep in the ionosphere, the middle years when periapsis rose and then fell, and finally, the reentry period in 1992.

4.3.3 An artist's conception of the Venus ionosphere as it is shaped by its interactions with the solar wind. The scale of the ionosphere has been exaggerated here by a factor of two to permit annotation. This drawing attempts to integrate many of the features of the ionosphere that are shown in greater detail in the remaining figures.

4.3.4 Comparison of the dayside ion density measurements with photochemical calculations of the individual ion densities. The general agreement between theory and measurement suggest that the fundamental ion production and loss processes that govern the Venus dayside ionosphere are understood.

4.3.5 Comparison of the ion and electron temperatures measured in the dayside ionosphere with theoretical profiles based on solar extreme ultraviolet heating within the ionosphere and solar wind heating at the ionopause. The close agreement demonstrates that the major aspects of thermal structure of the dayside ionosphere are understood.

4.3.6 Hydrogen ion measurements at 200 km altitude show that there exists a dawn-dusk asymmetry in the light ions. The dawn side bulge in H\(^+\) reflects changes in the composition of the neutral thermosphere cause by atmospheric superrotation.
4.3.7 The response of the electron density and temperature in the dayside ionosphere to changes in the extreme ultraviolet flux from the Sun. The densities follow the solar variations, while the temperatures are insensitive to the solar variations. This result suggests that the electron temperature is not controlled by solar radiation but by solar wind heating.

4.3.8 The variation of the ionopause altitude in response to changes in the magnetic pressure at the top of the ionosphere. The magnetic pressure is a proxy of the dynamic solar wind pressure. These results show that the ionopause altitude decreases when the solar wind pressure is high.

4.3.9 Ion mass spectrometer measurements of $H^+$ and $D^+$ at 250 km altitude. These measurements helped to establish the fact that the D/H ratio is about one hundred times larger at Venus than Earth.

4.3.10 Radio occultation measurements of the substantial nightside ionosphere at Venus. The large nightside ionosphere is believed to be produced primarily by the nightward flow of ions from the dayside, a condition permitted by the lack of a planetary magnetic field which would impede the flow.

4.3.11 Measurements of the electron density, temperature, the east component of the magnetic field, and the plasma waves made in a single nightside passage through an ionosphere having two holes. The causes of these holes and the origin of the large magnetic field within the holes remain a mystery.

4.3.12 Waves in the lower nightside ionosphere. These mysterious wavelike structures in the electron density, temperature, and magnetic field have a unique phase relationship that is not understood. They are believed to be produced by the supersonic nightward flow of ions as they interact with the more slowing moving neutral gases in the thermosphere.

4.3.13 Electron density measurements on a series of nightside passages at altitudes between 2000 and 3000 km showing examples of the tail rays that were illustrated in the drawing of Figure 4.3.3. The density profiles show the orbit to orbit changes in the tail ray structure that reveal their dynamic nature. Most of the planetary ions in these rays are believed to escape from the planet, a process that contributes to the loss of atmospheric oxygen and hydrogen.
4.3.14 Dayside electron density profiles at solar maximum (1980) and solar minimum (1986) which illustrate the large solar cycle changes in the density of the ionosphere. The depletion of the upper ionosphere at solar minimum is believed to be an important factor in the reduction of nightward ion flow and thus the less robust nightside ionosphere at that time in the solar cycle.
FIG. 4.3.2

Periapsis Altitude (km)

Periapsis Altitude

Calendar Year


0 500 1000 1500 2000

2000 1500 1000

0 500 1000 1500 2000
FIG. 4.3.4
FIG. 4.3.6

LOCAL TIME

ION CONCENTRATIONS [IONS/CM³]
FIG. 4.3.8

IONOPAUSE ALTITUDE (km)

MAGNETIC FIELD PRESSURE (10^{-8} \text{ Dynes/cm}^2)
FIG. 4.3.9
FIG. 4.3.10

ORB 55 ENTRY ORB 57 ENTRY ORB 62 ENTRY ORB 17 EXIT
\(X = 110.2^\circ\) \(X = 112.0^\circ\) \(X = 116.0^\circ\) \(X = 119.7^\circ\)

ORB 25 EXIT ORB 41 EXIT ORB 42 EXIT ORB 45 EXIT
\(X = 124.6^\circ\) \(X = 142.1^\circ\) \(X = 143.2^\circ\) \(X = 146.4^\circ\)

ORB 46 EXIT ORB 50 EXIT ORB 57 EXIT ORB 63 EXIT
\(X = 146.4^\circ\) \(X = 151.7^\circ\) \(X = 158.8^\circ\) \(X = 163.5^\circ\)
FIG. 4.3.13
SOLAR ZENITH ANGLE: 60°-70°

P-V RO EXPERIMENT

FIG. 4.3.14
4.4 IMPACT OF THE SOLAR WIND — C.T. Russell

4.4.1 KEY SCIENTIFIC QUESTIONS BEFORE THE PVO MISSION

Before the launch of the Pioneer Venus mission in 1978 the interaction of the solar wind with Venus was at a primitive stage of understanding. The intrinsic magnetic field of Venus was known to be much smaller than that of the Earth but whether it was strong enough to play some role in the interaction of Venus with the solar wind was questionable. There was no understanding of how, if there were no magnetic field, the ionosphere could deflect the solar wind. The solar wind could interact with the neutral atmosphere of the planet through processes of charge exchange of the solar wind with the neutral gas and the photo- and impact-ionization of the neutral gas, but how important such mechanisms were was unknown. Similarly there was the question of whether the solar wind was completely deflected well above the neutral atmosphere or whether some of it was absorbed by collisions with the neutral gas.

Planets that have large intrinsic magnetic fields have long, well-developed magnetic tails with embedded plasma sheets. Before 1978 it was not known whether Venus had such a magnetic tail and, if it did, whether there was a plasma sheet analogous to that of the Earth's tail. The terrestrial tail is dynamic, with internal releases of energy which are called substorms. Did the Venus tail have substorms also?

How the plasma flows around the planet, either in the solar wind or in the ionosphere, was not understood, nor was how the nightside ionosphere is maintained. There were often two peaks in the ionization at two different altitudes, but no one understood what caused them or why they were so variable. An airglow was thought to be present in Venus' atmosphere but its existence was uncertain and its cause was unknown; and a phenomenon called Ashen Light had been reported for centuries as radiating from the nightside of Venus. Its cause also was unknown.

Finally, there were questions about the more distant regions of the interaction of the solar wind with the planet. When a flow interacts with a body it often creates a boundary layer between the body and the flow. Also, as the fluid closes behind the body it has to expand and in so doing it creates a rarefaction wave. Would there be such features on Venus? Since the flow of the solar wind past Venus is supersonic, there must be a bow shock in front of Venus analogous to the bow shock of a supersonic aircraft when flying faster than sound. The Earth has such a bow shock. Furthermore, at the Earth there is a region of disturbance of field lines
which intersect the bow shock but which are upstream from it. An important question was whether at Venus, which presents a much smaller obstacle to the solar wind, the interaction would be different from the terrestrial one.

4.4.2 WHAT HAS BEEN LEARNED FROM PVO?

Solar Wind Interaction

The Pioneer Venus measurements clearly show that the intrinsic magnetic field of Venus is extremely weak, so weak that it can play no role in the interaction of Venus with the solar wind. This observation implies that the interior of Venus is much different from that of the Earth. Current theories of planetary magnetism assume that in the Earth the liquid iron core is solidifying. The heat released by the change in state together with the gravitational energy released as the solid iron sinks toward the center of the planet stirs up the fluid part of the core and helps generate the Earth's intrinsic magnetic field. For Venus this process is probably not occurring, so that Venus should have a completely liquid core which has not yet begun to solidify. This is believed to be the correct inference, rather than that the core is completely solid, because Venus' size should have kept the core at high temperatures until the present time. The slightly reduced pressure inside Venus because the planet is slightly smaller than Earth, would help slow the onset of solidification since the core would have to cool to lower temperatures than Earth's core to solidify.

The solar wind's interaction produces a magnetic cushion, or a magnetic barrier, which acts both as a lid on the ionosphere and as an obstacle to the solar wind's flow. Figure 4.4.1 illustrates how this occurs. The horizontal lines show the streamlines of the solar wind flow. They bend around the planet and do not enter the ionosphere. The vertical lines show the interplanetary magnetic field. These lines are carried along by the solar wind to the planet and drape around the ionosphere. The solar wind pushes the magnetic field down toward the planet, and the magnetic field in turn pushes on the ionosphere. The ionospheric pressure is usually sufficient to hold off the solar wind, and the strength of the magnetic field builds up to the value necessary to stand off the solar wind and to put a lid on the ionosphere. As a result, there is little or no direct coupling between the solar wind and the atmosphere of the planet except at the very highest altitudes where the atmosphere is extremely rarefied.

The results of the interaction of the solar wind with the rarefied atmosphere at high altitudes is illustrated in Figure 4.4.2. Here a neutral
atom of oxygen has become ionized and has been picked up by the solar wind flow. It then executes a spiral or cycloidal motion as it circles the magnetic field lines and drifts with the solar wind flow. This pickup process slows the solar wind even more than it would have been slowed by a purely ionospheric obstacle. Figure 4.4.3 follows three magnetic field lines being carried past Venus and shows how this slowing leads to the formation of a magnetic tail behind Venus. Figure 4.4.4 shows the region where the Venus tail is observed when the Pioneer Venus Orbiter is near apoapsis.

While this mass-loading process is important for the interaction of the solar wind with Venus, it is a very slow process for the removal of the neutral atmosphere. Approximately $10^{26}$ ions are removed each second. But at this rate only about three feet of water globally could be removed from the surface of Venus over the age of the planet.

A totally unexpected phenomenon was discovered in the Venus ionosphere; coils of twisted magnetic field which have been called flux ropes. These magnetic ropes appear to be connected to the solar wind's magnetic field, as sketched in Figure 4.4.5. The magnetic field is strongest and straightest in the center of the flux rope, as illustrated in Figure 4.4.6, and weakest and most twisted at the edges of the rope. These ropes appear to form at the ionopause, while in the boundary between the magnetic barrier and the ionosphere, as shown in Figure 4.4.7. They then sink into the ionosphere.

When the solar pressure is low the ionosphere is quite free of magnetic field, as shown in the top panel of Figure 4.4.8, with the exception of the flux ropes just discussed. However, when the solar wind pushes harder on the ionosphere the ionosphere becomes fully magnetized, as illustrated in the lower panel. To see why this occurs, look at a close-up of the interaction in Figure 4.4.9. To enter the ionosphere the magnetic field has to diffuse across the ionopause from the magnetosheath, or magnetic barrier, into the ionosphere. At the ionopause the plasma velocity is zero, but just below the ionopause there is some downward velocity, which is called convection. This convection carries the field lines deep into the ionosphere to low altitudes. However, at low altitudes the convection stops because the ionospheric plasma encounters the dense atmosphere and the field lines can leave the bottom of the ionosphere only by diffusion again. When the solar wind blows harder, the location of the ionopause drops, diffusion becomes more rapid, and the ionosphere fills up with magnetic field.
The solar cycle has a profound effect on the Venus ionosphere and on the solar wind interaction with the planet. Figure 4.4.10 shows the variation of the sunspot number during the 20th century. Pioneer Venus arrived at Venus just before the second largest sunspot maximum of the century. Solar activity then decreased. Now it is back to the level encountered at the beginning of the mission. In-situ data had not been obtained within the ionosphere for the entire solar cycle, but there have been changes in the solar wind interaction with Venus, revealed by monitoring the location of the bow shock, as illustrated in Figure 4.4.11. As sunspot numbers rise and fall the bow shock moves outward and inward respectively. This motion is due to the comet-like nature of the solar wind's interaction with Venus. At the peak of the solar cycle Venus has a very extensive hot oxygen atmosphere caused by the destructive recombination of electrons and molecular oxygen ions. Increased extreme ultraviolet radiation from the Sun at that time ionizes the hot oxygen atoms and adds greater mass to the solar wind flow than at solar minimum, thereby causing a larger magnetic barrier. In turn this pushes the shock further out.

