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MRSR: Rationale for a Mars Rover/Sample Return Mission

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The Solar System Exploration Committee of the NASA Advisory Council has recom mended that a Mars Rover/Sample Return mission be launched before the year 2000. The recommendation is consistent with the science objectives as outlined by the National Academy of Sciences committees on Planetary and Lunar Exploration, and Planetary Biology and Chemical Evolution. Interest has also focused on Mars Rover/Sample Return (MRSR) missions, because of their crucial role as precursors for human exploration. As a result of this consensus among the advisory groups, a study of an MRSR mission began early in 1987. The study has the following goals: (1) to assess the technical feasibility of the mission; (2) to converge on two or three options for the general architecture of the mission; (3) to determine what new

technologies need to be developed in order to implement the mission; (4) to define the different options sufficiently well that preliminary cost estimates can be made; and (5) to better define the science requirements. This chapter briefly describes Mars Rover/Sample Return missions that were examined in the late 1980s. These missions generally include a large (1000 kg) rover and return of over 5 kg of sample. More recently other concepts have been explored that utilize small (10's kg) rovers and return only small (~500 gm) samples. These later studies are not described.

Rationale for Mars

Mars is of special interest among the planets—first, because of what it may reveal about how terrestrial planets with atmospheres formed and evolved, second, because of the possibility that some form of life may have started there, and third, because Mars is certain to be the first planet other than the Earth to be explored by humans. The terrestrial planets are, of course, particularly important for what they might reveal about the Earth. In this respect Mercury, because it is inert and has no atmosphere, is of limited usefulness. Venus is Earth-like in many ways but it is difficult to study because of its thick, opaque atmosphere. Mars, however, is readily accessible to observation. Moreover, it is an active planet that has experienced many of the geological and meteorological processes that have occurred here on Earth. Mars is thus a natural laboratory where processes such as volcanism, crustal deformation, fluvial erosion, and atmospheric circulation can be studied where they have operated under very different conditions from those under which they operate on Earth.

Much of what we know about the formation of the planets is derived from meteorites and from the composition of the Earth and the Moon. A major question is whether the solar system was a relatively violent or a relatively quiet place toward the end of planetary accretion. The "violent" hypothesis suggests that, at that time, there were many Moon-sized objects in eccentric orbits, colliding with one another. In contrast, the "quiet" hypothesis suggests that the inner solar system was occupied by the accreting planets together with small debris in near-concentric orbits. The violent hypothesis is supported by the angular momenta and obliquities of the planets, by the probable origin of the Moon by a large impact, and by the apparent inhomogeneous accretion of the Earth. The quiet scenario is supported by evidence of poor mixing in the early solar system as indicated by radial zonation in the types of asteroids, by variations in the oxygen isotopes between meteorites and the Earth/Moon system, and by differences in noble gas abundances between various objects in the inner solar system.

Samples from Mars will be a major help in resolving this problem. The composition of the upper mantle can be inferred from surface rocks or measured directly in ultramafic inclusions. If Mars' upper mantle has a higher proportion of siderophile elements than is expected if it were in equilibrium with the core, or if the crust is in chemical disequilibrium with the rest of the planet, then inhomogeneous accretion would be indicated and the violent hypothesis would be supported. Conversely, oxygen isotope and noble gas abundance patterns that are unique to Mars would favor the quiet hypothesis.

