Scientific Rationale for Mobility in Planetary Environments

Committee on Planetary and Lunar Exploration
Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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COVER: An artist's impression of various forms of mobility that might be employed by future Mars exploration missions. Lander, rover, and balloon images courtesy of the Jet Propulsion Laboratory. Aircraft image courtesy of Malin Space Science Systems. Composite by Penny E. Margolskee.

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Preface

Planetary surfaces and atmospheres are complex, with physical and chemical properties that vary over a large range of spatial scales. To understand such variegated features we need multipoint measurements and/or mobile platforms.

1. For planetary atmospheres, scientific payloads carried by a fleet of balloons could enable synoptic measurements of chemical compositions and physical characteristics as functions of depth, latitude, and longitude. Measurements could be made for significantly longer times than those typical of entry probes.
2. For planets with solid surfaces, mobility is essential. The case is exemplified for Mars, where spacecraft mobility would enable major advances in understanding climate change and geologic history and in searching for direct evidence of past life. This would require landers that can reach identified targets and there analyze selected materials.
3. Given the extensive round-trip communication times involved in interplanetary exploration, a significant degree of autonomy may also be required. Power needs and communication rates will inevitably be major considerations, as will cost.

Given the importance of mobility-related issues to the achievement of priority objectives in the planetary sciences, the Space Studies Board charged the Committee on Planetary and Lunar Exploration (COMPLEX) to review the science that can be uniquely addressed by mobility in exploring the atmospheres and surfaces of planetary bodies. In particular, COMPLEX was asked to address the following questions:

- What are the practical methods for achieving mobility?
- For surface missions, what are the associated needs for sample acquisition?
- What are past examples of planetary mobility systems and how effective have they been in addressing important issues in the planetary sciences?
- What is the state of technology for planetary mobility in the United States and elsewhere, and what are the key requirements for technology development?
- What terrestrial field demonstrations are required prior to spaceflight missions?

Although this project was formally initiated in May 1997, presentations in support of it began in September 1995. They were conducted in a variety of contexts, including COMPLEX's standing oversight of NASA's planetary exploration programs and during the definition and development of the charge for this study. This report also draws on material presented to COMPLEX in the preparation of a number of additional reports. These include "Scientific Assessment of NASA's Solar System Exploration Roadmap'' (letter report to Jurgen Rahe, August 23, 1996), "Scientific Assessment of NASA's Mars Sample-Return Mission Options" (letter report to Jurgen Rahe, December 3, 1996), and the Space Studies Board's assessment of the draft Office of Space Science strategic plan (letter report to Wesley Huntress, Jr., August 27, 1997). Many of the presentations dealt primarily with technological issues, but the potential for science was explicitly discussed as well. Background material was also gathered during COMPLEX's February 1997 meeting at the Jet Propulsion Laboratory. In addition, three members of COMPLEX actively participated in one or more field tests of the Russian Marsokhod rover and the facilities of NASA Ames Research Center's Intelligent Mechanisms Group, and two were involved with operational tests of the Sojourner rover carried by the Mars Pathfinder mission. In conjunction with COMPLEX's June 1997 meeting in Flagstaff, Arizona, committee members participated in field trips to the Upheaval Dome impact feature in southeastern Utah and Meteor Crater in northeastern Arizona to gain direct experience of the mobility needed for the characterization of complex geologic features.

Although many COMPLEX members past and present worked on this report, the bulk of the task of assembling their many individual contributions was performed by George McGill with the assistance of Jeffrey Barnes, Richard Binzel, Ronald Greeley, Heidi Hammel, Bruce Jakosky, Hap McSween, Ted Roush, Gerald Schubert, and Everett Shock.

The work of the writing team was made easier thanks to the contributions made by Michael Carr (U.S. Geological Survey), Frank Carsey (Jet Propulsion Laboratory), James Cutts (Jet Propulsion Laboratory), Michael Drake (University of Arizona), Stephen Gorevan (Honeybee Robotics), Andrew Ingersoll (California Institute of Technology), Arthur Lane (Jet Propulsion Laboratory), John Langford (Aurora Flight Sciences), Daniel McCleese (Jet Propulsion Laboratory), Christopher McKay (Ames Research Center), Kenneth Nealson (Jet Propulsion Laboratory), Kerry Nock (Jet Propulsion Laboratory), Paul Schenker (Jet Propulsion Laboratory), Alan Treiman (Lunar and Planetary Institute), Koichiro Tsuruda (Institute of Space and Astronautical Science), Charles Weisbin (Jet Propulsion Laboratory), and Brian Wilcox (Jet Propulsion Laboratory).

