Venus Strategy for Exploration

Space Science Board, National Academy of Sciences,
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Advisers to the Nation on Science, Engineering, and Medicine

VENUS

Strategy for Exploration

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PREFACE

This is the report of a study convened by the Space Science Board in cooperation with the Lunar and Planetary Missions Board of the National Aeronautics and Space Administration to consider the scientific potential of missions to Venus based on the relatively low-cost Explorer technology concept. The participants considered a program initially estimated to cost approximately $100 million for the first three missions and $20 million to $25 million for each succeeding probe or orbiter mission; it must be borne in mind that these figures are preliminary and reflect planning estimates rather than contractual obligations.

This study was conducted during the week of June 7, 1970, under the cochairmanship of Richard Goody and Donald M. Hunten and involved twenty-one scientists representing a range of scientific interests in the exploration of Venus. The recommendations of the group were presented to NASA management on the morning of June 18 and endorsed by the Space Science Board at its meeting of June 22 and 23, 1970.

The Space Science Board is grateful to those who participated in this study, to Bruce N. Gregory, who served as Staff Director of the study, and to Mrs. Jacqueline Boraks, for her contributions to the report's publication. The Board acknowledges with appreciation the support of the National Aeronautics and Space Administration, which helped to make this study possible, and the special assignments undertaken by NASA in preparation for the study.

C. H. Townes, *Chairman*
Space Science Board

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SUMMARY OF PRINCIPAL RECOMMENDATIONS

1. We believe that the combination of scientific goals and the feasibility of contributing to these goals makes the exploration of Venus one of the most important objectives for planetary exploration in the 1970's and 1980's. And we *recommend* that exploration of Venus be prominent in the National Aeronautics and Space Administration program during this period.

2. We *recommend* the Delta-launched, spin-stabilized Planetary Explorer as the prime vehicle for the initial exploration of Venus by orbiters, atmospheric probes, and landers.

3. We *recommend* a mission strategy that will make use of the next three opportunities to launch a spacecraft to Venus and many subsequent opportunities. For the first missions we indicate desirable payloads with which to obtain new data in all scientific fields.

4. In the interests of maintaining minimal cost we *recommend:*

(a) that the National Aeronautics and Space Administration be prepared to accept a somewhat higher risk for the Planetary Explorer than has been its practice for previous planetary missions, if substantial over-all cost savings can be achieved;

(b) that experiments to be carried on early lander missions emphasize simplicity of operation and, where possible, avoid manipulation and processing of surface material.

5. To ensure adequate lead time for instrument development we *recommend* that the National Aeronautics and Space Administration announce the existence of a series of opportunities listing some of the more crucial needs.

To extend the lifetime of surface instrumentation we *recommend* that the National Aeronautics and Space Administration undertake and support engineering research and development to provide, if possible, lander systems and experiment components able to operate at temperatures up to 800 K.

6. We give reasons for believing that the probability of growth of terrestrial organisms in the atmosphere of

Venus is less than 10^{-6}, and we *recommend* that, with some precautions, spacecraft be allowed to impact the planet when scientific benefit is to be gained thereby.

7. We *recommend* that the National Aeronautics and Space Administration set up and maintain a continuing planning group for the exploration of Venus which will advise on strategy for the mission series and on conceptual payloads for each mission.

8. We point to the possibility that, in the 1980's, more elaborate spacecraft may be needed to continue the investigation of Venus beyond an exploratory stage.

9. We believe that the Planetary Explorer provides a particularly good opportunity for international collaboration, and we *recommend* that the National Aeronautics and Space Administration actively seek collaboration of other national space organizations in planning and carrying out these investigations.

10. We *recommend* that the National Aeronautics and Space Administration continue to support and develop earth-based studies of Venus, and we commend its past efforts in this respect.

11. We endorse the Venus/Mercury mission for the contribution it can make to Venus science.

Chapter 1

INTRODUCTION

In June 1968 the Space Science Board made a study of *Planetary Exploration 1968-1975,* in which the principal conclusion was that "the planetary exploration program be presented, not in terms of a single goal, but rather in terms of the contribution that exploration can make to a broad range of scientific disciplines."

This view was further expressed in a series of recommendations for missions to all targets that seemed practicable at that time, with measurements to forward the objectives of all disciplines involved in the space program. In particular the need for exploration of Venus was brought out.

To achieve such a broad and flexible program, the study emphasized the need for modest and relatively low-cost missions. A prime recommendation was "that NASA initiate now a program of Pioneer/IMP-class spinning spacecraft for orbiting Venus and Mars at each opportunity, and for exploratory missions to other targets."

While developments since 1968 tend to modify specific points made in the 1968 study, the spirit of the recommendations is as important today as it was then. Nevertheless, the program of the National Aeronautics and Space Administration contains no significant Venus missions (the Venus/Mercury flyby is essentially a Mercury mission with only a small contribution to Venus science) and no small missions to the inner planets in the Pioneer/IMP class (which includes the Planetary Explorer discussed in this report).

At the same time a strong Mars program has developed, with a very ambitious program funded for the early 1970's. There is also an ambitious program for Grand Tour missions to the outer planets proposed in the 1969 NAS study *The Outer Solar System: A Program for Exploration.*

The present study was convened to re-examine the question of Venus exploration in the light of the proposed NASA programs and the scientific developments since 1968. In the event that an imbalance in planetary-exploration strategy should be found, the study had, as a second objective, the task of recommending appropriate Venus missions.

The study was concerned with relative priorities within the NASA planetary-exploration program. There are, however, larger issues: the relative priorities between different parts of NASA's unmanned science program (astronomy, applications, lunar exploration, space physics, space biology); the relationships between manned and unmanned programs; and the effect of changing national priorities upon both programs. These issues are the concern of an extensive Space Science Board study, also carried out during the summer of 1970, under the chairmanship of Herbert Friedman. The two studies came together because a preliminary version of our recommendations was available to the Friedman study and influenced its conclusions.

The reason for the exploration of Venus is related to the justification for exploring the solar system, as well expressed in the NAS studies: *Space Research/Directions for the Future; Planetary Exploration 1968-1975;* and *The Outer Solar System: A Program for Exploration.* Nevertheless, it is appropriate briefly to address the question: Why explore Venus now?

On the most general level, the answer to the question is tied to the remarkable evolution of planetary studies during the 1960's. Not long ago planetary studies were a part of astronomy, often accorded a different treatment and status from solar physics and astrophysics but not yet related to any other discipline. The advent of the space probe in the 1960's provided the tool and some of the data for the detailed investigations and model building characteristic of, and essential to, terrestrial studies. Very rapidly studies of planetary meteorology, planetary aeronomy, planetology, and planetary biology emerged which involved, in the main, research workers from the parallel terrestrial disciplines. Earth and planetary studies suddenly merged and simultaneously diverged from astronomy. In some major universities, departmental and research center organization was changed to meet this development.

From an intellectual point of view we have moved to the position in which terrestrial studies have expanded to include the whole of the solar system. Problems such as the origin of the solar system, the origin of life, and the large-scale processes that control man's environment will in the future be considered in terms of many rather than a single object. The detail will obviously differ from one planet to another: from the immense detail required on earth for environmental purposes and made possible by the comparative accessibility to the very small amounts of information on Uranus, Neptune, and Pluto and the difficulty of substantially increasing this information.

Thus the call for a balanced approach to planetary exploration has a firm logical basis, although the word "balanced" is not clearly defined in terms of the relative priority of new objectives and the investigation in depth of more familiar problems. In whichever way the situation is viewed, however, the absence of almost any firm information about the solid surface and lower atmosphere of Venus is the most striking weakness in our information about the inner planets.

If we consider the need for Venus research in terms of particular examples we find striking examples of how knowledge of this planet can illuminate our knowledge of earth. The surprise effect of the unexpected ionospheric data on both Mars and Venus has led to timely re-examination of fixed ideas about the earth's ionosphere. Studies of atmospheric circulations in slowly rotating atmospheres have provided new ideas applicable to tropical meteorology. The extensive cloud systems of Venus have led to investigations of the coupling between clouds and motions not yet undertaken on earth. The question of why Venus has a complete cloud cover and a high surface temperature is beginning to interest those concerned with possible environmental changes on earth. This is not so much in the belief that earth might go the way of Venus if the atmosphere is sufficiently polluted but rather with the thought that Venus is an observable example of a class of problem that concerns our own environment.

One final answer to the question, "Why explore Venus now?" is that events have conspired to produce a situation in which exploration of Venus is unusually timely and rewarding. Despite Venera entry probes and Mariner flybys, we know very little about the lower atmosphere of Venus, and yet we have many competing theories the merits of which can be tested with relatively simple measurements. For example, we do not know how many and how thick are the cloud layers, let alone the composition of the uppermost. We know that lower-atmosphere motions are of central importance to all aspects of the physics and chemistry of the atmosphere, but we know nothing about them. At least three independent hypotheses exist with regard to the high surface temperatures.

In each of these major areas rather elaborate theories have been developed, generally of a quantitative nature, so that they can be tested by means of a few well-defined measurements with proven instruments. This is a situation that occurs but rarely and should be exploited when it does. It provides a further and powerful reason for a strong program of exploration of Venus in the coming decades.

The Study Group was able to determine at an early stage that the developments in Venus science since 1968 heightened the need for substantial effort to explore the planet. Considerable attention was therefore directed to the question of the appropriate exploration strategy.

Although since 1968, no programs have been approved or funded involving missions to Venus or small spacecraft, it has been a period of planning activity by NASA, its centers, and its contractors. This planning has taken place in close contact with scientific groups from outside the agency, and the result has been a particularly rewarding interaction among scientists, engineers, and planners, which in this group's opinion represents a significant advance in the planning of space missions. This Study Group was, therefore, presented with a series of detailed and careful studies of the exploration of Venus by means of Planetary Explorer spacecraft (see Chapter 6).

Our study benefited greatly from access to these NASA plans. In general, we found them to be well conceived and almost ideally suited to the requirements of scientific investigation in the 1970's and 1980's. As a consequence, our recommendations are detailed and circumstantial and often presented in terms of this particular spacecraft.

Chapter 2

RECOMMENDATIONS

SCIENTIFIC RETURN FROM VENUS MISSIONS

In this report we examine the state of knowledge of the atmosphere of Venus, the important questions that can now be asked, and the relatively straightforward means by which these questions can be answered.

Noteworthy in this context is the extraordinary flow of ideas since the U.S. Mariner 5 and the Soviet Venera 4, 5, and 6 missions. Compared to the range of questions of first magnitude that remain to be answered the contribution from these space missions was small. Nevertheless, the few pieces of information that they contributed made the investment of time and effort into the complex process of geophysical modeling worthwhile, and we now have stimulating quantitative theories about the atmosphere and surface of Venus.

A strong scientific interest in Venus now prevails among geophysicists and astrophysicists. This interest can best be maintained by a series of missions that will permit broad participation by scientists in the U.S. planetary program.

Another important reason to support the exploration of Venus is that we must have more information on that virtually unknown planet in order to obtain some of the data necessary to unravel the puzzle of the origin of the solar system--a question of major interest to laymen and scientists alike.

Furthermore, a better understanding of the atmosphere of Venus will make important contributions to our understanding of generalized atmospheric problems and, hence, lead to added understanding of our own atmosphere. The problems of Hadley circulations and interactions between clouds and atmospheric dynamics are two cases in point. The long-range climatic effects of pollutants on the transfer of solar and infrared radiation is another.

We believe that the combination of scientific goals and the feasibility of contributing to these goals makes the exploration of Venus one of the most important objectives for planetary exploration in the 1970's and 1980's. And we, therefore, *recommend* that exploration of Venus be prominent in the program of the National Aeronautics and Space Administration during the 1970's and 1980's.

THE VALUE OF SMALL MISSIONS

The idea of small, minimum-cost exploratory missions has immediate appeal to large sectors of the scientific community. This is in part accounted for by a feeling of responsibility toward the taxpayer and society. It also results, however, from the real advantages that accrue from projects involving minimum funding and therefore minimum complexities of planning and organization, personnel, and collaboration between organizations.

The Space Science Board study, *Planetary Exploration 1968-1975*, took place at a time when the Mariner program had established some of the fundamental physical parameters of the inner planets and most of the technology needed for future missions. As a result of this experience, the study chose, as the preferred course for the early 1970's to go in the direction of smaller, lower-cost missions. The first priority recommended by the study was "a program of Pioneer/IMP-class [Planetary Explorer] spinning spacecraft for orbiting Venus and Mars at each opportunity, and for exploratory missions to other targets." That entry probes were not included in this statement merely reflects the prevailing climate of engineering thought at that time: entry probes did not come to mind as practical, inexpensive spacecraft. Since then, the success of the Venera probes and a number of engineering studies have greatly changed the situation; moreover, it has become clear that the entry probe is an ideal vehicle for attacking a number of prime scientific questions.

There are many contributing reasons for this support for small missions:

1. If the cost is sufficiently low, a series of missions can be envisaged. This opens up many opportunities, novel to planetary exploration. One is that relatively high-risk experiments can be undertaken if a high return of scientific information can be foreseen. Initiative is encouraged if the cost of failure is reduced.

2. A series of missions can be planned. Missions can build upon the observations of previous ones and upon the new

theories and speculations to which they may give rise. Early observations can often be kept much simpler if there is an expectation of more elaborate measurements to follow, based upon the preliminary results. It is, of course, necessary to develop organizational techniques to take advantage of this possibility. It is barely possible to make some changes in instrumentation from one Venus opportunity to the next. It should, however, be relatively easy to ensure complete payload redesign, if necessary, every second opportunity (i.e., at approximately 3-year intervals).

3. A series of missions can stimulate the active participation and collaboration of many scientists and scientific disciplines. Moreover, with many opportunities, the value of the program to the educational process is enhanced because it becomes possible to involve less-senior experimenters--even to make use of graduate students under supervision.

4. A series of missions can, in times of fiscal stringency, be reduced in frequency without a complete cutoff of the program and the attendant loss of experimenters. Because of the nature of NASA funding, projects are not always funded as predicted, and it is therefore healthy to maintain the maximum flexibility in this respect.

5. It is difficult to plan science far in advance. On the other hand, a very expensive mission is often inflexible. This can lead to a mismatch between the desire for unfettered and innovative thinking on the one hand and responsible technical planning on the other. This gap closes as the cost of the mission decreases, although it cannot ever be expected to disappear. Scientists, engineers, and administrators each have to modify their attitudes when collaborating in a large project, but the Planetary Explorer concept should ensure that the difficulties are minimized.

6. The Planetary Explorer concept makes it possible to use probes, landers, and orbiters in combination, each supporting the other, in planetary exploration. There are examples in this report in which orbiter science can prepare for better probe science and vice versa, and lander science can benefit from both. Thus, atmospheric-probe measurements can establish the wind-noise spectrum that might be encountered by a landed seismometer--a parameter essential to define sensitivity.

When the above advantages of small missions are combined, the value of this concept becomes clear. We are not without previous experience of this kind of development. The exploration of the earth's atmosphere increased greatly in pace and became a different kind of program when the low-cost Aerobee rocket replaced the V2 and Viking rockets in the early 1950's. Although the Aerobee has only arrow flight stability and a relatively small payload, and it was a long step backwards in sophistication, it has been a workhorse for aeronomy and astronomy observations with which generations of experimenters have been well satisfied. We may expect that the Planetary Explorer will play a comparable role in NASA's planetary program.

The rest of this report summarizes the results of our examination of the scientific questions posed by Venus, of the potential for rapid advance in our knowledge of the planet, and of the Planetary Explorer as the prime vehicle for this advance in the next 10 years.

We *recommend* the Planetary Explorer as the prime vehicle for the initial exploration of Venus by orbiters, atmospheric probes, and landers, because this inexpensive, Delta-launched spacecraft has the capability and versatility to obtain answers to most of our prime questions about Venus and to aid in defining the environment of Venus for possible bigger missions in the future.