While we have considerable knowledge concerning the evolution of the surface of Mars, the structure of the interior and its thermal and dynamic state are almost completely unknown. Clarifying these issues will be a major goal of the Rover/Sample Return mission. Of particular interest are the size and composition of the core, when it formed, and how its formation affected the composition of the mantle. On Earth, the relatively high content of siderophile elements in the upper mantle suggests that core formation occurred early, before accretion was complete. Is this also true for Mars? In addition, because Mars lacks plate tectonics, it must dissipate its internal heat in a way different from the Earth, possibly with "hot spot" volcanism playing a more prominent role. The precise mechanism has probably affected the thickness of the lithosphere; the location, nature, and timing of volcanism; and the development of gross, planet-wide anisotropies. Lack of plate tectonics has probably also minimized mixing of mantle and crustal materials so that if a volatile-rich veneer accumulated late, as has been suggested for the Earth, then it is better preserved on Mars. Related key questions are as follows: What is the composition of the crust and how are crustal materials distributed? What is the thickness of the lithosphere, and how has the thickness varied with location and time? What is the current heat flow and are there areal variations? These are all questions that can be addressed by a combination of returned samples, a well-instrumented rover, and long-lived packages of instruments that a rover could deploy.

Features preserved on the Martian surface suggest that the planet has had a long and varied geologic history. The planet has a large-scale asymmetry, having most of the younger surfaces on one hemisphere and most of the older surfaces on the other. Volcanism appears to have occurred throughout the planet's history, possibly up to the present day. Deformation has occurred on both local and regional scales. The surface has also preserved a long record of impacts, despite having been extensively modified by wind, water, and ice. While many of the processes that have shaped the planet are familiar to us on Earth, the results on Mars are spectacularly different. Huge volcanoes have been constructed atop broad regional bulges on the surface. Extensive fault systems suggest a remarkable stability in the state of stress of the lithosphere. Vast canyons have formed. Ice appears to have caused pervasive modification of the surface at high latitudes, and the surface has been subject to episodic floods of enormous magnitude. Why do familiar geologic processes have such large-scale effects on Mars? In what ways do these various processes differ from and in what ways are they similar to geologic processes that occur here on Earth? What has been the nature and sequence of the events that resulted in the configuration of the surface that we see today? Answers to these and similar questions have been, so far, frustrated by lack of compositional, mineralogical, and age information on the surface materials. With appropriate samples in hand we could determine the composition of the crust and the nature of any hemispheric differences. From the planet's seismic activity, the structure of the crust, and the composition of volcanic rocks, we will be able to better understand Martian volcanic processes and how they differ from those on Earth. Seismic and electromagnetic sounding of the surface will also enable us to detect ice and water at depths.

Clarification of the role of water in the evolution of the Martian surface is of special importance. Water plays a crucial role in many geologic processes, including both deep-seated magmatic processes and surficial changes such as weathering, erosion, transportation, and deposition. It is also, of course, essential for any biology. Because most of the water is believed to have outgassed early, the near-surface inventory provides clues about the accretion of the planet, the thermal and fractionation history of the interior, and the formation of the atmosphere. The amount of water also has climatological implications which in turn affect the probability that life started on the planet. There may even be practical implications, for water is a potential source of fuel and sustenance for future piloted missions.

We know that water has extensively modified the surface, both as ice and liquid, but estimates of the amount of water outgassed, and retained close to the surface, range over two orders of magnitude. If the higher figures are correct, Mars may have had warm, wet conditions hospitable to life early in its history. If the lower figures are correct, warm climates could never have prevailed. An MRSR mission should provide a variety of data to resolve this issue. Samples of earlier atmospheres should be preserved in certain rocks, such as impact breccias. Abundant carbonates and other salts near the surface would indicate a large volatile inventory and moist conditions in the past. In addition, water-lain sediments and volcanic products that result from interaction with water and ice should be present if climatic conditions had formerly been warmer and wetter.

The formation, evolution, and dynamics of Mars' atmosphere are closely coupled to the role of water. The formation of the Earth's atmosphere appears to have occurred very early, possibly during global heating as the core formed at the end of accretion. The Mars atmosphere may have formed in a similar way. However, subsequent to the initial outgassing, the planet may have lost significant fractions of its initial volatile inventory as a result of a variety of processes including blow-off by large impacts, thermal escape from the top of the atmosphere, and photochemical escape. In addition, some of the volatiles, particularly CO_2, N_2, and H_2O, became fixed in the ground as carbonates, nitrates, and ices. The climatic history of the planet depends both on the initial inventory of volatiles and on the timing and magnitude of all the subsequent events. Clues concerning these issues will be present in the composition of the atmosphere, in the detailed chemistry of unweathered, igneous rocks, in the products of weathering at different times in the planet's history, and in the variety of past depositional environments. Data in all these areas should be acquired by an MRSR mission.