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and draft manuscripts remain confidential to protect the integrity of the deliberative process. COMPLEX thanks reviewers Benton Clark (Lockheed Martin Corp.), Larry Crumpler (New Mexico Museum of Natural History and Science), Larry Esposito (University of Colorado), Richard Greenberg (University of Arizona), Roald Sagdeev (University of Maryland), Steven W. Squyres (Cornell University), and Joseph Veverka (Cornell University) for many constructive comments and suggestions. Responsibility for the final content of this report rests solely with the authoring committee and the NRC.

Foreword

The cautious wanderings of the intrepid Sojourner rover across the martian surface in 1997 captured the attention of much of the world—the Jet Propulsion Laboratory's World Wide Web site broke records for the number of visitors hungry for the latest snapshots of the Red Planet. More to the point, Sojourner's ability to snuggle up to one rock after the other and assay its composition multiplied manyfold the scientific return of the Mars Pathfinder mission.

This report is a cross-cutting assessment of the role of mobility in meeting the scientific objectives of planetary research as previously set out by the Space Studies Board's Committee on Planetary and Lunar Exploration. For a wider range of scientific goals, the ability to sample multiple locations on a planet's surface or in its atmospheres is found to be of great importance. This leads to some technological and programmatic considerations for developing the most effective means of achieving mobility in planetary environments.

NASA's Space Science Enterprise Strategic Plan[1] presages a steady drumbeat of launches to Mars, Europa, and other planetary bodies over the next decade. As with Sojourner, careful attention to the most effective strategies for mobility will significantly enhance the capabilities of these future missions to explore the solar system, providing large scientific returns as they also stimulate public interest.

Claude R. Canizares, *Chair*
Space Studies Board

[1]National Aeronautics and Space Administration, *The Space Science Enterprise Strategic Plan: Origin, Evolution, and Destiny of the Cosmos and Life,* National Aeronautics and Space Administration, Washington, D.C., 1997.

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Executive Summary

For the last several decades, the Committee on Planetary and Lunar Exploration (COMPLEX) has advocated a systematic approach to exploration of the solar system; that is, the information and understanding resulting from one mission provide the scientific foundations that motivate subsequent, more elaborate investigations. COMPLEX's 1994 report, *An Integrated Strategy for the Planetary Sciences: 1995-2010,*[1] advocated an approach to planetary studies emphasizing "hypothesizing and comprehending" rather than "cataloging and categorizing." More recently, NASA reports, including *The Space Science Enterprise Strategic Plan*[2] and, in particular, *Mission to the Solar System: Exploration and Discovery—A Mission and Technology Roadmap,*[3] have outlined comprehensive plans for planetary exploration during the next several decades. The missions outlined in these plans are both generally consistent with the priorities outlined in the *Integrated Strategy* and other NRC reports,[4,5] and are replete with examples of devices embodying some degree of mobility in the form of rovers, robotic arms, and the like.

Because the change in focus of planetary studies called for in the *Integrated Strategy* appears to require an evolutionary change in the technical means by which solar system exploration missions are conducted, the Space Studies Board charged COMPLEX to review the science that can be uniquely addressed by mobility in planetary environments. In particular, COMPLEX was asked to address the following questions:

1. What are the practical methods for achieving mobility?
2. For surface missions, what are the associated needs for sample acquisition?
3. What is the state of technology for planetary mobility in the United States and elsewhere, and what are the key requirements for technology development?
4. What terrestrial field demonstrations are required prior to spaceflight missions?

APPROACH

Mobility may be achieved by a variety of techniques, including balloons, aircraft, rovers, and hoppers. In addition, the concept of mobility can be thought to encompass devices for instrument positioning, digging, drilling, and sample manipulation. Indeed, the history of planetary exploration contains a number of examples of the application of mobility. Conventional flybys and orbiters, together with entry probes, are explicitly excluded from consideration in this study because these mission modes have already been discussed extensively. Given that COMPLEX's expertise is in the planetary sciences rather than engineering or robotics, and that the primary reason for employing mobility is to enhance the return of valuable scientific data, this report is focused on scientific rather than technological issues. COMPLEX therefore restricted its attention to six case studies, representative of the goals, environments, disciplines, and technologies drawn from previous COMPLEX and NASA reports:

- What is the nature of the circulation in the lower atmosphere on Venus?
- What tectonic processes are responsible for the structural and topographic features present on Venus?
- Is there evidence for extinct or extant life on Mars?
- What is the physical and chemical heterogeneity within small bodies such as asteroid 4 Vesta?
- What drives the zonal winds in the jovian atmosphere?
- What is the internal structure of Europa?

These six case studies are discussed in Chapter 2.

CONCLUSIONS AND RECOMMENDATIONS

The most important conclusion from this study is that mobility is not just important for solar system exploration—it is essential. Many of the most significant and exciting goals spelled out in numerous NASA and National Research Council documents cannot be met without mobile platforms of some type.