ACHIEVEMENT OF MINIMUM COST

As discussed below, the cost of a given set of hardware can depend greatly on the philosophy adopted, especially the amount of testing required. Most of the benefits discussed in the previous section are a direct consequence of small project size, which implies a proportionately low cost. Every effort should be made to keep testing and paperwork to the minimum required for a reasonable assurance of success. As the total cost of a mission diminishes, the ideas of what is reasonable can be relaxed. Recent practice in the planetary program has been to require extra flight instruments just for testing and to undertake environmental and life tests whose total cost may far exceed that of the instrument itself. In most rocket work, on the other hand, reliance is placed on the use of high-quality parts and careful design, with only brief tests in a simulated environment. The quality of the product is still high. For a given mission the philosophy chosen should lie somewhere between these extremes, but we suggest a considerable relaxation of the standards previously applied to the large planetary missions.

Another area that can greatly affect costs is the choice of experiments. For example, complex mechanisms may need to be developed for some purposes, but they tend to be expensive and unreliable. In general, such equipment should be avoided unless there is an overriding scientific requirement.

We *recommend* that NASA be prepared to accept a somewhat higher risk for the Planetary Explorer than has been its practice for previous planetary missions, if substantial over-all cost savings can be achieved.

Because of our minimal experience in carrying out unmanned experiments on a remote planetary surface, and because of the high temperature and pressure of the surface of Venus, we *recommend* that experiments to be carried on early lander missions emphasize simplicity of operation and, where possible, avoid complex manipulation and processing of surface material.

INSTRUMENT DEVELOPMENT

Missions to Venus, particularly those entering the atmosphere, will require a wide range of novel scientific equipment. NASA has already shown its willingness to support the development of new instruments, for example, those needed for cloud studies. To publicize this fact, we *recommend* that NASA announce the existence of a series of opportunities listing some of the more crucial needs. Such an announcement, coupled with a general description of the expected spacecraft and their capabilities, should stimulate much of the necessary work.

Current technology appears to be unable to provide a landed mission with a lifetime of more than a day or two, because of the need to keep down the temperature of the instruments and batteries. Instruments such as seismometers can reap their greatest benefit only with a much longer period of operation. Therefore, we *recommend* that NASA encourage engineering research and development to provide, if possible, lander systems and experiment components able to operate at temperatures up to 800 K.

QUARANTINE REQUIREMENTS

A slight possibility exists that terrestrial organisms could grow on airborne particles near to the cloud tops of Venus. The problem was discussed at the 1970 COSPAR meeting, and some interest was expressed in investigations of airborne life. Life on Venus is no more than a remote contingency, but the possibility of contamination by terrestrial organisms must be considered.

The saving feature of all Venus missions is that there is no longer any doubt that a temperature of about 700 K prevails over the entire surface of the planet. There is no possibility that terrestrial organisms can grow at such temperatures, and we are therefore at worst concerned with a short period of transit through the cooler regions of the atmosphere.

According to the COSPAR agreements, the cumulative probability up to 1988 of contaminating the planet must be less than 10^{-3}. With 20 missions, the probability per mission must then be less than 5×10^{-5}. We are satisfied that this constraint is readily met, even if the bus or orbiter should enter the atmosphere. These unshielded vehicles will mostly vaporize in the upper atmosphere, and at most a few charred members may fall rapidly through the temperate region of the cloud tops. For numerical estimates we may start with the figures given in the Planetary Explorer, Phase A Report (Goddard Space Flight Center, October 1969, Section 6 and Appendix C). The number of spores is taken as 10^4. The probability of release in the atmosphere under the above circumstances is estimated to be less than 10^{-3}; we regard the Goddard figure of 0.3 as far too high for atmospheric release, because it was based on a hard-surface impact. The probability of growth was given as 10^{-4}, but this assumes the presence of a stable particle or droplet to grow on. However, droplets are subject to evaporation, while solid particles must be subject to rapid mixing to support them against fallout; they will therefore reach a hot region in a short time. We believe that the probability of growth in the atmosphere should be amended to less than 10^{-6} for a total probability of contamination per impact of less than 10^{-5}.

We therefore see no reason why the bus or orbiter should not be permitted to impact the planet whenever a scientific benefit is to be gained thereby. Low-periapses orbiters should also be open to consideration. Surface-sterilized entry probes, hermetically sealed and with a fully sterilized heat shield, present a far lower probability of contamination than do the bus or orbiter, and risk of contamination from them may be neglected.

We therefore *recommend* that, with some precautions, spacecraft be allowed to impact the planet when scientific benefit is to be gained thereby.

CONTINUING PLANNING GROUP

The fullest possible benefit of the Planetary Explorer concept can only be realized by an integrated series of missions, as discussed in Chapter 6. At any given time there will be a set of prime questions requiring answers; but some of them cannot be asked at present. Also, certain important experiments will require a further definition of the environment by a previous mission before they can operate to full efficiency. (For example, television is useless if there is dense fog at the surface.) The best available mechanism to assure that the scientific requirements are met is the planning group, which has already been used successfully for the Venus-Mercury Mariner and the Viking programs. But for a Planetary Explorer series it is not enough to have such a group for each individual mission: at least some continuity is necessary over the series.

In addition, the highly integrated nature of the experiments on a particular mission suggests that the traditional payload concept--a collection of separate experiments individually conceived--is not valid. Rather, each mission should be regarded as a single experiment with the individual experimental subsystems carefully chosen to complement one another and to maximize the scientific return within the mission constraints. Therefore, we *recommend* that NASA set up and maintain a continuing planning group for the exploration of Venus which will advise on strategy for the mission series and on conceptual payloads for each mission.

FUTURE MISSIONS

The strength of the Planetary Explorer concept as discussed in this report is due in great part to quite recent improvements in launch capability, communications, and science instrumentation. We have been able, therefore, to demonstrate how most of the important first-order questions about Venus can be answered by a series of Planetary Explorer missions. In a longer view, questions arise regarding the continuation of this strategy.

As far as we wish to predict, the study of planetary aeronomy and particles and fields can be continued indefinitely within the Planetary Explorer concept. The two requirements for a full investigation of the first-order questions are (1) measurements within the upper atmosphere from entering vehicles and from low-periapsis orbiters and (2) measurements of particles and fields from orbit, preferably with two vehicles at the same time.

Atmospheric studies made during the recommended Planetary Explorer missions will be extremely fruitful in defining the chemical and physical makeup of the atmosphere. The potentially great complexity of the cloud physics and of the circulation, however, leaves the possibility that these processes may remain poorly understood. Considering their great relevance to the determination of the high surface temperatures, it may become desirable, on the basis of the first missions, to have a more advanced effort to answer these questions. No guess as to the appropriateness of Planetary Explorer technology to advanced work is possible, although the recent rate at which capabilities have improved leaves ground for optimism.

Most basic questions about the solid planet itself can be answered only by measurements made on the surface. It appears possible to make some important measurements of this kind with missions of the modest scale proposed. However, the lander mission suggested in this report could be as far as currently defined Planetary Explorer technology can go in this direction. If passive seismology proves viable, future visits to the surface ought to be made at three sites simultaneously. Analysis of surface materials can be definitive only if several sites are visited and if several fairly complicated experiments are carried out, involving, for example, long lifetime, preparation of samples, and vacuum conditions. As far as we wish to foresee, this sort of thing goes beyond the current Planetary Explorer concept in cost and complexity. We think that such a program will not be desirable until the 1980's, and we suspect that improvements in launch vehicle and instrument technology in the interim will greatly increase the viability of any more ambitious type of mission.

INTERNATIONAL COLLABORATION

International collaboration projects in geophysics--the International Geophysical Year, the Upper Mantle Project, and the International Year of the Quiet Sun--have contributed greatly to the development of knowledge of man's environment. Further, the International Geodynamics Project has recently been launched by the International Council of Scientific Unions to study the fundamental dynamical processes within the earth's interior which are responsible for crustal movements--e.g., earthquakes. Development of international collaboration in planetary exploration is a natural extension of these successful scientific policies in geophysics, in the development of which the United States has played a leading role. The proposed program of investigation of Venus is scientifically the broadest yet proposed for a planetary investigation involving most of the subdisciplines of geophysics. Thus it is most suitable for collaboration with scientists of other nations.

We therefore *recommend* that NASA actively seek the collaboration of other national space organizations in planning and carrying out these investigations.

EARTH-BASED STUDIES

Optical and radio (including radar) studies of Venus have been valuable in the past and are expected to remain so. We *recommend* that NASA continue to support and develop earth-based studies, and we commend its past efforts in this respect. Improvement of radio facilities can be expected to give better thermal maps, as well as radar maps of the surface comparable to earth-based optical photographs of the moon. Optical work at the cloud tops can give long-term information on inhomogeneities and on the possible four-day atmospheric rotation. The techniques complement one another and give valuable supplementary information for the Planetary Explorer missions.

VENUS/MERCURY FLYBY

We understand that the Venus/Mercury flyby scheduled for launch in 1973 is intended primarily for the exploration of Mercury. However, the opportunity exists for valuable measurements during the flyby of Venus. These measurements, particularly high-resolution, high-contrast imaging of the cloud layer, would play an important role in advance planning for the Planetary Explorer program. Specifically, imaging is not contemplated on the early Planetary Explorer missions. Results from the Venus/Mercury flyby could help to optimize the payloads for later Explorer orbiters. For these reasons, we endorse the Venus/Mercury mission for the contribution it can make to Venus science.

Chapter 3

UPPER ATMOSPHERE AND PLASMA INTERACTIONS

INTRODUCTION

Observational data on the upper atmosphere of Venus are limited but have already produced promise of exciting results in future missions. Mariner 5 obtained a profile of electron density on the dayside, provided evidence for a very interesting interaction between the solar wind and the planetary ionosphere, and identified an extensive region of ionization on the nightside of the planet (the plasma tail). An ultraviolet airglow experiment on Mariner 5 detected a halo of Lyman-α emission around Venus. The emission showed an unexpected profile, suggesting that two distinct neutral species are involved in scattering the solar radiation.

The simplest model of the ultraviolet dayglow requires large concentrations of deuterium, as well as hydrogen, in the outer atmosphere and stimulated a number of theoretical discussions of planetary evolution. A question of great importance concerns the fate of water on Venus: Was Venus at some distant epoch covered by an ocean, and if so, what happened to the water? Alternatively, was Venus formed with much less water than was the earth? The isotopic ratio of hydrogen to deuterium should clarify these questions, and only upper-atmospheric measurements, where the fractional abundance of light elements is high, seem likely to provide the answers. An isotopic analysis of hydrogen compounds in the lower atmosphere is more difficult and does not appear feasible with mass spectroscopy in the present state of the art.

The interaction of the planet with the solar wind is an intriguing phenomenon in its own right. The 1968 report (*Planetary Exploration 1968-1975*) identified studies relevant to the understanding of the origin and evolution of the solar system as a prime goal in the planetary program. It should be emphasized that the upper atmospheres of Venus and Mars and their modes of interaction with the solar wind are similar, but they are very different from those of the earth. The solar wind can modify atmospheric composition in a variety of ways: it provides a source of hydrogen comparable to the present evaporation rate, gases ionized near the limb of the planet will be carried away by the solar wind, and the apparent absence of nitrogen on Mars may be a consequence of solar-wind scavenging.

The stability of carbon dioxide atmospheres on both Venus and Mars is poorly understood. Upper-atmospheric measurements are essential if the recombination process is to be established. Theoretical models for the primitive terrestrial atmosphere can be refined *only* if present conditions on Mars and Venus are understood.

THERMAL STRUCTURE OF NEUTRAL ATMOSPHERE

At present, observational data relating to the thermal structure of the upper atmosphere of Venus are extremely limited. They consist of a single profile of Lyman-α emission and a single dayside electron density profile provided by Mariner 5. The temperature information in these data is indirect. The airglow measurements suggest an exospheric temperature of either 350 K or 700 K, with the larger value appropriate if thermospheric concentrations of deuterium are comparable with those of hydrogen. The smaller value could be achieved if the upper atmosphere of Venus contained large amounts of H_2. Deduction of temperatures from the ionospheric data requires certain assumptions with regard to the composition of the neutral atmosphere and involves a detailed ionospheric theory which, although plausible, remains relatively untested. The simplest interpretation of the ionospheric data favors the higher value for exospheric temperature mentioned above. The lower value cannot, however, be categorically excluded.

Detailed radiative equilibrium studies of the upper atmosphere of Venus give exospheric temperatures in the range 500-700 K and are consistent therefore with the observational data. However, analogous studies of radiative equilibrium have been carried out for Mars, and in this case the agreement with observation is less convincing. The simplest interpretation of Mariner 4 data suggests that radiative calculations overestimate temperatures by perhaps a factor of 2. The apparent discrepancy for Mars has led some workers to question the agreement obtained for Venus. On the other hand, the difficulties encountered for Mars may simply reflect the importance of heat-transfer mechanisms such as eddy transport and dissipation of tidal waves, at present poorly understood and inadequately treated by theoretical models.

Resolution of the conflict is clearly desirable. The inference of large deuterium concentrations for Venus, and deductions relating to the evolutionary history of the planet, assumes that the exospheric temperature is known and large (∿700 K). The exospheric temperature plays an important role in the determination of the evaporation rate of atmospheric gases. It also determines the extent of the upper atmosphere and influences the details of the interaction of the planet with the solar wind. Reliable observational data on thermal structure would clarify matters not only for Venus but also for Mars. These data could be obtained from vertical distributions of neutral species, measured by mass spectroscopy in the approximate height range 150-300 km.

COMPOSITION OF NEUTRAL ATMOSPHERE

All measurements related to the composition of the atmospheres of Venus and Mars indicate one important and astonishing fact: the atmospheres are practically pure CO_2. On the other hand, CO_2 is only a minor constituent in the present atmosphere of the earth in which oxygen is present in the form of O_2.

These gross differences can be understood, at least qualitatively, if one postulates the absence of liquid water for Venus and Mars. Carbon on earth is locked in the crust mostly as $CaCO_3$, but in the absence of water on Mars and Venus and at the high temperature of Venus carbon freely enters the atmosphere as CO_2.

Another important question is raised by the persistence of molecular CO_2 on Venus (and Mars) into the upper atmosphere. Although solar ultraviolet radiation dissociates CO_2 into CO and O, above the cloud tops of Venus the concentration of CO is only about 2 parts in 10^5 and that of O_2 is less than about 10 parts in 10^5. The ultraviolet airglow experiments aboard the Venera probes indicate that the atomic oxygen density at 300 km in the upper atmosphere late in Venus's night is only 10^{-5} times the density at the same altitude on earth. For the atmosphere of Mars, similar conclusions can be drawn from the ionospheric chemistry, and resonance fluorescence measurements carried out on Mariners 6 and 7 give very low values for the

O density. The CO_2 atmospheres of Venus and Mars are astonishingly stable despite the low probability of recombination of ground state O and CO.

To account for the absence of O_2 and CO in the lower atmosphere, several possibilities exist. For example, in the presence of water photochemistry, CO and O_2 are efficiently recombined by OH and H in a catalytic cycle; but the process does not account for the low concentration of atomic oxygen above 100 km. The only scheme proposed to date in this altitude regime is speculative and invokes formation of an unstable radical CO_3 by a reaction in which the metastable oxygen atom is produced by the primary dissociation event. Recombination is achieved in a subsequent reaction of CO_3 and CO. The CO_3 scheme may also be important in the lower atmosphere, particularly if the concentrations of hydrogen compounds are as low as current models suggest.

The primary measurements needed to clarify CO_2 photochemistry appear to be determinations of the composition of the atmosphere, particularly below 200 km. Most interesting would be an observation of CO_3.

A further interesting compositional question concerns the interpretation of Lyman-α observations performed by Mariner 5. The deuterium hypothesis suggests an over-all enhancement of the D/H ratio in the atmosphere of Venus as compared with earth. As mentioned earlier, if this enhancement were confirmed, it would have profound implications for models of planetary evolution. By analogy with earth we should expect that Venus over geologic time should have released an amount of water equivalent to a surface pressure of approximately 270 atm. Such a large concentration of H_2O is not observed at the present epoch. Can we explain the loss of a whole ocean of water on Venus?

A model of a "runaway greenhouse" has been proposed in which an ocean might evaporate rapidly when the solar radiation is as strong as it is at Venus. Water vapor would be dissociated by sunlight, and H atoms would escape thermally from the upper atmosphere. Oxygen released in this manner could react with crustal materials. In a primitive atmosphere these processes could be very rapid, and it appears that they would indeed lead to a large depletion of water. After most of the water was gone, the atmosphere would begin to resemble the present one, with CO_2 as the major constituent and a similar exospheric temperature.