Lightning

One of the objectives of the Pioneer Venus Orbiter Electric Field Detector was to search for any electromagnetic evidence for lightning on Venus. On Earth lightning generates both visible and radio frequency radiation. If lightning occurs on Venus it would be expected also to create radio waves. Such radio waves have, in fact, been discovered on Venus, and they have properties that would be expected if they were generated by lightning in the Venus atmosphere. These radio waves occur over a broad spectral band, they occur most frequently at lowest altitudes, and they have the properties expected for electromagnetic (radio) waves. These waves appear to occur more frequently over some geographic regions than others, a property also of terrestrial waves generated by lightning. However, this association is not solely with highland areas and cannot be taken to be an association with volcanic regions as was once assumed.

An important property of these lightning-associated signals is that their occurrence depends strongly on local time. The high frequency signals, as on the Earth, do not propagate far into the ionosphere and they mark the source region clearly. This is shown by the dotted line in Figure 4.4.12. The source of the waves is at local times before 2230. The decrease in occurrence as dusk is approached is an effect of the increasingly dense ionosphere which alters the propagation of the waves. At the lowest frequencies, denoted by the solid line, the occurrence of signals is greatest in the region judged to be the lightning source region, judged to be due to
the ability of these signals to propagate large distances. The dashed line in this plot shows the region of occurrence of strong magnetic fields which peak just before midnight and clearly are not responsible for the observed local time distribution of "lightning" bursts. The strong local time dependence suggests the "lightning" is weather related. The height of the cloud layer above the surface of Venus is so large - approximately 55 kilometers - that these discharges are probably from cloud-to-cloud rather than from cloud-to-ground. An interpretation of these data is shown in Figure 4.4.13. Lightning probably occurs both in the afternoon and evening hours, but the signals get into the ionosphere only in the early evening hours.

One of the initial pre-PVO question of great interest because of its long standing, was the cause of the phenomenon known as Ashen Light. To date the PVO mission has been unable to determine whether visible emissions on the nightside of Venus are strong enough to be seen from Earth. However, night airglows on Venus have been observed both in ultraviolet and in visible light. Also the Ashen Light appears to have the same local time of occurrence on Venus as the lightning. However, if Ashen Light is caused by lightning on Venus, lightning must occur much more frequently on Venus than on the Earth. The evidence from optical means and from radio wave detection all suggest that lightning is, indeed, more prevalent on Venus.

4.4.3 IMPLICATIONS OF THE PIONEER VENUS RESULTS FOR THE EARTH AND OTHER PLANETS

A study of Venus provides information relative to processes occurring on the Earth and on other planets. The lack of a magnetic dynamo on Venus today has implications for the Earth. If the reason for the lack of a dynamo today, is that Venus has a totally liquid core, the Earth may not have had a magnetic dynamo and an intrinsic magnetic field until its solid inner core began to form. At present, the Earth is protected by its strong magnetic field which isolates its atmosphere from the pressure of the solar wind. Thus there is currently very little loss of the Earth's atmosphere to the solar wind. However, if the Earth did not always have a strong magnetic field, there were times when it was not protected from the solar wind. Also, during magnetic reversals the Earth's magnetic field is diminished. Thus Venus today can show us how the Earth might have interacted with the solar wind at such periods in the past.

Venus also provides a good indicator of the vigor of the solar cycle. The PVO measurements at Venus indicate that the extreme ultraviolet output of
the Sun is high and that the upper atmosphere of Venus is very dense. Since similar processes occur in the Earth's atmosphere, the upper atmosphere of the Earth is most likely being similarly affected if the orbits of Earth satellites become affected by additional drag as the solar activity increases in 1989-90.

Venus also helps an understanding of lightning here on Earth by providing examples of lightning in an atmosphere different in composition, temperature and pressure. Also on Earth the clouds consist of water and ice while on Venus they consist of sulfuric acid. The electrification processes on Earth are not yet well understood. Venus, because of its lack of a magnetic field, may have a more variable source of ions which lead to cloud charging. An understanding of what leads to variation in lightning on Venus may be applicable to understanding the processes on Earth.

Venus data are already helping U.S. plans for upcoming Mars missions. Figure 4.4.14 shows the known solar wind interaction with Venus in contrast to the possible modes of the solar wind's interaction with Mars. The middle panel shows the expected interaction if Mars has no intrinsic magnetic field. This latter picture is inferred from the knowledge of how Venus behaves when the solar wind's magnetic pressure is strong. Existing data is consistent with this picture derived from the Pioneer Venus data.

Another Solar System object that much resembles Venus in its interaction with its environment is Titan, the largest satellite of Saturn. Figure 4.4.15 depicts the present understanding of the interaction of Titan with its magnetosphere based on an understanding of the interaction of the solar wind with Venus. This understanding will help the planning for the Cassini mission which will make repeated encounters with Titan.

4.4.4 KEY SCIENTIFIC QUESTIONS CURRENTLY BEING ADDRESSED

Solar Wind Interactions

The solar cycle is now rapidly rising to a peak of activity that appears certain to exceed that of the previous solar cycle and is likely to rival that of the strongest solar cycle of this century, that of the International Geophysical Year (IGY). During the past solar maximum, however, the periapsis of the PVO spacecraft was being maintained at low altitude well below some of the interesting regions of the solar wind's interaction. Periapsis is currently at a rather high altitude where it can directly probe the solar wind's interaction with the planet. In particular, this period is
being used to study the subsolar bow shock to see if it responds to changing solar activity in the same way the bow shock responds above the terminator. This will reveal whether the magnetic barrier changes size or changes shape also being monitored.

Lightning and Ashen Light

At present the PVO star sensor is being used to perform two studies. First, the star sensor probe is being allowed to include part of the planetary disk in its field of view so that the resulting light intensity from the disk can be measured. The visible light glow on Venus is so intense that the sensor will saturate if its field of view is totally on the planet, but partial intersections with the planet will not result in saturation and will allow the intensity to be mapped. Second, the star sensor is being positioned to look slightly off the planet to search for impulses of scattered light from the planet which might be indicative of lightning. When the PVO spacecraft drops below 2000 kilometers altitude at periapsis the search will be resumed for radio emissions generated by lightning. Also an Earth-based telescopic Ashen Light survey has just been completed using amateur groups to do the observing. This study may be repeated during the next apparition of Venus.
Figure Captions

4.4.1  Simplified diagram to illustrate how the solar wind interacts with Venus and how the streamlines of solar wind flow past the planet.

4.4.2  Diagram of how the solar wind interacts with the rarefied atmosphere of Venus at high altitudes.

4.4.3  Illustrating how three magnetic field lines, starting with f1, are carried past Venus and distorted in the magnetotail.

4.4.4  The region where the magnetotail of Venus is observed from PVO at the time when the spacecraft is near apoapsis.

4.4.5  Coils of twisted magnetic field, which have been termed flux ropes, are generated in the ionosphere. These were quite unexpected.

4.4.6  Simplified diagram of the magnetic structure of a flux rope. The magnetic field is strongest and straightest at the center and weakest and more twisted at the edges.

4.4.7  The flux ropes appear to originate at the ionopause and sink into the ionosphere.

4.4.8  Variations in the ionosphere of Venus at periods of low and high dynamic pressure of the solar wind.

4.4.9  Diagram identifying the various regions between the incoming solar wind and the surface of Venus showing the balancing forces of ionospheric pressure and solar wind pressure.

4.4.10 Smoothed monthly sunspot numbers for the period 1900 through 1988.

4.4.11 Effects of the solar wind changes on the bow shock of Venus over the period of the mission.

4.4.12 Lightning associated signals and their dependence on local time on Venus.

4.4.13 Interpretation of data from PVO to illustrate how the signals enter the ionosphere only in the early evening hours.
4.4.14 Comparison of the effects of solar wind pressures on the ionospheres of Venus and Mars. Two alternatives are shown for Mars with and without an intrinsic magnetic field.

4.4.15 Present understanding of how the solar wind probably interacts with the Saturnian satellite, Titan; based on what has been learned from Venus of importance to planning a mission to Titan.
FIG. 4.4.1

- Magnetic field lines
- Streamlines of solar wind plasma flow
- Ionospheric pressure
- Solar wind pressure
FIG. 4.4.2

Ionosphere

Bow Shock

Magnetosheath

Magnetotail

$X(R_V)$

To Sun

$Z$

$-2$

$-4$

$-6$

$-8$

$-10$

$-12$

Pickup $O^+$
VENUS TAIL ENCOUNTERS

- Pioneer Venus
- Venera 9, 10
- Venera 4
- Mariner 5

WITHIN TAIL
- 91 - 100%
- 71 - 90%
- 51 - 70%
- 31 - 50%
- 11 - 30%
- 0 - 10%

Bow Shock
Tail Boundary

Fig. 4.4.4
Flux Rope Magnetic Structure
Low Dynamic Pressure

High Dynamic Pressure

ionosphere
SMOOTHED MONTHLY SUNSPOT NUMBERS
January 1900 - June 1984

FIG. 4.4.10
Solar Cycle Effects on Venus' Bow Shock

[Diagram showing the solar min and max positions and the Venus' bow shock region with distance markers of 2.1 $R_V$ and 2.4 $R_V$.]

[Graph showing the relationship between sunspot numbers and bow shock position over the years 1975 to 1989.]
FIG. 4.4.12

![Graph showing the percent occurrence of IBI > 15 nT and F < Ω ge bursts over the course of the day.](image)

- IBI > 15 nT
- F < Ω ge Bursts
- F > Ω ge Bursts

Local Time:
- Dawn
- Dusk
FIG. 4.4.14

Venus

Mars?

Mars?

solar wind pressure

ionospheric plasma pressure

solar wind pressure

intrinsic magnetic field pressure

solar wind pressure

ionospheric pressure including plasma plus ionospheric field pressure

ionospheric pressure including plasma plus ionospheric field pressure
When Pioneer Venus Orbiter reached Venus in December 1978, scientists already knew that the clouds which obscured the surface of the planet from telescopic view contained concentrated sulfuric acid. Earlier spacecraft had produced images showing dark absorbers of ultraviolet light in the clouds, but the nature of these absorbers was unknown. In fact, there were many unknowns about Venus' atmosphere. During the ten years of Pioneer Venus Orbiter's operations many discoveries have been made about the clouds and hazes, the sulfur dioxide distribution and chemistry, the winds in the thermosphere, changes during the solar cycle, aurora, and escape of gases from the exosphere.