A second conclusion is that the diversity of planetary environments that must be explored to address priority scientific questions requires more than one type of mobile platform. Thus, the simultaneous development of some combination of wheeled rovers, aerobots, aircraft, touch-and-go orbiters, and cryobots is not only justified but is also necessary, as long as there is a scientific justification for the development of each mobile platform. Technology development funds are likely to be scarce and so should be allocated only after a vigorous peer review of the proposed mobility device's technical feasibility and the scientific applications for which it will be used. Technology development activities should be undertaken by the best-qualified individuals and teams within NASA, industry, and academia, as determined by peer review.

With some exceptions, the current technical development efforts are appropriate and well focused. However, it is instructive to compare the tenor of recommendations in science-oriented presentations and of science-centered working groups with the thrust of technical development efforts. The science sources emphasize the need for very capable mobile platforms with these characteristics:

- Synergy of instruments, that is, a suite of mutually complementary instruments rather than either a small number of instruments or many instruments that are independently conceived and developed;
- Extensive range and long lifetime; and
- One or more manipulative devices, such as claws, drills, and the like, some of which are likely to be complex and difficult to develop.

These characteristics define a mobile platform that is fairly large and potentially rather complex. In contrast, the main thrusts of technical development, especially of rovers, are directed at reducing their size and increasing their autonomy. These tendencies create a tension between a model-driven approach to mobility and a technology-driven approach. Reconciling these apparently contradictory priorities and minimizing their impact on the scientific productivity of mobility missions will require close cooperation between engineers and scientists.

Most science objectives defined for future solar system missions call for mobile platforms, manipulative devices, and instruments with significant capabilities. Attaining this level of capability will require reducing the total mass of mobile platforms *while maintaining acceptable functional capabilities.* The size of a mobile platform needs to be considered as part of a systems optimization based on scientific needs and mission constraints. Although very small mobile systems, such as the micro- and nanorovers currently under development, involve a significant reduction of mass, their payload capacity may be too limited for widespread application unless particular attention is paid to the development of appropriate micro- and nano-instrumentation.

Long-range mobility, whether with rovers, aerobots, or other devices, poses significant navigational challenges. This is in part due to the constraints imposed by long, two-way communication times and in part to the limited data downlink capacity available. The more time and downlink capacity are used for navigation, the less they will be available for returning scientific data. Lessons learned in the Marsokhod field tests and during the operation of Sojourner suggest that descent imagers should be included on lander and rover missions to provide critical information on the context of the landing site for use in rover navigation and science-operations planning. Navigational tools for long-range mobility should be available in as near real time as feasible. The hardware and software for intelligent autonomous operation and efficient operational planning should be actively developed.

Many planned and possible future missions will require spacecraft and mobility devices to operate in hostile environments. An environment can be hostile because of the high levels of radiation (e.g., the surface of Europa), high pressure (e.g., the atmospheres of the giant planets), high temperatures (e.g., the lower atmosphere of Venus), low temperatures (e.g., the surface of Titan), and very low gravity (e.g., the surfaces of comets and asteroids). Such environments place unusual constraints on spacecraft and instruments, indicating the need for long-range advanced planning and development.

These conclusions suggest two fundamental recommendations:

- Technological development of mobile platforms must be science driven. Available funds will never be adequate to develop all possible types and variants of platforms, and these scarce funds should not be wasted on devices of limited scientific utility no matter how technologically intriguing they may be. Thus, there should be science input into technology development from the very beginning.
- Mobile platforms, ancillary devices, instruments, and operational procedures must be thoroughly tested on Earth. This involves laboratory tests of instruments, field trials of individual components of space missions, and field trials of complete systems (mobile platform and instruments) and all relevant personnel (operators, design engineers, and scientists). To be fully effective, such field trials require thorough testing and calibration of instruments in the laboratory before they are mounted on a mobile platform, extensive field testing of mobile platforms both with and without instruments aboard, and full operational field testing of total systems. Proposals to conduct field tests should be peer reviewed in advance, and the test results should be promptly published in peer-reviewed journals.

In addition, several more-specific recommendations derive from the six case studies:

- Data downlink rates must be significantly increased, perhaps through the use of new technologies, such as the ongoing efforts to upgrade the Deep Space Network to operate in the Ka band or an eventual transition to optical communications. This is a problem that is not unique to mobile platforms.
- A means to *control* aerobot motion, both vertically and horizontally, needs to be developed.
- The capability to obtain descent images should be included on *all* lander and rover missions to provide critical context for navigation and science.
- Navigation tools and operational plans should be developed so that the impact of navigational needs on science return can be minimized.

In summary, the various disciplines interested in solar system exploration and research have many common needs for mobility, and, thus, generally need not consider themselves as competitors for payload mass. For example, a rover carrying a suite of instruments designed to carry out a predominantly exobiology mission will differ very little from one designed to carry out a geology/geochemistry mission. Likewise, an aircraft or balloon mission designed to measure important atmospheric parameters at various altitudes can also collect surface spectral data important to geologists, geochemists, and exobiologists. Obviously, not all missions will satisfy all persons, but it seems clear that differences in mobile platform type and design are linked more to the target of the mission than to the interests of the scientists involved.

