NASA Technical Memorandum 89202

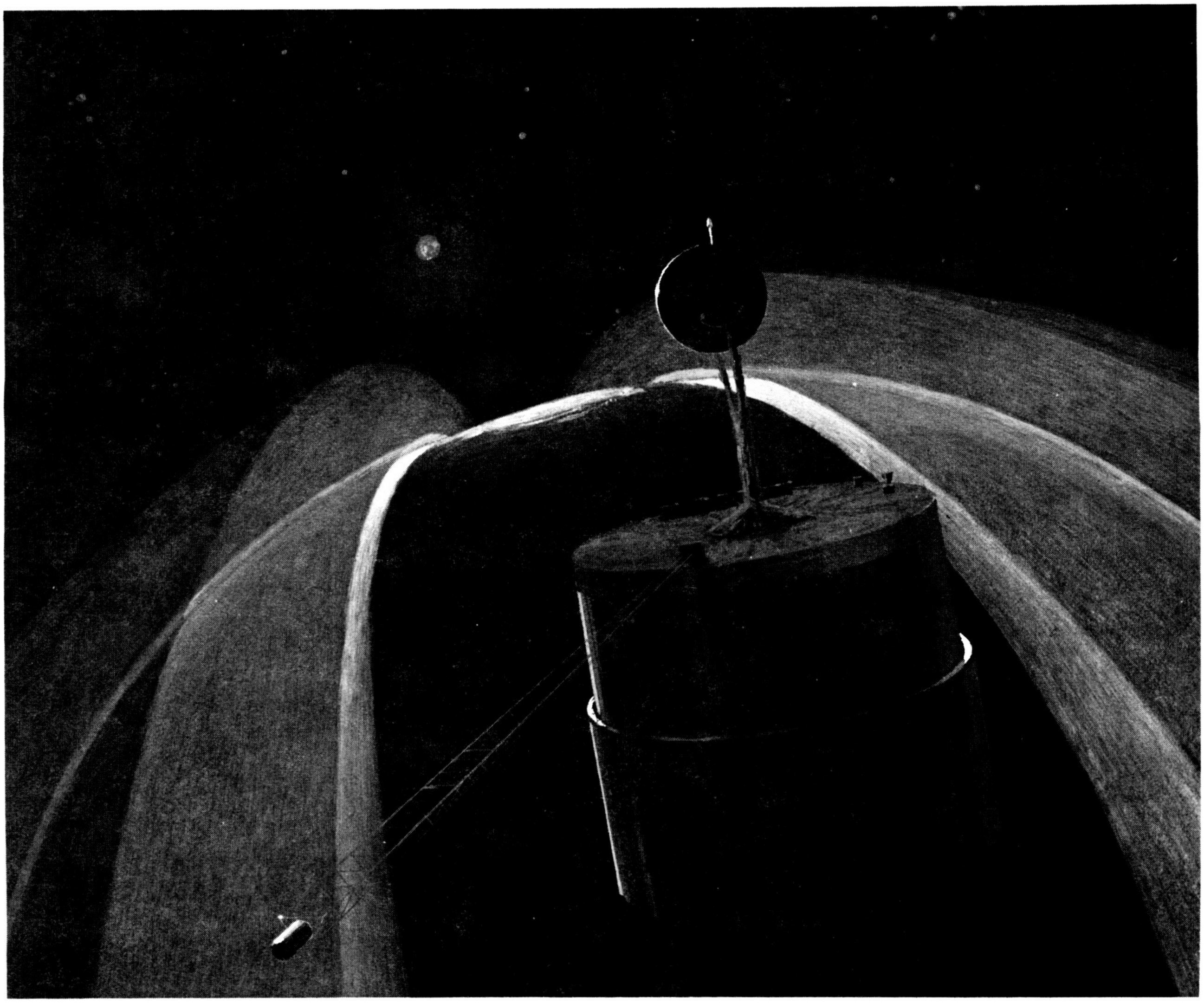
Mars Aeronomy Observer: Report of the Science Working Team

October 1, 1986

NASA

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California



The Mars Aeronomy Observer Science Working Team

Donald M. Hunten (Chairperson)	University of Arizona
James A. Slavin (Study Scientist)	Caltech/Jet Propulsion Laboratory
Lawrence H. Brace	NASA/Goddard Space Flight Center
Drake Deming	NASA/Goddard Space Flight Center
Louis A. Frank	University of Iowa
Joseph M. Grebowsky	NASA/Goddard Space Flight Center
Robert M. Haberle	NASA/Ames Research Center
William B. Hanson	University of Texas at Dallas
Devrie S. Intriligator	Carmel Research Center
Timothy L. Killeen	University of Michigan
Arvydas J. Kliore	Caltech/Jet Propulsion Laboratory
William S. Kurth	University of Iowa
Andrew F. Nagy	University of Michigan
Christopher T. Russell	University of California at Los Angeles
Bill R. Sandel	University of Arizona
John T. Schofield	Caltech/Jet Propulsion Laboratory
Edward J. Smith	Caltech/Jet Propulsion Laboratory
Yuk L. Yung	California Institute of Technology
Ulf von Zahn	University of Bonn
Richard W. Zurek	Caltech/Jet Propulsion Laboratory

TABLE OF CONTENTS

PAGE iv INTENTIONALLY BLANK

LIST OF FIGURES PAGE

LIST OF TABLES

I. EXECUTIVE SUMMARY

The Mars Aeronomy Observer (MAO) is a candidate follow-on mission to Mars Observer (MO) in the Planetary Observer Program. The four Mariner and two Viking spacecraft sent to Mars between 1965 and 1976 have provided a wealth of information concerning Martian planetology. The Mars Observer, to be launched in 1990, will build on their results by further examining the elemental and mineralogical composition of the surface, the strength and multipolar composition of the planetary magnetic field, the gravitational field and topography, and the circulation of the lower atmosphere. The Mars Aeronomy Observer is intended to address the last major aspects of Martian environment which have yet to be investigated: the upper atmosphere, the ionosphere, and the solar wind interaction region.

This report summarizes the results of the MAO Science Working Team (SWT) which held two workshops at Caltech/Jet Propulsion Laboratory (JPL) in late 1985. The MAO science objectives originally outlined by the Solar System Exploration Committee (SSEC) in its 1983 report have been refined and extended. They encompass the composition, structure, chemistry, and dynamics of the upper atmosphere and ionosphere, and the dynamics and energetics of the solar wind interaction with Mars. A knowledge of Martian aeronomy and its interaction with the solar wind will have the immediate effect of completing the initial exploration phase for this planet and allowing the first comprehensive picture of Mars, its environment, and evolution to be assembled. The second, and equally important, result of the MAO mission will be the opportunity for comparative studies of fundamental scientific issues common to the upper atmospheres and plasma environments of Earth, Venus, and Mars. Examples include the global circulation, photochemistry, and energy budget of the thermosphere and the role of the ionosphere in regulating magnetospheric reconnection, convection, and substorm processes. It is on this basis that the SWT strongly endorses the MAO science rationale originally set down by the SSEC.

The SWT has recommended a core payload that will accomplish the MAO science objectives. It consists of 10 instruments: neutral mass spectrometer, Fabry-Perot interferometer, ultraviolet/infrared spectrometer, ion mass spectrometer, retarding potential analyzer/ion driftmeter, Langmuir probe, plasma/energetic particle analyzer, magnetometer, plasma wave analyzer, and radio science. An enhanced payload was also recommended which adds an infrared atmospheric sounder, an ultraviolet/visual synoptic imager, and a neutral winds/temperature spectrometer to the mission. These three additional instruments would significantly increase the science returned by MAO on the atmosphere of Mars, but they are not essential to primary objectives of the mission. All of the instruments in the MAO recommended payload are based on mature experiment techniques and have been flown on previous missions. The SWT concluded that no significant new instrument development will be necessary for the MAO mission.

As detailed in this report, the MAO Science Working Team has reviewed the spacecraft and mission plan requirements for attaining the MAO science objectives. The mission plan is for one Mars year (i.e., 687 days) of observations from a highly inclined, eccentric orbit which will provide for in-situ observations in the upper atmosphere ($h < 150$ km), ionosphere, solar wind interaction region (or magnetosphere), and bow shock ($h > 6000$ km) over a wide range of latitudes and local times. Examination of these requirements in light of the anticipated capabilities of the MO spacecraft showed that the MAO mission can be carried out using this spacecraft with ample mass, power, pointing, and telemetry margins. All of these characteristics of the MAO mission are consistent with the low cost, level-of-effort approach of the Planetary Observer Program. It is the strong recommendation of the MAO Science Working Team that this mission be flown early in the Planetary Observer program.

II. INTRODUCTION

A. Historical Perspective

Aeronomy and planetary magnetism have been historically associated since the late 19th century when variations in the geomagnetic field were attributed to electrical currents flowing in a high-altitude conducting layer later recognized as the ionosphere. Aeronomy is defined as "the physics and chemistry of those parts of the atmosphere where ionization and chemical change are important." These regions extend all the way to the surface on Mars, and even on Earth, where photochemical pollution is a major problem. Comparisons can be very fruitful; an example is the concern about catalytic destruction of ozone in Earth's middle atmosphere. Some of the same processes operate at similar pressures on Mars and reduce the ozone by a large factor below what it would otherwise be, to the point where it is detectable only under favorable circumstances.

The nature of the planetary magnetic field determines to a large degree the type of interaction the planet undergoes with the solar wind. If the field is sufficiently large to stand off the solar wind, as at Earth and Mercury, then a very dynamic magnetic cavity, termed a magnetosphere, is created. Magnetospheres couple strongly to the high altitude atmosphere and ionosphere through field-aligned currents and charged particle precipitation. In turn, the ionosphere influences magnetospheric convection by acting as a resistive load on the system. The ionosphere is also a major source of magnetospheric plasma. If the planetary magnetic field is very weak, or even absent as at Venus, then the solar wind interacts directly with the upper atmosphere and ionosphere. An understanding of the solar wind interaction is essential to progress in upper atmosphere modeling because of the significant amounts of momentum and energy transported downward from the solar wind. Magnetospheric interactions are known to produce large spatial (e.g., high latitude versus low latitude) and temporal (e.g., storms and substorms) gradients in these energy inputs. The coupling between the ionosphere and magnetosphere is also responsible for the characteristic anti-solar convection of the ionosphere at high latitudes which, through ion-neutral collisions and heating, drives thermospheric winds. In the case of an ionospheric interaction, the transfer of energy and momentum from the solar wind takes place at the ionopause and is quite responsive to variations in the solar wind and interplanetary magnetic field. Mass loss from the planetary atmosphere is also enhanced at low-field planets with photoionization and charge exchange in the exosphere enabling the solar wind to carry off significant amounts of volatiles.

Every mission to Mars has carried out at least some aeronomical studies, as summarized in Table II.1. Unfortunately, the same cannot be said of planetary magnetism or solar wind interactions, which have not been investigated by a U.S. mission since Mariner 4 in 1965. We do know from Mariner 4, and the later Soviet missions, that any intrinsic field must be relatively small, and that close approaches (<< 1000 km) are therefore necessary for further progress. Groundbased spectroscopy and ultraviolet and radio occultation studies from the Mariners have established some of the basic properties of the neutral atmosphere and ionosphere, including the identification of CO_2 as the major gas, the general temperature field, and the presence of trace amounts of CO, O_2, H_2O, and O_3. Entry-science experiments on the Viking Landers provided neutral and ion composition measurements and temperature profiles at two locations, and the Mars Atmospheric Water Detector on the Orbiters provided copious information on the global distribution and seasonal variations of this important molecule. Regrettably, without a UV spectrometer on the Viking spacecraft the opportunity for detailed comparison with Mariner results did not exist, except

TABLE II.1. SUMMARY OF PAST AND PROJECTED MISSIONS TO MARS

Spacecraft	Year	Aeronomical Experiments*
Mariner 4	1965	UVS, RS, MAG, PA
Mariner 6,7	1969	UVS, RS
Mars 2,3	1971	UVS, RS, MAG, PA
Mariner 9	1971	UVS, RS
Mars 5,6,7	1974	UVS, RS, MAG, PA, ES
Viking 1,2	1976	RS, WD, ES
Mars Observer	Future	
Phobos	Future	

*UVS = ultraviolet spectrometer; RS = radio science; MAG = magnetometer; PA = plasma analyzer; WD = water detector; ES = entry science.

for radio science which did show the strong effect of solar activity on the ionosphere. Analysis of both soil and atmosphere samples by the Viking Landers failed to detect any organic molecules. Aeronomical models regard the destruction of CO, O_2, O_3, and organics as part of the same set of processes which involve powerful oxidants, especially OH, generated in the photolysis of water vapor. It has also been determined that hydrogen, oxygen, and nitrogen are escaping the planet at substantial rates; observed signatures are the corona of Lyman-alpha emission and a large depletion of the lighter isotope of nitrogen, which could hardly exist unless a large fraction of the original nitrogen had been lost. The forthcoming Mars Observer, and the Soviet Phobos Mission, are primarily devoted to other disciplines, but will probably carry some experiments with aeronomical and solar wind interaction capability. However, neither of them will reach sufficiently low orbits to conduct the in-situ studies of aeronomy and the solar wind interaction necessary to answer the fundamental issues discussed above.

Major aeronomical missions at Earth have included the Orbiting Geophysical Observatories (OGO's), the Atmospheric Explorers (AE's), and the Dynamics Explorers (DE's). Further work is also being done with Shuttle payloads. The Pioneer Venus Orbiter (PVO) payload and orbit plan were chosen in light of this experience, and this mission has advanced the knowledge of Venus aeronomy and the solar wind interaction enormously in the years since 1978. Important contributions were also made by experiments on the PV Probe Bus and by drag data from the individual Probes. Venus and Earth still present us with many puzzles, and the study of Mars, with its many similarities, should help elucidate them. For example, the outstanding mystery of Venus aeronomy is the extreme coldness of its nightside upper atmosphere; we have no measurement whatsoever of the corresponding region on Mars. The solution of these questions at Mars and other planets will yield still further benefits in terms of understanding the dynamics and evolution of the terrestrial atmosphere.

B. Mars Aeronomy Observer

The scientific merit of a Mars aeronomy mission has been apparent for some time. For this reason such a mission has been studied extensively by NASA and the European Space Agency (see Appendix). More recently, this mission was recommended to NASA by the SSEC as a Planetary Observer. The Observer Program is intended to provide missions to the inner solar system on a continuing basis with 2-3 years between launches. The funding profile will be flat, level-of-effort, as with the highly successful Physics and Astronomy Explorer Program. Significant cost reductions will be achieved through 1) limiting the missions to those possessing well defined science objectives attainable with mature instrument technologies, and 2) the exercise of the option to procure, at a reduced price, additional copies of the Planetary Observer spacecraft selected for MO. Accordingly, the candidate missions for the Observer Program will be required to demonstrate that their mission requirements can be met with the RCA spacecraft that was selected for the MO mission in early 1986. Cost considerations may preclude major modifications to the MO spacecraft or the procurement of a different spacecraft for later missions.

To follow up on the SSEC recommendation for a core program, NASA Headquarters requested that the Caltech/Jet Propulsion Laboratory form a Planetary Observer Planning Team. The MAO mission was further examined by a Science Working Team selected by Headquarters (D.M. Hunten, Chairperson; J.A. Slavin, Study Scientist) which met at JPL for two workshops on September 4-5 and November 11-12, 1985.