Mars, of course, is of special interest because of the possibility that Martian life may have once existed. The probability that living forms may still be present on Mars is very small. The reasons for doubting that life is currently present have been previously summarized. They are (1) the absence in the surface materials of the reduced carbon and nitrogen compounds that living forms are expected to produce; (2) the lack of liquid water, which is required for almost all biochemical reactions; (3) the low temperatures; (4) the high surface flux of ultraviolet (UV) radiation which tends to break down complex organic molecules; (5) the absence of gas disequilibria in the atmosphere; and (6) the adequate chemical explanations for the three Viking biology experiments. It has, nevertheless, been argued that the negative results at the Viking landing sites do not necessarily rule out survival of life forms in local, more hospitable environments elsewhere on the planet. However, warm, wet locations protected from the UV radiation, and with energy sources that could be utilized by living forms, must be very rare, if they exist at all. Moreover, because of the general hostility of the planet to life and the lack of a global, interconnected biota, colonization of local niches is unlikely. For all these reasons, the chances for finding present-day life on Mars are considered so small that it has not been included as one of the primary objectives of the MRSR mission being studied for the late 1990s. More definitive experiments to re-examine the possibility of present-day life on Mars could, however, be an objective of follow-on MRSR missions.

While the chances of extant living forms existing on Mars are extremely small, the probability of life developing early in the planet's history is quite different. Fluvial erosion of ancient surfaces and the presence of bedded sediments of possible lacustrine origin show that water was at least intermittently present on the Martian surface at times in the past. The most spectacular fluvial features on the planet are those that formed as a result of catastrophic floods. Possible causes are volcanic melting of ground ice or release of groundwater under high pressure. Spectacular as these features are, they are thought to have little implication for past climates. Indeed, they could have formed under the present very cold conditions which are hostile to life. The much smaller branching valley networks are, however, suggestive of former, warmer climatic conditions. They appear to have formed by the slow erosion of running water, much like terrestrial river valleys, and not by sudden catastrophic release. For such slow erosion to occur, temperatures at the surface probably had to be close to or higher than freezing; otherwise the streams would freeze. The valley networks are almost all on very old surfaces. This suggests that warm conditions prevailed mostly early in the planet's history.

Greenhouse calculations indicate that atmospheric pressure had to be at least 1 atmosphere to raise the mean surface temperatures to 273 K. Both warmer climatic conditions and a thicker atmosphere have, therefore, been suggested for early Mars, that is, for the period during, and shortly after, the early heavy bombardment by meteorites. During this early period the planet's interior was also warmer and the planet could have had a magnetic field, which would have protected the surface from the adverse effects of solar wind and solar flares, as in the case of the Earth. Indeed, conditions on Mars and Earth may have been similar prior to 3.5 billion years ago when life on Earth originated. Because of these considerations, the search for prior life is one of the major scientific goals of the MRSR mission.

A final reason for interest in Mars is that it is a likely site for future piloted missions. The MRSR mission is expected to be launched around the end of the century. At that time piloted Mars missions may be only a decade or two away and plans for such a mission could be well advanced. Before humans go to Mars we will need to know considerably more about its environment so that instruments, life support systems, return vehicles, and so forth can be relied upon to function at Mars for long periods of time. The omnipresent dust is of special concern since it might be carried into the spacecraft to contaminate the life-support systems and it might be ingested by the astronauts. In addition, various technologies necessary for piloted missions need to be tested at Mars before risking their use on human missions. Additional objectives of the MRSR mission will be, therefore, to gather environmental information and to test key technologies necessary for the eventual human exploration of Mars.