### 4.5.1 CLOUDS AND HAZES

The Pioneer Multiprobes found that the acid clouds formed several layers between 48 and 65 kilometers above the surface of the planet. What the Pioneer Venus Orbiter's Cloud Photopolarimeter found at the top of these clouds was a complex region of hazes, winds, and atmospheric waves. Images returned from the spacecraft show delicate fields of clouds blown by 100 meters/second winds. In the hours before dusk, these clouds are clearly outlined against the darker regions below, but at dawn and in the early morning, they are veiled by a high haze of fine acid droplets that disappear later in the day.

At high latitudes, these droplets persist, but the Infrared Radiometer detected a hot dipole beneath the permanent polar hazes. This is a double-lobed region rotating around the north pole and it may be where descending air clears of haze and allows the heat of the lower atmosphere to be seen from space.

Winds can be measured by tracking the clouds that they carry along. Images obtained over the ten years in orbit have shown that the winds circle the equator in five days. At higher latitudes this period decreases to three-and-a-half days, and under the polar hazes the infrared dipole rotates in three days.

Another phenomenon shows up near the equator; a wave of brightening which is perhaps due to a process that thickens the haze layer. The wave passes through the clouds and circles the planet in four days. In 1982 and 1983, however, this wave was mysteriously absent (Figure 4.5.1).
4.5.2 SULFUR DIOXIDE NEAR THE CLOUD TOPS

When Pioneer Venus entered orbit around Venus the nature of the gas that absorbed solar ultraviolet radiation and darkened the interior of the cloud layers was unknown. The Ultraviolet Spectrometer quickly found that sulfur dioxide made a large contribution to this absorption. Further, measurements showed that this gas was welling upward from below in quantities that matched the rate at which the acid droplets of the clouds were settling downward. The mystery of the acid clouds was solved when calculations showed that the sulfur dioxide was oxidized at the cloud tops by ultraviolet photochemistry, and then dissolved in water droplets to form sulfuric acid.

Several years of observation by Pioneer Venus showed that the amount of sulfur dioxide that could be seen in Venus' atmosphere decreased to between 10 and 20 percent of its value in late 1975 (Figure 4.5.2). One possible explanation is that Venus is volcanically active, periodically injecting massive amounts of gas into the atmosphere. A difficulty with this explanation is that since Venus lacks water the planet almost certainly also lacks an explosive style of vulcanism that could inject gases directly up to the cloud tops. However, there might be an episode of low-level activity after which the gases would be carried upward by normal atmospheric mixing processes.

4.5.3 WINDS IN THE THERMOSPHERE

Before the Pioneer Venus mission scientists knew that the carbon dioxide that makes up the bulk of the planet's atmosphere is mysteriously stable. It resists the tendency of solar ultraviolet radiation to decompose it into carbon monoxide and oxygen.

The Orbiter soon found part of the explanation for this stability. In the highest part of the atmosphere where rapid decomposition of carbon dioxide by sunlight is a continuous process, the heat released by this process drives a planetwide system of 300 meters/second winds that blow from dayside to nightside. On the nightside the winds descend to lower altitudes. The carbon monoxide and oxygen are carried from the high atmosphere to the low atmosphere by these winds. A striking confirmation of this process came from Ultraviolet Spectrometer images which showed atoms of nitrogen from the dayside 'burning' on the nightside with an ultraviolet 'flame' in the descending region where the pressure of oxygen increased lower in the atmosphere. Theoretical calculations show that once the dissociated gases reach lower altitudes they reform carbon dioxide
under the influence of chlorine-catalyzed photochemistry above the cloud tops.

Measurements by the Neutral Mass Spectrometer, and studies of aerodynamic drag on the Orbiter, show that the nightside high atmosphere is exceptionally cold (100 Kelvin), colder than any other planetary atmosphere closer to the Sun than Saturn (Figure 4.5.3). The measurements also show that the high atmosphere, like the cloud top region, is 'superrotating', turning much faster than the planet itself. Finally, the violent high-altitude winds are patterned by density waves that originate in the lower atmosphere and show as fluctuations in measurements made by the Neutral Mass Spectrometer and as bright streaks in images produced by the Ultraviolet Spectrometer.

4.5.4 SOLAR CYCLE CHANGES

The upper atmosphere and ionosphere were expected to respond in an observable fashion to changes in solar activity on short and long term time scales. During Phase I of the PVO mission, when the spacecraft was perturbed by atmospheric drag at periapsis, the OAD experiment produced clear evidence for drag response to 27-day variations of the Sun (Keating and Bougher, 1987).

Because the lowest point of the spacecraft's orbit rose out of the atmosphere in 1980 when solar activity was high, and will not return until 1992 when activity will again be high, the effect of low solar activity on the high atmosphere could only be studied by remote sensing. The Radio Occultation Experiment, which studies the effects of the ionosphere of Venus on the radio beam transmitted from the spacecraft to Earth, found that as solar activity declined the ionosphere shrank and became shallow. This indicated that the high atmosphere had become much cooler and, perhaps, changed in its composition. Studies of images made in light from carbon monoxide and oxygen by the Ultraviolet Spectrometer over ten years, also show that these gases have decreased relative to their 'parent' carbon dioxide. At the same time, the brightness of the ultraviolet nitrogen 'flame' on the nightside has decreased. All these effects have reversed as the Sun's activity has begun to climb toward its next peak, expected in 1991 (Figure 4.5.4).

4.5.5 AURORA

One of the unexpected discoveries by the Orbiter was the presence of ultraviolet emissions from oxygen in the high nightside atmosphere, which
could only be explained by energetic charged particles (electrons or ions) entering the atmosphere from space. Such emissions are commonplace on planets with magnetic fields - on Earth they are known as the 'northern lights' or aurora. But Venus has no magnetic field to trap and direct charged particles from the Sun, as Earth, Jupiter, Saturn, and Uranus have. The origin of the particles responsible for the aurora of Venus remains uncertain.

Because the brightness of the emissions is related to solar activity, it is possible that the particles are photoelectrons produced on the dayside by extreme ultraviolet sunlight and carried into the night atmosphere by the weak but turbulent magnetic fields produced by the action of the solar wind on the planet's ionosphere.

4.5.6 EXOSPHERE AND ATMOSPHERIC ESCAPE

The exosphere forms the outermost fringe of the atmosphere where atoms move in ballistic trajectories and rarely collide with one another. The Ion Mass Spectrometer of Pioneer Orbiter found that the number of hydrogen atoms increased steadily through the night but decreased precipitously during the day - in effect they are 'trapped' by the very low nightside temperature. In fact, they are so scarce in the daytime exosphere that their place as the dominant constituent is taken by atoms of oxygen. These oxygen atoms are themselves unusual in that they are very hot. They are produced by the decomposition of ionized molecular oxygen, a process that at lower altitudes is one of the mechanisms by which ultraviolet sunlight heats the atmosphere.

In the exosphere these fast-moving atoms of oxygen and hydrogen are not slowed by collisions with ambient gases. Instead they rise thousands of kilometers into space. There they form the first obstacle seen by the solar wind as it approaches Venus.

From this hydrogen/oxygen exosphere atoms of both kinds can escape into space. On the dayside, oxygen atoms are ionized by extreme ultraviolet sunlight, and the resultant ions are carried away by the solar wind. On the nightside, much larger numbers of hydrogen atoms (see Figure 4.5.3) undergo charge exchange collisions with hot protons in the nightside ionosphere. Hot protons capture electrons and become fast-moving hydrogen atoms that escapes into space. Cool atoms lose an electron and become cool protons. Pioneer Venus Orbiter measurements show, however, that the rate of loss of gas by these processes is much smaller.
now than escape rates estimated for other processes when Venus was young.

Figure Captions

4.5.1 Equatorial wind and wave speeds - The OCPP instrument has been used to study cloud-tracked winds and to perform time-series analyses on equatorial brightness variations (dominated by the Y-feature). On this figure wind speeds are shown as filled circles, and brightness periods, expressed as the speed of a prograde Kelvin wave, are shown as open circles. In 1982-3, for unknown reasons, the Kelvin wave disappeared and the brightness periodicity corresponded to the mean zonal wind speed.

4.5.2 Decrease in cloud-top sulfur dioxide - The OUVS instrument measures cloud-top sulfur dioxide by ultraviolet reflectance spectroscopy and multi-wavelength imaging. In 1978, SO$_2$ was readily detectable, although it had been searched for in vain for decades. In subsequent years it declined steadily. It is possible that a major volcanic episode earlier in 1978 injected vast amounts of sulfur dioxide into Venus' atmosphere.

4.5.3 The cryosphere and thermospheric winds - ONMS and OAD data revealed a very cold nightside thermosphere (referred to as the cryosphere). The resulting pressure gradients drive strong winds from subsolar to antisolar regions. Atomic hydrogen densities, deduced from OIMS H$^+$ and O$^+$, and ONMS oxygen densities show a strong cold-trapping effect on the nightside, and the displacement of the nightside peak of hydrogen toward the dawn terminator indicates that the thermospheric winds have a superrotating component.

4.5.4 Solar Cycle variations - OUVS measurements of dayglow emissions from atomic oxygen and carbon monoxide show strong solar-cycle effects. The global 130 nm brightness (due to atomic oxygen emissions) declined from solar maximum in 1979-80 to a minimum in 1986, coinciding with solar minimum. A sharp increase is seen in 1988. Similar variations seen at 139 nm (due to scattering of solar Lyman-alpha radiation by carbon monoxide) show a stronger dependence on the 10.7-cm solar activity index than does solar Lyman-alpha itself, demonstrating that the thermospheric ratio of carbon monoxide to carbon dioxide is controlled by solar activity.
FIG. 4.5.1

- ○ BRIGHTNESS
- ● MEAN ZONAL WIND

VELOCITY (M/S)

YEAR

80 81 82 83 84 85

79 80 81 82 83 84 85
Amount of SO$_2$ at cloud-tops

+ from spectral data

\(\Delta\) from multicolor images
FIG. 4.5.4

**Atomic Oxygen**

**Carbon Monoxide**

- **Venus 139 nm**
- **Solar 122 nm**
4.6 THE SURFACE AND INTERIOR

4.6.1 GEOLOGY — H. Masursky

The Pioneer Venus Orbiter and Multiprobes encountered Venus in early December 1978 (Colin, 1980). The Orbiter continued to acquire radar data for 3 1/2 seasons (8 months per season), until it rose too high to acquire altimetry. The orbital tracks were carefully adjusted for the extended mission (the second and third seasons) so that the new data points lay between those acquired earlier (Pettengill, et. al., 1980; Masursky, et. al., 1980). Eric Eliason (United States Geological Survey, Flagstaff) and Peter G. Ford (Massachusetts Institute of Technology, Cambridge) have enhanced the data set since 1980 so that the data presented here is the best adjusted altimetry data for Pioneer Venus.

Higher resolution data acquired in 1985-86 by the Soviet Union's Venera 15 and Venera 16 (Bogomolov and others, 1985; Kotelnikov and others, 1985; Barsukov and others, 1986) have been incorporated into the present Pioneer Venus data, and the two sets have been mutually coordinated. Hakim (personal communication) has enhanced the Soviet data set as much as possible and has cooperated in adjusting the two data sets.

The USA (R.M. Batson, shown below) has produced a shaded relief version of the synthetic aperture radar images that have been mosaiced by computer. The adjusted contour map and nomenclature are shown here with the morphologic map. A geologic map of the northern also is shown here (Basilevsky et. al., 1988).