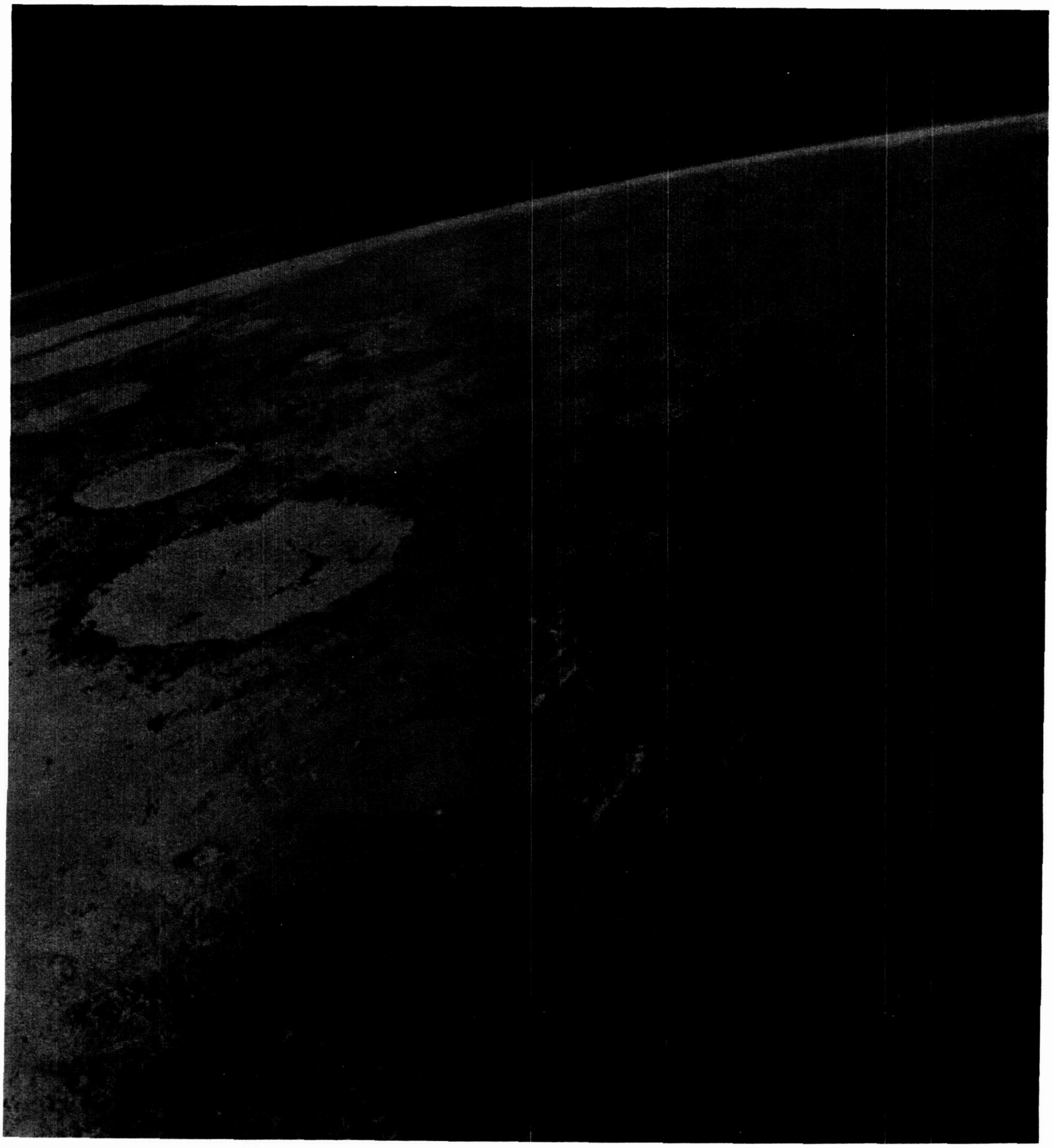
The main conclusion of the workshops, contained in this report, is that the MAO objectives and instrument requirements are extremely well matched to the scientific goals and capabilities of the Planetary Observer Program. The prior missions to Mars have laid the framework for posing specific scientific objectives which can be addressed by a combination of direct and remote sensing. Examples of these compelling science questions to be answered by MAO are:

- What is the altitude and solar zenith angle variation in the composition, density, and temperature of the neutral and ionized components of the upper atmosphere, especially on the nightside? The observations at Mars will allow the testing and further development of terrestrial models for an atmosphere which differs significantly from Earth's in many basic properties.
- Is there an intrinsic magnetic field at Mars and how does the solar wind interact with the planet? An understanding of the solar wind interac-

tion at Mars is essential to the modeling of the upper atmosphere and ionosphere. Due to the anticipated weakness of the planetary field, Mars has long been identified by the space plasma physics community as a unique type of magnetospheric/ionospheric solar wind interaction whose investigation will greatly benefit our knowledge of magnetospheric physics and solar terrestrial relations. Furthermore, the low altitude periapsis of MAO will allow for a definitive mapping of any anomaly or remanent magnetic fields.

- What are the major features of the circulation of the atmosphere at all levels, but particularly the middle and upper regions? The understanding of global circulation patterns is one of the most basic goals of atmospheric science, and comparative studies between the different planetary atmospheres are essential to its final solution.
- Is the oxidation of CO and organics, and the corresponding dearth of free oxygen and ozone, understood? Could there have been a time in the past when conditions were more benign, for example due to higher pressures and the presence of running or standing water? Previous observations suggested that this may have been the case, and the resolution of this question is critical to our understanding of Mars.

Such questions cannot be answered without the gathering and analysis of additional data which will form the basis for new theoretical modeling. The Mars Aeronomy Observer Mission will provide definitive answers to many of these questions and, undoubtedly, raise new ones as it performs the initial exploration of the high altitude environment of Mars.



III. SCIENCE REVIEW

A. Neutral Atmosphere

A.1 Overview

The atmospheres of our neighboring planets, Mars and Venus, are of particular interest to atmospheric scientists because they present us with the opportunity to find out how the relatively small differences in their mass, composition, and solar distance affect the evolution of planetary atmospheres. These atmospheres also provide new testing grounds for theoretical models that have been developed to accommodate and explain the behavior of the Earth's atmosphere. Clearly, the basic physical processes underlying the evolution of the atmospheres of Earth, Mars, and Venus, and those that now control their dynamic behavior, are similar for all three planets. However, the way that these processes combine in a particular atmosphere makes it difficult to separate the relative contribution of each process from the behavior of the whole.

The contrast between the composition, thermal structure, and dynamics of the thermospheres of Earth, Venus, and Mars is particularly fascinating. The composition and density of the lower and middle atmospheres of these planets differ significantly, albeit we know the least about Mars. Most knowledge about the Martian atmosphere is based on the remote measurements from the Mariner 9 and Viking orbiters, the Viking lander entry science, and Earth-based spectroscopy and laser heterodyne observations. The atmospheres of Mars and Venus are alike in that they are primarily CO_2, but their absolute densities at the surface differ by more than four orders of magnitude. In contrast, N_2 and O_2 are the major constituents of the Earth's atmosphere, and the density at the surface lies (logarithmically) about midway between those of Mars and Venus. The upper atmospheric composition of these three planets becomes more and more similar with increasing altitude due mainly to photodissociation processes.

Atomic oxygen is the major neutral constituent above 200 km for all three planets until hydrogen takes over as the dominant species at very high altitudes.

However, the thermal structure and dynamics of the upper atmospheres of Earth, Mars, and Venus are entirely different. Temperatures at Mars have been measured up to 25 km by radio occultation, up to 40 km by the Mariner 9 infrared spectrometer, and profiles up to 200 km were obtained during the two Viking lander entries. The shaded areas of Figure III.1 span the Mariner 6 and 7 temperature measurements as a function of height at various positions and times of day. The temperature gradient is not even close to the predicted adiabatic lapse rate of 5 K/km for a clear CO_2 atmosphere in radiative convective equilibrium as displayed in the left panel. The actual temperature profile is due mainly to absorption of direct solar radiation by dust in the atmosphere as indicated in the right panel. The effect is important even when the atmosphere appears to be clear. However, even though the lapse rate is more nearly adiabatic for clear conditions, it is rarely steeper than 3 K/km. Models of the large-scale circulation also give a smaller lapse rate than does convection.

The surface temperatures undergo large diurnal variations during the Martian day, as shown in Figure III.2, because the surface pressure is so low that the greenhouse effect is weak. The Earth's exospheric temperature is of the order of 1000 K on the dayside and 700 K at night, a 30% diurnal variation. At Venus the average dayside exospheric temperature is much cooler, 300 K, with a very cold nightside temperature of about 100 K, a striking diurnal variation of a factor of 3. This region has been called the "cryosphere," but we have few clues as to the nature of the heat sink that causes these low temperatures. From the Viking measurements we know that the daytime thermospheric temperature of Mars is about 200 K, even colder than that of Venus, but the night-time temperatures are unknown, as are all other characteristics of the nocturnal

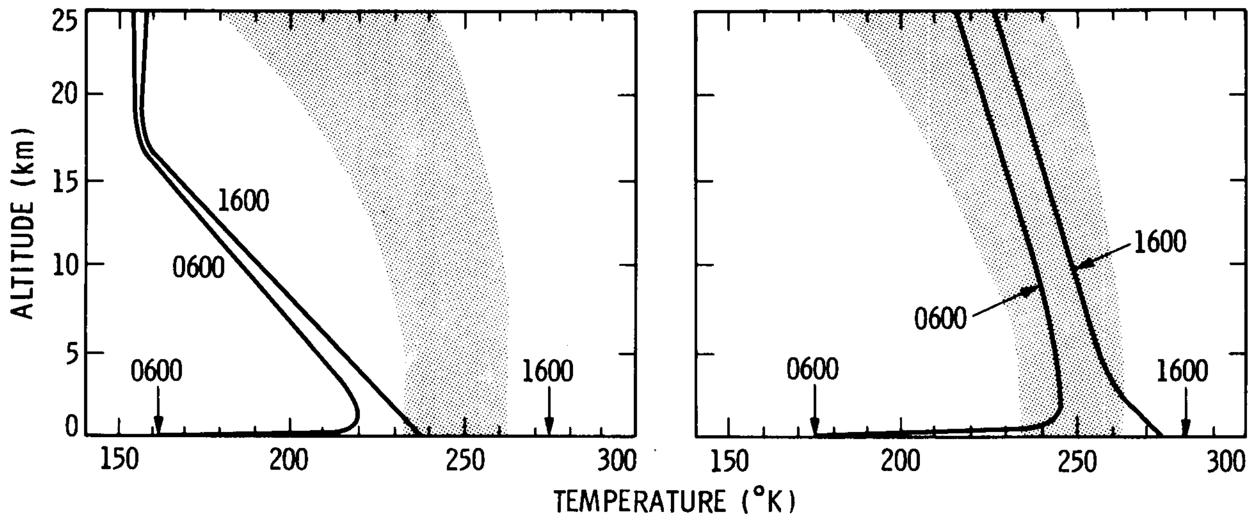


Figure III.1 Temperature profiles for Mars showing the effect of direct solar heating due to dust absorption are displayed. The shaded areas indicate the region of the Mariner 6 and 7 observations. The curves at the left are calculated for a clear CO_2 atmosphere and at the right for one containing dust.

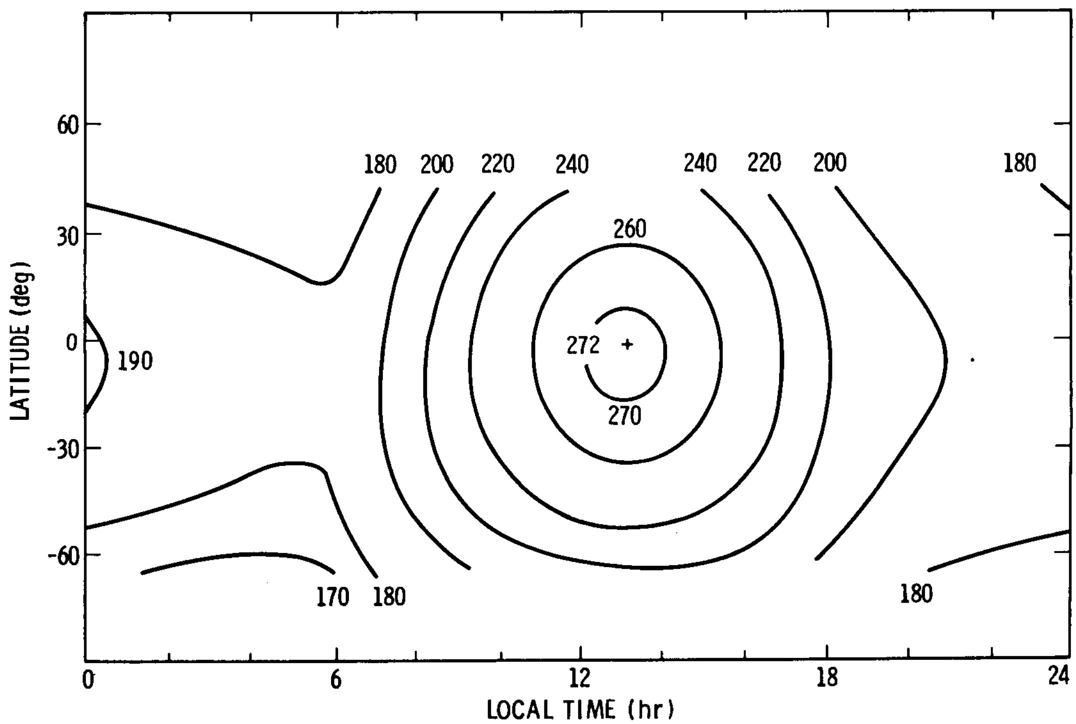


Figure III.2 Surface temperatures on Mars, calculated for a clear atmosphere based on Mariner 9 infrared radiometer observations, are displayed.

thermosphere and ionosphere. Therefore, it is not known whether the cryosphere is a universal feature of CO_2 thermospheres, or whether its existence depends upon the planetary rotation rate.

The thermospheres and mesospheres of the terrestrial planets are subject to strong in situ forcing due to the propagation of thermal tides and gravity waves from underlying regions of the atmosphere, as depicted in Figure III.3. These regions also experience chemical heating, radiative cooling, and molecular and eddy diffusive transport. The overall spatial structure and temporal variations of the lower thermosphere and mesosphere are still poorly known at Earth, but missions planned for the 1990's should begin to sort out these effects. The Pioneer Venus data are providing an initial examination of these effects at Venus, but they should be investigated at Mars as well. Thermospheric general circulation models have been applied to both Earth and Venus and are available for application to Mars when data become available from

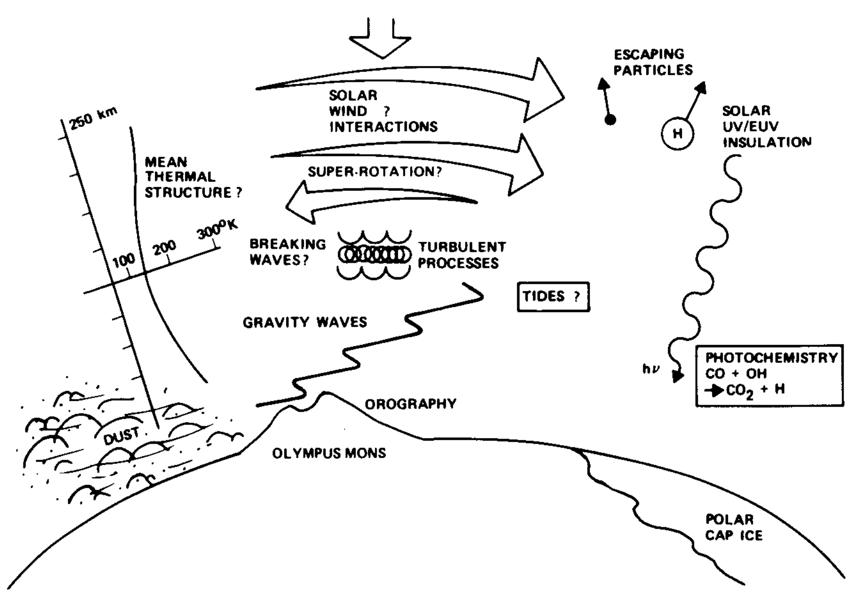


Figure III.3 The upper atmosphere of Mars is strongly influenced by conditions in both the solar wind interaction region and the lower atmosphere, as depicted schematically above.

MAO. Comparisons of the atmospheric dynamics of Earth and Mars will be especially fruitful because of the similarity of their diurnal periods and the much larger seasonal effects expected at Mars due to the large eccentricity of its orbit. The large component of Joule heating at high latitudes, which introduces great complexity in the Earth's upper atmosphere, may be weak or absent at Mars. However, only direct measurements can determine whether this is the case.

All planetary upper atmospheres encountered thus far have shown convincing evidence of super-rotation; i.e., the upper atmosphere rotates faster than the planet itself. In the Earth's thermosphere the super-rotation rate is only a few percent greater than the Earth's rotation rate. On the other hand, at Venus, the upper atmosphere is believed to rotate with a period of only a few days, while the planet itself has a rotation period of 243 days. This implies a high rate of super-rotation which must significantly affect the dynamics of the thermosphere and apparently produces large dawn-dusk asymmetries in the diurnal variation of both the neutral and ion composition. It will be of extreme scientific importance to determine if super-rotation exists at Mars.

Seasonal variations in the thermospheres of the planets are expected to be highly contrasted because of differences in orbital characteristics and polar tilt angles. Earth and Mars have almost identical rotation rates and tilt angles, but the larger eccentricity of the Mars orbit is anticipated to cause larger seasonal variations than are found in the Earth's atmosphere, as mentioned earlier. By contrast, Venus has almost no tilt and the eccentricity of its orbit is small. Thus, significant seasonal effects are not expected and none have been detected in the Pioneer Venus observations.

Water vapor is present at Mars in small, highly variable quantities. It can be observed from Earth when the Doppler shift is large enough to move the absorption lines away from the telluric ones. Water vapor was also studied in detail by the Viking Orbiters. In the illuminated part of the winter hemisphere the abundance can drop below 1 μm of precipitable water (10^{-4} g - cm^{-2}). The largest value observed by Viking was 100 μm near the north polar cap in summer just after it had shrunk to its smallest size. This residual cap was therefore deduced to be water ice. A value around 10 μm is fairly typical.

The atmosphere is usually dusty, and dust storms on several scales are frequent. The largest scale covers the whole planet; one of these global storms was in progress in 1971 when Mariner 9 arrived, and only the tops of the four huge volcanoes could be seen. Clouds and hazes of water frost are frequent, and CO_2 itself condenses over the winter pole. These polar caps disappear, except for small remnants, in the summer season. The marked effect on the atmospheric pressure is seen in the data from the Viking landers displayed in Figure III.4. Both vehicles were in low-lying basins, and, therefore, had annual mean pressures appreciably greater than the more typical 6 mbar. The global circulation is similar to that of the Earth in many ways. Although the latent-heat effects of water are essentially absent, there is the new feature of the seasonal migration of 25% of the atmospheric mass into and out of the polar caps. The enhanced weather activity during late fall and late winter is evident in the pressure data of Lander 2, which was further north (48° N) than Lander 1 (23° N).