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1

Introduction

HISTORICAL PERSPECTIVE

Exploration has traditionally involved the ability to move from one place to another, making observations and collecting samples along the way. European voyages of discovery in the 13th to 15th centuries were conducted primarily by ship. These were followed by scientific expeditions on land and sea, such as Captain Cook's voyages of the *Endeavour* in the Pacific during the 18th century. In many cases, these expeditions were followed by intensive investigations of local areas, spurred by economic forces.

The exploration of the American West serves to illustrate the role of mobility. Early expeditions were in part "feasibility studies" prompted by political and economic pressures. The pioneering trips of Alexander McKenzie across the Canadian Rockies in 1793, and of Meriwether Lewis and William Clark farther south in 1804-1805, served to define the geographical limits and accessibility of much of the West. The great scientific surveys conducted by John Wesley Powell down the Green and Colorado rivers through the Grand Canyon, and the extensive survey along the 40th parallel conducted in the 1860s and 1870s by Clarence King, served to map the West, survey its resources, and enable development. In these cases, "mobility" was provided by boat, horse, or foot, which enabled movement from one site to the next. A spectrum of observations was possible, from study of the horizon for the broad view of the terrain, to microscopic analyses of soils, rocks, and biota.

In the voyages of discovery and expeditions in the West, the ability to react to new discoveries along the way as new data were collected, analyzed, and synthesized was critical. In some cases, this involved staying at a scientifically rich site longer than originally planned. Sometimes, it meant rejecting specimens or samples in favor of better collections made later. In other cases, it meant changing the originally planned path because of unexpected hazards or to take advantage of new insight into the region.

In some respects, exploration of the solar system has followed a similar path to that of the exploration of our own planet. The first decades of planetary exploration have involved mostly spacecraft that have flown past, orbited, or probed the planets as initial reconnaissances. In some instances, limited mobility was provided by foot or rovers (manned and robotic) on the Moon, and on Mars by the short-range rover Sojourner (see Chapter 3, Box 3.1 and Box 3.2). With the exception of the Pluto-Charon system, every major planet and satellite has been visited by spacecraft, at least in a reconnaissance mode. The stage is now set to begin exploration in a mode analogous to the expeditions of the American West. This style of exploration has the potential to provide a new level of understanding of the diversity of planetary objects, their evolutionary histories, and the fundamentals of how they work. Mobility will be required for this phase of planetary exploration.

WHAT IS MOBILITY?

A variety of recent planetary exploration missions either have demonstrated the advantages that derive from the ability to move instruments from one location to another in planetary environments or have indicated that such a capability is a logical approach to conducting future priority studies. A prime example of the former is Mars Pathfinder's deployment of the rover Sojourner on the martian surface in July 1997. The data returned from this mission about the elemental composition of martian soil and rocks was a direct consequence of Sojourner's ability to position an alpha proton x-ray spectrometer against a variety of materials across an area of several hundred square meters. A prime example of the latter is provided by the release of Galileo's probe into Jupiter's atmosphere in December 1995. Although it returned important data, the probe was only able to sample a limited portion of Jupiter's atmosphere for a few tens of minutes. The probe's results and inherent limitations suggest that a next logical step in the exploration of Jupiter's atmosphere is the deployment of a long-lived, balloon-borne instrument package.

None of this is new—the value of mobility has been recognized from the earliest days of lunar exploration. Yet, more than a quarter of a century separates the Apollo 17 astronauts' last traverse across the lunar surface in their rover and Sojourner's first tentative excursion on the surface of Mars. In this interval, profound advances have been made in robotics, and a variety of technologies have been developed that make it feasible to build mobile devices with both unprecedented capabilities and masses that are compatible with current launch vehicles. Developing these technologies has required and will continue to require the expenditure of substantial resources and, thus, it is imperative that the technologies developed be appropriate for scientific applications.

The purpose of this report is to develop the scientific rationale for mobility in planetary environments. The Committee on Planetary and Lunar Exploration (COMPLEX) attempts to do this in Chapter 2 by discussing a series of case studies that, though not all-inclusive, are representative of the range of scientific applications that may be addressed by mobility in the near- to mid-term future. As such, this report is different from most other COMPLEX reports. It does not develop a series of scientific priorities that might be addressed by future planetary missions. Rather, it advances a series of arguments to support the idea that investments in planetary-mobility technology should be determined on the basis of the scientific priority of the expected observations and not on the basis of technological expediency. In an era of limited resources, NASA cannot afford to develop technologies and then search for possible scientific applications.