Rationale for Samples

Experience gained with the Moon emphasizes the enormous power of returned samples when placed in the context of other global data. Sample data are the basis for almost all of our current ideas on how the Moon formed, what fractionation events subsequently occurred, how the highlands and maria differ in origin, and when all the various events that led to the present configuration took place. The degree to which this understanding could have been achieved solely by remote analysis is a matter of conjecture, but there is ample reason to be skeptical. Having lunar samples in hand allowed the complete analytical and intellectual capacity of the scientific community to focus on the problem of the Moon's evolution. Instead of having a small pre-determined set of analytical techniques applied to samples, the approach could be both all-encompassing and flexible, with the analytical emphasis shifting as the meaning of each set of results became better appreciated. There is no reason to believe that these enormous advantages should be any less for Mars. Indeed, the apparently more complex geology on Mars and the biologic implications enhance the importance of the kind of comprehensive examination that a returned sample allows.

One of the main advantages of returned samples is that they permit the use of analytical techniques that are too complicated to be performed remotely. Among the most important are absolute dating methods, such as Rb-Sr, K- Ar, Sm-Nd, and U-Th-Pb. These fix the whole chronology of the planet's evolution and, in addition, provide essential information on fractionation mechanisms, on the formation of the crust, and on the extent to which surface materials are recycled. Knowledge of trace elements to the parts per million to parts per billion level is necessary for determining the bulk composition of the planet and for understanding a wide variety of processes of chemical differentiation. Examples of the value of trace elements are the use of rare earth elements in elucidating early events on the Moon and the use of iridium in understanding events at the Cretaceous-Tertiary boundary on Earth. Such determinations are difficult and strain the capabilities of laboratories on Earth. The only practical way to do them for Mars is on returned samples. Petrographic examination, while routine on Earth and commonly conducted in conjunction with other techniques such as microprobe analysis, is also very difficult to perform remotely because of the difficulties of sample preparation and the large amount of human judgment needed in the analysis. However, these techniques are necessary for identifying rock types, interpreting their origin, and recognizing secondary alteration. Similarly, returned samples are essential for the location and determination of complex organic compounds and for microscopic studies needed in the search for evidence of former life.

Apart from the difficulties of remote analysis, there are methodological advantages to having samples returned to Earth for analysis. Perhaps the most serious disadvantage to *in situ* analysis is its inflexibility. Planetary missions have long lead times so that the set of analytical techniques to be used must be chosen at least 10 years ahead of analysis. Once the choice is made it cannot be changed as our perception of the planet changes or when the first analytical results are acquired. As with Viking, it may take 20 years to respond to a new set of results in a program based solely on remote observations. In contrast, with samples in hand, different techniques can be applied as suggested by each set of new analytical results and new techniques can be developed if needed. Returned samples can also be preserved to be repeatedly re-examined as our ideas about the planet's evolution mature or as new techniques are developed. Finally, should we ever send humans to Mars, samples will be available to test for any potentially harmful effects that the reactive Martian materials may have on humans.

Rationale for a Rover

A Rover would have three main functions: (1) to support the acquisition of samples, (2) to perform *in situ* analyses, and (3) to explore. Support for sampling is needed to ensure that the samples returned to Earth are representative of the planet's variety. To accomplish this the Rover must be able to move; to have the appropriate analytical capabilities to recognize differences in the accessible materials; and to have the appropriate tools for sampling, packaging, and delivering to the vehicle samples that are to return to Earth. The Viking results emphasize the importance of mobility. Both landers set down on fine-grained debris. While there were rocks within reach, all the rock-like chips analyzed were highly weathered and were almost certainly clods of the local weathered materials rather than unweathered rocks. The debris is probably highly weathered and not comminuted material, with abundant fragments of unaltered rock as on the Moon. The material is thus of limited usefulness in understanding the evolution of the planet. Moreover, spectral characteristics of the rocks within the Viking fields of view suggest that no more than two types are present. Thus, a sample-gathering vehicle at the two Viking landing sites would have to move to get any rock samples, and to move beyond the field of view to get a variegated set.