A.2 Mars Thermosphere

The composition of the region above 120 km is shown in Figure III.5 for Viking 1 conditions with a thermopause temperature of just over 200 K. Mass-spectrometer data are shown as black dots, and the model as a whole is consistent

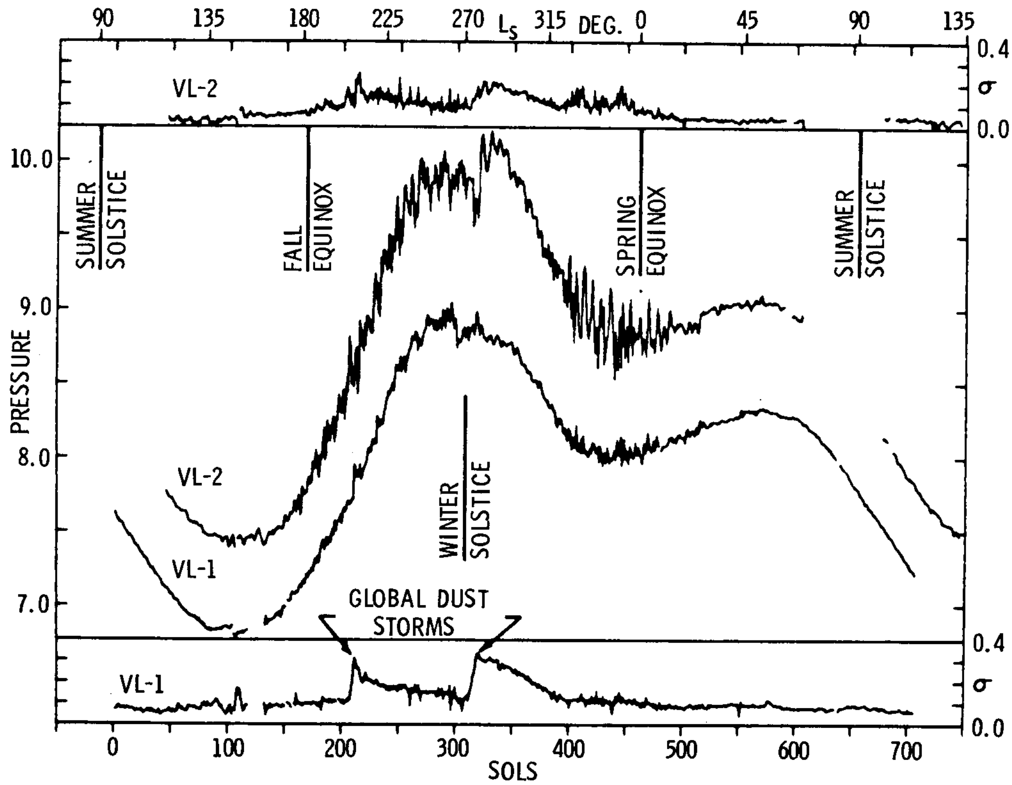


Figure III.4 The annual cycles of atmospheric pressure (mb) at the two Viking landers are displayed. The strips at top and bottom show the standard deviation for each Martian day.

with the ionospheric data. Except for the larger scale heights and the presence of NO, the resemblance to Venus is close. However, more detailed examination shows that Mars is relatively deficient in O and CO. A conventional place to make the comparison is at a CO_2 column density of 4×10^{16} cm^{-2}, which is at unit zenith optical depth for ionizing radiation, and can therefore be loosely called the ionospheric peak. The height happens to be near 140 km for the day sides of both planets. The O and CO mixing ratios on Venus are 13% and 9%; Figure III.5 shows that they are 1.5% and 0.6% for Mars. The factor ~ 10 difference in these ratios at Venus and Mars is mostly explained by the ratio of solar fluxes, 4.5, responsible for the photolysis of CO_2. The remaining factor of 2 must reflect different sink strengths, most probably due to down-

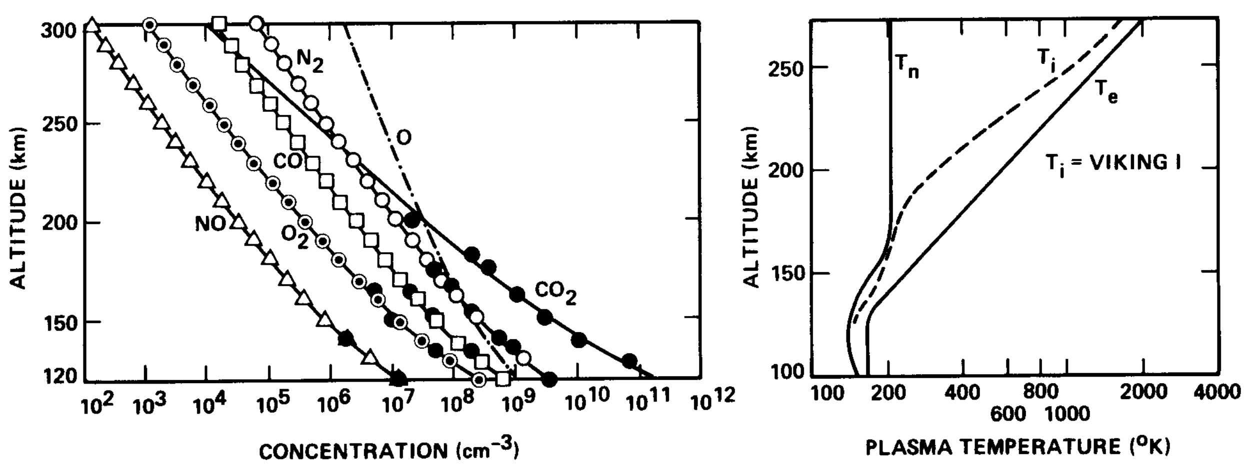


Figure III.5 A model Martian thermosphere consistent with the neutral and ion data from the two Viking landers is displayed. Neutral, ion, and electron temperatures are shown at the right.

ward transport of the gases out of the region where they are produced. This transport must be about twice as effective on Mars as on Venus.

The temperature rise across the thermosphere is predicted to be nearly the same at Mars and Venus. Mars seems to deviate from the theoretical expectations even more thoroughly than Venus. Thermospheric temperature profiles are shown in Figure III.6. They were observed less than two months apart, and both refer to the dayside. The mesopause height is predicted to be about 100 km. However, even the Viking 1 profile bears very little resemblance to the terrestrial thermosphere. Further information is available from radio occultation studies with the Viking Orbiters and Mariners 4, 6, 7 and 9. These results are collected in Figure III.7 (the crosses), along with a representation of solar activity. The measured quantity is the topside scale height of the electron density, shown by the scale to the left of the figure. A temperature can

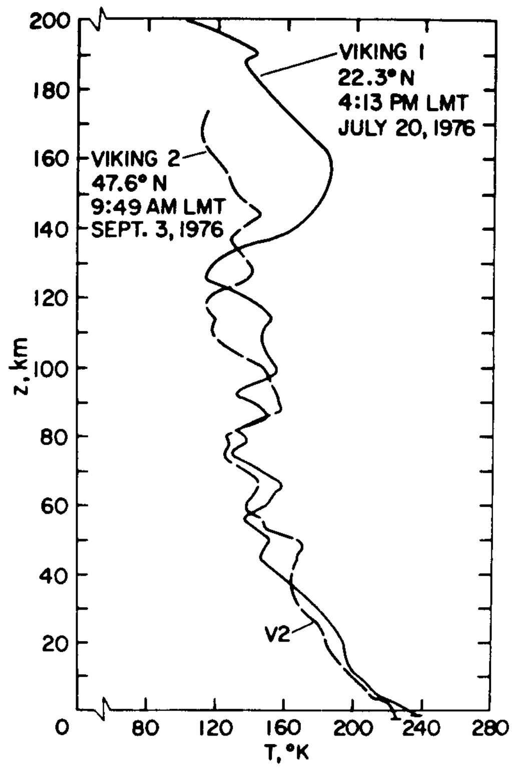


Figure III.6 Martian temperature profiles from a synthesis of the Viking entry data are displayed.

be obtained only through a model, and the one adopted for the scale on the far left assumes an atmosphere of pure CO_2, with ions of CO_2^+ only. The 1978 point from Viking is 200 K. On both Mars and Venus, O^+ and O_2^+ are important, and a model including them gives a lower temperature for the same observed electron scale height. A representative value from Figure III.6 is 150 K, perhaps even a bit lower. To a first approximation, therefore, the temperature scale in Figure III.7 should be multiplied by 0.75. The highest point (1969) becomes 300 K. This is comparable to the Venus temperatures in 1980, also a year of high solar activity. However, Venus conditions since then seem to be much less variable than indicated for Mars.

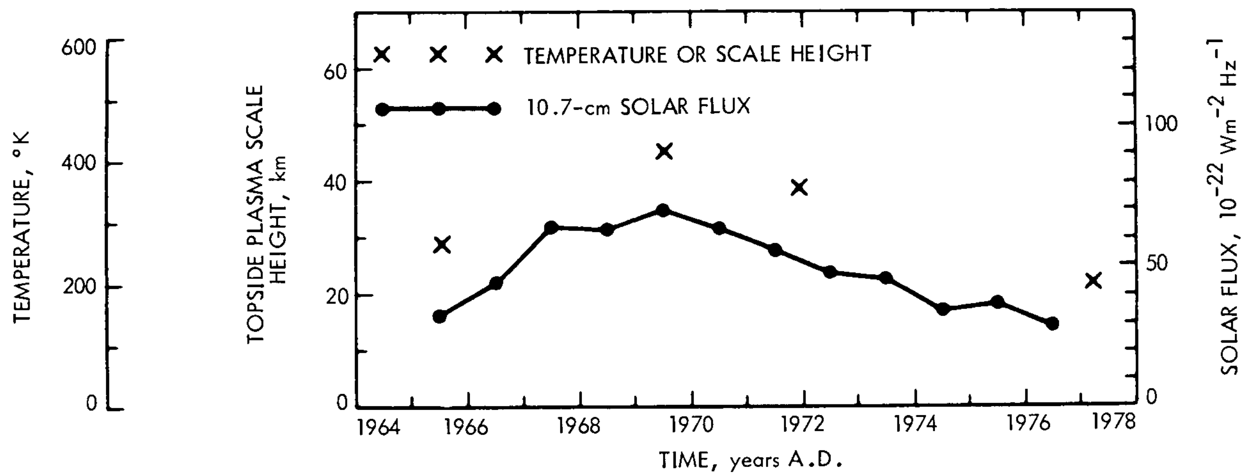


Figure III.7 Ionospheric scale heights inferred from Mariner and Viking radio occultation measurements are plotted with a solar-flux index for comparison. The temperature scale is valid only for pure CO_2 ions.

There are no data at all for the nightside thermosphere; radio science has detected the presence of only a weak nightside ionosphere. The rapid rotation of Mars leaves only 12 hours for cooling, which should be slow at the low temperatures observed on the dayside. This argument suggests that the diurnal variation should be small, but our understanding is too poor for a confident prediction.

In the Earth's thermosphere, photolysis of O_2 produces copious amounts of O atoms, which quickly come to dominate the composition at higher altitudes. On Mars and Venus, the same statements would be expected to apply to CO_2 and its products O and CO, because solar radiation dissociates O_2 and CO_2 at nearly the same rate. Figure III.5 shows, however, that O and CO are rather minor constituents at the lower altitudes and O becomes important at higher altitudes only because it has a much larger scale height than CO_2. The only possible explanation is that O and CO are rapidly swept downwards by atmospheric mixing processes, conventionally represented by a large eddy diffusion coefficient. On Venus there is strong reason to believe that the dominant motion is on a global scale, with gas rising on the dayside, sweeping away from the Sun, and descending on the nightside. Although the required mixing rate is similar on Mars, there is no evidence as to whether it occurs on a global scale (as on Venus) or operates more locally (as on Earth). In situ atmospheric composition and wind measurements from MAO will provide crucial information needed to understand the extremely rapid mixing at Mars. However, downward transport of O and CO may still leave the problem of recombining them through processes at lower altitudes, as discussed in the next section.

A.3 Lower Atmosphere and Photochemical Escape

In addition to the large ionospheric production of O and CO discussed earlier, a still larger quantity is produced at lower altitudes, all the way to the surface if the atmosphere is not too dusty. O atoms react with each other, producing O_2, much more readily than with CO. Yet the observed amounts of CO and O_2 are only around 0.1%, far less than is found in a simple laboratory simulation of the system. Apparently, the oxidation of CO is catalyzed by free radicals called odd hydrogen which are generated from the traces of water vapor in the atmosphere. This photochemical system is intimately linked to processes at the very top of the atmosphere through the escape of hydrogen and oxygen. Mars' gravity well is small enough to permit a variety of photochemical escape processes to operate on carbon and nitrogen, as well as oxygen. These processes are thought to have played a major role in the evolution of the Martian and Venusian atmospheres, as demonstrated by the strong isotopic signatures in nitrogen (Mars) and hydrogen (Venus), and in the maintenance of the present state of oxidation. The theory describing the photochemical and transport processes believed responsible for this balance is highly developed and internally consistent, but needs further experimental verification. The Mars Aeronomy Observer would make the first direct measurements of several key controlling factors, such as the photochemical escape rates and isotopic ratios for atomic oxygen, carbon, and hydrogen. Remote sensing of H_2O and O_3 would be a valuable supplement.

The basic reactions in a pure CO_2 atmosphere are:

$$CO_2 + h\nu \rightarrow CO + O \quad (1)$$

$$CO + O + M \rightarrow CO_2 + M \quad (2)$$

$$O + O + M \rightarrow O_2 + M \quad (3)$$

$$O_2 + h\nu \rightarrow O + O \quad (4)$$

CO_2 and O_2 do not react at the temperatures of interest. The rate of (2) is negligibly small, and (4) is very inefficient near the surface; thus, (1) and (3) should convert a large fraction of the CO_2 into O_2 and CO.

Odd hydrogen includes the radicals H, OH, and HO_2 illustrated in the central square of Figure III.8. The numbers beside each arrow give the reaction times, in seconds, under typical daytime conditions near the surface; a steady state is therefore reached in about 15 sec. The role of H_2O_2 is much harder to specify, because of its long time constant and its tendency to freeze out; but it can be regarded as a loosely bound pair of OH radicals. Oxidation of CO is part of the odd-hydrogen cycle through the reaction

$$CO + OH \rightarrow CO_2 + H \quad (5)$$

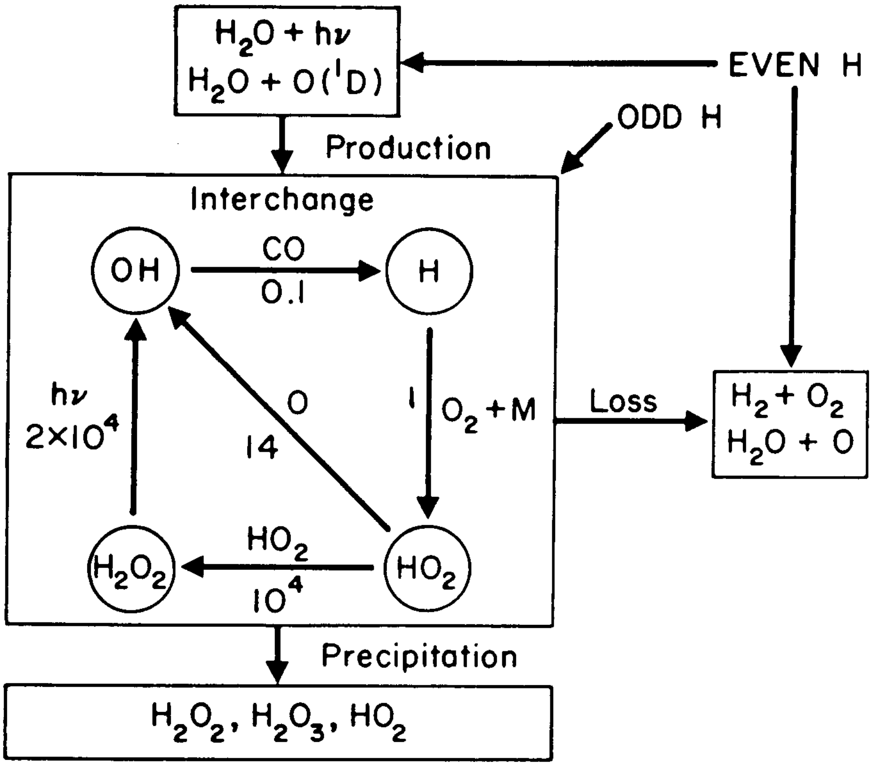


Figure III.8 Flow diagram for odd hydrogen near the surface of Mars is shown above.

With the observed amounts of water vapor (the main source of odd H, as shown at the top of Figure III.8), the observed amounts of CO and O_2 can be reasonably accounted for. Ozone is a part of the system not discussed here, but its rarity is also understood, as well as its observed tendency to be much more abundant under cold (that is, dry) conditions.

Escape of H atoms occurs by the thermal process at a rate of 2×10^8 $cm^{-2} s^{-1}$, computed from observed Lyman-alpha intensities and exospheric temperatures. Heavier atoms require nonthermal energy, generally supplied by exothermic reactions at high altitudes. Prominent examples are

$$O_2^+ + e^- \rightarrow O + O \qquad (6)$$

$$N_2^+ + e^- \rightarrow N + N \qquad (7)$$

The two atoms fly apart in opposite directions, and the one that is directed upwards can escape if the reaction occurred in the exosphere. A remarkable feedback process in the lower atmosphere regulates the flux of O to be half that of H, so that the escaping material has the stoichiometry of water; the regulation operates on a time scale of 10^5 years.