COMPLEX defines mobility to include any means to move manipulative, sampling, imaging, or measuring platforms from one place to another both horizontally and vertically in the atmospheres or on the surfaces of solar system objects and to move and manipulate instruments and sample materials. This includes but may not be restricted to balloons, rovers, hoppers, aircraft, and so-called touch-and-go orbiters. Many of these must carry devices for instrument positioning, digging, drilling, and sample manipulation. Flybys and orbiters around large bodies are explicitly excluded. Human exploration can, in principle, provide a high degree of intelligent mobility but is beyond the scope of this document. Similarly, issues such as the methods for storing and transporting sample-return materials, power sources, and the specific characteristics of instruments and spacecraft are not within the purview of this report.

A key concept relating to the need for mobility in solar system exploration is the realization that planetary phenomena exist on a variety of spatial and temporal scales. The scales on which measurements must be made are functions of the complexity of the environment under study, the characteristic scale lengths of important physical processes, the scientific objectives of the study, and the specific types of measurements required to address these objectives. These scales need to be clearly defined and related to the overall objectives of each mission involving mobility.

Planetary atmospheres are good examples of this diversity of scales. The general circulation in Venus's atmosphere is dominated by global spin, whereas that of Earth is dominated by mid-latitude jets and large-scale eddies. Mars's atmosphere migrates from pole to pole in response to the planet's seasonal cycle and periodically exhibits global dust storms. The giant planets have distinct belts and zones and several, particularly Jupiter and Neptune, display a variety of long-lived vortices. These phenomena can only be addressed by measurements made on the spatial and temporal scales appropriate to the environment under study. In other words, the key issue is placing appropriate instruments in the right places and at the right times.

In the context of a rover mission, for example, these characteristic scales will have a profound influence on the placement of observation and sampling sites and the timing of traverses. Certain types of observations (e.g., those concerning mineralogy and small-scale surface processes) are best addressed by very detailed sampling of a limited geographic region. Other questions (e.g., those concerning regional geology) are resolved only by samples collected from and observations made at widely separated sites. If the mission design philosophy does not acknowledge the interplay between scientific objectives and the relevant characteristic scales, the rover's capabilities and instrumentation may not be optimal to address the scientific goals of the mission. Alternatively, the rover capabilities may dictate that it address issues that are not of the highest scientific importance.

The interplay between the characteristic scales associated with important physical processes and those scales defined by the mobility-system's performance relate to the important concepts of model- and technology-driven missions. In the former, the capabilities of the mobility system are defined by the requirements necessary to address a particular set of scientific questions. In the latter, the scientific issues to be addressed are defined by the capabilities of the mobility system. Since the primary reason for placing a mobile device in a planetary environment is to carry an instrument package that will return valuable scientific data, COMPLEX believes it is important that missions incorporating some form of mobility be designed to test explicit hypotheses, i.e., that they be model driven. Unless missions adopt this philosophy, there is a distinct danger that mobile systems will be designed without clear science goals in mind. The result could be a solar system exploration program driven by technology rather than by science.

Mars Pathfinder is an example of a model-driven mission. That is, a depositional model, derived from studies of analogous terrains on Earth, was applied to images obtained by the Viking orbiters and used to select a landing site that would provide access to an abundance of diverse rock types. Likewise, current planning for future Mars Surveyor missions and advanced mobility devices, such as the Athena rover, recently deleted from the 2001 lander mission,* involves selecting candidate landing sites based on geomorphic and geological models likely to preserve evidence for past biological activity. Athena and its instruments are designed to address issues that require the rock types sought. As science goals become more specific in the future, it will be even more important that mobile systems be designed to test hypotheses.

Given this philosophy, COMPLEX's approach to this report has been to identify science objectives that require mobility. Then it will be possible to determine whether the current state of mobility technology is sufficient and, if it is not, address in at least a preliminary way the development necessary to achieve the science objectives. There will be insufficient resources to pursue all possible variants of mobile spacecraft, and the decisions concerning which variants to develop and which to abandon should be guided by science priorities. These science priorities should then lead to technological priorities that, in detail, are beyond the scope of this report, although COMPLEX indicates some very general priorities where appropriate. Achieving useful mobility is not easy, as has been demonstrated in field tests on Earth and by the operation of the Sojourner rover on Mars. This also must be kept in mind when science-driven priorities for development are set.

ORGANIZATION

This report includes the following:

1. A brief review of fundamental science goals in solar system exploration (Chapter 1);
2. A discussion of the observations required and the role of mobility in addressing six representative case studies designed to address questions derived from these fundamental goals (Chapter 2); and

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*This report is written on the assumption that Athena will not be deployed by the 2001 lander, as originally planned, but that its scientific payload will eventually fly on a later Mars Surveyor mission.