At this point in the argument we see the possibility of a relevant observable parameter, because in the present Venus atmosphere deuterium escapes slowly and light hydrogen perhaps a thousand times more readily. Continued escape should lead to a great enrichment of deuterium in the remaining water vapor. Some confirming evidence already exists from the Lyman-α measurements made by Mariner 5. The anomalous distribution of this radiation around Venus is most readily explained by a large relative abundance of deuterium. It is important to obtain an unambiguous confirmation of this inference and as much further information as possible on the vertical distributions. The latter can be compared with computed effects of a rapid upward flow to give a check on the escape rates.

Measurements of the D/H ratio could in principle be made from a probe in the lower atmosphere, where hydrogen is combined in molecular forms. But measurement of atoms in the upper atmosphere may be considerably easier, especially because several independent methods exist. Dayglow of Lyman-α gives the sum of both isotopes, but resolution can be obtained by use of absorption cells containing one or the other isotope. An undeveloped but promising method is to induce resonance scattering by a hydrogen or deuterium lamp aboard the spacecraft. A neutral mass spectrometer has the capability to make the measurement, and it should therefore be designed with this in mind.

The abundance of helium is also an interesting parameter. If the rate of emission of radiogenic helium (^{4}He) from the crust of Venus is similar to that of the earth, the flow should be of the order of 2×10^6 cm^{-2} sec^{-1}. This is probably more than is accreted from the solar wind if, as suggested by the Mariner 5 observations, the solar wind is diverted around the planet. Other sources of helium appear to be negligible.

The escape of helium from the top of the atmosphere by thermal evaporation is probably negligible. Thus the total atmospheric content should be essentially the total production since the planet was formed 4×10^9 years ago, namely, about 2×10^{23} atoms cm^{-2}. This is about 1000 times greater than the helium content of the terrestrial atmosphere, and it is sufficient to permit He$^+$ ions to play an important role in the formation of the topside ionosphere. Because helium is likely to play a major role in the formation of the topside ionosphere and plasma tail, and because the total abundance might contain information concerning the formation of the planet itself, observations of neutral and ionized helium are of prime importance.

Minor neutral constituents should be measured throughout the upper atmosphere with a neutral mass spectrometer. If the earth's atmosphere is a valid guide, the atmosphere of Venus should contain about 1% N_2, 0.01% Ar, and even less Ne. The inert gases are especially interesting because their distributions provide a good measure of the structure of the atmosphere, undistorted by chemical effects. Measurements of the relative abundance as a function of altitude of any two chemically inert gases yield important information on the degree of turbulent mixing of the lower atmosphere and on the location of the turbopause. It is necessary to measure at least the relative concentrations of two inert constituents at two altitudes, one in the lower atmosphere below the turbopause and one in the upper atmosphere where molecular diffusion is dominant. Then, because it can be assumed that the relative abundance of the two constituents is uniform below the turbopause, it is possible to estimate the altitude of the turbopause from considerations of diffusive separation in the upper atmosphere. It is advantageous to perform the measurements on gases of widely differing mass (e.g., He and Ar), and if the measurements can be made at more than two altitudes, more detailed information on the nature of the turbulence can be obtained.

Isotopic abundances can provide important clues concerning the origin of the atmosphere and the possibility of the extent to which there is a primeval component. Isotopes of Ne, Ar, Kr, and Xe are of interest in this respect. Argon-40, which is of radiogenic origin, is likely to be the most abundant of these isotopes and thus relatively easy to detect; its abundance should yield information on the constitution of the outer crust of the planet.

THE IONOSPHERE

Mariner 5 detected a well-developed ionosphere on the dayside of Venus. A peak electron concentration of about 5×10^5 cm^{-3} was observed at 140 km, and the dayside ionosphere was surprisingly extensive; the electron density is large ($\sim 10^4$ cm^{-3}) and approximately constant in the altitude range 300-500 km. The density decreases rapidly above 500 km, and this sharp cutoff in the dayside ionosphere presumably represents a transition from planetary to interplanetary plasma. The transition has been variously termed the ionopause or anemopause (wind pause).

An ionosphere was detected also on the nightside of Venus. Here the peak electron concentration is approximately 10^4 cm^{-3} at about 140 km. The nightside ionosphere is also extensive, with densities of order 10^2-10^3 cm^{-3} out to heights of approximately 3500 km.

Theoretical models seem to give a satisfactory description for the lower levels of the dayside ionosphere. Both the peak density and the scale height near the peak are satisfactorily described by photochemical equilibrium, if the major neutral gas is CO_2. The identity of the major positive ion is, however, unknown. Published models favor CO_2^+. On the other hand, even trace amounts of O can alter this picture, because the reaction $CO_2^+ + O \rightarrow O_2^+ + CO$ is rapid, and in this case O_2^+ would dominate.

Formation of an O_2^+ ionosphere has several important consequences. Molecular hydrogen is destroyed by the reaction $CO_2^+ + H_2 \rightarrow CO_2H^+ + H$ and is not affected by collisions with O_2^+. If O_2^+ dominates, the possibility of large concentrations of H_2 in the outer atmosphere is enhanced, and the evidence for D is correspondingly weakened. A measurement of ion composition is evidently very important. Additional electron-density profiles, measured over a range of zenith angles and solar-activity conditions, would provide valuable checks on contemporary theoretical models.

Measurements of the ionic and neutral constituents of the lower ionosphere region can provide information on a possible *D*-region formed by galactic cosmic radiation. The measurements should also provide some hints regarding the existence of attaching species.

Present understanding of the dayside ionosphere above 250 km is minimal. Several important questions arise: How does the ionopause remain in equilibrium? Are there temporal variations of the shape and characteristics of the ionopause and topside ionosphere? What are the main characteristics of the plasma in the topside ionosphere (especially the temperature, composition, and bulk motion), and where is it produced?

Two distinct classes of model have been invoked to explain the observations: one assumes that there is a magnetic field in the ionosphere (either of planetary origin or interplanetary origin), and the other assumes that there is none. In the first case the equilibrium of the ionopause is determined by a balance of the solar-wind pressure on the outside with the combined pressure of the magnetic field and plasma in the topside ionosphere. There is essentially no bulk motion of the ionospheric plasma, which is produced *in situ* by photoionization of light atmospheric gases (H, D, He). The plasma temperature is maintained at about 4000 K by suppression of heat conduction caused by the presence of the magnetic field.

In the second case, where there is no magnetic field, the plasma is not constrained and can flow around the planet to the nightside. In this way it seems possible to produce the "tail" of plasma having a density of about 10^3 cm^{-3}, observed on the downstream side of Venus by Mariner 5. Once again the mean temperature of the plasma must be about 4000 K, but it is conceivable that there is a substantial contribution to the pressure from photoelectrons, which can escape into the tail instead of being absorbed locally. Also, if these ions are produced by charge-exchange at low altitudes involving H, D, and He atoms, they can achieve substantial energies as they are ejected upwards by the vertical electric field which must exist in the lower ionosphere. The presence of substantial quantities of O atoms in the upper atmosphere could constitute a difficulty for this model as far as H^+ and D^+ ions are concerned, because these are lost rapidly by charge-exchange yielding O^+. He^+ ions can be lost by charge-exchange with molecules, and there is also a question concerning any model involving He^+ in that the helium abundance is unknown.

If these problems are to be resolved, it is evident that we need observations of the bulk motion of the plasma in the topside ionosphere and measurements of its composition, density, and temperature, both on the sunlit hemispheres of the planet and in the tail. In addition, we require measurements of the magnetic field in the ionosphere and of the abundances of H, D, and He in the neutral atmosphere.

It seems difficult to suggest appropriate sources of thermal energy and ionization in the upper atmosphere on the mightside. The most plausible source seems to be transport from the dayside ionosphere, whose temperature and density at about 500 km elevation are higher than required on the nightside. Alternative suggestions seem unlikely. Capture of the solar wind requires cooling and an increase of density by a factor of the order of 100; it seems more likely that the wake would diffuse out if transport across the interface is not strongly inhibited. Any possible observations of plasma flow and of magnetic field connectivity with either the denser atmosphere or the interplanetary region (which might be made by simultaneous measurements of magnetic-field direction and the anisotropies of energetic electrons) would help to resolve these questions. Observations of the strength, direction, and fluctuations in the magnetic field and of fluctuating electric fields on orbiters that in time survey an extensive region of the wake would be valuable. Interactions across the interface between the wake and the solar wind, whether by viscosity, hydrodynamic instabilities, or magnetic effects, are likely to be of great interest but seem unlikely to be the source of the nightside ionosphere.

Maintenance of a peak concentration of 10^4 electrons cm^{-3} on the nightside also poses problems, especially in view of the long duration of Venus's night ($\sim 10^7$ sec). It seems unlikely that the observed ionization peak can be maintained by direct nighttime ion production. A more likely source for this ionization may be lateral transport of light (atomic) ions (H^+, D^+, He^+) from the dayside. On the nightside these light ions can charge-exchange with the neutral molecular species (CO_2). The CO_2^+ ions formed in this manner would diffuse downward. A peak would be formed at an altitude where the divergence of the downward flux is balanced by the chemical loss rate caused by dissociative recombination. This mechanism seems to be able to provide a plausible explanation for the observed peak of the nightside ionosphere. There are, however, other possibilities, including scattered ultraviolet radiation from the dayside, photoelectrons from the dayside, leakage of solar-wind plasma into the tail, and cosmic radiation. The precise mechanism could be clarified by *in situ* measurement of ion composition and temperature and by direct measurement of possible ionization sources.

An additional phenomenon, of great interest on the nightside, is the mysterious ashen light reported by many visual observers. Its reality has not been established spectroscopically at the telescope, in part because of seeing difficulties, in part because of unavailability of a low-scattered light telescope. The phenomenon should be investigated, probably with airglow instrumentation on an orbiting vehicle. Reports that the intensity of ashen light varies with solar activity raise the interesting suggestion that it is an auroral phenomenon.

INTERACTION WITH SOLAR WIND

Almost all current ideas on interplanetary particles and fields in the vicinity of Venus are based on the Mariner 5 and, to some extent, Venera 4 observations. Although it seems likely that the main features described below are basically correct, it would be desirable to check the observations, to study the variability with time, and to fill in more detail. There are hints in these data of surprising features that need to be confirmed by further study.

The Mariner 5 magnetometer and plasma observations showed that Venus produced a bow shock in the solar wind at the position that would be appropriate if the wind flow could not penetrate a surface in the ionosphere about 500 km above the surface on the sunward side. This surface was located much more precisely by the Mariner 5 dual-frequency radio occultation data, which gave an abrupt drop in electron density from about 10^4 cm^{-3} to 10 cm^{-3} over a distance of less than 100 km at this elevation over the sunward side, clearly a transition from ionospheric to solar-wind conditions. Except for over-all scale, the observations of Mariner 5 and of Venera 4 show no difference between the bow shocks at earth and Venus and no essential difference in magnetic and plasma conditions outside and just inside the bow shock.

Well inside the shock, not too far from the presumed wake behind Venus, there are indications in the Mariner 5 data that the magnetic and plasma conditions may be different from those in the corresponding position near the earth. The magnetic field is stronger, the field direction more nearly toward the limb of Venus, and the plasma density and velocity lower than expected. A variety of explanations can be advanced. A transient change in solar-wind conditions that came and went at just the right times could explain everything. A lateral expansion into a cavity behind Venus might explain part, but not all, of these observations, but more recent observations near the moon where a similar cavity is known to exist do not particularly support this model. Alternatively, the magnetic field lines of the solar wind may be draped over the front side, moving slowly near the stagnation point but streaming in the wind, parallel to the shadow cylinder in the rear.

In the shadow and wake region on the side away from the sun, the observations are even less complete. Venera 4 entered this region and experienced substantial magnetic transients near the boundary of the optical shadow. It showed that the field inside the shadow is small, probably less than 10 gamma, but its spacecraft field is sufficiently uncertain that there might be essentially no field in this region, there might be a remnant of solar-wind field, or there might be a small field whose source currents are inside Venus. The

Mariner 5 dual-frequency radio occultation data show a remarkable increase in electron content along the line from Mariner 5 to the earth just when this line passed through the wake region. The most natural explanation is that above the ionosphere the wake is occupied by plasma with a density of about 10^3 electrons cm^{-3} and 10^3 protons cm^{-3}. If this had a temperature of the order of 1000 K, it would have a reasonable scale height, and along the roughly cylindrical boundary between the wake and the solar wind there would be an approximate pressure balance between the magnetic pressure of the field observed just outside the wake and kinetic gas pressure of the presumably stagnant gas inside. It must be emphasized that this model represents a large structure erected on the basis of a very small amount of somewhat uncertain data. A probe measurement of the magnetic and plasma properties over the elevation range from 6000 to 200 km would determine which model was appropriate. One such probe on either the bright or the dark side, but preferably one on each, would provide invaluable information for the design of all later missions. An orbiter that carried a magnetometer, a plasma probe, a dual-frequency occultation experiment, and a simple 40-keV electron detector would represent a large advance. Observations for 120 days, i.e., for half or more of a Venus year, with a periapsis of 1.2 radii of Venus and an apoapsis of 2 to 5 radii of Venus should establish the character of the wake, give considerable insight into the mechanism of the anemopause both in the stagnation region and along the wake, and establish the position of the bow shock and the solar-wind environment of Venus. Such knowledge is essential for a sound understanding of the ionosphere and upper atmosphere of Venus. It is possible that a study of the responses to major changes in the interplanetary field would yield information on the extent to which the interplanetary magnetic field diffuses into the ionosphere, atmosphere, and possibly even the surface of Venus.

It would be highly desirable if the plasma probe could make measurements in the high-density, low-temperature wake. It would be interesting to know the extent to which Venus has a tail resembling that of a comet and to see if there is any reason other than the gravitational field that makes the effect of the solar wind on Venus differ from that on a comet. It would be desirable to observe ions, atoms, and molecules heavier than helium both in and just outside of the wake.

INTERPLANETARY MEDIUM AND ENERGETIC PARTICLES

Plasma probes and magnetometers will be required on many of the Planetary Explorers in order to study the extreme upper atmosphere of Venus and its interaction with the solar wind. These instruments are also capable of making valuable observations in the solar wind both in the immediate vicinity of Venus and during cruise. Probe measurements during the day before encounter and orbiter measurements outside the bow shock are also part of the primary mission because they provide the only available data on the solar-wind environment of Venus at the time planetary observations are made. In addition, measurements made in the solar wind are valuable for their own sake and should be regarded as secondary objectives that significantly enhance the value of the mission. Comparison of such observations with those made elsewhere in the solar system will provide much needed information on the large-scale structure of the solar wind. If no other solar-wind observations are being made at this time, it will be even more important for those made on the Planetary Explorer to be as continuous as possible. Comparison with observations made 11 years earlier whether at 1 A.U. or between 0.7 and 1.4 A.U. will help to indicate the extent to which there is an identifiable 11-year cycle in solar-wind characteristics.

We emphasize the desirability of operating, near earth and during cruise, those instruments that are capable of producing useful information. They include plasma detectors, magnetometers, and Lyman-α detectors.

There is no evidence for the presence of radiation belts near Venus, and none are expected. However, by analogy with measurements near the earth's bow shock, moderately energetic electrons (10-10^2 keV) should be produced occasionally at the bow shock of Venus. These particles can be detected with a thin-window Geiger-Müller counter. Electrons in this energy range are also emitted by the sun following solar flares; because absorption will cause the flux in any magnetic field line that enters the atmosphere to become anisotropic, it should be possible to obtain information concerning the structure of the magnetic field around Venus from observations of the streaming direction of these particles.

Although observations of galactic and solar cosmic rays near the orbit of Venus are of considerable interest, there is much less interest in observations in the vicinity of the planet (e.g., from an orbiter), because interactions of the cosmic rays with the planet will distort the cosmic-ray distribution. As we noted earlier, cosmic rays (and also solar and galactic x rays) must produce an extensive lower ionosphere somewhat akin to the terrestrial *C* and *D* regions.