Important questions remain concerning the evolution of volatiles and the climate history of Mars. The magnitudes of the reservoirs of Martian volatiles are unknown, even for the present epoch. Several species are known to escape from the Martian atmosphere, including nitrogen, carbon, oxygen, and hydrogen. Isotopic abundances suggest that significant depletion of the planetary inventory has occurred for nitrogen, but not for carbon or oxygen. Escape of nitrogen depends on the atmospheric abundance of N_2, and the enrichment of ^{15}N places an upper bound on the size of any present reservoir which interacts with the atmosphere, as well as a lower bound on the size of the initial reservoir. Escape of oxygen depends on the abundance of O_2, which is regulated primarily by photochemistry in the Martian troposphere and by the escape of hydrogen. An upper bound on the isotopic enrichment of Martian oxygen may be used to place lower bounds on the present size of an exchangeable oxygen reservoir and the size of the initial oxygen reservoir, if the history of escape can be reconstructed. Escape of hydrogen depends primarily on the photochemical generation of H_2 from H_2O in the Martian troposphere and is influenced strongly by surface temperatures, which control the availability of water vapor. A measurement of deuterium enrichment on Mars could provide an independent constraint on the amount of primordial water incorporated into the planet, if we assume that the initial ratio of D to H was similar to that in terrestrial water.

The history of escape of Martian volatiles depends upon the previous climate of the planet. Climate affects vapor pressures of photochemically active volatiles which may condense or may be released from the regolith and polar caps; it controls the rates for kinetic reactions which depend on temperature and pressure. Escape of H and O depends on production of H_2 and O_2, which depends on atmospheric composition and photochemistry. If we may reconstruct the past evolutionary history of atmospheric composition, then we may place constraints on the escape of volatiles and previous climates.

The Martian atmosphere is conceptually simpler than the atmospheres of the other terrestrial planets. Photochemistry may be able to explain the present composition and past evolution. In contrast, the atmospheres of Venus and the outer planets are more complex, and require a complete description of the interaction between photochemistry in the upper atmosphere and the thermochemistry in the lower atmosphere. The terrestrial atmosphere is further complicated by interaction with the biosphere. For this reason the Mars Aeronomy Observer Mission has the potential of greatly advancing our knowledge of the fundamental principles governing the composition and evolution of planetary atmospheres.

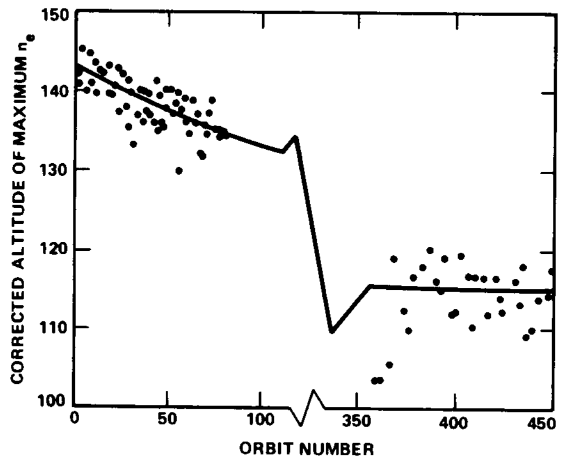
A.4 Energetics and Dynamics of the Martian Upper Atmosphere

The meteorology or dynamics of the Earth's thermosphere has been relatively well studied by a sequence of aeronomy satellite missions, culminating in the Dynamics Explorer Mission. The results from DE showed that thermospheric dynamics are controlled by both direct solar forcing (heating and tidal input) as well as magnetospheric forcing (Joule and particle heating at high latitudes, and ion drag). The experience of the DE and AE missions has further shown that a complete understanding of the aeronomical processes governing the state of the upper atmosphere requires detailed knowledge of the dynamics (winds) and thermodynamics (temperatures) in the various regions. This follows from the coupled nature of the processes involved and the importance of transport in governing the flow of mass, kinetic energy, and chemical energy of excitation.

The dynamics and energetics of the Martian upper atmosphere are essentially unknown, but are expected to be controlled by the same solar EUV and UV heating and wave forcing as the Earth's lower thermosphere. Since there may not be a significant intrinsic magnetic field at Mars, the magnetospheric forcing so important for the Earth's upper atmosphere might be unimportant at Mars. This means that the dynamics of the Martian upper atmosphere may be a good indicator of important effects in the lower atmosphere such as the generation of gravity waves, thermal tides, and their modification by eddy diffusion. These phenomena probably play a far more dominant role at Mars than at Earth in determining upper atmosphere dynamical structure. Thus, measurements of atmospheric composition, winds, and temperatures at Mars, while being of interest in their own right, would provide us with important insights into processes that occur in the Earth's upper atmosphere, but are generally masked by stronger forcing processes of magnetospheric origin. They should also provide detailed diagnostic information on wave and turbulent phenomena occurring in the Martian lower atmosphere.

A.5 Coupling of the Martian Upper and Lower Atmosphere

The lower atmosphere affects the upper atmosphere through the vertical transport of energy, of momentum and, photochemically, of important minor constituents. The seasonal loss and gain at the surface of CO_2, the atmosphere's primary constituent, and the thermal contraction and expansion of the atmosphere also change the air density at thermospheric and ionospheric altitudes as shown in Figure III.9. During great dust storms the atmosphere below 40 km is much warmer and more stably stratified than it would be in the absence of the airborne dust, which is a strong absorber of the incoming sunlight (Fig. III.10).



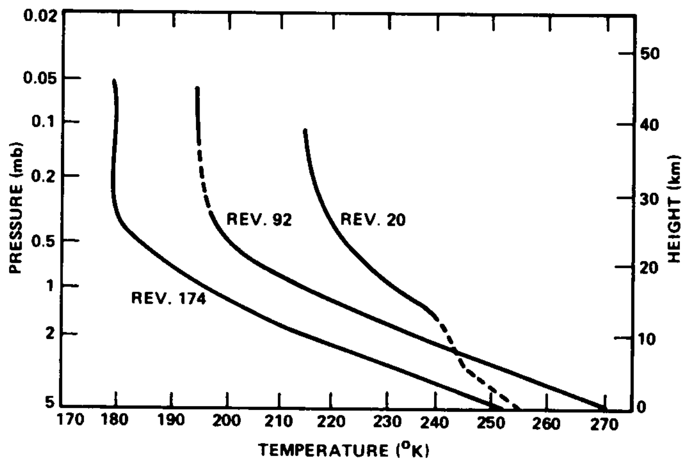


Fig. III.9 Altitude of electron density maximum as measured by Mariner 9 is plotted versus orbit number. The solid line is a model which allows for atmospheric contraction due to the dissipation of a great dust storm.

Fig. III.10 Temperature profiles from Mariner 9 are displayed. During revolution 20 the atmosphere was very dusty. By revolution 92 the dust was dissipating and clearing was well advanced by revolution 174.

The generation of vertically propagating gravity and planetary waves produced by air flow over the sizeable Martian orography and the thermal forcing of planetary-scale atmospheric tides in the lower atmosphere produce a large vertical flux of energy and momentum (Fig. III.3). The dissipation of this vertical flux provides a potent mechanical drive for the circulation of the middle and upper Martian atmosphere and should produce a strong zonally symmetric ("Hadley") circulation capable of reversing the radiatively imposed temperature gradient in the mesosphere, as appears to be the case for Earth and Venus. Recent Earth-based observations of Mars suggest that there is indeed a tendency for mesospheric temperatures to increase away from the subsolar latitudes.

Much of the vertical mixing which occurs in the middle atmosphere (40-90 km) is due to the turbulent mixing induced by these very same vertically propagating waves. Because these waves grow exponentially as they propagate upward into less dense air, at some height their wave amplitudes become large enough that the atmosphere locally becomes convectively or mechanically unstable. The resulting turbulence produces a vigorous vertical mixing which aids the transport of photochemically important atmospheric trace constituents and also determines the height of the homopause. The more vigorous the eddy or wave-induced vertical mixing, the higher the level at which diffusive separation of the various atmospheric constituents should occur. If atmospheric tides or orographically produced gravity waves do indeed control the homopause height, that height should vary significantly with latitude and, possibly, with time of day as well.

Through its interactions with surface ice deposits and subsurface reservoirs of adsorbed water, the lower atmosphere is a source/sink for H_2O, which is a photochemically important precursor molecule. Just as water vapor is transported up into the middle atmosphere where it is photo-dissociated, other molecules such as CO and O, produced by the photolysis of CO_2, are transported down into the denser, "wetter" lower atmosphere where they can more efficiently recombine. In this way, mass transport within the atmosphere appears to be a vital link in maintaining the predominantly CO_2 composition of the Martian lower and middle atmosphere.

B. Ionosphere

Our knowledge of the dayside ionosphere of Mars is extremely limited and is based primarily upon the remote sensing results from Mariner 9 and the retarding potential analyzer results from the Viking 1 and 2 landers. The neutral atmospheres of Mars and Venus are alike in many ways, suggesting similarities in some of the ionospheric processes. Therefore, both the direct information available on the Venus ionosphere from the Pioneer Venus Orbiter measurements and the related modelling studies have been used to gain the maximum possible insight about the Martian ionosphere from the limited data base. The ionospheric peak region is chemically controlled on both planets. The electron density peaks are located around 140 km and the major ion in this region is O_2^+ as shown in Figure III.11. It is interesting, however, to note that there is practically no O_2 in the atmosphere of either planet. The O_2^+ present is the result of charge exchange processes:

$$O^+ + CO_2 \rightarrow O_2^+ + CO \tag{8}$$

$$CO_2^+ + O \rightarrow O_2^+ + CO \tag{9}$$

O^+ is an important minor ion in the region of the peak, becoming the major ion near 200 km on Venus, but apparently only comparable to O_2^+ on Mars at around 300 km. A large variety of minor ions have been measured and modeled in the Martian ionosphere, but only CO_2^+, O_2^+ and O^+ were actually measured by the retarding potential analyzer on Mars. We know from the terrestrial ionosphere that minor ions and/or metastable species play an important role in the overall photochemistry, but at this time we have practically no direct information on these species at Mars.

The Viking retarding potential analyzer measurements indicate that the dayside ion temperatures rise from those of the neutral atmosphere at low altitudes to over 2000 K near the top of the ionosphere. We have no direct information available about the electron temperature. A number of simple ion energy balance calculations for the ionosphere, which incorporated a variety of free parameters, were successful in achieving agreement with the Viking measurements.

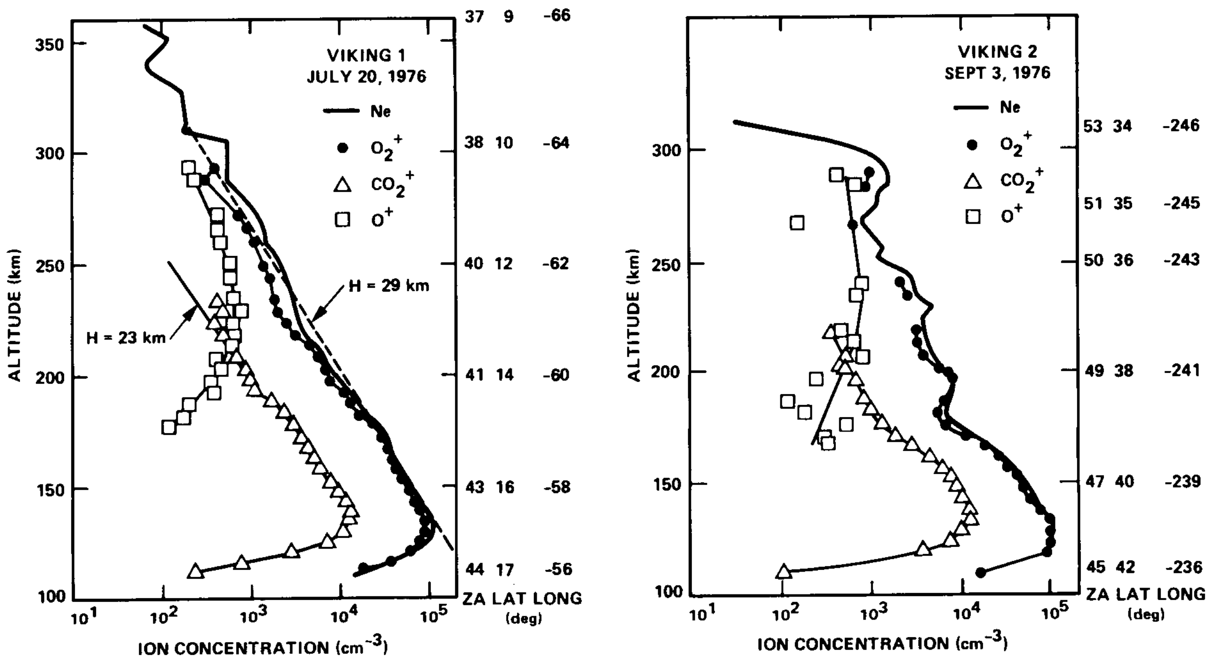


Figure III.11 Viking lander retarding potential analyzer observations have determined that O_2^+ is the dominant ionospheric species at Mars and that the ionization peak is at 130–140 km. However, the two high altitude profiles appeared quite dissimilar, perhaps reflecting temporal variations in the solar wind interaction.

However, these studies were not able to specifically establish the relative importance of Joule heating, horizontal and/or turbulent magnetic fields, and endothermic chemical reactions in the overall Mars ionosphere energy balance.

As noted earlier, essentially nothing is known about the nightside ionosphere of Mars, but the contrast between the nightside ionospheres of the Earth and Venus provides a basis for speculation on what might be found there. The existence of a Venusian nightside ionosphere was considered surprising because the Venus night is far longer than the time required to remove the ionosphere by chemical recombination. The Venera 9 and 10 discovery of energetic electrons high above the nightside ionosphere offered a potential source of ionization, but one that now seems inadequate. Pioneer Venus observations of large scale flows from the dayside to the nightside ionosphere may offer the final solution. In the absence of a large intrinsic magnetic field at Mars, no plasmasphere is expected to form to store ionization produced in the dayside as at Earth. The absence of a strong magnetic field may allow a substantial nightward transport of ionospheric plasma from the dayside as at Venus. However, even at Venus the relative importance of direct electron precipitation and transport in maintaining the nightside ionosphere has still not been fully settled.

Despite the many similarities between Mars, Earth, and Venus, there are also reasons to expect new, unusual ionospheric phenomena. Mars has the comparatively fast rotation rate of Earth, but a weak (or even non-existent) intrinsic magnetic field. The Martian gravitational field is substantially weaker than that of either Earth or Venus. The solar wind interactions on the dayside of Mars may be more Venus-like than Earth-like due to the weakness of its magnetic field. However, its greater solar distance and low atmospheric densities will produce a weaker ionosphere which can be more easily penetrated by the solar wind than is the case for Venus. Finally, its weaker gravity field may allow more neutral atoms to reach high altitudes where they can be ionized and interact directly with solar wind through "mass loading". Each of these factors is capable of producing ionospheric effects quite different from any observed previously and they can be investigated only through a dedicated Mars Aeronomy Mission such as MAO.

C. Solar Wind Interaction

C.1 Overview

There are four distinct classes of solar wind interaction in the solar system. The solar wind interacts directly with the surfaces of atmosphereless, weakly magnetized objects, such as the Moon, and is absorbed. The solar wind interacts with the magnetic fields of planets, such as the Earth and Mercury, to form a magnetosphere as shown in the left-hand panel of Figure III.12. The nearly impenetrable nature of the magnetospheric boundary, or magnetopause, causes a bow shock to stand upstream of the planet. The solar wind is also strongly deflected by well developed ionospheres and requires a detached bow shock as displayed on the right-hand side of Figure III.12. Finally, the solar wind can interact directly with neutral gases through charge exchange, photo-ionization, and impact ionization. The newly created ions "mass load" the solar wind and slow it down. This kind of interaction is dominant at comets, but it is also observed to take place at Venus on a more limited scale. These

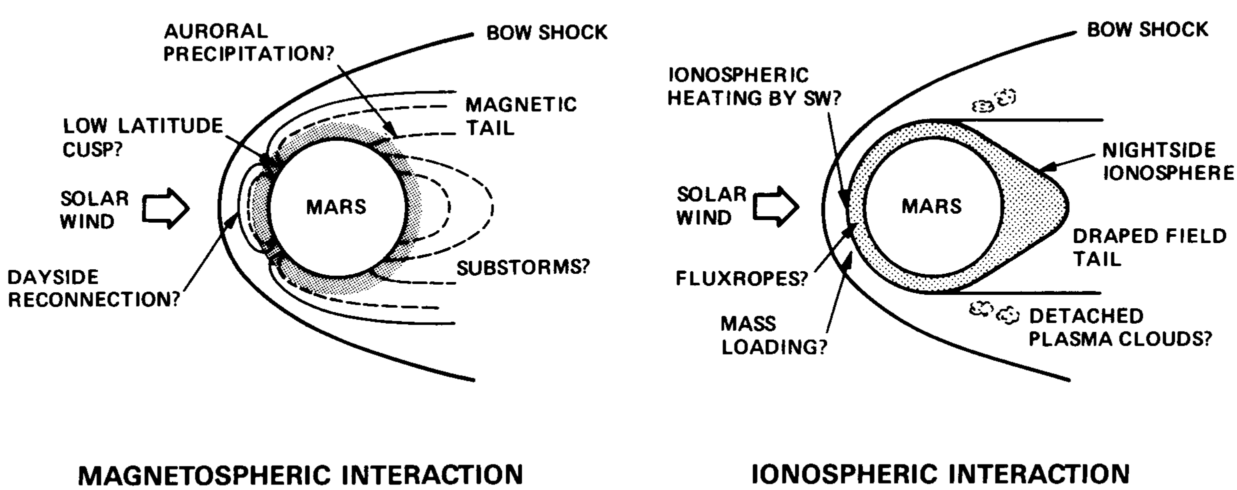


Figure III.12 Solar wind interaction scenarios at Mars are displayed under the assumptions of a significant intrinsic magnetic field (left) and a purely ionospheric interaction (right).

solar wind interaction processes have been studied at all of the planets from Mercury to Uranus with the exception of Mars. We know very little about Mars' interaction with the solar wind due to a lack of particles and fields instruments on previous NASA missions.