Selection of appropriate landing sites will be crucial for the success of the MRSR mission. To address a wide range of science questions we need a variety of samples such as volcanic rocks of old, intermediate, and young ages, ancient impact breccias, water-lain sediments, polar-layered deposits, soils, wind-blown dust, and ices. Landing sites with more than two major rock units exposed will be difficult to find. Moreover, the choice of site will inevitably be a compromise between the desire for safe landing and the desire to go to scientifically variegated locations to address a variety of science objectives. The mobility of a Rover both increases the chances of getting a variegated sample set and alleviates the conflict between the safety and science desires. With mobility, the landings could all be in safe, relatively uniform terrains, while the sampling is mostly done in nearby, variegated, more scientifically interesting locations.

The Rover must have capabilities in addition to mobility to support sample acquisition. It must, for example, be able to recognize differences in the materials available for sampling to guard against return of numerous samples of the same materials. This will require some remote sensing ability to indicate where different types of samples may be available and some sample analysis capability to identify more precisely the differences between samples. Such analytical capability should be directed at both the high-temperature major rock components and the low-temperature, more volatile rich components, that are of climatological and biological interest. Instruments necessary to do a first-order characterization of the area to be sampled should also be available so that sampling strategy can be guided by knowledge of the local variety in the available materials. Finally, the Rover must have instruments appropriate for documenting the location and geologic context of the sample site so that the subsequent analytical results can be appropriately interpreted. How far the Rover has to roam and how capable a set of instruments is needed to support sampling remain to be determined.

Biology places particularly stringent needs on site selection and sample acquisition. First we wish to sample at locations where former biologic activity is most likely. Prime candidates are ancient lake deposits since lakes would have provided the conditions necessary both to support living organisms and to preserve evidence of their presence. In many areas of the ancient highlands, valley networks converge on local basins. Lakes are likely to have existed in these areas. Unfortunately, these low-lying areas are also preferred sites for accumulation of volcanic deposits and identification of areas where sediments are accessible and not covered with volcanics will not be easy. If such areas are found and landed on then one is confronted with the task of selecting the most promising sample. We are likely to be able to return to Earth only 5-10 kilograms so every sample is precious. We are unlikely to be so lucky as to find direct visual evidence for life, such as stromatolite colonies. If life ever started on Mars the most likely means of detecting it will be through chemical evidence. But organics tend to be destroyed at the surface so we need to acquire samples that have spent much of Mars' history below the surface. Sampling debris from a relatively young impact crater in the lake sediments is one way of achieving this. In addition, we want to be able to do some preliminary testing for organics and possibly isotopic fractionation so that the samples that we bring back to Earth are the ones most likely to preserve biologic evidence.

In situ analyses are important in their own right, independent of sample acquisition. The COMPLEX report on exploration of the inner planets is very careful to emphasize the importance of both returned samples and *in situ* analyses. Certain characteristics of a planet are not susceptible to study by means of samples. The most obvious are the structure and dynamics of the planet's interior and the structure and general circulation of the atmosphere. In addition, some properties of the surface materials must be measured *in situ* because they change in response to local seasonal and diurnal changes in the environment. The extent to which such measurements will be part of an MRSR will depend on the capabilities of the various vehicles involved, and that remains to be determined. Most previous studies have recommended inclusion of various geophysical and meteorological objectives in the goals of an MRSR mission. Experiments such as active and passive seismometry, heat flow determination, and monitoring the atmosphere are, therefore, candidates for inclusion in the mission. The geophysical and meteorological instruments could be at a fixed location or deployed at various places by the Rover.