Chapter 4

LOWER ATMOSPHERE

INTRODUCTION

The significant scientific questions about the lower atmosphere of Venus involve its physical structure, its chemical constitution, the clouds, the levels of deposition of solar energy, and the planetary-scale flow patterns. While it is necessary to discuss these separately, it cannot be emphasized too strongly that each bears upon the others through complex cause-and-effect mechanisms. For example, the clouds, be they condensates or dust, must be produced by the circulation regimes, but by dictating the levels of absorption of sunlight they, in turn, profoundly modify the basic drive for atmospheric circulation. It may be necessary to unravel most of these interactions before one can reach a satisfactory understanding of any one element.

We recognize that it will take several missions to accomplish the necessary measurements, and so we unreservedly endorse the concept of low-cost flights carefully designed to answer well-posed questions of scientific concern, with each mission as part of a coordinated program.

An important feature of most of the planetary atmospheric problems identified is that they involve the three-dimensional distribution of various properties. Single-point measurements are inherently severely limited in their ability to provide the requisite solutions. A key consideration is, therefore, the capability of simultaneous multiple entries into the atmosphere at selected locations.

One of the most difficult planetary measurements is the determination of wind velocity in a way that is useful to the theory of general planetary circulations. Radar techniques can measure the motion of an entry probe as it approaches the ground. This too, however, is a one-time measurement and does not lead to three-dimensional data. The dense atmosphere of Venus permits an alternative approach. It is technologically feasible to eject a number of small packages during entry which will inflate modest constant-level balloons to drift with the wind at several levels. These can be tracked from earth or from an orbiter and can have lifetimes of a month or more.

Why should we explore the atmosphere of Venus from the point of view of planetary dynamics? First, because the massive and hot atmosphere is different from the other inner planets, and knowledge of how Venus developed to its present state could provide an important clue to the understanding of the evolution of the solar system. Second, the very slow planetary rotation and the dense, ubiquitous cloud cover indicate a different thermal and dynamical control of the planetary flow pattern. Thus we can present meteorological theory with a different set of circumstances than those presented by the earth. Both must be explicable by a correct and general theory, and so our comprehension of our own planetary atmosphere can be improved in the process.

It is instructive to compare the atmospheres of Mars, Venus, and the earth. On Mars the low atmospheric density, low water-vapor concentrations, and paucity of clouds all mean that the atmosphere is nearly in radiative equilibrium and that dynamical effects on the temperature distribution are of small consequence. This is a simple situation worthy of study in its own right. On Venus the very large densities and dense cloud cover act to minimize the effects of radiation so the temperature field is expected to be strongly controlled by dynamical wind systems. This is the opposite simplification from Mars. On earth, radiative and dynamical influences are more nearly of equal importance, resulting in a complex problem. Clearly, we can expect fundamental gains by studying these simpler atmospheric systems provided by nature.

The slow rotation of Venus means that Coriolis forces will be small, a situation found on earth in the tropics, where the significant part--the vertical component of the rotation vector--is also small. Thus the circulation of Venus may be fundamentally related to that in our own tropics, an area where our understanding is far less than for middle and high latitudes. Another potential relationship to terrestrial motions is to the part of oceanic circulation that is thermally driven. We know that the oceans absorb solar radiation close to the top boundary. We have reason to believe that much of the deposition of solar energy on Venus is in the upper part of the clouds, so the parallel to terrestrial oceans is apparent.

The highly clouded state of the atmosphere of Venus as compared with that of the earth represents a case in which the absorption of solar energy and the absorption and reemission of infrared energy are strongly controlled by the clouds. Appropriate observation of Venus can add to our understanding of this situation. Such understanding is potentially important to knowledge of the terrestrial atmosphere in which human activities are producing a progressive increase in turbidity. Any knowledge of the state represented by Venus may be overwhelmingly important.

PHYSICAL STRUCTURE OF THE LOWER ATMOSPHERE

Direct measurements of temperature and pressure, with simple and reliable instruments, are among the primary tasks that should be undertaken in any future investigation of the lower atsmosphere of Venus by spacecraft. These quantities are two of the most direct links existing between observation and the theory of atmospheric motion, and they are important in any attempt to understand the heating of the lower atmosphere. They are, moreover, often the final goal of complex methods of remote sensing.

Our first knowledge of the physical structure of the atmosphere of Venus came from the analysis of radio-astronomical observations. From studies of the variation of the intensity of radio emission with wavelength it was inferred that (1) the lapse rate in the lower atmosphere is adiabatic, and (2) the temperature T and pressure P at the surface of the planet are elevated by terrestrial standards, with $T \sim 700$ K and P in the range from 25 to 200 atm. The *in situ* measurements of the Soviet space probes Venera 4, 5, and 6, in conjunction with the S-band occultation experiment of Mariner 5, have confirmed these atmospheric conditions in significant detail. Recent interferometric radio observations from earth indicate that horizontal temperature gradients at the planet's surface are small, even on the scale of planetary dimensions.

Present knowledge, however, is too imprecise and limited in coverage to serve as the starting point for a theory of the general circulation of the atmosphere. For this purpose, simultaneous measurements of the vertical profiles of temperature and pressure are required over some grid covering the planet's surface. In its most rudimentary form, such a grid should consist of at least three or four widely separated points, located to yield information on the pole-to-equator and dark side-to-bright side gradients of P and T.

TYPES OF MISSION

The types of mission that are feasible for future planetary explorations of Venus with small vehicles are orbiter, entry probe, and balloon.

Orbiters

Infrared or radio-occultation experiments on an orbital probe can provide information about the upper 5 percent or less of the atmosphere, but this is inadequate for solving the major problems of the lower atmosphere of Venus.

Entry Probes

The instrumentation to perform measurements on an entry probe is lightweight, modest in power consumption and telemetry requirements, and comparatively inexpensive. It is thus well suited to simultaneous deployment on several small entry probes launched from a single bus.

It is important that three small entry probes should accompany a larger entry vehicle into the atmosphere of Venus. There are several factors, discussed later, which constrain the entry point of the main probe to lie within 35° of the subearth point. The small probes can then be independently targeted to lie 120° apart on the circumference of a circle not necessarily centered on the entry point of the main probe. We find it highly desirable from a scientific point of view that these small probes be separated by distances comparable to the planetary radius and that one probe lie within roughly 30° of either pole. It is then feasible and desirable for one of the remaining probes to enter at low latitude on the sunlit side of the planet and the other at low latitude on the dark side. If dual missions are flown, it may be desirable to select the target locations for the second set of probes after the first set has actually entered the atmosphere.

On both the main and small probes it is imperative that both temperature and pressure be measured down to the planetary surface. Some indication of actual or imminent contact of each probe with the surface is necessary in order to remove the possibility that termination of data transmission is merely an indication of instrument failure under the severe environmental conditions encountered. It is reasonable to expect that more accurate and frequent measurements will be possible on the main probe than on the small probes because of its greater size and weight.

Pressure measurements on the main probe should be made to an accuracy of at least 0.5 percent over the range from about 0.1 atm (or as determined by deployment) to 180 atm. Temperature should be measured to an absolute accuracy of 1 K and, if possible, with a relative accuracy of 0.1 K; it should be measured over the range 200-900 K. Both pressure and temperature should be measured and transmitted to earth at altitude intervals of at most 1 km. Doppler tracking of the vehicle will provide information about one wind component. A wind-drift radar will, if the probe rotates, give a vector wind measurement.

On the small probes, temperature and pressure should be measured over the same range as on the main probe. Pressure should be measured to an absolute accuracy of at least 1 percent. Temperature should be measured to an absolute accuracy of 2 K and a relative accuracy of 0.2 K. Measurements need not be taken at equal altitude intervals, but it is desirable that the intervals should not exceed 2 km. With feasible telemetry systems, several hundred measurements of both pressure and temperature should be possible before impact with the ground.

Balloons

We see important advantages in the use of constant-density-level balloons situated at pressure levels of 50, 500, and 1200 mbar. The balloons at the lower levels can carry instruments to make global measurements of atmospheric temperature and pressure. This kind of measurement will complement and reinforce the data obtained from entry probes.

RADIATIVE HEAT BUDGET

Venus is characterized by two features that provide a challenge to our understanding of atmospheric science: high surface temperatures (700 K) and an extremely turbid atmosphere. These features are believed to be interrelated: Solar radiation is attenuated within the turbid atmosphere and heats the interior of the atmosphere. This heat energy is then reradiated at infrared wavelengths. However, the clouds are believed to trap the infrared radiation. This trapped infrared radiation has been assumed by some investigators to be solely responsible for heating the lower atmosphere of Venus. This mechanism is generally called the "greenhouse" effect. While this effect provides a qualitative explanation of some features of the temperature structure, quantitative estimates of the heat budget show that it is necessary to invoke dynamical as well as radiative considerations for any explanation of the thermal profile. One of the main purposes of the recommended atmospheric probes should be to provide the data required to understand these mechanisms.

A quantitative measurement of the solar radiation flux absorbed at various altitudes will be an essential part of the data required. Measurements of the penetration of solar radiation, the emission of infrared, and the characteristics of the clouds as a function of altitude are made most definitively from probes that actually enter and penetrate the entire atmosphere.

The radiative heating at each altitude is given by the divergence of the net radiation flux. Entry probes can measure this quantity directly from the difference between upward and downward directed fluxes as a function of altitude. Appropriate flux sensors can be placed on the upper and lower surfaces of a probe descending through the atmosphere. Such sensors have been employed extensively in terrestrial meteorology to measure fluxes to 2 percent accuracy. It would be desirable to obtain such measurements to better than 5 percent accuracy, which can be realized if suitable care is taken in the design and testing of the solar-flux sensing system.

The relative simplicity and compactness of solar-flux sensors renders it feasible to place such sensors on board all probes.

Thermal flux plates have been employed in terrestrial meteorology to measure infrared cooling rates. These instruments are light and rugged, and they should also be employed on all probes.

It has been our experience on earth that clouds in temperate and polar regions differ from those found in tropical regions. We have no prior knowledge about the latitude dependence of cloud structure on Venus. Distributing solar flux and infrared sensors on several probes will enable us to ascertain whether there are morphological differences in the clouds which affect the radiative heat budget at different latitudes. If more than one instrument package is sent to Venus, this opportunity should be taken to provide us with more global coverage on radiation measurements.

ATMOSPHERIC CHEMISTRY

Knowledge of the chemical and isotopic composition of the atmosphere of Venus is essential to the understanding of the conditions of origin of the terrestrial planets and the solar system in general. We can expect that the total abundances of certain volatile elements on Venus are very sensitively dependent on the temperature of that portion of the solar nebula in which proto-Venus accreted. Those volatile elements, such as nitrogen, mercury, and the rare gases, which would be incapable of forming condensed compounds at the present surface temperature of Venus, would currently reside in the atmosphere. Thus an analysis of the abundances of these elements in the atmosphere would contribute directly to an understanding of the origin of the entire planet and, by comparison with the atmospheres of the earth and Mars, might permit the development of consistent models for the origins of the terrestrial planets.

In a very different way, knowledge of the atmospheric composition contributes to our understanding of the mechanisms by which planetary atmospheres are produced, maintained, and buffered. The chemical interaction between reactive gases and the surface rocks of Venus may well be a study in essentially pure and unperturbed chemical equilibrium. Understanding the emission of gases from terrestrial volcanoes and fumaroles is made tremendously more complicated by the competing effects of equilibrium, kinetic barriers, temperature and pressure gradients, compositional variations in the rocks in contact with the gases, and, finally, contamination and oxidation by the oxygen-rich atmosphere. Venus may therefore be the ideal laboratory in which to isolate and study the effects of chemical equilibrium and thus open the way to the understanding of the processes governing the initial generation of the earth's atmosphere and its composition as a function of time.

It is clear that the atmospheric composition also reflects the current mineralogy of the surface. We thus may make plausible models for the mineralogical composition of the surface from atmospheric compositional data alone. In the absence of precise temperature and pressure data on the surface of the planet, it is even possible to estimate these parameters by searching for a limited temperature and pressure regime within which the observed abundances of atmospheric constituents are compatible with already-known buffer reactions. This latter technique leads to some ambiguity, because more than one pressure-temperature point may satisfy all the available data. This leads to uncertainty concerning the exact reactions responsible for the atmospheric composition and thereby generates a list of "plausible" minerals and mineral assemblages which *may* be present. This ambiguity may be removed by applying some additional constraints on the surface conditions, such as *in situ* measurements of the surface temperature and pressure. The composition of the atmosphere reflects the equilibrium conditions in that portion of the planet's surface which acts as a "cold trap," and thus we need a minimum temperature more than just the mean or maximum temperature of the surface. The use of several lightly instrumented probes to make direct determinations of the surface temperature at widely separated points on the planet presents an ideal solution to this problem. Among the regions which must be probed to answer these questions, the polar and antisolar regions are of paramount importance. It can be seen that compositional data on the lower atmosphere and surface temperatures at widely separated points are both relevant to the surface mineralogy and petrology, and that the results of such measurements would be useful in the design of future petrological, mineralogical, and geochemical experiments.

Current opinion on the nature of the clouds of Venus favors the view that the clouds are formed by condensation of gaseous constituents of the atmosphere. (The possibility of airborne dust cannot, however, be ruled out, and a discussion of this and related problems is presented in the following section.) We can learn about the cloud composition and structure from compositional analyses of the atmosphere itself. The most direct application of the atmospheric composition determinations is in the search for regions in which the atmosphere is saturated with respect to any constituent or reaction product formable from the gas. Compositional discontinuities should occur at levels where clouds condense, and adequate models for the cloud structure might follow from a simple thermodynamic treatment in which the only input parameters are the atmospheric composition and the local temperature. It is clear that cloud-physics measurements in the absence of such compositional data are incapable of identifying the chemical nature of cloud condensates.

The atmospheric composition as a function of altitude, tied as it is to the problem of the location, mass, and optical properties of cloud layers, assumes considerable importance when one attempts to understand the thermal structure and thermal balance of the atmosphere. The atmospheric opacity in the infrared regions is strongly dependent on the abundances of trace atmospheric constituents. Even as little as one part of SO_2 per 10^7 parts of CO_2 may have a significant influence on the greenhouse effect, and the atmospheric opacity at wavelengths less than about 3 cm may be largely due to trace constituents. One must therefore expect that knowledge of the atmospheric composition could help considerably in explaining the thermal structure of the atmosphere.

Finally, detailed knowledge of the atmospheric composition near the visible clouds permits investigation of photochemical processes and products whose existence might not be readily apparent to an outside observer.

Mass spectroscopy is the most effective method of carrying out an adequate analysis of the atmosphere. We shall attempt to describe the performance requirements for such an analysis in light of the uses to which the results will be put.

In order to permit the determination of isotopic abundance ratios for a variety of elements, it is essential that the resolution be no worse than one mass number. If cloud-producing condensates are to be detectable down to the limits at which the clouds become vanishingly important, then the detection limit should be 10^{-5} to 10^{-6} of the CO_2 abundance. The mass range which must be covered by the analysis is not so easy to define specifically. It is certainly of great importance to cover the range up to at least $m/e = 44$. This will ensure coverage of H_2, He, H_2O, HF, Ne, CO, N_2, H_2S, HCl, Ar, and CO_2. It is unfortunate that some of the interesting constituents will not be sufficiently abundant relative to CO_2 to be visible in the same mass spectrum. Of these, the rare gases might possibly be subjected to a separation step to remove CO_2 and N_2, as well as species such as $H^{35}Cl$ which may interfere at certain interesting mass numbers. For planetological purposes one should not hastily dismiss the significance of the heavier rare gases. The relative abundances of fissiogenic and solar Kr and Xe and the possible existence of the extinct-radionuclide decay product of ^{129}Xe would be of great interest, particularly in comparison with terrestrial and meteoritic evidence. Thus the mass regions near $m/e = 80$ and 125 are also of considerable value. In the immediate vicinity of the Kr and Xe masses are found the other volatile elements, bromine and selenium (near $m/e = 80$) and iodine and tellurium (near $m/e = 125$).

Several other plausible atmospheric constituents are also of interest, such as the gases SO_2, COS, $FeCl_2$, Hg, and Hg halides up to HgI_2. We believe that coverage of the range from $m/e = 1$ to 140 is possible and highly desirable. The feasibility and utility of a chromatographic column in conjunction with the mass spectrometer should be studied with later and more sophisticated mission opportunities in mind.