If Mars has a small intrinsic field, then the interaction may resemble that of the Earth and Mercury. However, the configuration and dynamics of the magnetosphere will differ greatly from those previously observed due to its small dimensions and electrically conducting ionosphere. MAO observations in a small Martian magnetosphere would add significantly to our understanding of fundamental plasma processes in planetary magnetospheres.

A Venus-type interaction at Mars is the other possibility. In this case, however, there would also be major differences as compared to what has been previously observed. The weakness of the thermal pressure in the Martian ionosphere relative to the solar wind ram pressure will insure strong interactions with the neutral atmosphere. Based upon what has been learned at Venus, it is also anticipated that the interplanetary magnetic field will frequently be able to penetrate and magnetize the Martian ionosphere. The end result should be much stronger modifications of the Martian upper atmosphere by the solar wind and interplanetary magnetic field than the already sizeable effects observed at Venus.

The solar wind interactions with the Martian satellites Phobos and Deimos are also of interest. Most probably they will be similar to that observed for the Earth's moon, where nearly all of the incident solar wind is absorbed. However, finite gyroradius effects should be more important at Phobos and Deimos due to their small diameters. For this reason it is scientifically desirable for MAO to make observations in the wakes of these moons, if it can be done without compromising the primary science objectives. We note that possible outgassing of Deimos has been reported by Soviet scientists, but the observations are controversial even within the Soviet community.

C.2 Present Knowledge

The only well-documented feature of the solar wind interaction with Mars is the bow shock which was first detected by Mariner 4 and subsequently observed by the Soviet Mars 2, 3 and 5 missions. The existence of the bow shock implies that the solar wind is being strongly deflected about Mars. However, in the absence of low altitude (i.e., <<1000 km) in situ observations it cannot be determined if the solar wind is being stood off by an intrinsic magnetic field at a magnetopause or the thermal pressure of the ionosphere at an ionopause. In principle, the shock shape can be used to find the distance to the subsolar boundary beyond which the solar wind cannot penetrate (i.e., the magnetopause or ionopause). However, estimates of this distance involve large uncertainties with values between 400 and 1000 km being derived by different investigators. This uncertainty makes it impossible to predict with confidence the type of solar wind interaction MAO will find.

If the solar wind boundary is located at relatively high altitudes of 400 km and above, then the ionosphere appears unable to provide suitable pressure to balance the incident solar wind. Profiles of ion density and temperature obtained by Viking imply that the ionospheric pressure is about a factor of four too low at an altitude of 400 km; the solar wind would have to reach altitudes of ~ 200 km before being stopped by the ionosphere. It has, therefore, been suggested in some studies that the needed pressure is being supplied by an intrinsic magnetic field. The strength of the inferred field at the surface is estimated between 20 and 50 nT.

If the solar wind interaction with Mars is magnetospheric, many of the features associated with Earth, Mercury, Jupiter, Saturn, and Uranus are to be expected. However, the smallness of the magnetic moment and the presence of an ionosphere should give rise to phenomena which are unique to Mars. In particular, MAO may provide extremely valuable observations of substorm processes in a small magnetosphere where convection is strongly influenced by a conducting ionosphere. The time scales for dynamic processes and the magnitude of the electric potential drop across the magnetosphere, which is responsible for charge particle energization, will be affected. The possibility also exists, based on Soviet orbiter results, that the magnetic dipole of Mars may have an unusual orientation (e.g., equatorial) or be dominated by higher order magnetic multipoles. However, even if the dipole field is nearly aligned with the rotation axis of the planet, as at Mercury and Earth, the scaling of various features leads to the prediction of significant differences in magnetospheric structure between these two planets. For example, it has been suggested that the auroral zones will extend to middle or even low latitudes on Mars and that magnetospheric convection will be significantly affected by newly created ions at high altitudes.

On the other hand, the solar wind plasma may interact directly with the ionosphere and upper atmosphere as shown in Figure III.13. Such a situation will involve the interaction of a magnetized plasma (the solar wind) with a conductor (the ionosphere) as well as effects due to charged particle-neutral particle interactions. The prototype for this kind of interaction is Venus. Venus has been visited by many spacecraft, including the Pioneer Venus Orbiter, one of whose objectives was to study how the solar wind influenced the Venus atmosphere/ionosphere. Despite the fact that Venus has no detectable intrinsic magnetic field, the solar wind is deflected about the ionopause with the formation of a detached bow shock. The solar wind depresses the top of the ionosphere until ionospheric plasma pressure balances the solar wind dynamic force and

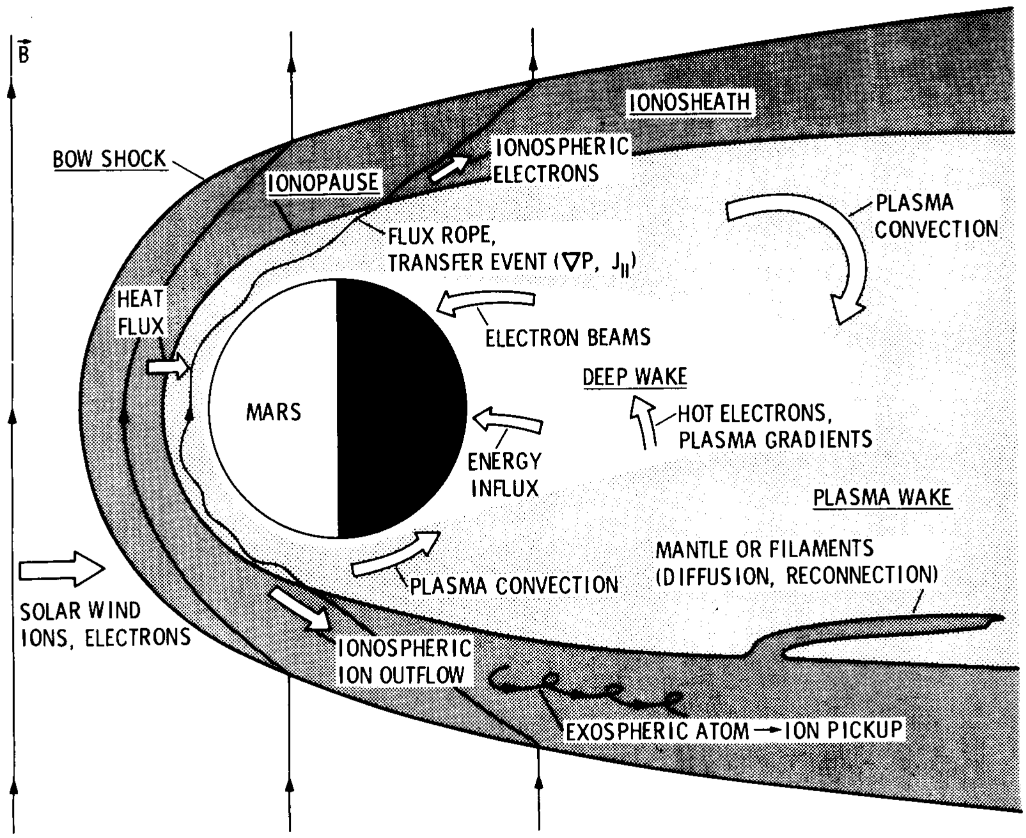
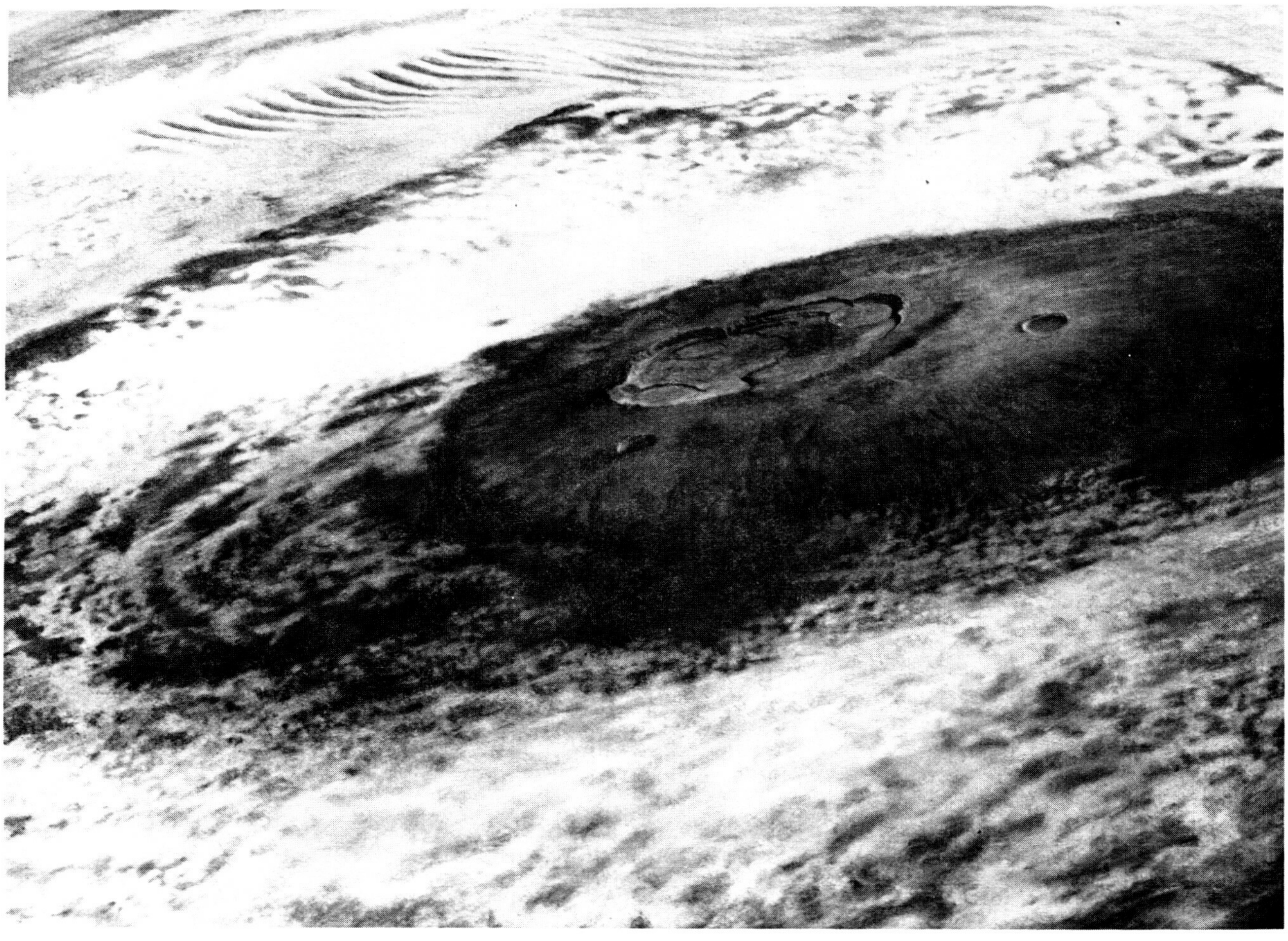


Figure III.13 A schematic diagram of the solar wind interaction with an unmagnetized Mars is presented. As discussed in the text, such an interaction is expected to be rich in plasma processes.

deflects it about the planet. However, at Venus the interplanetary magnetic field is able to penetrate the ionospheric barrier in two ways. First, bundles of magnetic field about 20 km across, termed "flux ropes", are created at the ionopause and slip into the planetary ionosphere. The ionosphere sweeps these flux ropes to the nightside where they may combine to form high field-low plasma density "magnetic holes". Secondly, when the solar wind dynamic pressure becomes too high to be stood off by the ionosphere, there is a large downward transport of interplanetary field lines into the ionosphere which becomes magnetized. The supply of field lines from the ionosheath is ultimately balanced at low altitudes by a combination of horizontal convection and electrical dissipation. Magnetic field observations in the Martian ionosphere should add greatly to our understanding of these processes at Venus, and elsewhere.

Finally, the Mars 5 orbiter had a high altitude nightside apoapsis and detected the presence of a magnetotail at Mars. The observations, however, were insufficient to determine whether the Martian magnetic tail was associated with the existence of a magnetosphere or due to the draping of interplanetary field lines about the ionosphere as at Venus. If the Mars magnetotail is magnetospheric in origin, then the existence of substorm activity (i.e., particle acceleration precipitation into the upper atmosphere and aurorae) becomes possible. As discussed earlier, such observations would be of major significance for our understanding of planetary magnetospheres.



IV. MAO SCIENCE OBJECTIVES AND MISSION REQUIREMENTS

A. Overview

Our information on the upper atmosphere/ionosphere and the solar wind interaction with Mars is almost as completely lacking as was our knowledge of these regions at Venus prior to the arrival of the Pioneer Venus spacecraft in 1978. Almost nothing is known about the local time, latitudinal, or seasonal behavior of either the thermosphere or ionosphere, not to mention the effects of the solar wind interactions on these regions. Therefore, the goals of the MAO mission have not changed significantly from those recommended by COMPLEX (1978) and the SSEC (1983). These goals are to:

- Determine the diurnal and seasonal variations of the upper atmosphere and ionosphere
- Determine the nature of the solar wind interaction
- Verify whether Mars has an intrinsic magnetic field
- Measure the present thermal and nonthermal escape rates of atmospheric constituents and determine what these rates imply for the history and evolution of the Martian atmosphere.

These goals are refined and extended in the next two sections on MAO aeronomy and solar wind interaction science objectives.

B. Aeronomy Objectives

The principal MAO aeronomy objectives identified by the SWT are to gain an understanding of the following processes and characteristics of the Martian upper atmosphere and ionosphere:

- Spatial variations of the upper atmosphere and ionosphere (altitude, local time, latitude, longitude)
- Energy budget for the ionospheric plasma populations (heat sources and energy loss processes)
- Dynamics of the atmosphere (energy and momentum transport processes)

- Temporal variations (seasonal, solar EUV variability, solar wind events)
- Sources of the nightside ionosphere (transport from dayside versus local production)

The broad scientific goals outlined above are generalizations of a vast number of specific questions one asks when exploring a new atmosphere for the first time. In large part these questions are based on what we know of other planetary atmospheres and how we might imagine that Mars will be different. The following are just a few of the specific questions that should be addressed:

1. How does the temperature and density of the upper atmosphere respond to seasonal variations caused by the large eccentricity of the Mars orbit combined with the tilt of its pole?
2. Do the current photochemical models adequately explain the composition of the Mars ionosphere and upper atmosphere?
3. Is the plasma pressure of the dayside ionosphere sufficiently large to exclude the solar wind and the interplanetary magnetic field (IMF), or does the solar wind penetrate the ionosphere and interact directly with the thermospheric neutrals?
4. What are the primary processes for atmospheric escape from Mars? Does oxygen escape by photochemical energization exceed the loss rate due to ion scavenging by the solar wind at the top of the ionosphere?
5. What are the sources and sinks for the nightside ionosphere? Are the intrinsic or induced magnetic fields large enough to inhibit the nightward flow of ions produced on the dayside by solar EUV? Are there important ion acceleration processes that cause planetary ion escape from the nightside ionosphere as observed at Venus?

6. Does Mars have a super-rotating thermosphere and mesophere as do Earth and Venus; i.e., is super-rotation a universal feature of planetary atmospheres, even those having very rapid and very slow rotation rates?
7. Does Mars have a cryosphere of the type observed in the lower thermosphere on the nightside of Venus?
8. Do lightning-like electrical discharges take place in the Martian atmosphere which generate whistler mode waves as are thought to occur at Venus, Jupiter, and Saturn?
9. Do the large amplitude thermal tides and gravity waves that are believed to be generated in the lower atmosphere by solar heating, dust storm effects, and high winds flowing over high relief surfaces propagate into the upper atmosphere? Does the possible absence of aurorally generated waves make Mars a better testing ground for the study of wave propagation from the lower atmosphere to the upper atmosphere?
10. What is the global mean circulation of the Martian upper atmosphere? What are the altitudinal, latitudinal, diurnal, and seasonal dependencies of the global dynamic state?
11. What is the global mean thermal structure of the upper atmosphere? What are the mesopause and exospheric temperatures? Does a temperature minimum exist near 100 km on the nightside?
12. What are the altitude, spatial, and temporal variations of the homopause?
13. What are the main forcing processes for the dynamics of Mars' atmosphere? What is the relative importance of in situ thermal insolation, eddy diffusion, tidal forcing, etc.?