The third function of the Rover is to explore. At present we have detailed knowledge of the surface of Mars only at the two Viking landing sites, so having a Rover on the surface will greatly extend our knowledge of Mars at ground level. This capability is important for understanding the processes that control the small-scale morphology of the surface and for understanding the environment in which human explorers will ultimately have to work. This attribute of the mission is also the one most readily appreciated by non-scientists. The

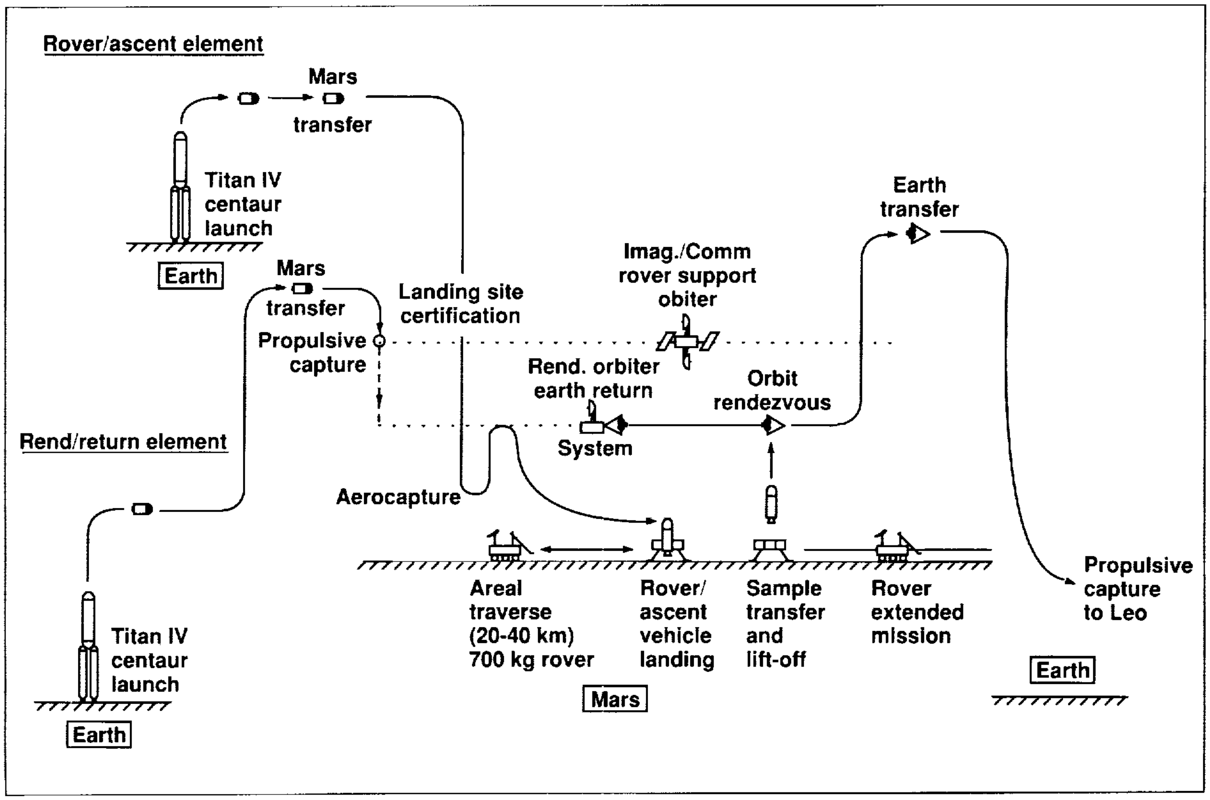

Figure 14-1. Possible scenario for a Mars Rover-Sample Return mission.

main exploration requirements are high mobility and imaging. The three functions—sample acquisition, *in situ* analysis, and exploration—place different demands on the Rover. What emphasis should be placed on the different functions is being debated.