Soviet scientists have made their data available to American scientists before publication, to assist the Americans in planning the Magellan radar mapper mission to Venus. Masursky et. al. (1980) and Schaber (1981) have analyzed geologically the Pioneer Venus data acquired earlier; they have recognized and described a multitude of tectonic features and volcanic centers from these data. Many of these features are shown more clearly in the Pioneer Venus and Venera data than any other planetary or satellite features discriminated either by spacecraft or groundbased data (Goldstein, 1976; Aleksandrov, 1980; Head, et. al., 1983; Campbell, 1984).

Figure 4.6.1 through 4.6.6 graphically illustrate some of the results of this work in defining the surface features of Venus. Figure 4.6.1 illustrates the filtered combination of PVO and Venera data on a mercator projection from 20 to 80 degrees north latitude. Figure 4.6.2 is another stage in the processing showing combined and filtered data, and Figure 4.6.3 shows the
new combined data, color-coded to the old version of the PVO map of the surface. Figures 4.6.4 through 4.6.6 show a similar sequence of image files for the north polar region covering the surface of the planet down to a latitude of 20 degrees above the equator.

The PVO orbit is now decreasing in height; altimetry data could be obtained again for an additional six months before the spacecraft burns up in the Venus atmosphere. Whether or not the PVO ORAD will be reactivated awaits the results of Magellan, now enroute to Venus.

4.6.2 GRAVITY FIELD — W.L. Sjogren

Before PVO, knowledge of the Venussian gravity field was very primitive, being derived from the analyses of Mariner 2 and Mariner 10 data in 1969 and 1974, respectively. The information gleaned at that time was an upper bound value for the oblateness (i.e., \( J_2 < 1^{-5} \)). The Soviets in 1978 also published a value for the oblateness of \( 4 \times 10^{-6} \), determined from Venera 9 and Venera 10 spacecraft data.

Doppler radio tracking from PVO during its periods of low periapsis altitudes have provided a wealth of detailed gravity measures, which allows one to directly correlate the gravity signatures with surface topography. Both global and regional areas have been mapped and analyzed for measures of internal relaxation or compensation of surface topographic load.

Figure 4.6.7 displays gravity contours obtained from line-of-sight acceleration profiles. Note the high correlations of gravity-highs with topographic-highs (light areas) and similarly the gravity-lows with topographic-lows (dark areas). The gravity contours are spaced at 5 milligal intervals and have amplitudes that are more Earth-like than those gravity anomalies on the Moon and Mars which are much larger. The large low-frequency gravity variations on Earth do not correlate well with continental topography, whereas they do on Venus. The relatively low gravity values confirm that significant relaxation or isostatic adjustment has occurred, much like what happens on Earth with old mountain ranges.

Individual features such as Beta Regio, Ishtar and Aphrodite Terra have been analyzed. The results reveal that different internal histories must have occurred. If one assumes an isostatic model for each of these features, then the depth of compensation varies greatly. Aphrodite Terra is compensated at 65 km, whereas Beta Regio is compensated at greater than 300 km. No one believes that Beta is deeply compensated, so a more
realistic model may well be that Beta is relatively young and is being supported by some internal convective process, whereas Aphrodite is old and could well be near isostasy. Ishtar appears to be somewhere between these two models.

If one plots the ratio of observed gravity to theoretical gravity from topography, there is a definite trend of an increasing ratio eastward from western Aphrodite all the way around to beyond Beta Regio (some 270 degrees of longitude - see Figure 4.6.8). A possible explanation for this is that there is a convection system that is moving eastward and the trailing topography is being more compensated at larger distances from the most active region. Presently, there is a debate as to whether Aphrodite Terra is a spreading center or not, like Earth's mid-Atlantic ridge. Gravity data are being used to constrain the various models; however, at this point it is still an open issue. The new data from PVO in 1992 may well provide an answer, for better detailed profiles will be obtained since periapsis will be at 10 degrees south and directly over Aphrodite Terra.

In addition to the line-of-sight profile mapping, a global spherical harmonic expansion to degree and order 10 has been extracted. The gravity field contours from this model are shown in Figure 4.6.9, and again one can clearly see the high correlation with topography.
Figure Captions

4.6.1 Mercator projection of PVO and Venera data combined and filtered; latitude 20 to 80 degrees north.

4.6.2 Shaded relief mercator projection of filtered data from PVO and Veneras.

4.6.3 Mercator projection of PVO data combined with Venera data and color-coded to the old version of the PVO map.

4.6.4 Polar stereographic projection to 20 degrees north latitude of PVO and Venera data combined and filtered.

4.6.5 Shaded relief polar stereographic projection of filtered data from PVO and Veneras.

4.6.6 Polar stereographic projection of PVO and Venera data color-coded to the old version of the PVO map.

4.6.7 Gravity contours superimposed on topography (5 milligal intervals).

4.6.8 Ratio of observed gravity to theoretical gravity from topography versus the anomaly longitude.

4.6.9 Venusian free-air gravity anomalies. Contour interval is 20 milligals. The heavy solid curve is the zero level, and negative anomalies are hachured. Accelerations are evaluated at 6052 km radius.
FIG. 4.6.7

GRAVITY AND ALTIMETRY MAP OF VENUS
FIG. 4.6.8

LETTERS REPRESENT NEGATIVE FEATURES
NUMBERS REPRESENT POSITIVE FEATURES

VENUS LONGITUDE (deg)

GRAVITOPO

0.8

0.4

0

60 120 180 240 300 0 60
4.7 VENUS: LESSONS FOR EARTH — D.M. Hunten

4.7.1 ARE VENUS AND EARTH REALLY TWINS?

It has been known for a long time that Venus and Earth are near-twins in terms of size and mass, and there are plenty of stories in the older science-fiction literature based on the assumption that living conditions might also be similar. With its total cloud cover, Venus was usually taken to be warm and steamy, with vegetation like that of the Carboniferous era. With the increasing power of telescopes and spectrographs in this century, many of the fancied similarities began to disappear; oxygen could not be detected, and it became almost certain that the clouds were not made of water or ice. Instead, there was an abundance of carbon dioxide, and refined analysis showed the cloud particles to be concentrated sulfuric acid. Radio astronomy showed the surface temperature to be 750 Kelvins (477 deg.C), although this interpretation was controversial for a long time. From 1967 on, several space missions, both U.S. and Soviet, confirmed and extended these results, finding that carbon dioxide is the principal atmospheric gas and that its pressure at the surface is a little more than 90 atmospheres (by definition, the sea-level pressure on Earth is one atmosphere).

Although it is clear that the two planets are very different now, the question of "nature or nurture" remains: Could they have been much more similar originally, but evolved differently? Venus receives almost exactly twice as much solar energy as Earth; could this difference account for all the others? As is discussed later, the answer could be "yes" to both questions, but of course there is no way to be certain of what happened such a long time ago. If beaches or wave-generated cliffs are ever found on Venus, we can be nearly certain that there were large bodies of water, but we are very far from that as yet.

The total absence of detectable free oxygen is as remarkable as the high surface temperature, because oxygen is copiously produced by the action of sunlight on carbon dioxide. This process is found on Mars, where the fraction of oxygen in the atmosphere is at least ten thousand times larger than on Venus. Even this amount is actually surprisingly small, and for both planets the answer may be that the chemical effects of "pollution" are at work. The quotation marks are used as a reminder that this particular "pollution" is natural, but the effects are, of course, the same whether the chemicals are generated naturally or artificially. Venus is a clear example of what chlorine can do to an atmosphere, and it is important to regard this example as an object lesson.
It is natural to ask whether Earth is in any danger of turning back into a true twin of today's Venus. Nobody has seriously suggested this; rather, Venus should be regarded as an example of an end state towards which Earth is edging. The greenhouse effect is real, and its magnitude is certainly increasing. As discussed later, the basic idea of the greenhouse is easily comprehended; the question is not "whether?" but "how much?" Free chlorine is damaging the ozone layer, especially in the Antarctic; Venus is a reminder of how much worse a greenhouse effect can get, with the planet's near-total absence not only of ozone but also of oxygen.

4.7.2 VENUS TODAY

Greenhouse

In the greenhouse effect, illustrated in Figure 4.7.1, solar energy is at least partly transmitted to the planetary surface, where it is converted to heat. On an airless body like the Moon, the energy is radiated back to space at much longer, infrared, wavelengths, and the surface temperature adjusts itself so that input and output are in balance. An atmosphere can help to hold back the infrared and permit the surface temperature to rise. Although it is often likened to the window or roof of a greenhouse, the atmosphere is really more like a blanket. The radiation wanders around, sometimes upward, sometimes downward, sometimes sideways, eventually finding the "top" of the blanket from where it can reach space. This "top" has the temperature that the ground would have if there were no blanketing. The greenhouse heating therefore tends to increase as the thickness of the blanket increases.

On Venus, this thickness is around 60 kilometers or 200,000 feet, as illustrated by the temperature profiles in Figure 4.7.2. The heavy line indicates measurements by the probes of the Pioneer Venus mission, and the lighter lines show the results of mathematical greenhouse models under various assumptions about the gases (carbon dioxide and water vapor, as well as cloud particles) that do the blanketing. Although there are some minor bends in the lines, the general tendency is a pair of straight lines joining at 60 kilometers, which is also in the region of the cloud top. A straight line on such a graph corresponds to a constant gradient of temperature: it drops a bit more than eight degrees for each kilometer. This is close to the so-called adiabatic temperature gradient, which is found in places where the atmosphere is in rapid vertical motion. A rise or fall of the major bend in the plot (i.e., the top of the blanket) by one kilometer would tend to raise or lower the surface temperature by this same eight degrees.
The figure also shows the average surface temperature of the Earth; about 300 Kelvins, or 27 deg. C. The top of the blanket here is around 30,000 feet or nine kilometers, at the base of the stratosphere, and the average temperature gradient below is about 5 deg. C per kilometer. Addition of enough carbon dioxide to raise the level by a kilometer would raise the surface temperature by 5 deg. C. The principal uncertainty is the effect of a change of cloudiness. A warmer world would probably be somewhat more cloudy, and less solar heat would reach the surface. This is the main factor that prevents us from being fully confident of the exact size of a temperature rise.

Pollution

Two-thirds of the atoms in a carbon dioxide molecule are oxygen, and at high altitudes this molecule is readily broken up by the action of sunlight; the products are an oxygen atom and a carbon monoxide molecule, which have been measured by the Pioneer Venus Orbiter. On the Earth, molecular oxygen is destroyed in a similar way, and the upper atmosphere is dominated by the atoms of oxygen. At corresponding altitudes on Venus, oxygen atoms are much rarer, and the conclusion is that they are rapidly swept down to lower altitudes by a huge downdraft on the nightside, part of a global wind system sketched in Figure 4.7.3.

Oxygen atoms recombine rather readily into molecules, and on Earth this readily closes the cycle. When the same thing happens on Venus, two carbon dioxide molecules are left stranded, and a large buildup of carbon dioxide and molecular oxygen would be expected. This is just what happens in a laboratory flask of carbon dioxide if the proper kind of ultraviolet light is introduced (Figure 4.7.4). The remarkable thing is that molecular oxygen is not detected at Venus' cloud tops, even though one molecule in ten million could be detected. Clearly there is something happening on Venus that is absent from the laboratory experiment. Chlorine and its compounds are probably responsible.