14. What are the main perturbations from the global mean dynamic and thermal state? What are the causal mechanisms for such perturbations?

15. What is the deuterium-to-hydrogen ratio in the Martian atmosphere? What is the helium abundance?

We recognize that the above scientific questions cannot all be fully answered by a single mission, but the fulfillment of the measurement requirements identified below will result in major strides in our understanding of Mars. As discussed in the section on orbit requirements, the mission plan will require a careful trade-off among the various measurement requirements which, in turn, are driven by the scientific objectives. To the extent that we are now able to quantify and prioritize those objectives, the following is a list of the measurement requirements for MAO:

1. Measure the characteristics (i.e., composition, density, temperature, and winds) of the neutral upper atmosphere and ionosphere as a function of altitude to the lowest possible altitudes ($h \geq 130$ km in situ, $h \geq 70$ km remote).

2. Measure the diurnal variation of the upper atmosphere throughout the entire range of altitudes ($h \geq 70$ km).

3. Measure these variations over the widest possible range of latitudes consistent with obtaining good diurnal coverage and resolution.

4. Measure the effects of changing season and solar activity upon the atmosphere and ionosphere.

MAO science objectives pertaining to the lower atmosphere have been included when they are required to support primary MAO upper atmospheric investigations, or the lower atmosphere objectives involve capabilities or viewing geometries unique to MAO. The pursuit of the primary MAO goals requires the characterization of the lower atmosphere with regard to its thermal structure and the portion of the circulation which extends into the ionosphere and upper atmosphere. This, in turn, requires temperature sounding of the lower and middle atmosphere with either remote sensing of winds or their inference from the retrieved temperature field using the (geostrophic) thermal wind approximation. Temperature and/or wind sounding with vertical resolution of better than one atmospheric scale height could detect vertically propagating atmospheric tides and large-scale gravity waves. The context of changes in upper atmospheric structure or circulation can be provided by synoptic imaging which would show the presence or absence of condensate clouds, of both localized and large-scale dust storms, and of seasonal changes in the polar cap ice deposits. The observation of the vertical and horizontal distributions of photochemically important species such as water vapor would provide information needed to understand the photochemistry and circulation of the Martian middle and upper atmosphere. Thus, secondary scientific objectives with regard to the lower atmosphere and surface of Mars have been identified for MAO. They are to determine:

1. the thermal structure and circulation of the lower and middle Martian atmosphere

2. the presence and extent of condensate clouds

3. the presence and evolution of dust storms and their influence on the upper atmosphere

4. the spatial distribution of water vapor and other photochemically important species.

The theoretical framework relating upper atmosphere dynamics and thermodynamics to the momentum and energy forcing from below is partially in place. General circulation models of the upper atmosphere and chemical/dynamical models of the Earth's middle atmosphere exist, and these can be configured for Mars. Their testing at Mars should add greatly to our understanding of planetary atmospheres everywhere.

C. Solar Wind Interaction Objectives

A major MAO scientific objective will be to characterize the solar wind interaction with Mars. This knowledge will reveal which physical processes dominate the interaction and what their implications are for Mars' upper atmosphere and ionosphere. Structures and regions to be investigated in detail include:

- Bow Shock - The structure of the collisionless shock waves upstream of the planets is of fundamental interest to plasma physics. Furthermore, the strength, position, and shape of the bow shock are indicators of the nature of the interaction and the manner in which the flow is deflected about the planet.

- Magneto-ionosheath - The shocked solar wind plasma between the bow shock and the magnetopause or ionopause forms the high altitude boundary condition on the atmosphere. It is in this region that escaping atoms and molecules are most likely to be ionized, picked up by the solar wind, and transported away from the planet. A variety of important plasma wave and MHD phenomena, such as drift mirror waves and the plasma depletion layer, are also found in the sheath region.

- Magneto-ionopause - The interaction between the solar wind and either a planetary magnetic field or ionosphere results in the formation of a relatively thin current layer separating the two regimes. The structure and stability of this boundary determine the rate of mass and energy transport downward into the upper atmosphere. In the case of an ionospheric interaction, it is also the region where magnetic flux ropes are believed to be formed.

- Magnetotail - The interaction of the solar wind with both planetary magnetic fields and ionospheres results in the formation of long, bipolar magnetic tails. In the former case large magnetic stresses can build up which must eventually be released in the form of magnetic storms and substorms which accelerate charged particles and deposit large amounts of energy in the upper atmosphere. Magnetotails formed as part of the interaction with an ionosphere are not as well understood. However, their study is also very important to progress in the modelling of cometary magnetic tails which are thought to be generated by a similar mechanism.

As described, these features are expected to occur independently of whether the interaction is magnetospheric or ionospheric. If Mars possesses a significant planetary field, additional features are expected to be observed, such as a magnetopause boundary layer, a magnetospheric region containing quasi-trapped energetic particles, a cusp representing the demarcation between closed and open field lines, and a system of field aligned currents in the vicinity of the auroral zone. If, on the other hand, the interaction is ionospheric, it will be important to investigate the occurrence of flux ropes at low altitudes, nightside ionospheric "holes", and high altitude charged particle populations which might assist in maintaining the nightside ionosphere.

MAO will also address the influence of the solar wind interaction on the upper atmosphere. Because the solar wind penetrates to low altitudes, there will be significant transfer of energy, momentum, and mass from the solar wind into Mars' upper atmosphere. The corresponding atmospheric effects are heating (which appears to be required to account for Viking ionospheric observations), the generation of winds, possibly the control of global circulation patterns in the upper atmosphere, and changes in atmospheric abundances on evolutionary time scales. In the latter case, the removal or "scavenging" of atmospheric ions by the solar wind is also likely to be important.

Measurements of the charged particle distributions above the Martian atmosphere will directly determine their contributions to (a) heating of the Martian atmosphere, (b) the ionization rate in the ionosphere, and (c) the production of certain species (e.g., ozone). In particular, the existence of auroras can be decided with a combination of in situ particle measurements and sensitive, planet-wide imaging. The interaction of the solar wind with the planetary atmosphere and/or magnetic field is also expected to generate convective motions in the ionosphere, which are in turn coupled by collisions to the neutral atmosphere. The importance of precipitating charged particles in heating of the Martian upper atmosphere depends critically upon the effectiveness of local acceleration and heating mechanisms and the accessibility of these plasmas to the atmosphere.

The primary acceleration and heating mechanisms for plasmas in the vicinity of Mars are expected to be (a) heating of plasmas at the bow shock, (b) electric fields yielding magnetically field-aligned acceleration of plasmas into and away from the Martian atmosphere, (c) pick-up of atmospheric neutral atoms via charge exchange and/or photoionization within solar wind or magnetospheric flows, (d) magnetic reconnection, and (e) adiabatic and nonadiabatic transport of the plasmas in the magnetic and electric fields near the planet. An important objective of the in situ fields and plasma measurements will be to distinguish between these mechanisms. The identification of significant particle acceleration is important in (a) determining the associated energy influx into the upper atmosphere, (b) understanding the global dynamics of the interaction of Mars with the solar wind, and (c) extending our direct knowledge of the interaction of the streaming plasmas with planets, moons, and comets in the solar system.

There are currently no plasma wave observations available from the vicinity of Mars. Hence, we know nothing of the plasma wave spectrum associated with the Martian ionosphere or its interaction with the solar wind. It is, however, possible to speculate on the types of plasma waves present at Mars on the basis of Pioneer plasma wave measurements at Venus. For example, we can be quite certain that the bow shock upstream of Mars will be accompanied by strong, Doppler-shifted ion-acoustic and whistler mode waves. Electron plasma oscillations should be common primarily upstream of the shock. In the sheath region, whether it be an ionosheath or magnetosheath, it would be reasonable to expect ion-acoustic waves and whistler mode turbulence. At Venus, it has been demonstrated that whistler mode waves in the ionosheath can deposit a significant amount of energy into the topside ionosphere. Hence, the Mars Aeronomy Observer science objectives require that these regions be scrutinized by a plasma wave analyzer.

It is anticipated that the Mars Observer Mission will carry a magnetometer and determine the nature of the planetary magnetic field prior to the arrival of MAO. The MO magnetic field observations will, therefore, be very useful in the pre-launch optimization of the MAO particles and fields instrument parameters for either an ionospheric or magnetospheric interaction. The primary objective of the MAO magnetic fields investigation will be the study of the solar wind interaction and the support of the other particle and wave instruments (none of which will fly on MO). However, the low altitude periapsis of MAO will also allow for the study of crustal magnetic anomalies which will not be resolved by the higher altitude MO.

Finally, relatively little is known about optical emissions from the Martian atmosphere. Our primary knowledge has been gained from airglow spectroscopy at ultraviolet wavelengths with Mariners 6, 7 and 9. The primary dayglow emissions are associated with carbon dioxide with substantially lesser contributions from atomic oxygen. Resonantly scattered solar Lyman alpha from atomic hydrogen is also observed in substantial quantities. Although there are no reports of emissions associated with the influx of charged particles into the upper atmosphere, it is also true that there are no global images that could be used to show their existence. The flow of solar plasma around the Martian magnetosphere or ionosphere is expected to produce some transport of particles into the upper atmosphere. Imaging of the emissions is the only means by which an instantaneous global survey of the particle influx can be achieved. In turn, these patterns of emissions can be correlated with simultaneous in situ spacecraft observations to develop a global model for the dynamics and topology of the plasma regimes above the atmosphere. Such objectives can only be achieved when global imaging is combined with simultaneous in situ measurements of ionospheric and magnetospheric phenomena. The use of auroral imaging at Earth has proven extremely successful in providing a global reference for ionospheric and magnetospheric phenomena, such as responses to the solar wind, global maps of the regions of major particle influxes, and the behavior of these energy influxes during magnetic substorms. A similar instrument on the Mars Aeronomy Observer would provide the best possibility for achieving a global reference point for the in situ fields and plasmas measurements.

V. INSTRUMENTATION

A. Recommended Payload

After reviewing the science objectives of the Mars Aeronomy Observer Mission, the MAO SWT has recommended a core and a secondary payload. As detailed in Table V.1, the core payload consists of ten instruments distributed among the neutral atmosphere, ionosphere, and solar wind interaction areas. All of the instrument technologies required by MAO are well developed and have been flown on previous missions. Indeed, in the best spirit of the Planetary Observer Program it is not unreasonable to expect that some flight spare hardware from other missions may be eventually be used on MAO. No prioritization has been specified for the core payload on the grounds that all ten instruments contribute key measurements and all are essential to the mission objectives. In both the aeronomy and solar wind interaction disciplines most scientific questions are resolved only through the synergistic combination of observations by multiple instruments.

The secondary payload consists of three instruments which the SWT recommends be included on MAO, if resources permit. The infrared atmospheric sounder and the ultraviolet/visual synoptic imager would enhance the core payload by providing information about the state of the lower atmosphere and enable the investigation of the coupling between the lower and upper atmosphere. The UV observations would also allow for the observation of global patterns of energetic particle precipitation which might correspond to Martian analogues of the Earth's auroras or the weak aurora-like emissions detected by the Pioneer Venus Orbiter. Finally, a separate neutral winds/temperatures spectrometer would significantly augment the neutral mass spectrometer in making vector wind measurements by increasing both angular and temporal resolution. In this case no prioritization was specified by the SWT because the anticipated increase in MAO science return as a result of including any one of these instruments was

TABLE V.1 MAO SWT RECOMMENDED INSTRUMENTS

	MASS	POWER	TELEMETRY[1]
CORE PAYLOAD			
Neutral Mass Spectrometer[2] (NMS)	10.0	8.5	180
Fabry-Perot Interferometer (FPI)	13.5	5.5	30
UV + IR Spectrometer (UV + IRS)	5.0	7.0	130
Ion Mass Spectrometer (IMS)	2.5	1.5	60
Retarding Potential Analyzer + Ion Driftmeter (RPA + IDM)	4.5	4.0	80
Langmuir Probe (ETP)	2.0	4.0	30
Plasma + Energetic Particle Analyzer (PEPA)	10.0	9.0	320
Magnetometer (MAG)	3.0	3.5	200
Plasma Wave Analyzer (PWA)	5.5	3.5	130
Radio Science[3] (RS)	4.5	12.5[4]	-
	60.5 kg	59.0 W	1160 bps
SECONDARY PAYLOAD			
Infrared Atmospheric Sounder (IAS)	8.0	7.5	260
UV + Visual Synoptic Imager (UV + VSI)	9.0	8.0	1000
Neutral Winds/Temperature (NWTS) Spectrometer	10.0	9.0	180
	27.0 kg	24.5 W	1440 bps
TOTAL	87.5 kg	83.5 W	2600 bps

1 Individual instrument rates can be highly variable and will depend upon the final payload and orbit selection. The rates listed are based upon typical duty cycles for each experiment and they have been averaged over the orbit (i.e., 6,000 x 150 km orbit has been assumed).

2 Includes limited wind measuring capability.

3 Consists of S-band transponder and stable oscillator.

4 10 W (continuous) for the stable oscillator and 25 W (10% duty cycle) for the S-band transponder.

comparable, and because various programmatic considerations at the time of final selection will likely play a large role in the ultimate decision regarding instruments in the secondary payload. A brief description of the measurement requirements in the neutral atmosphere, ionosphere, and solar wind interaction regions is given below, along with a description of the state-of-the-art instrumentation available for MAO. Table V.2 lists the major MAO regions and processes to be investigated and the main instruments which contribute to each area.

B. Instrument Descriptions

The parameters measured by the instruments in the core and secondary payloads are outlined in Table V.3. The upper atmosphere is addressed by four instruments, one in situ (neutral mass spectrometer) and three remote (Fabry-Perot Interferometer, radio science and UV+IR spectrometer). The ionospheric instruments are also four in number, three in situ (ion mass spectrometer, retarding potential analyzer, and Langmuir probe) and one remote (radio science). Finally, the solar wind interaction is examined by 3 instruments, all in situ (plasma + energetic particle analyzer, magnetometer, and plasma wave analyzer). In many cases the instrument capabilities extend outside of these main regions (e.g., the ion mass spectrometer and Langmuir probe can make some measurements in the shocked solar wind, while all of the solar wind interaction instruments can make observations in the ionosphere), but this categorization reflects the regions where observations from each instrument will make their major contributions.

Neutral mass spectrometers (NMS) have been flown on numerous earth orbiting aeronomy missions as well as the Viking and Pioneer Venus planetary missions. All of the spectrometers are alike in that the neutral gas is collected, ionized, accelerated, and then separated electromagnetically using either

TABLE V.2 MAO SCIENCE OBJECTIVES AND INSTRUMENTS

Regions		
Neutral Atmosphere Structure	Ionospheric Structure	Solar Wind Interaction
NMS	IMS	PEPA
FPI	RPA + IDM	MAG
RS	ETP	PWA
UV + IRS	RS	IMS
IAS*	MAG	RPA + IDM
NWTS*	PWA	ETP
UV + VSI*	PEPA	RS
		UV + VSI*

Processes					
Photochemistry + Escape Rates	Global Energy Balance (Thermal+Winds)	Nightside Ionosphere	Dayside SW Interaction	Pickup Of Planetary Ions	Magneto-tail Dynamics
NMS	NMS	IMS	PEPA	PEPA	PEPA
IMS	FPI	RPA + IDM	MAG	MAG	MAG
UV + IRS	NWTS	ETP	PWA	PWA	PWA
ETP	ETP	PEPA	IMS		
IAS*	IMS	MAG	ETP		
NWTS*	RPA + IDM	PWA	RPA + IDM		
	PEPA	UV + VSI*			
	PWA				
	IAS				
	UV + VSI*				

*Secondary payload instrument

TABLE V.3 INSTRUMENT CAPABILITIES

Instrument Type	Measurements
CORE PAYLOAD	
Neutral Mass Spectrometer	Number densities of neutral species, isotopic abundances, temperatures, and two components of cross-track wind velocity.
Fabry-Perot Interferometer	Atmospheric vector wind and temperature altitude profiles in the lower thermosphere ($h < 200$ km), metastable densities, volume emission rate profiles, rotational temperatures, and velocity distributions for escaping atomic oxygen.
UV+IR Spectrometer	H, O, C, and N altitude profiles from limb observations and nadir column densities of O_3 and CO_2 which allow for modeling of escape rates and surface densities; IR channel measures water vapor.
Ion Mass Spectrometer	Number densities of ion species and their isotopic abundances.
Retarding Potential Analyzer and Ion Driftmeter	Ion temperatures, densities, and velocities in the ionosphere.
Langmuir Probe	Electron temperature and density; solar EUV flux monitor.
Plasma and Energetic Particle Analyzer	Solar wind and magnetospheric particle velocity, density, temperature, and composition.
Magnetometer	Magnetic field properties in the solar wind, magnetosheath, magnetosphere, and ionosphere.
Plasma Wave Analyzer	Plasma wave properties in the solar wind, magnetosheath, magnetosphere, and ionosphere.
Radio Science	Atmospheric and ionospheric density and temperature altitude profiles.
SECONDARY PAYLOAD	
Infrared Atmospheric Sounder	CO_2, H_2O, aerosols, thermal structure, and winds ($h \leq 70$ km).
UV + Visual Synoptic Imager	Global observations of stimulated emissions due to charged particle precipitation and NO, O_3, and dust in lower atmosphere.
Neutral Winds and Temperature Spectrometer	Thermospheric winds and temperature.

double-focusing deflection or quadrupole filtering to identify the various molecular and atomic species present. In addition to number densities, information on gas temperature and neutral winds can also be determined from the NMS measurements. Derived parameters from these observations include vertical profiles and scale heights by species, altitude of the homopause, eddy coefficients, isotopic composition for atmospheric evolution studies, thermospheric wind patterns, and amplitude/wavelengths of density waves in the lower thermosphere.