Possible Mission Scenarios

An MRSR mission would involve several vehicles, which can be packaged for launch to Mars in different ways. Figure 14-1 shows one possible mission scenario. Most of the scenarios considered in the late 1980s involved two separate launches for each mission. However, if the nation developed a high lift vehicle then the mission could be accomplished with a single launch. In the configuration shown in figure 14-1, the Earth-Return Vehicle for the samples and the Orbiter that is used to support ground operations at Mars are combined in the first launch; the Rover and Mars Ascent Vehicle are combined in the second launch. This combination has the advantage that the Orbiter can be sent to Mars well ahead of the Rover to certify and characterize the landing site. In other possible combinations, the Rover and Ascent Vehicle are launched separately and land separately at Mars. While this has advantages in terms of launch mass margin, it has the disadvantage that the Rover and Ascent Vehicle must rendezvous on Mars. In the scenario in figure 14-1 the Rover and Ascent Vehicle land together, so rendezvous is not a problem.

After a trip to Mars of approximately 1 year, the Earth Return Vehicle and the Orbiter will be injected into Mars orbit. The Orbiter will then proceed to examine the preselected landing sites to make sure they are safe for landing and to provide a detailed map of the landing area for Rover operations. Meanwhile the Rover/Ascent-Vehicle combination will have been placed into Mars orbit using aerocapture to conserve fuel. Once the landing site has been judged safe, the Rover and Ascent Vehicle will descend to the surface probably using a combination of aeromaneuvering, deceleration by parachute, and finally, terminal propulsion. After landing, the Rover will be free to separate from the Ascent Vehicle and perform its mission.

How mobile the Rover will be, what analytical capability it will have, and how sophisticated its sampling tools will be are currently all undefined. Missions of different complexities are being studied from those in which the Rover is tethered to the Ascent Vehicle and can rove only 100 meters from it, to missions in which the Rover can traverse distances of several tens of kilometers. In all the scenarios the Rover makes looped traverses, returning repeatedly to the Ascent Vehicle to deliver samples. The Rover is expected to have a remote sensing capability to navigate and to recognize compositional variations in the surrounding scene. It will also have tools necessary to collect loose rocks, to sample bedrock and large boulders, and to extract samples from 1-2 meters below the surface. The Rover should also have the capability of analyzing major elements and volatile compounds in samples and nearby materials and to deploy geophysical/ meteorology stations. After several months on the surface the samples that have been collected will be launched from the Martian surface into Mars orbit. Once the samples have been launched, the Rover will continue exploring the surface.

After launch, the Ascent Vehicle will rendezvous with the Earth-Return Vehicle, in orbit around Mars, and transfer to it the sample capsule. The Earth-Return Vehicle will then be injected into the Earth transfer orbit for the trip back to Earth which will take approximately 1 year. At Earth approach various options are possible. A sample capsule could be released for direct entry into the Earth's atmosphere or the sample capsule could be placed into Earth orbit either propulsively or by aerocapture. What procedure is followed will depend strongly on how much emphasis is placed on back contamination issues.

More recently, ways of implementing sample returns have been examined that are very different from that just described. Miniaturization of spacecraft components, rovers and analytical instruments, together with advances in analytical techniques that permit comprehensive analysis of very small samples, has stimulated the design of much smaller, and substantially lower cost sample return missions. It may be feasible, for example, to launch a sample return mission with a miniature rover on a Delta launch vehicle. This being so, a different exploration strategy might be followed in which sample return missions of limited capability are sent to many sites rather than emplacing a substantial capability at few sites, as described above.

Conclusions

In 1992 the United States will place in orbit around Mars a vehicle designed to systematically map chemical, mineralogical, and topographic variations of the surface and to monitor atmospheric activity for a full Martian year. This will be followed in 1994 and 1996 by a Soviet mission consisting of rovers and balloons. Both U.S. and Soviet advisory groups agree that the next step should be a Rover/Sample Return mission to the planet. Such a mission could be launched in the late 1990s. It would address a broad range of planetological and biological issues and is expected to have an impact on Mars science comparable to the impact that Apollo samples had on lunar science. Major objectives of the mission are to determine whether life ever started on Mars and what conditions were like on Mars very early in its history when life began on Earth. The mission is also expected to pave the way for human exploration by acquiring key environmental data about Mars and testing technologies necessary to place humans on the planet and return them safely to Earth.

Additional Reading

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