The hydrochloric acid molecule, HCl, was detected by Earth-based spectroscopy with an amount of 45 molecules per million of carbon dioxide. Chlorine atoms are freed from the HCl molecule by the action of sunlight, and enter into a cycle of reactions, shown in simplified form in Figure 4.7.5. The cycle itself does not require any solar radiation; a single chlorine atom can catalyze the recombination of many carbon monoxide molecules and oxygen atoms into carbon dioxide. An oxygen molecule is also used and then released. The system has been modeled in great detail,
with the addition of many more reactions including those of sulfur and its oxides. Figure 4.7.6 shows a sampling of the results, along with experimental data (dashed lines) for sulfur dioxide, oxygen molecules, and carbon monoxide. The agreement suggests that the main features of the model are correct. The sulfur chemistry has its analog on Earth as well, but it is glossed over here to keep the main argument uncluttered.

The quantity of chlorine on Venus is about a thousand times more than in the Earth's stratosphere, where the ozone layer resides, and where the biggest sources are artificial. Scientists are just at the point of developing a consensus that there is a significant effect on the ozone. The real problem, of course, is not the present amount of chlorine but the fact that the amount of chlorine is steadily increasing. Nobody expects it to go as high as it is on Venus, but keeping it from considerable further rise will be difficult. An outline of the principal chemistry is shown in Figure 4.7.7, which resembles Figure 4.7.5 to a considerable degree, but does not involve carbon monoxide which is rare on Earth. Atomic oxygen and ozone are rapidly interchangeable; when they are caused to react, as shown in Figure 4.7.7, the result is equivalent to the destruction of two ozone molecules.

The last few years have seen an enormous surge of interest in the phenomenon of the "Antarctic ozone hole" which occurs just after the end of the polar night. It is largely responsible for the general acceptance of the role of chlorine in destroying ozone (as if the example of Venus were not enough!). As indicated in Fig. 4.7.7, much of the chlorine outside the polar regions is bound in inert forms, and must be released by solar radiation to be effective. It is believed that the responsible molecules can be soaked up by ice particles that are present during the coldest parts of the polar night, so that all the chlorine is available for destruction of ozone. As Figure 4.7.7 (right) indicates, chlorine (Cl) atoms and ClO molecules are again involved, but now the concentration of the latter is so large that two can get together and form Cl₂O₂. Chlorine atoms are readily regenerated by the action of sunlight. Unlike the cycles shown in Figures 4.7.5 and 4.7.7 (left), this one does not require any oxygen atoms; it runs on ozone and solar radiation. During the month after the sun rises (September in the southern polar region) the inert forms of Figure 4.7.7 build up again and the hole is filled in.

Now that both Venus and the Antarctic examples are available for study, it is suddenly fashionable to take seriously the threat to the Earth's ozone layer. The principal carriers are the halocarbons, CCl₂F₂ and CFC₁₃, which have many uses including refrigeration. Most other compounds are destroyed or rained out before they reach the stratosphere. Serious
attempts at cutting back on the use of halocarbons are just beginning; substitutes do exist but they are more expensive and may have other drawbacks.

4.7.3 VENUS YESTERDAY

Did Venus have an "ocean"?

Most of the differences between Earth and Venus can be traced to the respective presence and absence of liquid water. Even if Venus started out with an amount similar to the Earth, much or all of it could have resided in the atmosphere. This is the reason for using quotation marks; the question really means "Did Venus have a large endowment of water?". The question of the water being in the form of liquid or of vapor is discussed later.

As near as the amounts can be evaluated, Earth and Venus actually have very similar quantities of carbon dioxide. On Venus it is all, or nearly all, in the atmosphere; on Earth it is in limestones and other carbonate rocks. Formation of these carbonates occurs under water, and is greatly assisted by living organisms. If all the carbon dioxide were removed from Venus' atmosphere, the remainder would be mostly nitrogen, about twice as much as on Earth. Precipitation of sulfur compounds would eliminate the clouds, and there would be nothing left to drive the enormous greenhouse effect.

All of this was known shortly after the first successful space missions to Venus, and there was considerable debate about the fate of a putative "ocean". The basic idea is that the stratosphere could have been much more humid than that of the present Earth. Water vapor could be dissociated by sunlight into hydrogen and oxygen; the hydrogen would escape, and the oxygen would react with iron in the crust. Another 20 years of study has made such ideas all the more reasonable. They were given an enormous boost by the 1982 discovery of a very large enhancement of the heavy hydrogen isotope (deuterium, D) relative to the normal one (hydrogen, H). This ratio is about 1/3000 on Earth and 1/100 on Venus. Such enrichment is exactly what is to be expected after a large-scale escape event, because the proportion of the lighter isotope in the material lost is greater than in the atmosphere. As the upper part of Figure 4.7.8 illustrates, the extreme assumption can be made that only hydrogen escapes, and thus obtain a minimum estimate of the original amount: this is 30 times the present amount. Unfortunately, the present amount is not really known because it is difficult to measure, and the data so far suggest a large geographical variability. Estimates (expressed as the equivalent depth of liquid) range from 10 to 100 centimeters; the minimum original amount
is therefore 300 centimeters or three meters. The Earth's oceans are equivalent to slightly less than 3000 meters.

If deuterium atoms also escape, the required original amount becomes greater. An example is shown in the lower part of Figure 4.7.8, where the original amount is 3000 times the present amount, or 300 to 3000 meters. This last figure is just the required "ocean". This example is, in fact, more reasonable than the first, and favors the "ocean" hypothesis. But the conclusion can hardly be called unique.

A further complication is that the observed water vapor could be in a steady state with some source, external or internal, with all signs of the initial endowment having vanished long ago. All that is needed, besides a source of the required size, is that the ratio of hydrogen to deuterium (H/D) in the escaping material be enriched 30 times. A possible source is occasional impacts by cometary nuclei, which are rich in ice.

Runaway Greenhouse

Suppose that Venus started out in a state resembling the present Earth. It is almost certain that the output of the Sun was less than it is now by around 30 per cent; thus, the temperature of Venus could have been only slightly warmer. Abundant clouds could have helped. Such a situation is unstable under some circumstances, and might be too unstable to have ever occurred. In any case, the instability would have become more and more likely as the solar output increased. A more humid atmosphere has a stronger greenhouse, which warms the surface and causes more water to evaporate. If this effect is strong enough, it can run away, and is only stopped when all the water has evaporated. An Earth ocean is equivalent to a surface pressure of nearly 300 atmospheres, and the steam would therefore have dominated the 90 atmospheres of carbon dioxide present on Venus today. It would have been even more dominant if most of the carbon dioxide was in carbonate rocks. The greenhouse temperature would have been much greater than it is now, and would probably have caused such rocks to decompose and release the carbon dioxide. With a steam atmosphere, decomposition and escape would be highly probable.

All these processes have been modeled numerically, and no problems have been found with the scenario. Thus, there is a perfectly reasonable path from an Earth-like Venus to the one known today. But there is a long way to go before the path is anything more than decisive discovery are minuscule. As has been shown, even the striking deuterium enhancement does not decide the issue.
Figure Captions

4.7.1 Mechanism of the greenhouse effect. At least part of the radiation from the Sun reaches the surface and is converted to heat. Heat radiation, in the infrared, can move only a short distance through the atmosphere before being re-absorbed and sent off in a different direction. Eventually it reaches a layer from which it can be released to space. A temperature gradient is set up across the region between this layer and the ground.

4.7.2 Temperatures in the atmosphere of Venus up to a height of 90 kilometers. The heavy line represents measurements by the Pioneer Venus probes; lines (a) to (d) are the results of model calculations with different assumptions about the amounts of various greenhouse gases and cloud particles. From Seiff (1983), after Pollack et al. (1980).

4.7.3 Illustration of the behavior of oxygen atoms in the upper atmosphere of Earth, and of carbon monoxide and oxygen in the corresponding region of Venus (above about 100 kilometers in both cases). They are products of the breakup of oxygen molecules and carbon dioxide, respectively. On Earth, the atoms are carried downward by a stirring process, while the oxygen and carbon monoxide on Venus are carried by downward-moving winds on the nightside, which are much more effective.

4.7.4 In the laboratory, carbon dioxide in a vessel irradiated by ultraviolet light is eventually converted to carbon monoxide and molecular oxygen. Although the first stages are similar on Venus, additional reactions are able to recycle the carbon dioxide with high efficiency. Oxygen remains in molecular form in the laboratory experiment, with a substantial amount of ozone.

4.7.5 A simplified flow diagram for converting carbon monoxide and oxygen back to carbon dioxide in the middle atmosphere of Venus. The cycle uses chlorine as a catalyst: It promotes the reactions but is not used up.

4.7.6 Results of detailed calculations for carbon monoxide and molecular oxygen (as well as sulfur dioxide) in the middle atmosphere of Venus. Reactions such as those shown in Figure 4.7.5 are able to reduce the fraction of oxygen molecules by a factor of 1000 between the top altitude shown on the figure and the cloud tops at 65 kilometers, and still more at 58 kilometers (Yung and DeMore, 1982).
4.7.7 Flow diagrams for destruction of ozone in the normal Earth stratosphere (left) and in the Antarctic ozone hole (right). There are strong similarities to the Venus system shown in Fig. 4.7.5.

4.7.8 Enrichment of deuterium (D) relative to hydrogen (H) in two hypothetical escape scenarios. The original H/D ratio is 3000, the Earth value, and the final is 100, the present Venus value. If only hydrogen is lost, the original amount is 30 times the present, as shown above. If both are lost, but at different rates, this factor is much larger; in the lower example in the figure it is 3000.
GREENHOUSE EFFECT

SOLAR ENERGY TO GROUND

HEAT (INFRARED) RADIATION WANDERS OUT

TO SPACE

POSSIBLE CLOUDS

FIG. 4.7.1

FIG. 4.7.2
UPPER ATMOSPHERE

\[ \text{O}_2 \xrightarrow{\text{SLOW MIXING}} \text{O} \text{ ATOMS} \]

100 km level

MIDDLE ATMOSPHERE

\[ \text{O} \text{ CONVERTED BACK TO} \text{O}_2 \]

RESULT: ABUNDANT O

CO, O CONVERTED BACK TO CO\(_2\)

RESULT: SCARCE CO, CO

SOLAR ULTRAVIOLET

EARTH

VENUS

Fig. 4.7.3

LABORATORY

BEFORE

\[ \text{CO}_2 \xrightarrow{\text{ULTRA-VIOLET LAMP}} \text{O}_2 \]

AFTER

\[ \text{CO}_2 \xrightarrow{\text{VENUS: CO, O, ARE VERY RARE}} \text{O}_2 \]

\[ \text{O}_2 \xrightarrow{\text{EARTH: O, IS ABUNDANT}} \text{CO}_2 \]

Fig. 4.7.4
VENUS

NET: CO + O → CO₂
(CATALYZED BY CHLORINE)
WORKS IN THE DARK!

FIG. 4.7.5

FIG. 4.7.6
EARTH

NORMAL

\[ \text{O} \rightarrow \text{Cl} \rightarrow \text{ClO} \rightarrow \text{INERT FORM (HCl, ...)} \]

SUN

\[ \text{ClO} \rightarrow \text{O}_3 \]

NET:

\[ \text{O}_3 + \text{O} \rightarrow \text{O}_2 + \text{O}_2 \]

ANTARCTIC OZONE HOLE

\[ \text{Cl} \rightarrow \text{ClO} \rightarrow \text{Cl}_2\text{O}_2 \]

NO INERT FORMS!