The sampling scheme for a mass spectral analysis should obey certain general constraints. The vertical sampling frequency should be sufficient so that at least two analyses could be conducted at widely separated altitudes above the visible cloud layer, at least two more between the 250 and 400 K levels, and at least one or two in the deep atmosphere. At least one analysis capable of giving the He, Ne, and Ar isotopic composition is essential. There are no clear reasons for preferring any particular area of the planet for conducting these analyses. A bright-side entry of the large probe at low latitudes would be completely acceptable.

Certain other data are essential for full utilization of the compositional information. These include pressure and temperature profile measurements at several widely separated points on the planet, nephelometer and condensimeter measurements as will be discussed in the next section, and some independent estimates of one very important parameter--the H_2O vapor mixing ratio. A number of special-purpose instruments are possible candidates for measuring the water-vapor abundance. Our present remarks shall be confined to stressing one extremely important point: the water detector must be *sensitive* but highly *specific*. The presence of soluble hydrogen halides such as HCl and HF must be taken into account in the design and calibration of such detectors; otherwise the measurement would not be acceptable.

Venus orbiters may also make a long-term contribution to the study of atmospheric structure above the critical refraction level (total pressure near 6 atm) via single- or dual-frequency occultation experiments. Attenuation and phase-shift data for the atmosphere over a wide range of latitude and solar phase angle would be most useful in understanding the structure of the upper troposphere.

CLOUD PHYSICS

The essential questions that can be approached by cloud-physics measurements are:

1. Are the clouds condensation (reaction) products or wind-blown dusts?
2. Are the clouds cumuliform, stratiform, or haze?
3. What are the processes involved in cloud formation and dissipation?
4. How do the clouds affect the planet's heat budget?

In addition, detailed knowledge of the physical characteristics of the clouds are important for the interpretation of earth-based and orbiter measurements.

Because optical measurements from earth are necessarily limited to an examination of the upper regions of the atmosphere of Venus, the structure of the bulk of the clouds is unknown. Much larger particles and denser clouds are likely between the upper atmosphere and the planet's surface. Particle concentration may well increase and the particle-size distribution function broaden; however, large spatial variations in size and concentration should be expected. One may speculate about the lower regions of the atmosphere, but the actual situation can only be revealed with certainty from *in situ* measurements. The measurement of the particle-size distribution is necessary to establish the mechanisms by which the cloud particles form and are removed from the cloud. Scavenging by coagulation and agglomeration alone will lead to larger particles and may ultimately cause sedimentation and some form of precipitation. If the particles are condensation products, particle-size information will provide important information on latent heat fluxes as well as insight into particle-growth regimes.

In the event that the cloud particles are not condensation products, the changes in the particle-size spectrum may provide clues to electrostatic processes active in agglomeration and coagulation that increase particle size. Carbon dioxide is an excellent insulator, and frictionally produced electrification is a distinct possibility.

Certain aspects of cloud particulates are easier to explain if the cloud is formed by condensation from a relatively pure parent phase. Such a process in our terrestrial atmosphere is responsible for spherical water droplets and ice crystals of hexagonal habit. On the other hand, the latent heat released by condensation drives vertical motions and turbulent mixing processes causing a high variability of cloud properties in space and time. Likewise, when the parent phase is impure, particles of irregular shape and nonuniform optical properties result; terrestrial pollution is an example. In view of the high surface temperature and pressure of Venus, a number of condensable vapors may exist and their particulate condensation products may thus be vertically layered. Whether cloud particles are condensation elements or dust scoured from the planet's surface has important ramifications in the atmosphere's dynamics and heat budget.

The solar flux transported through the atmosphere depends on the absorption and scattering properties of the atmospheric constituents. The high albedo, $A = 0.77$, of the planet suggests that the scattered solar flux will be of marked significance. The solar flux is scattered predominantly by the clouds. The cloud particles most assuredly will affect the infrared cooling of the atmosphere. The radiation scattering and absorption characteristics of clouds depend on the size and shape of the particles and the material of which the particles are composed.

Instrumentation and Measurements

Particle-Size Spectrometer To provide adequate size resolution and dynamic range, multiranged instruments are desirable. Size measurements over a 2-500 μm range, subdivided into 2-20, 10-100, and 50-500 μm ranges with ten size intervals, would provide adequate size resolution with 50 percent overlap in range. Such an instrument is within the present state of the art. The instrument should be capable of making single-particle-size measurements at high concentrations (10^3 to 10^4 cm^{-3}) and be relatively insensitive to particle orientation, shape, or refractive index, because particle morphology is completely unknown. These constraints make particle-size detection by imaging or extinction techniques more suitable than by scattering. However, detection of number density of submicron particles by scattering is both practical and desirable. It is desirable to transmit a complete size spectrum every 100-300 m inside cloud layers.

Aureole Sensor System Primary scattering by cloud particles will give rise to a halo or aureole around the sun caused by the forward diffraction lobe of the phase function. As the light penetrates more deeply into the atmosphere it is multiply scattered and the aureole broadens. The forward-scattered light is thus a function of the size and number of particles between the sun and the sensor and provides a relatively simple observation from which these parameters of the clouds may be inferred.

An instrumental configuration on the main probe to measure the aureole would consist of collimated tubes which would subtend angles of 3×10^{-4} sr disposed within 20° of the center of the solar disk. The instrument package should have vanes so that the package spins as it descends through the atmosphere.

It is desirable to determine the local uniformity of the cloud cover, for which purpose one simple collimated sensor can spin scan the cloud. One of the aureole sensing units could be monitored to meet this objective.

Extinction Measurement The intensity of solar radiance as a function of altitude can be related to the extinction coefficient, which is a function of the number of particles, their size, and their composition. Although no unique inference of all these quantities is feasible with only a measurement of the extinction coefficient, the results obtained from all measurements obtained from the probe should be consistent with the measured extinction coefficient. The extinction of solar radiance could be measured by means of the center sensor on the aureole sensor system.

Nephelometer The simplest means of measuring the presence of clouds is to carry a light source on board the probe and to measure the light scattered back to the probe at a fixed angle by atmospheric particles. A rugged apparatus (nephelometer) based on this principle is feasible. Lasers, suitable for spaceflight have been produced, and solid-state light detectors are readily available. Television pictures of the surface of Venus may be of interest to planetology. A measure of the solar flux level at the planet's surface is a prerequisite to the design of such a television system. A nephelometer will allow the visibility near the planet's surface to be determined.

Infrared Cloud Sensor Infrared sensors may be employed to derive data on the vertical distribution of cloud particles that emit the measured infrared radiances. A thermal radiometer should be mounted looking downward. In a near adiabatic atmosphere the difference between the brightness temperature measured in a CO_2 window at 7 μm and a CO_2 absorption region at 10.4 μm is proportional to the transmission characteristics of the clouds. Small differences correspond to opaque clouds, large differences to thin or absent clouds. The instrument thus provides a vertical profile of effective cloud density in a particularly simple way.

Condensimeter-Evaporimeter An essential datum in studying the clouds is whether they are in equilibrium with the gas phase or whether they are solid matter raised from the planet's surface by the action of winds. The distinction between these two types of cloud is not necessarily complete. It is possible that condensed and gaseous phases are in equilibrium low in the atmosphere, but that at higher cooler levels the cloud particles have such a low vapor pressure and lag-time constant that they are essentially equivalent to a dust cloud.

A valuable measurement to illuminate this problem would be development of a frost-point or dew-point hygrometer. A test surface or volume slightly below atmospheric temperature should copiously increase in solid matter if the cloud is condensing, i.e., in equilibrium with the vapor. If the temperature is higher, on the other hand, the solid matter should disappear. A device to cycle temperature above and below ambient would show unmistakably whether the cloud is condensing.

A number of devices could be considered. A mirror with variable temperature is one. A small cloud chamber, which can both expand and compress the atmosphere, is another. Both instruments have been developed for terrestrial investigations, and one should be installed on the main probe.

Particle Composition

If the cloud particles are in equilibrium with the gas phase, it should be possible to infer their composition by the methods described earlier. If they are dust, on the other hand, the problem is quite different.

It is not clear at this point whether the best way to proceed with dust particles is to measure their chemical composition directly, to determine the composition of the planet's surface from a lander, or to do both. The instrumentation for particle collection and analysis is straightforward conceptually, but it is not yet developed and may involve a lengthy development program. It cannot, therefore, be placed on high priority for an early mission. However, it is possible that there will be no acceptable alternative to this kind of measurement on one of the Planetary Explorers in the 1980's.

Cloud Forms

We do not know whether the Venus clouds are stratiform, cumuliform, or more analogous to a terrestrial haze. The nature of the physical processes depends greatly upon which general cloud type prevails. We cannot hope to obtain this information for all cloud layers in a simple manner, but the uppermost cloud layer can be observed directly by visual and thermal imaging. A limited number of high-contrast images with a horizontal resolution of about 2 km or better (such as might be obtained by the Venus/Mercury flyby) are, therefore, a prime requirement for cloud-physics studies.

Such imaging measurements can be made from an orbiter. The data rate requirements are not excessive because only an occasional image is required. The specification of a cloud-imaging experiment depends to some extent on the results of the Venus/Mercury flyby. It is possible that the visual images from the spacecraft, although very few in number, may be sufficient to answer some of the main questions about cloud morphology. On the other hand, if the spatial resolution of the system is insufficient, no definitive answer may be obtained from this mission.

ATMOSPHERIC MOTIONS

State of Knowledge

There have been no direct measurements of atmospheric motions below the clouds, but there are two pieces of evidence that indicate movement. The most direct indication is given by the time variability of the undulations of the cloud surface as seen at the terminator. Less direct is the observation that the temperature variations over the cloud tops and over the surface are small. This can only be explained by a rapid transport of head by wind systems.

Because Venus rotates slowly, Coriolis forces are much weaker than on earth and may be neglected to a first approximation. Theoretical arguments and laboratory experiments suggest that a simple convective circulation will be set up with air rising in warm regions and sinking in cold regions. The location of the heat sources and sinks is crucial in determining the form of the circulation. Heat loss to space is by infrared cooling from the upper strata of the cloud deck. The altitude at which the solar energy is deposited in the atmosphere is not known; this is one of the most fundamental questions in the dynamics of Venus's atmosphere. Enlightened guesses may be made, however. The extensive cloud and high albedo make it improbable that much of the sunlight incident on the atmosphere reaches the planetary surface. Detailed calculations on plausible clouds have indicated that most of the solar heating takes place in the clouds.

The response time of the atmosphere of Venus to solar heating is long compared to a Venus day, up to a level approximately coincident with the cloud top. The atmosphere below that level experiences an average heating like the earth, symmetric about the rotation axis, highest at the equator, and vanishing at the poles. We may anticipate a Hadley circulation in which the flow is up over the equator, poleward at high levels, down over the poles, and equatorward at low levels. This circulation is not relevant to middle latitudes of the terrestrial atmosphere, but it does bear a relationship to the tropical atmosphere.

Another possibility occurs if the solar energy is deposited in a region in which the response time of the atmosphere of Venus is short compared to the Venus day. The circulation in that case would be expected to be up over the subsolar point, toward the antisolar point at high levels, down over the antisolar point, and back to the subsolar point at low levels.

An analysis of a Hadley circulation, driven by solar heating and infrared cooling at the upper surface, has been performed. The model is perhaps primarily of heuristic value, as the numerical values used are quite uncertain. However, two important features emerge. First, the circulation will transport a sufficient amount of heat to reduce the temperature contrast well below that of a model which neglects large-scale motions. This is in agreement with both the infrared measurements of cloud-top temperatures and with microwave surface-temperature measurements. Second, the deep circulation could be adiabatic, creating an adiabatic lapse rate. If this circulation extends nearly to the surface, it could produce the observed high surface temperature through compressional heating, without requiring any solar radiation at the surface.

Several features of this model must be established before it will be possible to consider more detailed questions. First, is the circulation of the equator-to-pole type? Second, how deep is the return layer? Third, how large are the velocities at the cloud top and in the return layer?

Observations in blue and ultraviolet light have sometimes shown faint cloud markings that move around the planet in 4 days, in a direction opposite to that of rotation. Because they are seen at ultraviolet wavelengths, they are presumed to be above the visible surface. Some recent Doppler-shift measurements tend to support such motions.

Such a circulation cannot be explained on the basis of the Hadley cell. An explanation has been put forward based on momentum transport by thermally created eddy stresses. Laboratory studies have shown that retrograde motions can be created, but further work must be done to demonstrate the relevance of this work to Venus.

The existence and morphology of such disturbances needs to be established, along with such temperature measurements as will test the proposed explanation. Further, the relationship between the Hadley and the 4-day circulation, if any, needs observational and theoretical elucidation.

Motions of planetary atmospheres result from horizontal and vertical density gradients. The questions raised above require that we measure spatial variation of temperature, pressure, solar energy deposition, and motion. The number of measurements necessary to define these fields depends upon the questions posed. With our present knowledge, only the most fundamental questions may be realistically asked; i.e., where is the energy deposited, what is the stability of the atmosphere, what is the general form of the temperature differences and flow regimes?

Measurements

Probes The major question concerning the lower atmosphere can only be answered by *in situ* measurements at several locations. In particular, we need measurements of temperatures and pressures in the three regions of particular interest--the subsolar, the antisolar, and one of the poles--plus an intermediate region.

In each of the regions we should like to measure the pressure at all levels to an accuracy of 1 percent. To integrate the hydrostatic equation, a temperature measured to 1 percent accuracy is also desirable. To determine the lapse rate between successive determinations to within 3 percent of the adiabatic value, a relative accuracy of 0.2 K will be required, but even 1 K is useful. Solar-flux measurements should be made from as high as possible to the surface, but at least a few measurements should be made above the clouds. These measurements are easily within the capabilities of the state of the instrumentation art and the weight and telemetry limitations of small probes. Wind-velocity measurement accuracy of a few meters per second is useful in the upper cloud levels. At lower levels, higher accuracy is desired, with a few centimeters per second as the goal. This accuracy may be achieved from Doppler tracking data or, better, from a wind-drift radar on the probe itself.

Balloons Balloons are useful primarily to examine the atmospheric circulation of Venus by means of range and Doppler measurements. A complete analysis of the obtainable accuracy of wind measurement has yet to be made, but it is likely to be at least 1 or 2 m sec^{-1}, which is precise enough for our purposes. The discovery of scales of motion smaller than the planetary radius is quite possible and would offer important clues to the details of the atmospheric circulation.

As the balloons drift with the atmosphere of Venus, temperature, pressure, and solar and thermal flux can also be sampled. These latter allow determination of the variability of the high cloud structure and thermal irregularities.

To provide a three-dimensional picture of the wind structure, balloons should be placed at two or three levels. The 50-, 500-, and 1200-mbar pressure levels appear to be possible.

Orbiter and Bus Experiments Great insight into the nature of the circulation of earth's atmosphere has been gained with the planetwide data coverage available from satellites. We may confidently expect the same results for Venus. Two types of experiment recommend themselves in particular.

A high-resolution spin-scan camera can resolve features smaller than 2 km from an altitude of 600 km. This will tell us whether there are small holes in the cloud deck, or cumulus towers, as have been suggested. On a large scale, the undulations in the cloud surface probably reflect dynamic processes in the lower atmosphere. These will indicate the scale of such motions and their direction. Such observations will give invaluable clues to lower-atmosphere motions and possible longitude variations of the type that is crucial to an understanding of the earth's atmosphere.

The payload of a mission to fly by Venus and Mercury in 1973 has not been settled, but it very likely will include a TV camera. The flyby distance is expected to allow a few thousand pictures, with resolution from 0.1 to 40 km during the time of passage. This will provide essential information on light levels and contrast of the cloud features of Venus, but it will pass by too rapidly to provide the coverage in time desired for wind measurements.

A simple thermal radiometer, looking down in a window region of the spectrum, would allow temperature maps of the cloud surface to be drawn. For best results, a resolution much less than 100 km is desirable, and it should be boresighted with the TV camera.

Measurements of Venus from earth have already shown a few degree temperature anomaly near the top of the clouds near the south pole. With a closer view, smaller and weaker anomalies may be seen which will act as tracers of events that have been described as storms.

The temperature structure above the clouds has been measured twice when Mariner 5 passed behind the atmosphere of Venus. These measurements reached roughly the 5-bar level. Simple *S*-band tracking of an orbiter would allow this kind of determination to be made many times over. The obvious advantage of this is the need for no additional weight or power on the orbiter. On the other hand, there are only two determinations per orbit (~17 h), and they will be made in very nearly the same place for many orbits in a row. The geographical coverage is limited.