3. A discussion of technical capabilities for a variety of mobile devices (Chapter 3). Some of these systems embody well-established technologies with heritages from past planetary missions (e.g., balloons and rovers); others employ technologies that have yet to be exploited by planetary scientists (e.g., aircraft and cryobots). This chapter also discusses the development and field testing required if mobility devices are to meet science needs. This discussion is structured according to the specific questions in the charge to COMPLEX (see the preface).

Chapter 4, "Conclusion and Recommendations," summarizes the importance of mobility for the successful completion of the diverse tasks required to address many of the key questions in solar system science and also summarizes development priorities for mobility technology with respect to these tasks.

SCIENTIFIC GOALS FOR SOLAR SYSTEM EXPLORATION

The science objectives to be addressed by mobility relate directly to the broad scientific goals for solar system exploration, as stated by the Space Studies Board. These objectives are the following:[1]

- Understanding how physical and chemical processes determine the main characteristics of the planets, thereby illuminating the workings of Earth;
- Learning how planetary systems originate and evolve;
- Determining how life developed in the solar system and in what ways life modifies planetary environments; and
- Discovering how the simple, basic laws of physics and chemistry can lead to the diverse phenomena observed in complex systems.

These broad scientific goals lead to some 35 primary objectives in eight subject areas (Table 1.1), ranging from protoplanetary disks to planetary atmospheres. These primary objectives, in turn, lead to a great many more specific objectives and questions.

SPECIFIC OBJECTIVES AND CASE STUDIES

The diversity of planetary environments found in the solar system is matched by the range of scientific disciplines needed to address them. Researchers with expertise in the geosciences and atmospheric sciences, together with those expert in exobiology and the study of particles and fields, have discovered a myriad of important topics to study on bodies as diverse as Sun-scorched Mercury and the frigid Kuiper Belt objects.

Reviewing the science that can be uniquely addressed by mobility in exploring the atmospheres and surfaces of solar system objects is a daunting task. Indeed, conducting a comprehensive review was not feasible within the constraints of the current study. Rather than tackle the challenging task of performing a detailed analysis of the mobility required to meet each of the 35 primary objectives listed in *An Integrated Strategy for the Planetary Sciences: 1995-2010*,[2] COMPLEX performed a preliminary examination, which indicates that mobility will be required to address a significant number of them, as listed in Table 1.1.

TABLE 1.1 Mobility Needed to Meet the Primary Objectives Identified in COMPLEX's *Integrated Strategy*

Subject Area / Primary Objective	Need for Mobility*
Protoplanetary Disks	
• Develop (through theoretical modeling) a detailed understanding of the aggregation of stellar and planetary systems, starting at the formation phase of dense molecular cloud cores.	Low
• Observe nearby star-forming regions to obtain data that can guide and constrain our understanding of protostellar formation.	Low
• Define the conditions and processes during the evolution of the solar nebula through laboratory analysis of meteorites and interplanetary dust particles and observations of primitive solar system objects, such as comets and asteroids.	Low
Planetary Systems	
• Construct an internally consistent, quantitative theory of the formation of our entire planetary system that contains sufficient details to permit comparison with as much observational evidence as possible, including the meteoritic record.	Low
• Detect and determine the orbital properties of planetary systems circling enough nearby stars to yield a statistically significant estimate of the frequency of planetary systems.	Low
• Ascertain, as is technically feasible, the atmospheric temperatures and compositions of those extrasolar planets.	Low
Primitive Bodies	
• Describe the nature and provenance of carbonaceous materials in cometary nuclei, especially as they pertain to the origin of terrestrial life.	Medium
• Identify the sources of the extraterrestrial materials that are received on Earth.	Low
• Delineate how asteroids and comets are related and how they differ.	Medium
• Determine the elemental, molecular, isotopic, and mineralogic compositions for a variety of samples of primitive bodies.	High
• Characterize the internal structure, geophysical attributes, and surface geology of a few comets and asteroids.	High
• Understand the range of activity of comets, including the causes of its onset and its evolution.	High
• Ascertain the early thermal evolution of primitive bodies, which led to the geochemical differentiation of these bodies.	Medium
Life	
• Define the inventory of organic compounds in the cores of molecular clouds, and improve our understanding of the prebiotic organic chemistry that took place in the solar nebula.	Low
• Improve knowledge of the processes that led to the emergence of life on Earth, and determine the extent to which prebiotic and/or protobiological evolution has progressed on other solar system objects, specifically Mars and Titan.	High
Surfaces and Interiors of Solid Bodies	
• Understand the internal structure and dynamics of at least one solid body, other than Earth or the Moon, that is actively convecting.	Medium
• Determine the characteristics of the magnetic fields of Mercury and the outer planets to provide insight into the generation of planetary magnetic fields.	Low
• Specify the nature and sources of stress that are responsible for the global tectonics of Mars, Venus, and several icy satellites of the outer planets.	High
• Advance significantly our understanding of crust-mantle structure, geochemistry of surface units, morphological and stratigraphic relationships, and absolute ages for all solid planets.	High
• Elucidate the chemical and physical processes (impact cratering, surface weathering, and so on) that affect planetary surfaces.	Medium
• Characterize the surface chemistry of the outer solar system satellites, and determine the volatile inventories and interaction of the surface and atmosphere on Triton and Pluto.	Medium
• Establish the chronology of at least one other major body in the solar system.	High