NET:

\[ \text{O}_3 + \text{O}_3 \rightarrow \text{O}_2 + \text{O}_2 + \text{O}_2 \]

NEEDS NO O!

CATALYZED BY CHLORINE

HOW MUCH WATER?

FIG. 4.7.7

FIG. 4.7.8
4.8.1 HALLEY

Comet Halley passed within 40 million kilometers of Venus only five days before perihelion in February 1986. The Science Steering Group agreed to forego normal PVO observations of Venus for a period of 70 days from late December 1985 to early March 1986, so that resources could be devoted to observations of the comet by the Ultraviolet Spectrometer of PVO. The spacecraft was maneuvered daily to allow the spectrometer to observe the region near the nucleus, while maintaining solar panel illumination and downlink antenna pointing criteria. These strenuous operations were a complete success; the only losses of data were due to superior conjunction in January and to interruption of the downlink by a major solar flare on 3 February. All of the more than 40 maneuvers were successfully completed, and the special system put together to supply the Ultraviolet Spectrometer investigators with near-real-time data also performed without hitches.

The PVO Ultraviolet Spectrometer measured ultraviolet emissions from hydrogen, oxygen, carbon and hydroxyl radicals in Halley's coma, and from these data the production rates of water and carbon-bearing ices from the nucleus were calculated. It was found that the rates for the water ices satisfied the relationship $Q(\text{H}_2\text{O}) = 4Q(\text{CO}) + 7Q(\text{CO}_2)$. The water production rate $Q(\text{H}_2\text{O})$, Figure 4.8.1, rose from 10 tonnes per second at one astronomical unit inbound to 50 tonnes per second shortly after perihelion, and then fell slowly to 40 tonnes per second at the time of the Vega 1 spacecraft's encounter on 6 March. The water production rate after perihelion showed a pronounced variability with a complex 7.4-day periodicity. These results are all in good accord with data from other platforms during the inbound and outbound phases of Halley's orbit, and they provide a unique description of the comet's behavior during the otherwise poorly-observed perihelion passage. In particular, the 7.4-day periodicity agrees in phase and amplitude with later ground-based and IUE data, and the values of $Q(\text{H}_2\text{O})$ agree well with the overlapping values deduced from the IUE observations of the hydroxyl radical. The PVO and IUE measurements taken together show that Halley lost about 270 million tonnes of water during this perihelion passage, corresponding to about 10 meters of material from its active areas if its density is 0.3.

From February 2 to February 6, a special series of operations allowed the PVO's Ultraviolet Spectrometer to acquire a spin-scan image of Halley's entire hydrogen coma, which at that time was about 25 million kilometers...
across. The image clearly shows the effects of solar radiation pressure on the trajectories of cometary hydrogen, and also shows the signature of the different hydrogen atom velocities associated with the two main production processes; photodissociation of water molecules and of hydroxyl radicals.

4.8.2 OTHER COMETS

In addition to Halley, PVO has observed six other comets to date; Encke (April 1984), Giacobini-Zinner (during the ICE flyby in September 1985), Wilson (March-April 1987), Nishikawa-Takamizawa-Tago (April 1987), McNaught (November 1987), and Machholz (September 1988).

Encke was observed at 0.58 astronomical units outbound, and the water production rates deduced from measurements of atomic hydrogen, together with rates deduced from later measurements of the hydroxyl radical by IUE, demonstrated profound and unexpected differences between the visual and the ultraviolet light curves. The activities of the other comets fell within a factor of two of expectations. Comparisons of the carbon/hydrogen ratios in Nishikawa-Takamizawa-Tago with those in Halley and Wilson led to a prediction that Nishikawa-Takamizawa-Tago, like Halley but unlike Wilson, is a periodic comet. This prediction was subsequently confirmed by accurate determination of the orbit.
4.8.1 Water production in Comet Halley - Analysis of OUVS measurements of Halley's atomic hydrogen coma yielded daily values of the water production rate from the nucleus (circles). The peak value of about 50 tonnes per second occurred a few days after perihelion (day 86040.45). The rate declined only slowly after that, and it showed a complex 7.4-day periodicity. The solid curve, symmetric about perihelion, is a model for a clean 5-kilometer nucleus.
FIG. 4.8.1

WATER VAPOUR

PRODUCTION RATE, MOL SEC⁻¹

0 0.5x10³⁰ 1.0x10³⁰ 1.5x10³⁰ 2.0x10³⁰

1985 365 10 20 30 40 50 60 70 1986

DAY OF YEAR

0.5x10³⁰ 1.0x10³⁰ 1.5x10³⁰ 2.0x10³⁰

1985 365 10 20 30 40 50 60 70 1986

DAY OF YEAR
5.0 EXPECTATIONS FOR 1989-1992

5.1 SPACECRAFT AND SCIENTIFIC EXPERIMENT CAPABILITY — J.W. Dyer, D.W. Lozier, M.A. Smith

The Pioneer Venus Orbiter Spacecraft is basically cylindrical, about eight feet in diameter and four feet high (Figure 5.1). It carries a parabolic reflector antenna for communications with Earth above one end, the same end platform that carries most of the scientific instruments. A fifteen foot boom protrudes from that platform to keep the sensitive magnetometer away from the spacecraft. The cylindrical axis is generally at a north-south orientation, except for the parabolic antenna which is held steadily pointed toward Earth by an electric motor. Small (one pound) thrusters protrude from each end and through the peripheral panels to facilitate velocity and turn maneuvers and control spin rate.

After burn of the 400-pound, solid propellant of the retrorocket to get the spacecraft into orbit around Venus in 1978, more than 50 pounds of liquid hydrazine remained aboard for initial adjustment of the orbit, for keeping the altitude of periapsis down in the upper atmosphere for two Venus years, and for control of spin rate and orientation for an indefinitely long life.

The spacecraft features much flexibility and redundancy in its design. Either of two electronic components can be selected for nearly all critical functions: receiving commands; storing and executing commands over an extended time interval; processing data; transmitting telemetered data; storing and replaying telemetered data; controlling the despin of the antenna and other spin-synchronous functions; firing thrusters; and the like. In addition, the antenna despin motor, the liquid propulsion thrusters, and electrical storage batteries are duplicated.

After ten years of operation in 1988, the Pioneer Venus Orbiter spacecraft continues in excellent working order. Thanks to conservative design and redundancy, all functions are serviceable with only modest reductions from original service. Power production from solar panels has diminished with age to limit future operations to somewhat less than continuous 24 hours daily, but the design provides for regular battery operations with intermittent loads. Scientific instruments that operate for long hours are operated in a time-sharing mode to maintain power balance in late 1988. Data collection and handling for the scientific instruments is normal, except that storage and replay capacity is reduced by failure of one unit. Telemetry communications continue normal, although the alternate
transmitter has a slightly diminished power throughput, but the same efficiency. The command receiving, decoding, storage, and execution system performs perfectly; although the secondary receiver responds only to a narrow radio frequency band. All of the control systems for spin axis orientation, spin rate control, antenna despin and elevation control, and synchronization timing signals work perfectly.

Only four random failures (including the two partial failures) in spacecraft subsystems have occurred over the ten years, and no complete failure of a critical component has occurred. Thus, all critical subsystems are still backed with substantial redundancy. Hydrazine propellant consumption has been conservative relative to prelaunch projections; budgeted usage has retained an ample supply of control to entry; and maneuvers with the residual propellants are expected to sustain 20 to 40 passes through the upper atmosphere just before entry.

Although the solar panels were not designed for the long exposure at Venus through which they have served, their rate of decline is sufficiently slow to provide for collection of scientific data until atmospheric entry in 1992. The batteries, heretofore relied upon to provide power during eclipses within about 40 per cent of the orbits, will be relied upon even more in future orbits when usage and recharge will be cycled once or twice each day.
Figure Caption

5.1 Diagram of the Pioneer Venus Orbiter spacecraft identifying the main components.
5.2 SCIENTIFIC OBJECTIVES

Pioneer Venus Orbiter still has important scientific work to perform during the next few years, exploring the atmosphere of Venus to lower altitudes than ever before, performing correlated experiments, and taking advantage of the reduced solar activity predicted for 1992.

5.2.1 UPPER ATMOSPHERE — D. M. Hunten

There are still many opportunities for PVO to investigate the thermosphere and the lower atmosphere of Venus in the period of a Venus year or two before final atmospheric entry of the spacecraft. These opportunities fall into three categories:

1. Measurements at a lower altitude than was attained previously.
2. Use of modes and correlated measuring programs that are now seen to be valuable, based on knowledge gained during the past decade of operations in orbit.
3. The possibility of observing Venus at a different phase of the solar cycle.

These opportunities are now discussed in detail.

5.2.1.1 LOWER ALTITUDES

No previous in-situ measurements were made below 140 kilometers, a conservative limit imposed by the project manager. It is known that an Atmospheric Explorer satellite was able to operate successfully around the Earth in an orbit with a periapsis of 129 kilometers. The same atmospheric densities as those experienced by Atmosphere Explorer at 129 kilometers in the Earth's atmosphere are found at heights of 138 (day) and 131 (night) kilometers in Venus' atmosphere. Figure 5.2.1.1 illustrates a model (Massie, Sowell, and Hunten, 1983) which attempted to bridge the gap between 140 and 100 kilometers by use of the best available aeronomical theory. While results from this model are better than nothing, they still contain major uncertainties. As mentioned in an earlier section of this report, other "models", which are really elaborate curve-fits, have been provided by Seiff (1983), Hedin et al. (1983), and in VIRA, the COSPAR Venus International Reference Atmosphere. Some of these do not venture below 140 kilometers. Work still in progress uses the NCAR Thermospheric General Circulation Model (Bougher et al., 1988), but it still contains enough arbitrary parameters so that its predictive power is limited. Even a few really good data points below 140 kilometers could
make an enormous difference in refining such models of Venus' atmosphere.

Figure 5.2.1.2 shows the predicted behavior of the periapsis altitude of PVO during the last 200 (hopefully more) orbits. The scale of local time shows that periapsis will be on the nightside after Orbit 4950 or so. Thus, measurements below 140 kilometers (the dashed line) will be limited to late afternoon and the first half of the night. However, there is still a leeway of around 10 kilometers, depending mostly on how the remaining hydrazine propellant is used. The regular attitude-control maneuvers are being made with a single jet, chosen to reduce the periapsis altitude. After about Orbit 5000, when atmospheric drag begins to be appreciable, all remaining propellant will be used to keep the periapsis above 130 kilometers or so and prolong the spacecraft's life in orbit as much as possible.

The discussion so far has centered on measurements made by the Neutral Mass Spectrometer (ONMS), but there are a number of questions about the nightside ionosphere as well. From radio-occultation measurements it is known that the density peak is frequently below 140 kilometers, but the positive-ion composition, which is highly diagnostic of the source mechanism, can only be measured by the in-situ instruments. Although it is clear that many of the nightside ions have been transported from the dayside, there remains a possibility of electron precipitation, probably sporadic. The PVO's payload cannot detect such electrons in a critical range of energies, but they could be inferred from the presence of ions that must have been locally produced.

The great enrichment of deuterium relative to hydrogen is one of the most striking discoveries of PVO, but it is being called into question on the basis of IUE measurements analyzed by Bertaux and Clarke. Available PVO measurements extend over only a small height range, and the confidence could be greatly increased by going as low as possible. The best local time for such measurements is after midnight, a region that may or may not be accessible, but this is all the more reason to prolong the useful lifetime.