Vertical infrared sounding can also be performed, as it is done on the earth, with a multichannel radiometer looking at the emission of the 15-μm band of carbon dioxide. This has modest weight and power requirements and gives much more geographical coverage. However, analysis of downward vertical soundings yields only rather poor vertical resolution. Further, layers of particulates may modify the signal but not be detected.

The technique of limb scanning overcomes some of these limitations. By looking along long paths through the edge of the atmosphere, much higher altitudes may be probed. It appears that temperatures at heights up to the base of the thermosphere of Venus may be determined. Much greater vertical resolution is possible; 2 or 3 km has been obtained in simulations of the terrestrial atmosphere and seems easily obtainable in the atmosphere of Venus as well. Layered particulates, if sufficiently opaque, will be more easily located. The weight and power requirements are similar to those of a nadir-viewing multichannel radiometer. The geographical coverage can be extended by scanning off the plane of the orbit.

A final use of the orbiter is to obtain thermal maps from microwave images. We have reason to believe that there is no thermal boundary layer on Venus. There may even be a few kilometers of isothermal atmosphere. If this is so, the surface temperature will provide a measure of the atmospheric temperature in the lowest one or two scale heights. The importance of such data cannot be overstated. We do not anticipate any large local differences of temperature, but it is possible that 1 K over several hundred kilometers will produce highly significant local circulations, possibly of greater importance than the planetary-scale circulation. Such temperature contrasts may well come about if there is a significant internal heat source on the planet as has been postulated by some investigators.

We cannot expect to measure all such local effects, if they exist, with probes. Some kind of remote thermometer is essential. The problem with a microwave radiometer is that of distinguishing between changes of emissivity and changes of temperature. Atmospheric investigations, by themselves, are unlikely to solve the problem; however, these data are also of interest for planetological purposes. It has been suggested that this imaging can be done almost as well from the ground as from an orbiter about Venus, and that development of the necessary radiometers for orbiters is not yet sufficiently advanced. Consequently, ground-based measurements are recommended for the immediate future. This conclusion must not, however, be taken to imply a low priority for the thermal maps. By one means or another this mapping must be performed in order to study atmospheric dynamics. The allocation of time on large radio telescopes must be adequate for this purpose, and continuing effort should be directed toward development of orbiter radiometers.

Chapter 5

PLANETOLOGY

INTRODUCTION

The long-range aim of planetological studies is to obtain basic knowledge concerning the nature of planetary bodies of various masses and chemical compositions, in order to infer the processes that determine their origin and evolution and to understand why different planets evolve in different ways. The most important development in this field in recent years has been the possibility of directly studying planetary bodies other than the earth, particularly the moon. The Mariner and Viking missions to Mars are extending our understanding to that planet, and future missions to Mercury and the major planets will also be important in this context.

Venus, so similar to the earth in mass and radius, nevertheless appears to have evolved quite differently. Thus its study promises to reveal new insights into planetary evolution. Because of its opaque atmosphere and the absence of satellites, our present knowledge of Venus is not comparable even with that of Mars; consequently there are numerous highly valuable planetological measurements to be made. Ideally, these would include such things as the chemical composition and mineralogy of the surface materials, the heat flux coming from the interior, the presence or absence of an iron core, and the variation of elastic-wave velocity with depth and density. The difficulties of making many of these necessary measurements under the conditions prevailing on Venus are severe; nevertheless, a program of measurements on the scale proposed for the Planetary Explorers will permit some highly significant measurements to be made. These include measurements made from orbiters, probes, and landers. For example, surface elevations can be measured with a radar altimeter on an orbiter, and some information regarding the distribution of mass in the planet can be obtained from perturbations of the orbit of the satellite. The internally generated magnetic field can be measured as a function of altitude, latitude, and longitude from multiprobe missions. In addition, there are important measurements that can be made from a probe which will provide data needed for the planning of lander missions. Examples of these are miniature seismometers to be carried on probes to provide measurements of the seismic noise background subsequent to their impact and measurements of the near-surface opacity and illumination, which will be necessary in the planning of lander missions which will involve television imaging. While it is questionable whether television should be carried on Explorer landers, it may prove useful in the next stage of exploration of Venus, and its feasibility should be evaluated.

There are some important experiments which are sufficiently well defined and simple to be carried out by a lander on the surface of Venus within the framework of the Planetary Explorer concept. These include passive and active seismic measurements and measurements of elemental composition using natural and induced gamma radiation. These are suggested for one or more lander missions following the early probe missions which should, in addition to their intrinsic importance, serve to define the problems of making scientific measurements in the deep atmosphere of Venus. These lander experiments will be discussed in more detail below.

Beyond these proposed early experiments to be carried out on the surface of Venus, someday it will be desirable to carry out further geophysical and geochemical measurements of a more difficult nature. These will require experience in performing fairly complex manipulations on a remote planet. Similar requirements will arise in the study of Mars and future unmanned exploration of the moon, e.g., by an unmanned lunar roving vehicle. It seems wise to acquire such experience and assess the reliability of these techniques on a body such as the moon or Mars, where the physical environment is less rigorous, and where, in the case of the moon, the relevant quantities have already been studied at some sites, as a result of a program of manned explorations. Although it is difficult to see too far into the future, it does not seem that this more advanced stage of exploration of Venus should, at this time, be considered in the framework of relatively inexpensive Planetary Explorers. This is particularly true because in many cases it will prove most desirable to carry out a number of different measurements on the same material at the same site, rather than one by one on a series of missions to different sites. In order to preserve the integrity of the Planetary Explorer concept it would be preferable to emphasize the highly valuable data obtainable on the more simple missions and leave the next stage of exploration of the surface and interior of Venus open for future evaluation.

ANALYSIS OF SURFACE COMPOSITION

Knowledge of the elemental composition of the surface of a planet is fundamental to an understanding of the processes of geochemical differentiation which the planet has undergone, and these processes are strongly coupled with its thermal and tectonic history. Consequently, measurements of composition constitute a first-order problem. Ideally, such measurements should be made at a number of places on the planetary surface. However, as was the case for the Surveyor analyses of the moon, one or a small number of such analyses constitute a major advance in knowledge.

In accordance with the point of view expressed in the introduction to this Chapter, high priority is assigned only to those experiments that do not require complex manipulations. Consequently, it would be most desirable if a device could be developed which could be placed on the surface of Venus and, within a period of a few hours, would provide analytical data for at least the most abundant elements. Such measurements might be combined with the knowledge of the concentrations of condensible and permanent gases in the lower atmosphere to permit some understanding of the mineralogy of the surface, in addition to the directly measured elemental composition.

Previous experience with unmanned chemical analysis of a planetary surface is limited to alpha backscatter measurements made by Surveyor on the moon. It is also reasonable to suppose that a simple device adequate for the moon or Mars could be based on x-ray fluorescence. However, the short range of alpha particles and of x radiation, combined with the high atmospheric density at the surface of Venus probably preclude instruments of this kind. Their use would require detaching a sample from the surface, transporting it to an air lock of some kind, and then transferring it to a low-pressure or vacuum environment within a pressure vessel. Such manipulations are in conflict with the criteria proposed for these early studies.

However, it does seem likely that a device based on the much more penetrating nuclear gamma radiation could provide the data desired. A simple sodium iodide gamma-ray spectrometer placed on the surface would permit measurement of the natural radioactivity of potassium, uranium, and thorium. An operating lifetime of several hours should permit measurement of these elements even at the low concentrations found in chondritic meteorites. These elements are especially indicative of processes that have fractionated material of chondritic composition to form rocks such as basalts and granites, containing characteristic enrichments of these elements. The gamma radiation will be sufficiently penetrating to be transmitted through the wall of the pressure vessel and through several inches of thermal insulation. Therefore, it would probably be feasible to use an ordinary thallium-activated NaI crystal, although it is possible that some other scintillator, such as sodium-activated CsI, would be preferable.

The value of the data obtained would be greatly enhanced if, instead of using only the natural radioactivity of the planetary surface, a neutron source were used to irradiate the surface and thereby produce neutron-capture gamma radiation characteristic of particular elements. Devices of this general type have been developed at the Goddard Space Flight Center using as a source the intense flux of neutrons from the spontaneous fission of microgram quantities of ^{252}Cf. With such a source, combined with the gamma-ray scintillation spectrometer described above, such elements as Si, Al, Mg, Fe, Cu, Mn, and Ti could probably be determined in an operating time of 1 h. These neutron-capture gamma rays are more penetrating than those of the natural gamma emitters and consequently could penetrate considerably more thermal insulating material surrounding the detector. The neutron source could be operated at the high surface temperature.

There are undoubtedly many design problems which would have to be overcome in modifying the existing instruments for operation on the surface of Venus. These appear to be surmountable. Studies would be necessary regarding such questions as the need for including material for the moderation of the high-energy neutrons produced by the source or whether the surface material itself would provide adequate moderation. The necessary quantity of moderator and of shielding material to isolate the detector from the source would be important factors in determining the weight of the instrument. It seems possible that the weight of the entire instrument, including these materials, could be held down to approximately 15 lb, although a much more detailed design study would be necessary to determine a reliable value for the weight.

Inclusion of the neutron source would probably preclude the simultaneous measurement of U and Th, because of interferences of the induced gamma radiation with the natural radiation, although measurement of K might still be possible. In order to measure U and Th, it might prove feasible to jettison the neutron source following completion of the other measurements. At the risk of complicating the experiment, consideration should be given to the possibility of moving the source to two or more different distances (~1 m) away from the detector. If the instrument were made of hydrogen-free materials (e.g., if necessary, deuterated), this could permit measurement of the hydrogen concentration of the surface as well as of the surface density.

The question of whether this surface analysis could be carried on the same lander as a seismic experiment must await a more detailed design study. It does not seem out of the question that this may be possible, provided that the weight of explosive used for an active seismic experiment is appropriately limited.

SEISMOLOGY

Seismology represents the most potentially useful method of learning about the bulk properties of the interior of Venus. Information may be obtained from a variety of frequency bands, from 0.01 to 100 Hz, and for natural or artificial sources. This includes time-of-travel measurements for the rays and the dispersion characteristics of surface waveguide modes. The most important type of result is a global-scale determination--involving several source-receiver distances in the 15-180° range.

Clearly, such a program is possible only if enough sources of adequate magnitude are available. The quantitative meaning of "enough" or "adequate" depends critically on the shape and amplitude of the ambient ground-noise spectrum. In a first visit, any experiment that depends strongly on assumptions about the noise spectrum would be risky. The existence of natural seismic sources is of great intrinsic interest, in addition to their importance as signal sources. Terrestrial earthquakes are known to be caused by the interactions of large, slowly advected plates of the lithosphere. Their frequency is a rough measure of the rate of thermally driven motion. A determination of seismicity on another planet, by comparison with the earth, provides a comparative measure of its thermal evolution rate. For Venus, a lack of seismicity would be quite important, since the volume-to-surface ratio of Venus is so like that of the earth. The presence of seismic activity would be equally interesting and would provide sources for determining the interior structure.

TABLE 1 Number of Useful Seismic Events per 24 h

	Seismicity[b]			
Noise Level[a]	Very Small	1/10	1	5
Earth noise 10-500 mμ	0	<1 luck required	Earth situation 1-5	5-25
∿1-5 mμ	0	∿1	5-25	Many
≲0.1 mμ (Lunar level)	<1 (Indeterminate)	5-25	Many	Many

[a] Noise level is in millimicrons peak-peak in the band 0.3-5 Hz.

[b] Seismicity is the number of quakes per 24 h compared with earth, assuming the same magnitude/number law.

The situation may be summarized by the matrix of Table 1, in which the possible situations with respect to seismicity and noise level are used as coordinates. An educated guess of the noise level of Venus would put it roughly in the 1-5 mμ range; some natural sources could then be seen even if the seismicity were one tenth that on earth.

An active source--from a bomb probe--is necessary to provide any sensing of the interior, if the seismicity is too low. In any event, such a controlled source would be highly desirable as a means of calibrating the signals from natural sources. It is highly desirable that the bomb probe be as far away from the receiver as signal-to-noise considerations permit. This, of course, makes it desirable that as large as possible a coupling of energy into seismic waves be achieved.

We, therefore, propose a three-stage strategy for the seismic exploration of Venus, based on the use of Planetary Explorer missions.

1. One of the early atmospheric probes should survive impact long enough (a few minutes) to transmit information on the magnitude of the seismic noise. This could be in the form of pressure data or one axis of accelerometer data. The noise

signals of interest at 5 Hz (the band 1-10 Hz) would have: (rms) acceleration, 250 x 10^{-6} cm sec^{-2}; displacement, 10^{-6} cm; pressure, 10^{-5} bar. Only mean rms power in some band would be required. This information would make it possible to choose the best distance for the bomb in stage 2. Unusually high noise level would reduce the prospective worth of the subsequent missions. We hope that the entry-probe sensors can be designed with the aim of including information on turbulent-wind fluctuations as a function of height; this can also be used to estimate the magnitude of the seismic noise.

2. A Planetary Explorer seismology mission from a lander should be undertaken on the basis (if possible) of the noise data from the first probe. A passive three-axis seismo-accelerometer would go in the main lander probe. A bomb probe at a distance of 100-200 km would be used as an active source of signal. For passive operation and detection of natural seismicity, the lifetime should be at least one day, but preferably longer.

3. Further exploration should be based on the knowledge gained at stage 2, and on engineering advances to that time. In particular, we foresee that, in the best of circumstances, future passive systems should have surface lifetimes of several months.

Referring to Table 1, we emphasize our feeling that a fair strategy requires the seismic program to be given reduced priority if unfavorable conditions are found. This would occur after stage 1, if very high noise levels are found, or after stage 2, if no useful signals are obtained.

LOW-FREQUENCY SEISMOLOGY

If a stable low-noise vertical accelerometer based on the quartz fiber or LaCoste suspension can be operated on the surface of Venus for about 2 solar days, certain important new information on the bulk properties of the planet may be collected. The existence of a liquid core as large as the earth's would be detectable by a measurement of the solar gravity tide for 2 solar days. Such an undertaking is technologically out of the question at this time--because the appropriate instrument is not yet ready for adaptation to planetary use and the long-lifetime technology is not available. Nevertheless, if seismic methods are ineffective for reasons already discussed, the surface measurement of solar tides would be the best way to answer questions about a core. In addition, this instrument with response at periods near 1 cycle/h would be a detector of free oscillations from large quakes.

RADAR AND THERMAL MAPPING OF THE SURFACE OF VENUS

Radar experiments are capable of precise measurements of range and velocity between an orbiting vehicle and a remote, passive planetary surface. Determination is also possible of surface scattering from which bulk electrical properties, surface structures at wavelength and larger size, and mean surface slopes may be inferred. Both monostatic- and bistatic-radar experiments specifically directed toward studies of surface electromagnetic properties and structure may be carried out from vehicles orbiting a planet.

Radar measurements may be used to study Venus in a number of ways. The surface topography may be measured by direct altimetry from an orbiter. Radar observations from earth may also determine surface topography. But, with the exception of a relatively narrow band of latitudes near the equator, the topographic accuracy available from these observations does not approach that given by relatively simple Venus-orbiting systems. If polar orbits are flown, altimetry from an orbiter of Venus can determine the planetary shape (flattening); from this the gravitational figure may be inferred.

Bistatic radars are those employing a well-separated transmitter and receiver. Bistatic-radar observations may be carried out using transmissions between a ground station and an orbiting radar probe. A radar transmitter located on the earth is used to illuminate Venus with radio-frequency energy. Reflections from the planet's surface are detected by an on-board receiver; this permits observation of the forward-scattered energy. The reflected signals are distinguished from the much stronger, directly propagating wave, by a substantial Doppler shift. The strength and polarization of the echo are related to the planet's surface material; the spectral properties of the echo are related to surface roughness. Such observations are extremely valuable in the construction of surface models and cannot be carried out from the ground alone.