A Fabry-Perot interferometer (FPI) was part of the Dynamics Explorer payload and is planned for a number of future atmospheric missions such as UARS. The instrument uses a Fabry-Perot interferometer to measure Doppler shifts and temperature broadening of selected metastable atoms and molecules in the upper atmosphere (h > 70 km). Using these measurements vertical profiles of thermospheric winds and temperatures may be derived. The FPI observations are particularly powerful when combined with in situ wind measurements as is planned for MAO. Observations of this type have been of major importance to studies of ionosphere - magnetosphere coupling and the deposition of energy at high latitudes associated with auroral current systems and particle precipitation.

The UV + IR spectrometer will allow the measurement of escape fluxes of H, O, C, and, possibly, N from their altitude profiles at the planet's limb. Nadir column densities of ozone and carbon dioxide (and hence the surface pressure) are accessible through measurements of the absorption of surface-scattered sunlight (for ozone) and Rayleigh scattering of sunlight (for carbon dioxide). Raster imaging of the disk from near apoapsis will build up simultaneous maps at many wavelengths. A two-dimensional detector in the image plane of a suitable spectrograph can record the spectrum along one dimension, while spatial resolution along the slit is preserved in the other. The capability of recording a complete spectrum in a single short exposure, in which all wavelengths are integrated simultaneously, opens the possibility of performing extremely useful observations of stellar occultations by the atmosphere. From these measurements of atmospheric absorption (as a function of wavelength and altitude) vertical profiles of CO_2 (from the surface to above 150 km), O_3 (from 0 to perhaps 70 km, depending on abundance) and O_2 can be derived. These profiles can be interpreted in terms of the vertical temperature structure from the surface well into the thermosphere, on both day and night sides.

The ion mass spectrometer (IMS) performs the same functions for the charged ions in the ionosphere that the NMS does for the neutrals: measurements of composition, densities, and isotopic abundances. An inlet pointing in the ram direction allows for collection of ionospheric plasma which is accelerated by an electric field and the electromagnetic separation of the various species. The IMS measurements will be used to study spatial and temporal structure of the ionosphere and other regions where low-energy ion densities exceed a few ions/cm^3 (ionosphere, ionosheath, and inner magnetosphere). These instruments have a long history of flight experience beginning in the 1960s, including the OGO's, AE/DE, and Pioneer Venus.

A retarding potential analyzer (RPA) is used to measure the energy distribution of low energy charged particles normal to its entrance aperture. Measurements of the ram energy distribution of thermal ions allows for the deduction of the temperatures, concentrations, and the ram velocity components of the various ion constituents. If an ion mass spectrometer is used as the standard for composition, then the RPA operation and data reduction can be simplified. The RPA can also be used to measure electron temperature. These devices have a long heritage going back over two decades, but have been flown most recently on OGO-6, Atmosphere Explorer C, D, and E, Dynamics Explorer 1 and 2, Viking, and Pioneer Venus. The ion drift meter (IDM) is an extension of the RPA which can measure two mutually perpendicular angles of arrival of thermal ions in a spacecraft frame of reference. In conjunction with the ram velocity component measured by the RPA these data allow the deduction of the two transverse bulk ion velocity components (e.g., the horizontal and vertical components from a circular orbit). A very successful heritage for this device was established on the Atmosphere Explorer and Dynamics Explorer satellites. The combination of the RPA and IDM provides the full bulk velocity vector of the low energy thermal ions. In earth orbit this permits the measurement of not only the perpendicular (E x B) ion velocity components, which can be derived from electric and magnetic field measurements, but also the velocity component parallel to the magnetic field. The capability to directly measure the velocity vector is essential for the Martian ionosphere, where the convection electric fields are expected to be too small to measure with double probe techniques.

The Langmuir, or electron temperature, probe (ETP) is a small cylindrical sensor that is mounted at the end of a short boom (25-100 cm) and used to make in situ measurements of the ionospheric electron temperature and density as well as the spacecraft potential. The voltage of the collector is changed while the collected current is measured and inflight processing of the volt-ampere characteristic provides measurements at rates of 2 to 10/s. In addition to the plasma measurements, sampling of the collector photo-emission current in regions of low plasma density allows the total solar UV and EUV flux to be monitored for use in understanding solar induced variations of the state of the thermosphere and ionosphere. The ETP data are needed for the study of ionospheric thermal structure and photochemistry and for the study of solar wind interactions. Finally, the occultation of the solar UV and EUV flux can provide height profiles of the lower thermospheric density above the terminator. The recent heritage of ETP consists of instruments on Atmosphere Explorers C, D and E, Pioneer Venus Orbiter and Dynamics Explorer.

The plasma and energetic particle analyzer (PEPA) will measure the ion and electron environment of Mars from 0.5 eV to 1 MeV. The plasma analyzer portion of the package will cover the energy range below 50 keV and characterize the upstream solar wind, the ionosheath region including picked-up atmospheric ions, and the plasma in the magnetosphere or solar wind interaction regions. A number of different plasma instrument designs are in use today with most based upon either curved plate analyzer or Faraday cup techniques. The energetic particle analyzer, a small cluster of solid state detectors, will cover the energy range 30 keV to 1 MeV and will provide measurements of the number and energy fluxes of higher energy solar and magnetospheric charged particles entering the upper atmosphere. All aspects of the PEPA package are well developed and have been used successfully on many missions over the last 25 years, including the Explorer, Pioneer, IMP, OGO, Voyager, and ISEE spacecraft.

Vector magnetometers (MAG) based upon optical pumping and fluxgate techniques are available and have been a part of all U.S. planetary missions with the exception of Mariner 6-9 and Viking. Present day magnetic field instruments have absolute accuracies and stabilities of better than 0.1 nT over the 0-10 Hz passband. They are generally boom mounted up to 10 m from the spacecraft to avoid contamination of the observations by spacecraft magnetic fields. However, with a modest magnetic cleanliness program and opportunities to measure the spacecraft fields using variance methods when apoapsis is in the solar wind, the contamination issue is not expected to be serious for MAO. The MAO magnetometer will extend our knowledge of any intrinsic field detected by the Mars Observer Mission to low altitudes where crustal anomalies can be mapped and to high altitudes where the magnetic fields and currents in the solar wind interaction region and magnetosphere will be investigated. These measurements will also be essential to the studies of the ionosphere where magnetic fields of all types (intrinsic, induced, and fluxropes) affect the thermal and electrical conductivities and the global convection patterns.

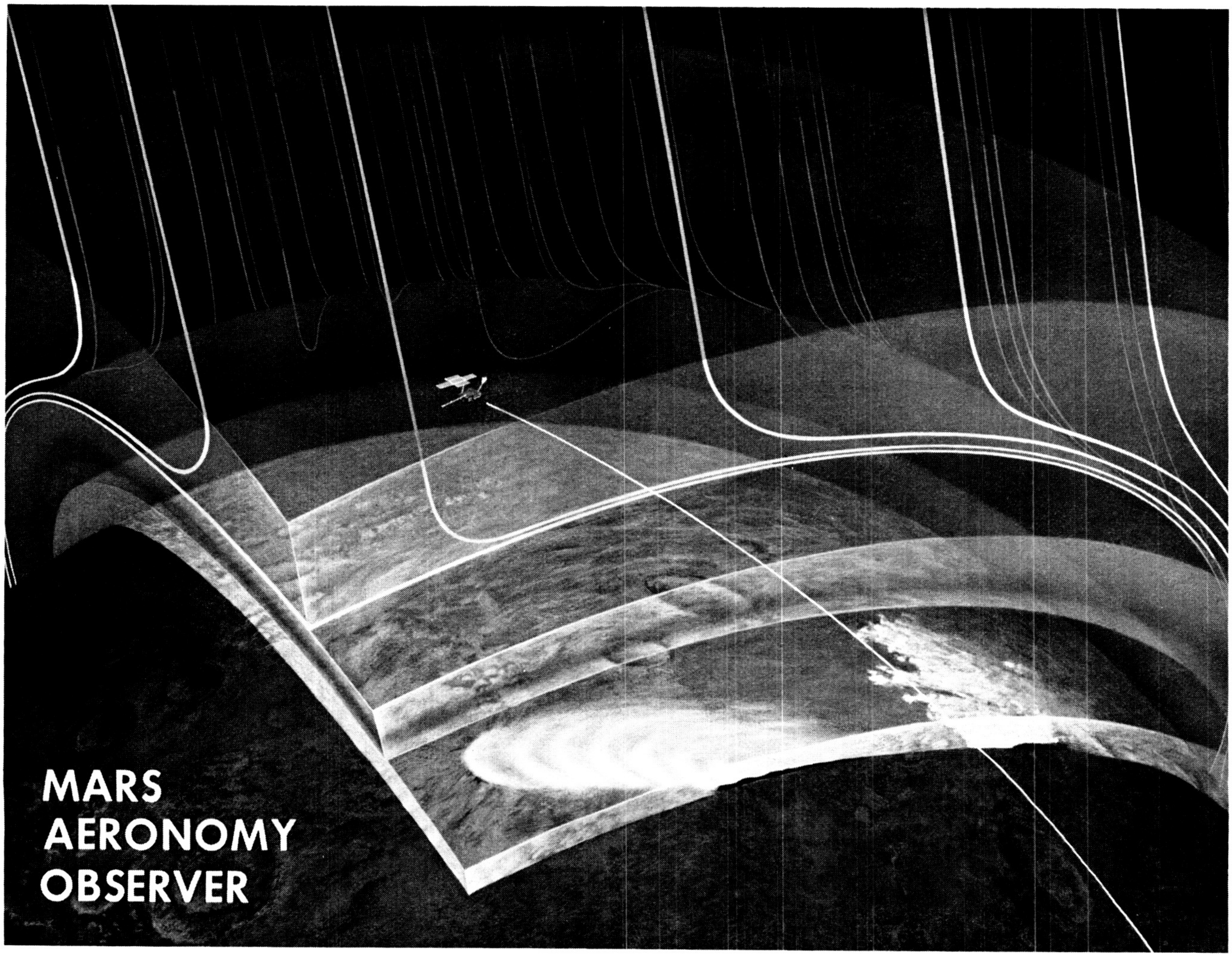
Plasma wave analyzers (PWA) measure the electric and magnetic components of ambient waves over a wide bandpass of 0-3 MHz. The data rate of these instruments is usually reduced through onboard spectral analysis with only peak/mean wave power per frequency channel and occasional waveforms being telemetered. The sensors are electric dipole antennas and magnetic search coils located on the spacecraft or the magnetometer boom. The PWA measurements will be used to study plasma micro-processes and also as a diagnostic for energy dissipation through wave damping. Numerous important processes in the Mars plasma environment will generate unstable, non-Maxwellian particle distributions (i.e., super-critical current layers, pickup of cold ions, etc.) which must give up kinetic energy as they relax toward equilibrium. This energy goes into plasma waves which ultimately deposit it, often after propagating from one region to another, back into the plasma as heat. PWA instruments are well developed and have flown on many terrestrial and planetary missions such as IMP, OGO, ISEE, DE, AMPTE, and Voyager.

Radio Science (RS) has been a part of all US planetary missions. The "instrument" is the S and X band telemetry system and an onboard stable oscillator. During orbits when the spacecraft occults the Martian ionosphere and atmosphere, vertical profiles of the index of refraction are computed on the ground and used to infer altitude profiles of the electron density and the neutral atmosphere temperature and pressure. An important feature of radio science is that the locations of the occultations are generally spread over a wide range in latitudes. In this way the RS measurements extend the overall coverage of the mission in solar zenith angle. Since the transponders used for the Planetary Observer spacecraft telemetry system may not include the frequency range necessary for radio science measurements, the hardware for this experiment will consist of a separate S-band transponder and a stable reference oscillator.

The infrared atmospheric sounder (IAS) employs filtering and pressure modulation to provide atmospheric temperature profiles (0-70 km) as well as surface temperatures, and information on water vapor mixing ratio and dust loading. Global maps are obtained with a typical horizontal spatial resolution of 10-100 km. Inclusion of this secondary payload experiment would provide significant data on the state of the lower atmosphere at the time of the MAO mission and allow for additional science results concerning the coupling of the lower to the upper atmosphere. Similar instruments have been used extensively on earth orbiting meteorological satellites, for example, NIMBUS 6/7, and on the Pioneer Venus Orbiter.

The UV and visual synoptic imager (UV + VSI) represents a merger of two global imagers with the primary optics and much of the supporting electronics being shared. The ultraviolet and visual wavelength sensors would remain separate. The ultraviolet portion of the experiment provides measurements of stimulated emissions (Lyman alpha, OI 1304, 1356 Å and CO, CO_2^+ molecular bands) from the upper atmosphere due to the influx of solar and magnetospheric particles. Although the solar wind interaction at Mars probably will not generate the particle fluxes necessary to produce intense terrestrial-type auroras, the UV synoptic images are expected to be very useful in organizing global aspects of the solar wind interaction and its coupling to the upper atmosphere. The visual portion of the synoptic imager has as its primary objectives the detection and monitoring of dust storms, condensate clouds, and seasonal changes in surface albedo and polar ice deposits. These daily images will extend the MAO science results into the lower atmosphere and allow for the study of how conditions in the upper atmosphere depend upon the variations at much lower altitudes. In this way, the inclusion of the UV + VSI instrument from the secondary payload would provide significant new information on both the high and low altitude boundary conditions on the upper atmosphere, MAO's primary objective. The ultraviolet portion of this instrument has flown on DE and will be part of the International Solar Terrestrial Program's "Polar" spacecraft payload. A version of the visual imager is under development and has been selected for MO.

The neutral winds and temperature spectrometer (NWTS) is a neutral mass spectrometer dedicated and optimized to make three dimensional velocity and temperature measurements by means of a system of movable baffles. The modulation in the flux of neutrals reaching the spectrometer as a function of the inlet-baffle geometry provides the information required to derive the three wind components and temperature parameters. The NMS in the core payload has a limited winds/temperature measuring capability. It will be primarily directed toward composition and density. The inclusion of NWTS as part of the secondary payload would significantly enhance the MAO winds/temperatures observations. The NWTS observations would constitute an important addition to the upper atmosphere dynamics and energy balance results derived from the mission. The NWTS technology has been developed over the last decade in the AE series of aeronomy missions and was most recently flown on Dynamics Explorer.


MARS
AERONOMY
OBSERVER

VI. MISSION DESIGN

A. Spacecraft Requirements

In early 1986 a spacecraft was selected for the first mission in the Planetary Observer Program, the Mars Observer (MO). It is anticipated that subsequent Observer missions will use the MO spacecraft with minimal modifications. Since the selection of this spacecraft has only recently taken place, the MAO requirements have been compared with those of MO as specified in the Planetary Observer Request-for-Proposals issued by NASA in 1985. Table VI.1 displays the mass, power, and telemetry requirements for the two missions. As indicated, the MO spacecraft will be able to accommodate the MAO core payload instrument pointing requirements and maintain good mass and power margins. Inclusion of the three secondary instruments also appears possible depending upon the actual capabilities of the selected spacecraft. A magnetometer is included in the MO strawman payload and a moderate level of DC magnetic and AC electromagnetic cleanliness has been specified in the RFP. Therefore, it is expected that the MAO particles and fields instruments will find the MO spacecraft a suitable platform for

TABLE VI.1 MAO AND MO SPACECRAFT REQUIREMENTS

	Mass (kg)	Power (W)	Telemetry (kbps)	Pointing (Knowledge, Stability, Control) (mrad)
MO	85	91	1.5-6.0[1]	10, 3, 2
MAO				
Core Payload	61	59	1.2	10, 3, 2
Core + Secondary Payload	87.5	83.5	2.6	10, 3, 2

[1]Continuous tape record rate based upon Planetary Observer guideline of one 32 m DSN pass per day. The rate varies in response to changes in down-link performance as Earth-Mars distance varies.

making measurements without any major modifications to the spacecraft subsystems. Finally, the MO spacecraft will be equipped with variable speed tape recorders which will be played back during one 8 hour Deep Space Network tracking pass per day. The playback rate is expected to be the factor limiting the quantity of data taken per day by the science instruments. The anticipated average instrument record rates of 1.5 - 6.0 kbps will allow the MAO instruments to make far higher time resolution observations than were generally available for the aeronomy and particles and fields experiments on the Pioneer Venus Orbiter. In addition, the use of tape recorders and new onboard data compression techniques will add greatly to the overall capability and flexibility of MAO for sending back comprehensive, high resolution data sets.

A subtle difference between MAO and MO is that the aeronomy mission science objectives require an eccentric orbit, as will be discussed later in this section. As a result, during some portions of the mission the spacecraft will be in the shadow of Mars for periods of up to several hours. These occultations will correspond to periods when the spacecraft is in the magnetotail (see Figure III.12) and a number of the instruments, such as PEPA, MAG, and PWA, will wish to make tail measurements. For this reason it is strongly recommended that the MAO project examine the battery capacity of the spacecraft selected for MO and, if necessary, investigate the cost and science benefits of modifying the existing battery power system to allow for magnetotail observations while the spacecraft is in occultation.