5.2.1.2 NEW KINDS OF MEASUREMENTS

Investigations of the ionosphere are discussed in detail in the next section (5.2.2) including the ionospheric holes. These nightside ionospheric holes are one of the more tantalizing phenomena observed by PVO, because there is a strong suspicion that they may be magnetically connected to the tail or to some other region such as the magnetosheath. Such ideas are based on the near-absence of ionospheric plasma and on the tendency of the
local magnetic field to be radial. High-altitude measurements made in recent years provide a suggestion of nonthermal ions streaming away from the planet (Kasprzak et al., 1989). Such data are taken by the ONMS in a nonstandard ion mode, taking advantage of the fact that this instrument is mounted at a considerable angle to the spacecraft's spin axis. This mode was not used in the first part of the mission, but should be exercised at low altitudes where ion densities are larger. The possibility of reaching all the way down to the ionospheric peak is particularly interesting.

Voyager data obtained during the close pass of that spacecraft by Saturn's satellite Titan (another unmagnetized object with an atmosphere) showed the presence of ions streaming away from the limb. These were explained as being from the ionosphere of Titan. It may be possible to learn more about both Venus and Titan by making a comparison.

There is a long-standing, and so far unexplained, discrepancy among the ion and electron data from three instruments, Ion Mass Spectrometer (OIMS), Retarding Potential Analyzer (ORPA), and Electron Temperature Probe (OETP, a Langmuir probe). The Science Steering Group has authorized a small committee to investigate and try to resolve the conflict, but this may not be possible with existing data. It would be very useful to put together a joint experiment designed to shed more light on the problem. Such an experiment does not require the lowest altitudes; a suitable local time might be around 15 hours.

5.2.1.3 EFFECTS RELATED TO SOLAR ACTIVITY

All the previous low-altitude measurements were taken during 1979-1982, a period of high solar activity. Although 1992 is almost exactly one solar cycle later, current predictions suggest that activity may, in fact, be down to half the peak value. The radio-occultation experiment has shown a large change in ionospheric structure, strongly suggestive of a reduction of temperature at low activity, but also explainable as a reduction of atomic oxygen density. If the predicted low activity actually occurs, there will be a good chance to resolve this ambiguity. The VIRA model atmospheres include tables for low activity, based on guesswork and analogy with Earth; perhaps it will be possible to replace the guesswork with real knowledge.
Figure Captions

5.2.1.1 Illustrates a model (Massie, Sowell, and Hunten, 1983) which attempted to bridge the gap between 140 and 100 kilometers by use of the best available aeronomical theory.

5.2.1.2 Shows the predicted behavior of the periapsis altitude of PVO during the last 200 (hopefully more) orbits.
THERMOSPHERIC MODEL

(Massie, Hunten, and Sowell, 1983)

FIG. 5.2.1.1
Dawn Ionopause

Subsolar Ionopause

Periapsis

Transterminator Waves

Deuterium Lightning Holes

Reentry

Alt (km)

LT (hrs)

ORBIT 4800 4900 5000

1992
5.2.2 IONOSPHERE — L.H. Brace

During the next four years, as periapsis returns to low altitudes, PVO will in sequence explore the ionotail, examine the ionopause, and eventually return to the lower ionosphere. This period will present the opportunity to confirm earlier judgements about ionosphere behavior and to learn some new things that could not have been observed earlier in the mission. Some goals for further investigation of the ionosphere during this period are outlined below.

Solar Cycle Variations.

The solar cycle variations of the ionosphere have not yet been measured, except for the changes reflected in the total electron density profiles obtained by radio occultation during the decline in solar activity between 1980 and 1986. Figure 5.2.2.1 shows how the altitude of periapsis has changed during the mission. Also shown are the daily PVO measurements of the solar flux of extreme ultraviolet radiation (VF10.7) made thus far. The expected future changes in solar activity are indicated by the F10.7 index predictions for the solar cycle which began in 1987. Solar activity is expected to increase two to three times between early 1988 and late 1989, then it is expected to fall to a moderate level during the reentry period in the fall of 1992 when periapsis will again be low. Based on the projection of Figure 5.2.2.1 the following investigations are planned for the final four years of the PVO's mission.

Ionotail Measurements at Solar Maximum.

In 1989-1990, a period of expected maximum solar activity, the PVO instruments will measure the ionotail density, composition, and temperature and will examine the configuration of the ionospheric tail rays. These data, when contrasted with the solar minimum measurements from 1985-87, will define how the ionotail changes with solar activity. Combining these ionosphere data with the solar wind, magnetometer, and superthermal ion measurements will allow the variation in ion escape flux with solar activity to be evaluated. At the same time, the radio occultation measurements will determine the diurnal variation of the lower ionosphere at solar maximum.

Ionopause, Mantle, and Near Ionotail Measurements in 1990-91.

During these years of high solar activity and declining periapsis altitude, PVO will measure the transition region from the ionotail, with its
superthermal ions and electrons, to the nightside lower ionosphere with its cold plasma and ionospheric holes. At other local times, periapsis will skim the terminator ionopause, measure the mantle plasma just above it, and examine the high speed nightward ion flow just below. These regions were measured earlier only at the lower levels of solar activity of 1983-84.


The reentry measurements in 1992 promise to provide not only another look at the composition and temperature of the main body of the ionosphere, but also a look at a time of much lower levels of solar activity than in 1979-1980. Figure 5.2.2.2 shows the periapsis altitude planned for the reentry period. The orbits between 4815 and 4850 will skim the dawn ionopause in the vicinity of 450 kilometers. Those periapsis passages in orbits near 4900 will parallel the subsolar ionopause when it is near 350 kilometers to observe directly the effects of solar wind.

Interactions at the stagnation point.

The orbits between 4945 and 4990 will examine the transterminator plasma waves and gravity waves in the thermosphere that are observed primarily at altitudes below 200 kilometers. The orbits beyond 4990 (as long as the hydrazine propellant lasts) will be at the right local times and low enough altitudes to measure three important effects which were seen earlier only at the maximum of solar cycle 21 (1979-80). These are the deuterium ions, the VLF lightning signatures, and the ionospheric hole phenomenon. Thus 1992 will be an extremely important year for the study of the planet's ionosphere. It represents a final opportunity to make in-situ measurements in this region, and to complete an evaluation of the solar cycle behavior of the ionosphere.

Remaining Questions about the Ionosphere of Venus

Some remaining questions about Venus cannot be answered adequately by PVO owing to limitations in its orbit and in the relative simplicity of its instruments. Venus turned out to be a far more complex world than can be fully resolved in such an exploratory mission. But the knowledge gained by PVO will certainly be an excellent jumping off point when future Venus missions are undertaken.
Figure Captions

5.2.2.1 Change in altitude of the periapsis of PVO's orbit during the mission

5.2.2.2 Periapsis altitude planned for the period of reentry of PVO into the atmosphere of Venus in 1992
FIG. 5.2.2.2

- Dawn Ionopause
- Subsolar Ionopause
- Periapsis
- Transterminator Waves
- Deuterium Lightning Holes
- Reentry
When the periapsis of PVO drops to a sufficiently low altitude during the entry phase, many of the studies begun during the initial phase of the mission may be extended and the interaction can be studied at a different phase of solar activity than during the initial phase of the mission. In particular, data can be obtained at the ionopause near the subsolar region on the inbound leg of the orbit, which was impossible during the initial phase, to help determine if the flute instability acting at the subsolar point is responsible for generating flux ropes. Also, it should be possible to determine whether the occurrence of flux ropes depends on solar activity. Perhaps under conditions of low solar activity the ionosphere is more fully magnetized. The lower boundary of this magnetized layer can be probed during the extended mission whereas very few observations of this lower boundary were obtained during the prime mission.

In addition, the magnetic structure of the night ionosphere can be probed to depths unattainable during the prime mission, which should help determine how the magnetic field in holes closes. At present it is not known whether the magnetic fields close in the ionosphere or extend into the planet.
The entry period of PVO is critical for lightning studies because it provides low altitude radio emission data right over the region that has been identified as the source region through the observation of high frequency emissions. Terrestrial studies have shown that the electric fields of lightning discharges can penetrate deep into the ionosphere even though such penetration is not expected in simple theoretical treatments. These "forbidden" transmissions do not travel far and are observed only right over the lightning source. Very little data was obtained over this region during the initial mission because one of the three possible observing periods was lost due to an unfortunately timed solar conjunction.

Most importantly, no data have been obtained at the highest bit rate of 4096 bps which would provide eight samples per second to the plasma wave instrument and would allow it to measure the true source rate of bursts in the detector. In the continuing mission these rates can be used during probes to altitudes lower than ever before. Finally, the entry period data will be obtained over a different geographical region than during the prime mission so that the question can be answered as to whether there is a geographic correlation in the VLF data or whether it is, instead, due to the strong local time variation combined with the uneven sampling of geographic regions at any one local time.

Finally, the rates of occurrence of emissions observed during this entry period can be compared with those obtained during a different phase of solar activity.
5.2.5 THE ATMOSPHERE SEEN FROM ORBIT — A.J.F. Stewart

Clouds and Hazes

During the remainder of the mission, the Cloud Photopolarimeter (OCCP) experiment will continue to measure winds by tracking cloud features. It will continue to determine the zonal-average velocities of the winds and of the planetary-scale waves seen in planetary brightness variations. These waves are not always present, and further studies will be directed towards a better characterization and understanding of the phenomenon. In 1992, the descent of the periapsis will improve the OCPP's altitude resolution on the limb to the point where observations of the high altitude (70-90 kilometers) hazes can be resumed. Comparisons will be made with the northern hemisphere hazes seen during the nominal mission, and with the results of the proposed Galileo observations in 1990.

Sulfur Dioxide at the Cloud Tops

The OUVS experiment will continue its long-term program of monitoring sulfur dioxide. The primary goal is to look for a further increase of sulfur dioxide, such as that seen at orbit insertion, that might indicate either a new episode of vulcanism or a major dynamical overturning event in the atmosphere.

Winds and Vertical Transport in the Thermosphere

In 1992 the OUVS experiment will regain altitude resolution on the limb as periapsis descends. During the last passage of periapsis across the dayside, limb profiles of carbon emissions at 139 nm (from the lower thermosphere) and 160 nm (from the upper thermosphere) will establish the vertical distribution of carbon monoxide and hence will characterize vertical transport in the dayside thermosphere. After periapsis crosses the evening terminator, measurements of the limb profiles of nitric oxide emissions will yield the altitude of the emitting layer and hence the strength of the descending arm of the global thermospheric circulation system.

Solar Cycle Variations

OUVS images in light from hydrogen, oxygen, carbon monoxide, and nitric oxide will document the changes in the thermospheric composition and temperature as the sun climbs to the peak of activity cycle 22. These measurements are our only source of information on the trends in the
neutral thermosphere over a solar cycle, since the in-situ ONMS measurements will be confined to solar maxima (cycles 21 and 22).

Aurora

OUVS measurements to date have shown that the brightness ratios of oxygen emissions are similar to those in the terrestrial aurora, and the source is thought to be soft precipitated electrons. A crucial piece of information is the altitude of the emissions. This will be obtained after periapsis crosses the evening terminator in 1992, when the altitude resolution on the limb will be restored to nominal-mission values.