More elaborate, orbiting, monostatic-radar systems can map the radar-scattering properties of the surface over a wide area and would yield maps similar in appearance and usefulness to photographic maps of the same region--if these were possible for Venus. Maps of radar-scattering properties may also be used to yield statistical information on local surface slopes, wavelength-sized roughness, and the bulk electrical properties of local regions of the surface. Here, however, great weight and complexity are required for an orbiting system with resolution comparable to that available from terrestrial, ground-based radars. Such imaging of Venus is directly competitive with ground-based observations and would provide similar data. These experiments would provide somewhat more coverage of the planet than ground-based radars can do in the next decade, but it is not yet clear whether the high cost of the additional information could be justified.

Earth-Based Radar Studies

Virtually all our present knowledge of the radius, rotation, and surface of Venus has been obtained using ground-based radars. The general picture that emerges is of a planetary surface that is considerably smoother and denser than that of the moon. The surface dielectric constant of Venus as determined by both radiometric and radar techniques appears to lie between 4 and 5, substantially higher than that for any other solar-system target except the earth.

On a lateral scale of hundreds of kilometers in the equatorial region, Venus exhibits very little topographic relief. Only one region is known that departs from the mean radius by as much as 2 km, in contrast to Mars where peak-to-valley variations up to 15 km are observed. Using delay-Doppler techniques, maps showing local departures from the mean scattering law have been prepared. These have been obtained at wavelengths of 3.8, 12.5, and 70 cm, with a linear surface resolution varying from 100 to 500 km, and are in remarkably good agreement. Perhaps a dozen permanent scattering anomalies have been shown to exist, although the precise nature of these anomalies has not been established. That they arise from local variations in surface roughness at a scale of the observing wavelength is clear, but whether they represent young mountainous regions, flows of lava, large meteoritic impact craters, dune fields, or simply debris is not known.

In the next decade, more sensitive observatories will come into existence. We may reasonably expect radar images of Venus from these with a linear surface resolution comparable to present ground-based astronomical photographs of the moon (3-5 km). Topographic maps with a height resolution of 0.1 to 0.2 km will be prepared for the region within about 10° north and south latitude in the vicinity of the subradar point at inferior conjunction and for a complete equatorial band of diminished width elsewhere.

Orbiter Radar Altimeter

A relatively simple radar altimetry experiment from an orbiter of Venus can complement the equatorial topographic information available from earth. From a planetary orbiter, measurements of vertical relief averaged over a lateral extent of some 5 to 50 km may be made with relatively simple low-power systems. It is likely that such an instrument would achieve sufficient precision to permit a meaningful comparison of the geometric and gravitational figure of the planet and would be adequate for the detection and characterization of continent-size trends in elevation and the characterization of morphological surface features comparable in size to the crater Copernicus on the moon. If carried out from a polar orbit, the variations in surface radius could be measured over most of the planet with accuracies consistent with those that will be obtained from the earth for the equatorial region of Venus. The connection of the two sets of measurements, one (from the earth) taken along an equatorial swath and the other (from polar orbit) along displaced polar tracks, should permit the construction of a highly accurate map of the planet's geometric shape, from which the figure and smaller-scale topography can be extracted.

Measurement of variations in the echo amplitude with planetary location will provide a large-scale, normal-incidence reflectivity map for the same position of the planet, which may also be tied to the ground-based observations. These maps would be of considerable importance in the interpretation of the radar maps which will be prepared from the ground in the same period. It is essential to obtain both total echo power and some measure of surface dispersion effects.

Bistatic Radar Measurements from an Orbiter

Bistatic radar measurements provide a direct measurement of large-scale surface slopes and the bulk electrical properties.

Experiments comparable to those carried out on the moon, using the telemetry transmissions from orbiting spacecraft, can be carried out at Venus, provided that earth-based transmitters, with reception on the spacecraft, are employed. Measurements of both total echo power and the spectral broadening imparted by surface roughness are required. To be most useful, two orthogonal polarizations should be received. Bistatic radar measurements provide a unique capability for the determination of surface slopes in the region removed from the equator of Venus. Slope determinations for the moon, which are in good agreement with those determined by more direct (and laborious) optical means, photoclinometry, and photogrammetry, have been carried out using bistatic-radar observations on Explorer 35. These methods are presently undergoing further development and are expected to become highly reliable within the next few years. Bistatic-radar observations of small- (wavelength-) scale scattering phenomena have also been carried out on the moon. While the interpretation of the observations is at present uncertain, it is clear that such observations, when combined with monostatic (ground-based) observations strictly constrain the range of possible surface models. Planetologically, such observations provide unique data on both large- and small-scale surface structures and bulk electrical properties. These quantities are in turn intimately related to such questions as the evolution and erosion of surface topography, mountain building, weathering, and surface density.

RADIOMETRIC MEASUREMENTS OF THE SURFACE OF VENUS

The surface temperature of a major portion of Venus can be measured by observation of the thermal emission from the surface at (microwave) wavelengths for which the atmosphere is optically thin. Such an experiment by itself is currently of some general interest to both planetology and the study of the lower atmosphere. It would be possible to obtain thermal maps from a properly designed radar apparatus with only a small extra effort.

The wavelength requirement that the atmosphere be optically thin is compatible with the radar and implies frequencies lower than about 5 GHz. The temperature measurements, however; require a more elaborate antenna system than that needed for the simple radar. Assuming a 10-cm wavelength and a 5-ft parabolic antenna, the beamwidth would be 4.5° and provide a planetary resolution of 1/13 of the spacecraft altitude. So large an antenna may not be justified for the radar measurements alone and would have to be considered as the cost of including the thermal measurements. Relative brightness temperature measurements would have an accuracy of ±2 K, based on an absolute accuracy of ±1 K. If a spinning antenna system is employed, the experiment will be limited in integration time by the motion of the antenna beam. Hence it is desirable to minimize the spin rate. Rates as low as five revolutions per minute can be achieved and are suitable for this kind of observation.

Radiometric measurements do not give actual surface temperatures unless the emissivity is known. This quantity can be inferred from the radar measurements, which therefore give valuable support to the radiometer.

Current earth-based observations indicate that the broad-scale variation in the surface temperature is less than 20 K. Improvements in these observations can be expected during the 1970's. If such improvements are realized, and if *in situ* measurements confirm a small temperature variation over the planet, then the need for the microwave radiometric experiment is appreciably less and should be re-evaluated.

The temperature of the lower atmosphere could be measured by using a wavelength less than 6 cm. The height range probed will depend on the wavelength chosen and could be estimated from model atmosphere computations based on the direct entry probe measurements. However, such an experiment could not make such convenient use of the radar receiver. More stringent constraints on the mechanical properties of the antenna would also be required.

Conclusions

Given our present knowledge of Venus we believe that the determination of the topography and geometric figure of Venus, measured by a radar altimeter, is the most significant radar experiment concerning the solid planet which can be carried out from orbit. We also believe that bistatic-radar experiments, in conjunction with ground-based observations, can provide a significant insight into the details of the surface structure and electromagnetic properties of Venus. Microwave thermal mapping of the planet from orbit offers a potentially powerful tool for high-resolution (10-40 km) temperature maps of the surface. If such questions develop in the future, or if such measurements may be carried out easily in conjunction with other radio-frequency experiments, then they should be given serious consideration. In view of the rapidly improving capabilities of radar observatories on the earth to image Venus, high-resolution, oblique, monostatic radar mapping of the planet from orbit seems relatively less important at the present time.

GRAVITATIONAL FIELD

The coefficients in the spherical-harmonic expansion of the gravitational field may, in principle, be determined by analysis of the perturbations of orbits of planetary orbiters. From a finite number of orbits and spacecraft, least-square fitting to a truncated set of low-order coefficients may be undertaken. In addition, local perturbations in orbiter acceleration may be determined directly from residuals in the Doppler tracking data. From this method comes a series of profiles of local variations in gravity. This information summarizes the shorter wavelengths in the field, which the low-order coefficients may not describe very well. The possibility that useful numbers can come out of these undertakings depends on the orbits being quite low: fields of order n decay radially as r^{-n-1}; and distant orbits have longer periods, hence fewer orbits, as input data.

The importance of the gravity coefficients may be summarized as follows:

1. The J_2 coefficient reflects the distribution of mass in the rotational equatorial bulge. It dominates on the earth, with a value of approximately 3×10^{-3}. The earth's high spin rate gives a precession, which, combined with J_2, gives the moment of inertia. The low rate of rotation of Venus implies a $J_2 \sim 10^{-5}$ and a precessional period $\sim 10^5$ years. The latter appears unmeasurable, and the former is at the noise level defined by the other coefficients.

2. The full range of coefficients contains the information about the non-centro-symmetric mass moments--namely, those due to the departure of the planet from hydrostatic equilibrium. These tend to be of the order of 10^{-5} at low order and decay in magnitude with increasing order. The magnitude and decay rate of these coefficients are the primary outcome of the work and

differ according to the mechanical properties and history of the interior.

The rotation of Venus appears to be coupled to the relative orbital motion of the earth. This seems to require an asymmetrical equatorial bulge, which is worthy of special attention.

3. The local variations in gravity as determined by acceleration residuals in the tracking may be modeled in terms of near-surface masses and are of intrinsic interest along with other planetological imaging.

Feasibility

A good gravitational experiment would require orbiting transponders in low (<300 km), near-circular orbits, at several inclinations. Orbits with large apoapsis permit only a degraded look at the gravitational field: it should be possible to infer the second-order coefficients but not the spectrum. Surface-mass concentrations corresponding to a horizontal scale of 400 km or more and a surface gravity variation of 100-1000 mg would be detectable during near-periapsis tracking. This level of gravitational experiment is useful and interesting because it does not impact the spacecraft design. Too frequent orbital changes would degrade this experiment.

Because of the great value of low, near-circular orbits, careful attention should be given to the possibility of using atmospheric drag to lower the apoapsis. The low periapsis required for this purpose is useful for aeronomical studies. Once the apoapsis is low enough, the periapsis can be raised by a short burst of propulsion.

MAGNETIC FIELDS

Magnetic-field measurements are readily made from the orbiter, the bus, the probes, or the lander. We therefore discuss what such measurements would reveal about the interior of Venus.

The Mariner 5 and Venera 4 observations enable an upper limit to be placed on the internally produced field of Venus of about 0.5×10^{-3} to 1×10^{-3} that of the earth.

Magnetometer observations inside the anemopause are important for two quite distinct reasons. Some models of the anemopause structure and mechanisms require an ionospheric magnetic field, and some exclude it. The extent to which the interplanetary magnetic field can diffuse into the ionosphere, the possibility that ionospheric gas can be caught up in the solar-wind flow because of the interchange instability, and the possibility of field-line reconnection across the anemopause all require study.

Venus may also have a small magnetic field of its own. If so, its strength, its relation to the axis of rotation, and its spatial distribution need to be determined. Because there are no natural satellites, the moment of inertia factor of Venus is unknown: density and radius provide only an insecure basis for a model of its physical constitution. Thus the size of a possible iron core of Venus cannot be estimated. Also the theory of the geomagnetic dynamo is still in many respects unsatisfactory. It is probable that the dominance of the rotation on the core motions is essential to the generation of a field. Thus the very low rotation rate of Venus may be unfavorable to dynamo action, but any quantitative statement is lacking. The discovery at Venus of a small magnetic field of internal dynamo origin would, therefore, be of fundamental interest, both from the viewpoint of its physical constitution and also for the theory of planetary magnetic fields.

Other magnetic fields of the order of 10-100γ with internal sources occur in the earth: steady fields from permanent magnetization of the crust and varying ones induced by varying external fields. At the high surface temperature of Venus, most minerals will be near or above their Curie points, and magnetic anomalies may be much weaker than on earth. There is a possibility of strong magnetization remaining from a strong planetary field in the past, but it seems unlikely.

The variations in conductivity, height, flow patterns, and other properties of the ionosphere should be fixed in position relative to the sun. Were the ionosphere sufficiently conducting and firmly fixed in place, the short-period (of the order of 1 min to 1 h) fluctuations in the solar wind would be screened out and not observed near the surface. If the ionosphere is such that short-period variations are present, they would induce electric currents in the upper parts of the planet, and these would contribute a measurable fraction of the field observed below the ionosphere.

Although magnetometer observations near the surface provide information on a variety of interior and exterior characteristics, conclusions will in most cases be very ambiguous unless the effects of interior and exterior sources can be separated and unless some information can be obtained on the structure of these sources. This requires simultaneous observations at more than one point, preferably enough observations to make a harmonic analysis as for the earth. In principle, probes similar to the miniprobes of the multiprobe mission could be used. Each would have a slow spin about the vertical, controlled by fins or grooves, and three samples per revolution by an inclined single-axis magnetometer would determine a static field. The characterization of the sources is greatly improved if an adequately long vertical profile can be measured by each probe. A careful analysis should be made to determine how many probes are needed to obtain significant results. If four are enough, a serious effort should be made to include these magnetometers on the first probe mission. It is likely that no sound analysis can be made until magnetic observations have been made down to 150 or 200 km elevation by the bus for the first probe mission, and that the more ambitious study is more appropriate for one of the later missions when it can be designed with better knowledge of the requirements and conditions.

Magnetometers should also be given very serious consideration for the balloon missions because these will give both the simultaneous measurements at widely spaced positions and the observations of temporal variations needed to determine the conductivities of the ionosphere and surface layers as well as the extent to which the anemopause (ionopause) and ionosphere screen out the effects of changes in the interplanetary magnetic field and in solar-wind pressure.

Chapter 6

SCIENTIFIC CAPABILITIES OF THE PLANETARY EXPLORER

Chapters 3, 4, and 5 of this report define the principal scientific questions and measurements which we feel should be performed on, and near, Venus. This study was primarily concerned with how these questions should be answered and was prepared to consider all types of missions. We were, however, presented with a series of studies of the Planetary Explorer concept made by NASA.* This concept includes a relatively low-cost, universal bus, which can carry entry probes, orbiters, balloons, or landers to the planet. The studies of entry probes and orbiters were extensive, and we concluded that weight and cost figures were firm; balloon capability was based on extrapolation from thorough studies and was thought to be relatively secure but not in the same category as the probe and orbiter data; lander studies were only sufficient to demonstrate that a capability existed.

We reviewed these studies and considered that the Planetary Explorer was almost ideally suited to answering the science questions posed, and one of our most important conclusions is that the Planetary Explorer should be the prime vehicle for exploration of Venus in the next decade. We have, therefore,

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*The most important documents are:

Comprehensive Study of Venus by Means of a Low-Cost Entry Probe and Orbiter Mission Series, by J. E. Ainsworth, GSFC Rep. X-625-70-203 (June 1970).

Planetary Explorer, Phase A Report, Technical Plans, GSFC Rep. (Oct. 1969) [deals with orbiters only].

Final Project Report for Delta-Class Venus Probe Mission Study, AVCO Government Products Division Rep. AVSD-0433-69-RR (Oct. 1969) [available from GSFC].

Final Project Report for Planetary Explorer Universal Bus Study, AVCO Government Products Division Rep. AVSD-0346-70-RR (Oct. 1970) [available from GSFC].

Delta-Class Balloon and Lander Missions for the Exploration of Venus, Martin Marietta Corp. Rep. MCR-70-211.