continued on next page

TABLE 1.1 Continued

Subject Area	Primary Objective	Need for Mobility*
Planetary Atmospheres		
	• Ascertain the key chemical balances and processes that maintain the current compositions of the atmospheres.	Medium
	• Specify the processes that control dynamics on the outer planets, on Mars, and on Venus.	High
	• Understand Mars's inventory of volatiles and its evolution and how these relate to historical climate changes.	High
	• Determine reactive-gas isotopic ratios, rare-gas abundances, and isotopic abundances for all the planets with substantial atmospheres, to help understand atmospheric origin, history, and maintenance.	Low
Rings		
	• Measure the radial, azimuthal, and vertical structure of all the ring systems at sufficient spatial resolution and clarify whether the observed variability is spatial or temporal in nature.	Low
	• Determine the composition and size distribution of the ring particles at a few places in several different systems.	Low
	• Develop kinematic and dynamic models of ring processes and evolution that are consistent with the best ground- and space-based observations. Insofar as possible, connect these processes to ones that were active as the solar system originated.	Low
Magnetospheres		
	• Determine how, and the degree to which, plasma and electromagnetic environments affect planetary gas (including the atmosphere), dust, and solid surfaces.	Low
	• Understand how solar wind and planetary variations drive magnetospheric dynamics, including substorms, for various magnetospheric conditions.	Low
	• Determine the roles of microscopic plasma processes in the mass and energy budgets of planetary magnetospheres, and ascertain the energy conversion processes that yield auroral emissions.	Low
	• Discover how differing plasma sources and sinks, energy sources, magnetic field configurations, and coupling processes determine the characteristics of both intrinsic and induced planetary magnetospheres.	Low
	• Determine what studies of contemporary planetary magnetospheres tell us about processes involved in the formation of the solar system.	Low
	• Characterize the plasma environments and the solar-wind interactions of Pluto-Charon and Mars.	Low

*Low, little or no mobility required; medium, robotic arms or other types of sample collection devices needed; and high, mobile platform equipped with sophisticated instrumentation required.

COMPLEX then went on to consider a subset of the priority activities identified in past reports, in particular the *Integrated Strategy,* and performed a series of case studies designed to illustrate important issues relating to the use of mobility in planetary exploration. These case studies address the following important scientific questions:

- What is the nature of the circulation in the lower atmosphere on Venus?[3]
- What tectonic processes are responsible for the structural and topographic features present on Venus?[4]
- Is there evidence for extinct or extant life on Mars?[5,6]
- What is the physical and chemical heterogeneity within small bodies such as asteroid 4 Vesta?[7,8]
- What drives the zonal winds in the jovian atmosphere?[9]
- What is the internal structure of Europa?[10]

COMPLEX emphasizes that the questions listed above do not necessarily represent the highest-priority issues to be addressed by planetary scientists in the near future. Nor does the ordering of the questions imply any particular priority. Rather, they are chosen to be representative of important issues, defined in past reports by COMPLEX, concerning a broad range of planetary environments (i.e., the terrestrial planets, giant planets, and primitive bodies), questions that also figure prominently in the five "campaigns" outlined in NASA's *Mission to* *the Solar System: Exploration and Discovery—A Mission and Technology Roadmap*.[11] These questions involve studies spanning a broad range of scientific disciplines (i.e., the geosciences, atmospheric sciences, and exobiology), and, as Chapter 2 indicates, can be best addressed by a broad range of mobility techniques, including the use of traditional devices such as balloons and rovers (which understandably dominate the discussion since these technologies are the best developed), as well as by devices less familiar to planetary scientists, such as aircraft and cryobots.

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2

The Role of Mobility in Solar System Exploration

The six case studies selected to illustrate the role of mobility in the intensive study of planetary bodies address important goals relevant to atmospheric structure and dynamics, the composition of small bodies without atmospheres and with negligible gravity, the composition of larger bodies with significant gravity, tectonic processes on the terrestrial planets, and the search for evidence of present or past life in the solar system beyond Earth. As such, they address priority goals in a range of scientific disciplines. These questions derive directly from previous National Research Council (NRC) reports.

Subsequent sections discuss the scientific importance of each of these questions, describe the observations that need to be made to answer them, and outline the associated need for mobility in obtaining the relevant observations.