Exosphere and Atmospheric Escape

The lower exosphere of Venus is dominated by hot atoms of oxygen which provide the first obstacle seen by the impinging solar wind. The densities of this 'corona' derived from early OUVS measurements are large enough that the ONMS experiment should be able to detect it directly with the lower gas background expected during the reentry phase. Accurate ONMS measurements of density and altitude distribution in the lower exosphere will answer many questions about the collisional thermalization of these hot atoms at the base of the exosphere, and their importance in promoting loss of hydrogen (by 'knock-on' collisions) and oxygen (by ion pickup) from the present atmosphere.
A large number of scientists, engineers, and contractors support the PVO science experiments, spacecraft operations and management. Table 6.0.1 summarizes the total participation for the PVO program. Included in the Table are statistics on advanced degrees earned as a result of the program; the number of science participants from federal, industrial and academic institutions; and the number of U.S. states and foreign countries that have been involved.

Table 6.0.2 lists the 17 graduate students, titles of their theses, and awarding institutions for the advanced degrees.

A total of 161 scientists have participated in the PVO program, 72 of whom are located at colleges and universities, 75 in federal laboratories, and 14 in private industry or non-profit research organizations. The 34 universities and colleges are listed in Table 6.0.3. The 14 federal laboratories and 15 private organizations are listed in Table 6.0.4.

The U.S. scientific participants are located in 18 states. Foreign participants represent 10 countries. The states and countries are listed in Table 6.0.5.

Program management is the responsibility of the Solar Systems Exploration Division in NASA Headquarters. Project Management is the responsibility of the Space Exploration Projects Office at Ames Research Center. Key individuals in both Program and Project Management for PVO are listed in Table 6.0.6.
Table 6.0.1

PIONEER VENUS ORBITER — TEN YEARS OF DISCOVERY

PARTICIPATION.

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<td>Guest Investigators</td>
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<td>Program Scientist</td>
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<td>Project Scientist</td>
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<td>Project Manager</td>
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<tr>
<td>Navigation and Flight Support Office - JPL</td>
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<tr>
<td>Contractor Technical Support</td>
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<tr>
<td>Ground Control - Bendix</td>
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<td>Advanced degrees earned</td>
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<td>Master of Science</td>
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<td>Institutions</td>
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<td>Federal laboratories</td>
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<td>Universities</td>
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<td>Private industry</td>
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Table 6.0.2

PIONEER VENUS ORBITER — TEN YEARS OF DISCOVERY

ADVANCED DEGREES AWARDED

• Palmer, J.M., PhD, University of Arizona, 1975
  A Solar Flux Radiometer for the 1978 Pioneer Venus Mission

• Chen, R.H., PhD, University of Michigan, 1977
  The Ionosphere of Venus

• Durrance, S.T., PhD, University of Colorado, 1980
  The Carbon Monoxide Fourth Positive Bands in the Venus Dayglow

• Bougher, S.W., MS, University of Colorado, 1980
  The Ultraviolet Night Airglow of Venus-Morphology and Implications

• Mihalov, J.D., Engineers Degree, Stanford University, 1981
  Comparison of Gas Dynamic Model for Solar wind Flow Around Venus With Pioneer Venus Orbiter Data

• Cimino, J.B., PhD, California Institute of Technology, 1982
  The Composition, Vertical Structure and Global Variability of the Lower Cloud Deck of Venus as Determined by Radio Occultation Techniques

• Elphic, R.C., PhD, University of California at Los Angeles, 1982
  A Study of Magnetic Flux Ropes in the Venus Ionosphere

• Slavin, J.A., PhD, University of California at Los Angeles
  Solar Wind Interactions With the Terrestrial Planets

• Steffes, P.G., PhD, Stanford University
  Abundance of Cloud Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity

• Swanson, R.A.L., PhD, University of Colorado, 1983
  Carbon Monoxide Fourth Positive Ultraviolet Emissions on Venus
Table 6.0.2 — Continued

PIioneer Venus Orbiter — Ten Years of Discovery

Advanced Degrees Awarded

• Paxton, L.J., PhD, University of Colorado, 1983
  Atomic Carbon in the Venus Thermosphere: Observation and Theory

• LeCompte, M.A., PhD, University of Colorado, 1984
  Analysis and Interpretation of Observations of Airglow at 297nm in the Venus Thermosphere

• Bougher, S.W., PhD, University of Michigan, 1985
  Venus Thermospheric Circulation

• Arghavani, M.R., MS, University of California at Los Angeles, 1985
  Disturbances in the Magnitude of the Interplanetary Magnetic Field

• McComas, D.J., PhD, University of California at Los Angeles, 1986
  Earth, Venus and Comet Giacobini-Zinner

• Philips, R.J., PhD, University of California at Los Angeles, 1987
  Interplanetary Magnetic Field Effects on the Interaction of the Solar Wind with Venus

• Shinagawa, H., PhD, University of Michigan, 1987
  A One-Dimensional Multi-Species MHD Model of the Ionospheres of Mars and Venus

• Williams, D.R., PhD, University of California at Los Angeles
  Regional Structure and Tectonics of Venus Inferred from Admittance Analysis of Gravity and Topography
Table 6.0.3

PIONEER VENUS ORBITER — TEN YEARS OF DISCOVERY

ACADEMIA PARTICIPATION

UNIVERSITIES AND COLLEGES

- University of Arizona
- Augsberg College
- Arizona State University
- University of British Columbia
- University of California at Berkeley
- University of California at Los Angeles
- California Institute of Technology
- University of Colorado
- Cornell University
- University of Delaware
- Georgia Institute of Technology
- University of Graz
- Harvard University
- University of Hawaii
- University of Liege
- University of Maryland
- University of Massachusetts
- Massachusetts Institute of Technology
- University of Michigan
- University of Minnesota
- Universidad Nacional Autonoma de Mexico
- University of New Hampshire
- Northern Arizona University
- Oxford University
- Rice University
- San Diego State University
- University of Southern California
- Southern Methodist University
- Stanford University
- Santa Clara University
- State University of New York
- University of Tokyo
- Utah State University
- University of Wisconsin
Table 6.0.4

PIONEER VENUS ORBITER — TEN YEARS OF DISCOVERY

FEDERAL LABORATORIES & PRIVATE PARTICIPATION

**FEDERAL LABORATORIES**

- Los Alamos National Laboratory
- National Aeronautics and Space Administration
  - Ames Research Center
  - Goddard Institute for Space Studies
  - Goddard Space Flight Center
  - Jet Propulsion Laboratory
  - Langley Research Center
  - Lunar and Planetary Institute
- National Center for Atmospheric Research
- National Oceanic and Atmospheric Administration
- Naval Research Laboratory
- Smithsonian Astrophysical Observatory
- United States Geological Survey
- Woods Hole Oceanographic Institute

**PRIVATE ORGANIZATIONS**

- Atmospheric & Environmental Research, Inc.
- Beers Associates
- Bendix Corporation
- Berkeley Research Associates
- Carmel Research Center
- Hughes Aircraft Company
- Knudsen Geophysical Research Inc.
- Lockheed Missiles and Space Company
- National Center for Supercomputing Applications
- Sandia Labs
- San Jose State University Foundation
- Stanford Research Institute
- STX Corporation
- TRW Space and Technology Group
- Vigyan Research Inc.
Table 6.0.5

PIONEER VENUS ORBITER — TEN YEARS OF DISCOVERY

U.S. STATES & FOREIGN PARTICIPATION

U.S. STATES PARTICIPATION

- Arizona
- California
- Colorado
- Delaware
- District of Columbia
- Georgia
- Hawaii
- Illinois
- Maryland
- Massachusetts
- Michigan
- Minnesota
- New Hampshire
- New Mexico
- New York
- Texas
- Utah
- Virginia
- Wisconsin

FOREIGN PARTICIPATION

- Austria
- Belgium
- Canada
- ESA
- France
- FRG
- India
- Japan
- Mexico
- United Kingdom
Table 6.0.6

PIioneer Venus Orbiter — Ten Years of Discovery

Key Management Personnel

Program Management - NASA HQ

Program Manager
A. Merwarth - Acting (1)

Program Scientist
H.C. Brinton (2)

Project Management - ARC

Project Manager
R.O. Fimmel (3)

Project Scientist
L. Colin

Tracking - JPL

Operations Planning
R.E. Ryan

Tracking/Data Systems Manager
A. Berman (4)

Spacecraft Management - HAC

Program Manager
S. Dorfman

Orbiter Manager
J. Fisher

Ground Support Services - Bendix

Manager
T.E. Young (5)

(3) C.F. Hall 1972-1980
7.0 PVO FUNDING

Funding statistics are given in Table 7.0.1. Note that only the funding associated with the Orbiter is estimated; Multiprobe costs which were all incurred in the period 1972-1980 are excluded. Also, science, spacecraft and operations costs are separated because the large percentage of funding dedicated to science during the 10-year PVO mission is extremely important for delivered results.
TABLE 7.0.1

PIONEER VENUS ORBITER — TEN YEARS OF DISCOVERY

FUNDING DISTRIBUTION

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<th>Category</th>
<th>Actual Dollars</th>
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<td>Orbiter (Excludes launch costs)</td>
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<td>Multiprobe (Excludes launch costs)</td>
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<td>Average annual funding (PVO only) 1978 - 1988</td>
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<td>Science</td>
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<td>Operations (Excludes DSN costs)</td>
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8.0 BIBLIOGRAPHY OF PUBLISHED PAPERS

The scientific results of the PVO mission are described in Section 4.0. Table 8.0.1 lists the annual number of scientific papers published as a result of the program. Note that papers for both the Orbiter and Multiprobe missions are included, as it is often difficult to separate them since data from all the spacecraft have been used in many scientific analyses.

A detailed bibliography is published as a separate document.
Table 8.0.1

PIONEER VENUS ORBITER — TEN YEARS OF DISCOVERY

ANNUAL RECORD OF PUBLISHED PAPERS

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* Pioneer Venus Orbiter and Multiprobe
CONCLUSIONS

The evidence presented in this report supports well the assertion that PVO is a mission that provides a high scientific return for a low cost. Perhaps it represents the most scientifically productive-lowest cost unmanned mission beyond the Earth that NASA has accomplished to date. Ten years of continuous operation is a major reason for this, but there are other ingredients as well: dedicated, hardworking engineers and scientists who never underestimated the value of what they were doing, a lean-and-mean project management and operations organization, and a varying set of orbit parameters that opened up new vistas for study.

PVO is the kind of mission that has much more appeal and excitement for the scientist than for the layman. Why is this? Firstly, the nature of the planet Venus, which is "dull" in visual appearance and which has a cloud shrouded surface, and, secondly, the nature of the experiments themselves which were designed to obtain answers to complex, scientific questions. The PVO mission has performed magnificently with regard to these latter objectives. On the other hand, considerable popular, photogenic perspective was achieved in describing the general topography of the planet revealed by remote sensing instruments, and in showing in some detail the cloud top circulation.

Most important, the mission is not yet over. There are still 3.5 years of very useful life to the veteran spacecraft before it enters the upper atmosphere of Venus and burns up as a brilliant meteor there, a fitting end to a wonderful machine. It is possible that penetration into the second complete solar cycle will demonstrate newsworthy interaction with the non-magnetic planet. Every space enthusiast will appreciate the excitement of successively deeper atmospheric samplings to the end. The scientific expectations are as exciting as those that existed at orbit insertion, in the continuing quest to understand more about Venus and, in turn, more about our own planet. As the mission continues as planned we will surely not be disappointed.