The spacecraft which was selected for the Mars Observer mission is three-axis stabilized. For most of the MAO instruments, NMS, IMS, RPA+IDM, ETP, MAG, PWA, RS, IAS, and NWTS, either a 3-axis or spinning spacecraft is acceptable with each experiment experiencing only modest science losses if its preferred mode of orientation is not always available. For example, it would take the ram-oriented instruments somewhat longer to complete a measurement if the spacecraft spin periodically rotates them into the wake. For three instruments the science compromises are more severe. A spinning spacecraft would make it very difficult for the FPI to perform its high precision spectral measurements and the UV+IR spectrometer would have to give up its stellar occultation mode where individual stars are tracked as they pass beneath the limb of the planet. Airglow measurements would also be severely compromised. There is one instrument whose measurement capability is significantly enhanced by a spinning spacecraft and degraded by 3-axis stabilization. The plasma and energetic charged particle analyzer differs from the ionospheric and atmospheric particle instruments in that at higher altitudes the spacecraft is generally moving slowly with respect to the charged particles being measured. As a result there is no single preferred direction for the PEPA sensors that will allow them to observe all of the ambient particle populations. The standard solution is for magnetospheric plasma and energetic particle experiments to make measurements over an angular range, or fan, in the plane containing the spacecraft spin axis so that the rotation of the spacecraft will fill in the azimuthal angle to provide 4π steradian coverage. On the 3-axis stabilized spacecraft selected for MO, it may be necessary for PEPA to incorporate additional sensors or accept degraded angular resolution through the use of wide angle detectors. Given the conflicting requirements of FPI, UV+IR, and PEPA, the optimum spacecraft for MAO would be of the dual-spin variety where one section is fixed relative to the planet, while the other spins. However, it was the sense of the SWT that, overall, the stabilization mode of the spacecraft selected for the Mars Observer Project will not seriously affect the ability of MAO to achieve its science objectives.

B. Launch Opportunities

Figure VI.1 shows the Mars Observer propulsion requirements for a launch in 1990 followed by possible MAO opportunities for the remainder of the decade. The vertical bars indicate both the ΔV necessary to inject the spacecraft into an interplanetary trajectory to Mars and the additional ΔV needed to insert it into orbit once it gets there. Note that all of the 1992-6 Mars opportunities require less ΔV, both at Earth (Δ-inject) and at Mars (Δ-insert) than MO. How this margin can be used to benefit the mission science objectives depends upon the type of propulsion system that is proposed and on the structural margin of the payload shelf. If the injection motor is solid-fueled, then it either will be off-loaded or the MAO spacecraft ballasted from the Mars Observer specifications. This would not allow any science advantage. However, the insertion motor may well be an integrated liquid fuel system which could use the extra fuel to allow extended lifetime, more time in high-drag low-periapsis orbits, additional plane changes, or a heavier payload than Mars Observer (provided adequate structural and other spacecraft resource margins exist). These alternatives all offer substantial scientific benefits.

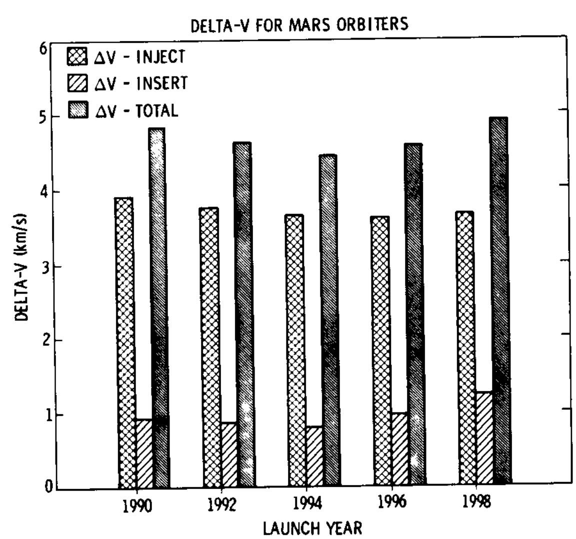


Figure VI.1. Propulsion, or Δ V, requirements for missions to Mars in the 1990's are displayed as a function of year. MO will launch in 1990 and MAO is a candidate for 1992.

C. Mission Plan

The orbit requirements specified in Section IV are quite diverse with both low (h<150 km) and high (h>6,000 - 10,000 km) altitude observations being essential. There is the further need to map out to the greatest extent possible the three dimensional space between these altitudes during the nominal mission. The length of the nominal mission, 1 Mars year = 687 Earth days, is set by the expected capabilities of the MO spacecraft and the focused science philosophy of the Planetary Observer Program. Finally, in order to obtain maximum information on the spatial structure of the upper atmosphere and solar wind interaction region it is desirable for the spacecraft altitude, latitude, and local time parameters to be uncorrelated over the duration of the mission (i.e., sampling a given range in altitude only near certain latitudes or local times will leave ambiguities as to the nature of any gradients observed).

These orbital requirements are common to many aeronomy and particles and fields missions. The degree to which they are met for any given mission is always limited by the resources available, principally, cost in the form of spacecraft propulsion capability and mission lifetime. An approach that has been used extensively in the past (i.e., AE missions at the Earth) is to allow the natural decay of the orbit due to atmospheric drag to gradually lower apoapsis and cause the spacecraft to sweep out a broad volume. Such Mars orbiter scenarios have been investigated extensively by the Goddard Space Flight Center (L. H. Brace, Study Scientist). Figure VI.2 displays the evolution of one candidate aeronomy orbit at Mars over a period of about two Earth years (note: only a small number of representative orbits are displayed). An inclination of 63.4° is used to keep periapsis near the equatorial plane (i.e., zero apsidal rotation rate) and to provide for rapid diurnal motion of periapsis (i.e., high nodal rotation rate). Onboard propulsion is used to prevent re-entry into the

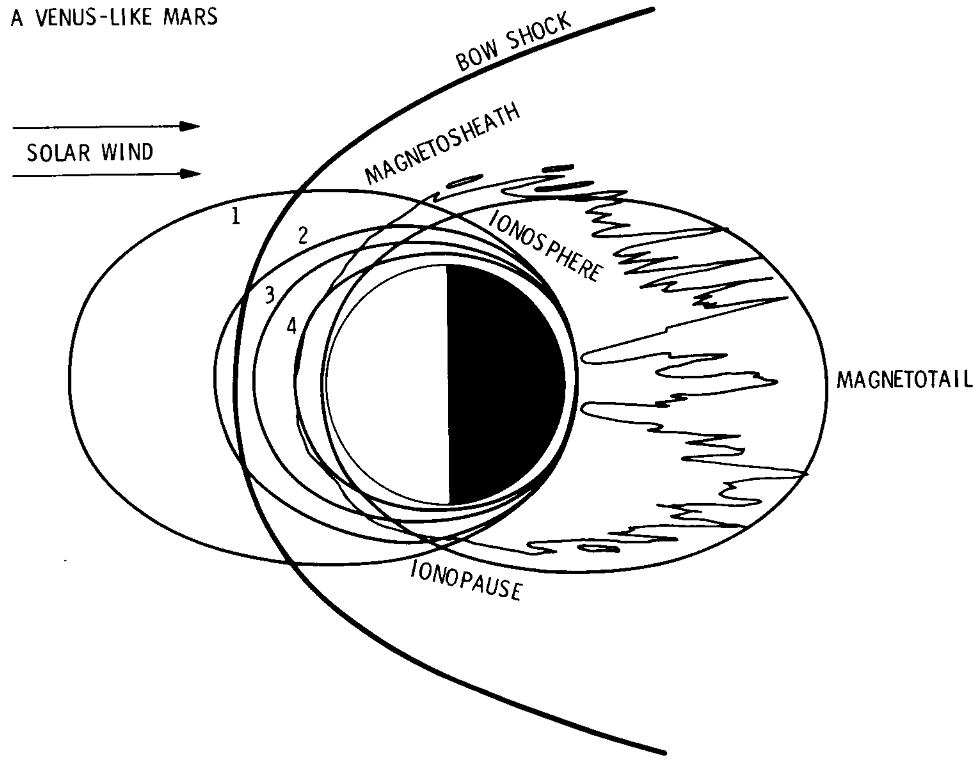


Figure VI.2. The evolution of a low apoapsis MAO candidate at Mars under the influence of atmospheric drag is displayed. Note the excellent in situ sampling of the various interaction regions.

atmosphere, maintain the final near-circular phase, and boost the spacecraft into a safe quarantine orbit at the end of the mission. This approach has a number of advantages, including good volume and diurnal coverage. The disadvantages are its lack of high latitude in situ atmospheric observations until the very end of the mission (i.e., the circular phase) and its possible violation of planetary quarantine requirements concerning orbit lifetime and dwell time at low altitudes.

An alternate orbit scenario was developed by the JPL Planetary Observer Planning Team which has the advantages of providing both local time and latitude coverage during the 687 day nominal mission and meeting anticipated quarantine requirements. Initially, the spacecraft is inserted into a 42,000 by

130 km reconnaissance orbit, Phase I in Figure VI.3. This orbit is expected to satisfy quarantine requirements (i.e., it will not re-enter before 2009) and it still provides for the essential low altitude aeronomy measurements and high altitude passes through the magnetotail and into the solar wind. After a period of 130 days, during which the effects of atmospheric drag are assessed, the project will order a burn to take apoapsis down to 6000 km (or lower if the reconnaissance drag measurements show that quarantine safety merging can be maintained). In this lower altitude Phase II portion of the mission the orbit inclination remains 102°, the same as for Phase I, and the resultant apsidal rotation carries periapsis through almost 360° in 320 days. During this period of mapping latitude variations, the nodal rotation is such that MAO

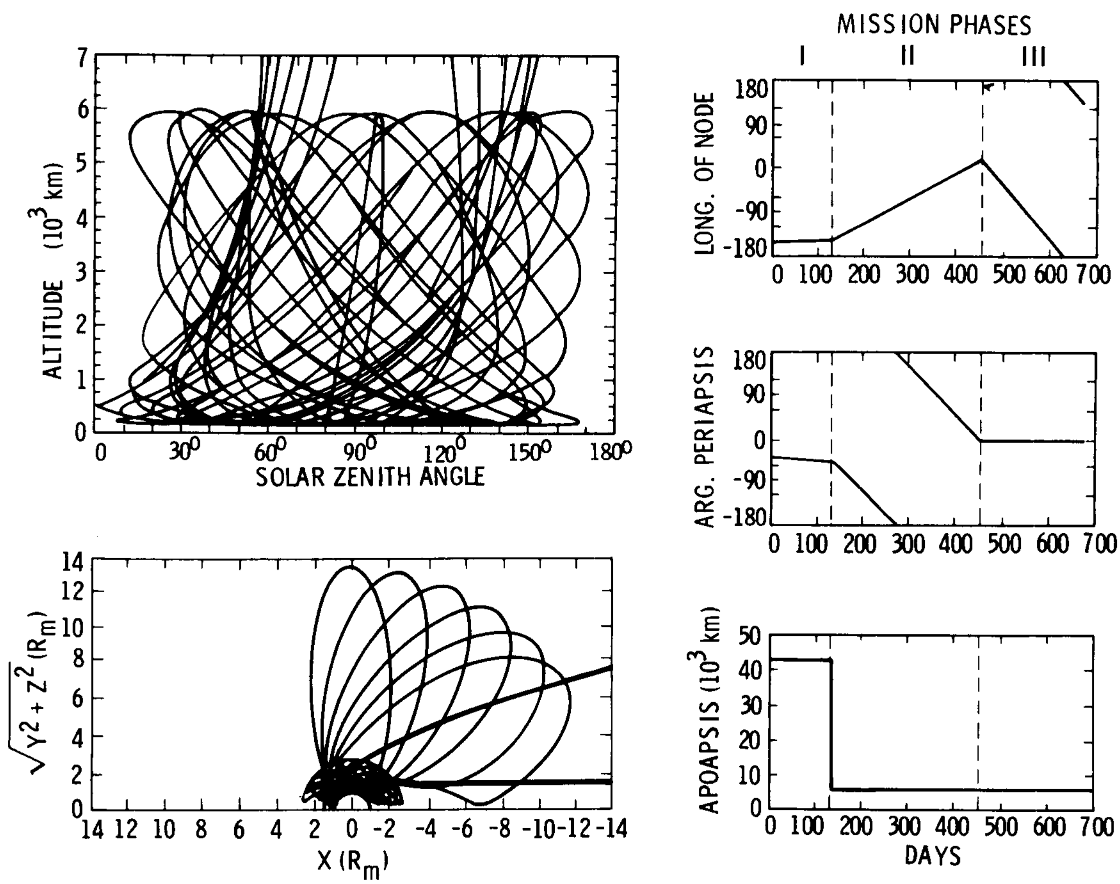


Figure VI.3 A three-phase MAO mission scenario is displayed. Propulsion is used to decrease the orbit period and the orbit inclination at the end of phases I and II, respectively.

remains in a sun synchronous noon-midnight orbit. Phase III begins with an orbital plane change to 63.4° which will maintain periapsis at 0° latitude while the increased nodal rotation rate moves periapsis to the nightside and allows the mapping of diurnal variations. Orbit lifetime calculations based on the nominal Mars atmosphere used in MO planning indicates that a 6000 x 150 km orbit will last without re-boost until 2009, a possible quarantine restriction. Onboard propulsion margins will allow observations down to 130 km. The dwell time at low altitudes in this orbit is sufficiently short that quarantine restrictions will require, at most, an alcohol wipe of the spacecraft prior to launch. The overall volume mapping, as shown in Figure VI.3, is good, but not so complete as would be obtained in the AE scenario "aerobraking" scenario displayed earlier in Figure VI.2. The MAO SWT did not see fit to endorse any single mission plan at this early (pre-phase A) stage in the mission design. It was, however, the sense of the SWT that acceptable orbit options are available to meet the MAO science objectives.

D. Effect of Planetary Quarantine on MAO

The existence of international standards concerning the avoidance of bacterial contamination of Mars complicates the planning for MAO because of the aeronomy requirements for in situ measurements at very low altitudes (i.e., < 150 km) where unassisted orbital lifetimes are short. Although there exist quarantine safe orbits that are acceptable for MAO, this approach discourages the consideration of mission scenarios that would provide significantly greater science returns. Under a strict interpretation of the contamination restrictions such approaches may be possible only if costly, highly reliable, and redundant spacecraft and propulsion systems are used.

The task of the MAO project will be to quantify the contamination concerns and their effect on MAO cost and scientific yield. For example, there may be good aeronomy orbits that are of less concern than others to those interested in Mars biology. Discussions with NASA's Space Biology Office indicate that its main concern is that an unsterilized spacecraft might impact at high latitudes where there may be sufficient surface water to sustain either Earth or Mars life forms. If this were the main concern, lower inclination orbits might be acceptable to the life scientists, even if there were a significant probability of impact at lower latitudes. Although such low inclination orbits are less desirable for aeronomy, the reduced costs and the opportunity to reach lower altitudes might make them the compromise choice for MAO. Therefore, it is the sense of the MAO SWT that questions of planetary quarantine be addressed early in the mission planning phase by the MAO Project and NASA Headquarters to ensure that the impact on science is minimized.

APPENDIX: BIBLIOGRAPHY OF SUPPORTING DOCUMENTS

1. Low Cost Exploration of the Solar System Mission Descriptions for Venus and Mars Aeronomy, R.E. Ryan, JPL Interoffice Memorandum 374-80-643 (JPL internal document), June 5, 1980.

2. Limited Scope Mission Studies, Mars and Venus Aeronomy Missions, R.E. Ryan, JPL Interoffice Memorandum 379-80 (JPL internal document), November 20, 1980.

3. Mars Polar Orbiter Mission-Orbit Studies, R.E. Glickman, Ball Aerospace Systems Division Report B6240-81.010, February 6, 1981.

4. Study of Mars Orbiter Spacecraft Derived from Existing Designs, Ball Aerospace Systems Division Technical Report, Contract NAS-2-11023, July 14, 1981.

5. Mars Orbiting Water Mission Study-Final Report, NASA/Ames Research Center, August 1981.

6. Mars Orbiter Study Final Report, Vol. 2, NASA Contract NAS-2-11224, Hughes Aircraft Company (HAC), September, 1982.

7. KEPLER, An Interdisciplinary Mars Orbiter Mission, Report on the Phase-A Study, European Space Agency, SCI(82)5, December, 1982.

8. Planetary Exploration Through the Year 2000, A Core Program, The Solar System Exploration Committee of the NASA Advisory Council, Washington D.C., 1983.

9. Planetary Observer Mission Descriptions, W.H. Blume, G.D. Low, and P. Tsou, JPL D-1248 (JPL internal document), September 1983.

10. Mars Orbiter Conceptual Systems Design Study Final Report, Contract NAS-2-11223, performed by TRW, Inc., for NASA/Ames Research Center, September 20, 1983.

11. Planetary Observer Planning: FY 84 Final Report, JPL D-1846 (JPL internal document), ed. J.E. Randolph, 21 September, 1984.

12. Planetary Observer Planning: FY 85 Final Report, JPL 642-901 (JPL internal document), ed. J.E. Randolph, 15 November, 1985.

13. Kepler Mars Orbiter, ESA SCI(85)6, December, 1985.

14. Planetary Observer Planning: FY 86 Mission Studies Report, JPL D-3649 (JPL internal document), ed. R.A. Wallace, September, 1986.