TABLE 2 Instrumented Probes--1975 Mission

BUS	
Science weight	25 lb
Science power	19 W
Lifetime (from 15 radii to loss of communications)	4 h
Communications loss altitude	130 km
Telemetry rate	~350 bps
Spin rate	30-85 rpm
MAIN PROBE	
Descent time	90 min
Science weight	68 lb
Science power	90 W
Telemetry rate	80 bps ($p < 1$ atm) 40 bps ($p > 1$ atm)
Landing site (with 40-bps telemetry rate)	Limited to a 35° circle from subearth point
Impact velocity	17 m/sec
Spin rate	Variable
Lifetime	Survival after impact not currently planned
SMALL PROBES	
Descent time	95 min
Science weight	4 lb
Science power	3 W
Telemetry rate	1 bps
Landing sites	Limited to annular region from ~20° to ~60° from the subearth point
Impact velocity	6 m/sec
Spin rate	Variable
Lifetime	Survival after impact not currently planned

TABLE 3 Planetary Explorer Orbiter

Lifetime	>6 months
Science power	50 W (sunlight) 25 W (shadow)
Shadow duration	~30 min (12-h orbit period)
Orbit inclination	20-90°
Velocity at periapsis	8-10 km/sec

TABLE 4 Planetary Explorer Orbiter--1976-1977 Mission (Launch Date: December 1976; Travel Time: 169 Days)

	Periapsis of Orbit	
	400 km	1000 km
Periapsis change capability (km)	0	1500
Apoapsis low high (km)	26,000 61,000	22,000 52,000
Experiment weight (lb)	100 170	50 130
Orbital period (h)	8.2 21.8	6.9 17.9
Communication distance at arrival (AU)	0.54	
Maximum communication distance (AU)	1.64	
Bit rate at arrival to 85-ft dish (bits/sec)	440	
Minimum bit rate to 85-ft dish (bits/sec)	25	
Bit rate at arrival to 210-ft dish (bits/sec)	4600	
Minimum bit rate to 210-ft dish (bits/sec)	550	

TABLE 5 Atmospheric Balloon Mission

Number of separate packages	2
Number of balloons per package	3
Float levels (typical)	50, 500, 1200 mbar
Float altitude	70, 57, 51 km
Initial target sites	10°N, 40°N latitude 20° on dark side of terminator
Lifetime	30 interrogations
Duration of interrogation	5 min
Tracking accuracy	±200 km

	Float Level		
	50 mbar	500 mbar	1200 mbar
Science weight	4.3 lb	4.8 lb	4.8 lb
Science power	22 W	23 W	23 W
Telemetry rate	Tracking only	20 bps plus tracking	20 bps plus tracking

TABLE 6 Planetary Explorer Lander[a]

Impact site	Subearth point
Lifetime	2 h minimum
Lander weight	245 lb
Total power	127 W average 220 W peak
Science weight	55 lb
Telemetry rate	∿2000 bps

[a] Values given depend on payload and number of landers derived from the primary vehicle.

continually referred to this specific concept in foregoing chapters, for our ideas were clarified by considering the science within a framework of known practicability.

The Planetary Explorer is a small, 850-lb, spin-stabilized, spacecraft launched by a Delta rocket. For a typical mission designed to send instrumented probes through the atmosphere to the surface of Venus, the spacecraft consists of a bus that will operate down to 130 km altitude, a main probe to carry ∿70 lb of instruments to the surface, and three smaller probes, each carrying 4 lb of instruments, which are separated from the bus and provide measurements from three widely separated regions of Venus. Some of the important characteristics of the spacecraft are given in Table 2.

A second mode of operation of the Planetary Explorer is to place a 470-lb spacecraft in orbit about Venus. The total weight for scientific experiments depends on the desired orbit (or orbits) during the mission lifetime, but representative figures on this, and other mission parameters, are given in Tables 3 and 4.

A third mode of operation which can be accommodated within the Planetary Explorer framework is a mission to place constant-level balloons in the atmosphere of the planet. Preliminary study of a typical mission shows that six balloons, two each floating at levels of 50, 500, and 1200 mbar, corresponding to altitudes of 70, 57, and 51 km, respectively, are feasible. One set of balloons can be placed at 40°N and the other at 10°N latitude and 20° on the dark side of the terminator. Representative parameters are given in Table 5.

Finally, the Planetary Explorer can be utilized to soft-land an experiment package on the surface of Venus. This aspect of the Planetary Explorer concept has been studied less than the others, but typical mission parameters are given in Table 6. If desired, such as for a seismic experiment, several small stations can be soft-landed on the surface by releasing more than one lander from the bus.

The numbers given in Tables 2-6 should be taken as representative of the potential of the Planetary Explorer spacecraft, bearing in mind that some values will be perturbed by particular constraints imposed by the dynamics of a specific Venus opportunity and each scientific payload. In any event, we conclude, without reservation, that most important scientific measurements of Venus fall within the capability of the Planetary Explorer spacecraft as currently envisioned.

Our study has pinpointed several ways in which the scientific utility of the spacecraft and its systems can be improved. These can be summarized as follows:

1. The data-taking lifetime of the main bus in the upper atmosphere can be significantly improved by targeting it to have a low angle of arrival. This increases its useful life and provides an increase in its total telemetry capability.

2. The atmospheric probes, both the main probe and the small probes, are greatly enhanced in value if they can be designed to operate after impact on the surface. This is true even if their useful surface life is only a minute or two. We anticipate that, with normal contingencies, a probe designed to reach the surface will have a capability for brief survival. If it does not inflate the cost or complexity of the mission, this feature should be incorporated.

3. All instrument packages designed to operate, even briefly, on the surface of Venus pay severe penalty in terms of scientific payload or lifetime or both because of the high-temperature environment. The primary concern appears to be the power supply, usually a battery, but all equipment must be provided with extensive thermal shielding. A significant increase in payload or lifetime could be obtained if spacecraft and experiment components could be developed to withstand temperatures of ∿800 K. It is recognized that this may, and probably will, require extensive (and expensive) development, but there should be many auxiliary applications for such components and materials both within and outside the space program.

4. Near-circular orbits, which are desirable for many experiments, can be achieved by using atmospheric drag. The low periapsis required is also useful for measurements of the upper atmosphere. When the orbit has decayed sufficiently, the periapsis can be raised out of the sensible atmosphere by means of the orbit-changing motor.

The concept of the Planetary Explorer, as a lower-cost alternative to Mariner, was the basis for recommendations made by this study. We were presented with cost estimates for a three-mission sequence involving bus, probe, and orbiter development costs and new instrumentation on each mission. The sequence consisted of a dual-launch multiprobe, a single multiprobe, and a single orbiter and was estimated to cost $130 million, for an average cost of $33 million per launch. Subsequent probe or orbiter missions, with substantial new instrumentation, were estimated to cost close to $20 million. These costs are for outside contractors but with a significant manpower contribution by Goddard Space Flight Center.

The cost of a Mariner launch, averaged over the whole series, is considerably higher than the cost of a Planetary Explorer. Estimates prepared by NASA for the Mariner 1971 Mars orbiter compared to a 1975 Planetary Explorer orbiter to Venus show that, including all development costs, the Mariner costs at least twice as much as the Planetary Explorer.

Although elaborate equipment for the Planetary Explorer could greatly increase its cost, it is clear that the Planetary Explorer is fundamentally cheaper, because, as compared to Mariner, it has about half the capacity, a booster costing about 40 percent as much, and a simpler stabilization system. Even on the basis of a fixed cost per pound, a costs factor of 2 lower can be anticipated.

In practice the cost saving should be greater than this. The smaller and simpler system may well allow economies in the number of development models, less stringent controls during construction, and less paper work. The savings on these accounts can be substantial. If the concept of a standard bus is strictly adhered to, further savings are possible.

Thus the important features of the Planetary Explorer are that it is adequate, but minimally so, for the exploration of Venus, and that we recommend a policy of maximum standardization of hardware and restraint in instrumental complexity. This represents a novel approach to planetary exploration with a flexibility and possibility for quick reaction that make it most attractive for the coming decade.

Chapter 7

AN EXPLORATION STRATEGY

In this chapter we address the question of what sequence of missions should be followed as opportunities present themselves. We have identified several types of mission to Venus for the Planetary Explorers. These are listed together with their characteristics in Tables 2-6.

The following constraints are important in the determination of what options are at our disposal and to a certain extent dictate the sequence that logically ought to be followed.

1. No more than two launches are possible during each window. This is because of the number of launch pads available--two--and the turn around time for the Delta vehicle--greater than the length of the window.
2. Hybrid missions are impractical or impose severe penalties in compromises. Thus, to combine, say, orbiter and balloons in one payload is not feasible.
3. There is an economic advantage in preparing two identical payloads for a given opportunity. Hence if there are scientifically valid reasons for launching two missions with identical payloads (though not necessarily identical objectives or targets at Venus) these ought to be exploited.
4. More than the 18 months between windows is required between mission definition and launch. Hence the results of one mission cannot be used to design for the next following window in any essential way. On the other hand, 36 months provides an adequate interval for digesting the results of a mission and using the information to design a succeeding one.
5. The system has a varying capability to perform a mission of a given type--say, an orbiter--during a metonic cycle. Hence it is not practical to build and store spacecraft to be used for all opportunities. Each mission must be tailored to fit a given window.
6. Certain missions depend for optimum design on the results obtained from others. In fact, the multiprobe and orbiter missions tend to provide data which are needed for proper definition of the various lander and balloon missions. For this reason it seems clear that the first two windows should be reserved for probes and orbiters.

In choosing between probes and orbiters for the first opportunity we are moved by the following consideration to select the multiprobe mission.

To a certain extent the sort of information an orbiter will provide is or will have been made available from previous Mariner missions (including Mercury/Venus) and from ground-based radar studies. On the other hand, the data that the probes will deliver concerning cloud composition, illumination conditions below the clouds and on the surface, magnetic fields in and below the ionosphere, seismic noise background (from microbarographs on the probes), atmospheric pressure, temperature, and composition will all be novel and will be badly needed in planning both lander and balloon missions. Indeed, the multiprobe missions appear to offer the greatest return of information which is essentially of a new class for each of our disciplines except perhaps for that of particles and fields.

We have considered the argument that an orbiter should be selected for the first mission because placing a spacecraft in orbit around another planet has already been performed, whereas landing probes has not. On the other hand there is extensive experience in sending probes to the moon. We regard the scientific, technical, and logistical reasons for beginning with a probe mission as overriding the others. Hence, we *recommend* sending two multiprobe Planetary Explorers to Venus during the 1975 window.

We *recommend* two probes rather than one because of the desirability, particularly for ionospheric, solar plasma, and aeronomic studies, of observing properties of the planetary environment on the dayside and nightside of Venus at very nearly the same time. Thus we *recommend* that the first mission target the bus and main probe on the dayside of the planet. Then, if the first entry is successful, a midcourse correction should redirect the second spacecraft to send the bus, at least, in on the nightside. If the first probe fails, the second should be allowed to follow the same trajectory as the first. This element of redundancy, making a successful mission almost certain is, in any case, desirable for the first of a long series.

Because of the requirement that the probe data be used in planning and designing balloon and lander missions and because of the wide variety of information useful to many disciplines available from successful orbiters, we *recommend* that during the 1976-1977 window an orbiter be sent to Venus. To take advantage of the payload bonus associated with a large apoapsis, we *recommend* that apoapsis be in the neighborhood of 36,000 km initially and the orbital period be 12 h in order to synchronize with earth rotation for maximum coordination with the Arecibo and Goldstone facilities. (We note that during the 1976-1977 opportunity Venus will enter the Arecibo beam just as the Explorer arrives and will remain in the beam all summer, i.e., during most of the nominal lifetime of the orbiter. This is true only for this window during the metonic cycle.)

We also note the aeronomy requirement to study *in situ* the region between 150 and 400 km. We, therefore, *recommend* that periapsis be lowered during the course of these missions down to 150 km. The possibility of using periapsis drag to give an almost circular orbit should also be considered for this mission, but not until after substantial results have been obtained from the initial high-apoapsis condition.

It has been suggested that the 1976-1977 orbiter mission should also be dual-launched. There are definite scientific advantages to be gained by so doing, but we believe them to be insufficient to justify an increase in cost of approximately 50 percent of the first orbiter. The question should, however, be kept under review by the Continuing Planning Group.

It is less clear than for these first two missions what criteria should be used in selecting missions for subsequent opportunities. Other classes of orbiters, landers (composition, seismic, and imaging), and balloons are candidates. However, because less information will have been provided by earlier studies concerning the solid planet than any other aspect of Venus it would seem most rewarding to reserve the 1978 window to a lander. The mission of this lander should be to study the composition of the crust with a gamma-ray spectrometer and neutron source and to measure seismic properties with an active source and a seismic probe. The distance between source and probes will be determined in part on the basis of information obtained during the 1975 probe mission. We note that it may be possible to use information obtained from the 1976-1977 orbiters concerning surface features of Venus to select the exact site for the 1978 lander.

Until some results have been obtained from the first two basic missions it would not be wise to fix too rigidly the scenario for launches in 1980 and beyond. It is conceivable that the results of the first multiprobe experiment will call for another probe series at this time. Or it may have been that desirable experiments were excluded from the first orbiter and a different type of orbiter ought to be scheduled. Nevertheless, from our present vantage it would appear most

TABLE 7 Proposed Missions

Mission (wt/year)	Description
Multiprobe (881 lb/1975)	Bus Large probe Three miniprobes
Orbiter (746 lb/1976)	Aeronomy; particles and fields Imaging and radar
Lander (845 lb/1978)	Crustal composition; seismicity; atmospheric pressure, temperature, and winds
Balloon	Two sets of three balloons at 50, 500, and 1200 mbar

reasonable to plan tentatively in 1980 to launch a balloon mission. Otherwise it will be 1981 at least before many data are available concerning atmospheric dynamics. A summary of the resulting mission sequence is shown in Table 7.

It is also clear that with the completion of this sequence of four launches we shall have acquired only the first round of basic information. We foresee the need to plan as a matter of policy to take advantage of every subsequent launch opportunity until we have adequately exploited the scientific potentialities of these Explorer-type probes. Planning for the series beginning in 1981 should begin after the results from the 1975 and 1976-1977 experiments are available.

We note that eventually this sequence of controlled and modest observations can lay the basis for a more ambitious series of probes of the orbiter-lander class. We endorse the concept which the Planetary Explorers express of preparing for such an elaborate venture with a well-thought-out series of preliminary observations carried out with moderate resources.

The scientific requirements outlined in preceding sections will most effectively be satisfied, we believe, with the payload assignments shown in Tables 8-10. The time available to the Study Group did not permit a complete evaluation of all the considerations needed to arrive at a firm opinion regarding the optimum payload. These tables give a first attempt at this evaluation, which must be reviewed by the Continuing

TABLE 8 Multiprobe Payloads

Experiment	Weight (lb)	Priority
BUS		
Dayglow photometer	2	1
Dayglow spectrometer	6	2
Solar wind	7	2
Magnetometer	4.7	2
ac electric field	2.5	3
Neutral mass spectrometer or ion mass spectrometer	13	1
Ion trap or Langmuir probe	4	1
Fluorescence	5	2
MINIPROBES		
Temperature	1.0	1
Pressure	0.8	1
Solar radiation	1.2	1
Surface approach	2.0	1
Magnetometer (unclean)[a]	1.3	1
MAIN PROBES		
Temperature	1.2	1
Pressure	1.3	1
Acceleration	4.0	1
Mass spectrometry (1-140 AMU)	10.	1
Solar flux	4.0	1
Infrared flux	3.0	1
Transponder	3.6	1
Altimeter	6.0	1
Magnetometer (unclean)	1.3	1
Nephelometer	4.0	1
Wind drift radar	12.	1
Condensimeter/evaporometer	2.0	1
Cloud particle-size distribution	5.0	1
Aureole	2.0	1
Hygrometer	1.0	2
Cloud-particle composition	20	2
Omniantenna	1.4	1
Miniseismometer	1.0	1

[a] High priority is contingent upon further feasibility studies.

TABLE 9 Orbiter Payload[a]

Experiment	Weight (lb)
Thermal infrared/sounder	6
Radar altimeter/bistatic/radio	20
Ion mass spectrometer	3
Neutral mass spectrometer	10
Electron temperature probe	2
Solar wind probe	7
Magnetometer	5
ac electric field	2.5
Geiger counter	2.5
Dual-frequency radio propagation	7
Topside sounder	15
Airglow	5
Spin-scan TV	10
Data storage	15

[a] The data transmission rate and the power available for experiments in the Planetary Explorer orbiter may be insufficient to handle these experiments simultaneously. If this is the case, time-sharing of experiments would be required.

TABLE 10 Lander Payload

Experiment	Weight (lb)
Active seismic experiment	25-45[a]
Source	
Seismic instrument	
Surface composition experiment	∿15
Gamma-ray scintillation spectrometer	
Neutron source	
Pressure probes	2.5
Temperature probes	

[a] Depending on mission.

Planning Group. We have satisfied ourselves that these payloads lie within the capabilities of the spacecraft proposed. We note that, in the case of the orbiter, periapsis probably will be behind the planet during the first one or two months of satellite life. Hence adequate data-storage capability will be needed. We note also that it is possible to reduce apoapsis drastically by taking advantage of the high drag in orbit at temporarily very low periapsis. By using the technique of lowering apoapsis in this way we add an entirely new class of missions based on near-circular orbits. We envision taking advantage of this maneuver relatively late in the lifetime of the orbiter to ensure accomplishment of other major mission objectives before risking very low periapsis.