CIRCULATION IN THE LOWER ATMOSPHERE OF VENUS

Importance

Among the most important parameters for understanding Earth-like environments are the physical and chemical properties of planetary atmospheres. Only by studying current conditions can we understand the origin and evolution of atmospheres. Thus, this case study directly addresses one of the specific objectives of the campaign, Evolution of Earthlike Environments, outlined in NASA's solar system exploration roadmap.

Beginning with Earth-based ultraviolet observations of Venus's clouds[1] and data from the former Soviet Union's Venera 8 mission in 1972,[2] it has been established that the planet's entire atmosphere rotates at a faster speed (though in the same basic retrograde direction) than the underlying surface. At high levels in the atmosphere, the speed of this so-called atmospheric superrotation is very large: at cloud-top levels (~50 to 60 km) the east-west (zonal) wind speed is ~100 m/s near the equator. As a result the atmosphere completes one rotation every 4 days, but the planet itself rotates much more slowly. Although the fastest winds are found near the cloud tops, most of the atmosphere's angular momentum is concentrated in the very dense lower atmosphere well below the clouds.

General theoretical considerations of atmospheric circulation show that superrotation at the equator can only be produced by eddy, or longitudinally asymmetric, motions that act to transport momentum either vertically or horizontally in a countergradient sense.[3–5] Some possible eddy motions are suggested by theoretical and modeling studies, including planetary scale waves, thermal tides, and vertically propagating gravity waves. These are probably of greatest importance above the lowest one to two scale heights (~20 to 30 km), but gravity waves could have their dominant source at the ground as a result of winds blowing over surface topography.

It is likely that a Hadley circulation also exists in the lower atmosphere, with mean flow toward the equator at lower levels and toward the pole at somewhat higher levels. Such a circulation would tend to transport angular momentum upward and poleward and could be important in governing the zonal wind structure.

The circulation of the atmosphere in the lowest one to two scale heights and the maintenance of the atmospheric superrotation are among the outstanding problems in planetary atmospheric science.[6] Venus is a very slowly rotating body, with a thick atmosphere in which considerable heating occurs at relatively high altitudes. Titan is the other example of such an atmosphere, and there is indirect evidence that its atmosphere may also superrotate.[7,8]

Recent modeling[9] provides a suggestion that superrotation might be a general feature of slowly rotating bodies with thick atmospheres. Thus far, however, modeling has not been able to reproduce the very strong superrotation of Venus's atmosphere. By comparison, the atmospheres of Earth and Mars exhibit only very weak, if any, superrotations. Both are rapidly rotating bodies with relatively thin atmospheres in which the bulk of the solar heating occurs at the ground.

Even in the case of Venus, where only a small fraction of the incident sunlight reaches the ground, the transfer of heat from the surface to the atmosphere contributes significantly to the forcing of lower atmospheric circulation. Similarly the transfer of momentum between the ground and atmosphere is very important. Both of these processes take place through a planetary boundary layer, of which essentially nothing is known at present for Venus. Observations of very high vertical resolution are crucial to resolving the boundary layer and the transfer processes that occur within it. The boundary layer can be strongly affected by the nature of the surface, and this may vary considerably on Venus from place to place.

Necessary Observations

The following measurements are needed to achieve a better understanding of the circulation in Venus's lower atmosphere:

- Multiple, geographically dispersed, simultaneous, and temporally extended measurements of pressure and temperature as a function of altitude and horizontal location to determine the basic structure of the lower atmosphere;
- Multiple, geographically dispersed, simultaneous, and temporally extended measurements of the winds in the lowest one to two scale heights, with sufficient accuracy and sampling rate to enable the definition of the circulation itself and the determination of horizontal- and vertical-momentum fluxes as a function of altitude and horizontal location; and
- Multiple measurements of radiative fluxes, both solar and infrared, as a function of altitude and at different locations to determine the radiative forcing of the atmospheric circulation.

Need for Mobility

A geographically dispersed series of entry probes could obtain valuable measurements, but would provide only a snapshot of the atmospheric circulation. Temporally extended measurements are essential because the atmospheric eddies involved in the superrotation are expected to vary on time scales of hours to days and longer. Remote-sensing techniques appear to be feasible for higher atmospheric levels, but probably would not reveal the atmospheric structure within one to two scale heights of the ground because of the extremely high density of the atmosphere. Mobility within the atmosphere provides an efficient approach, and the relevant measurements could, potentially, be made using the following modes of mobility:

- A number of balloons, capable of semi-autonomous flight for an extended period, to obtain simultaneous measurements in the lowest one to two scale heights over a significant fraction of the planet; and

- Balloons with the ability to land and monitor surface and near-surface processes at multiple locations.

Both mobility requirements could, in principle, be accomplished by using a single type of balloon. Practical considerations, however, suggest two types of balloons flown on sequential missions. One type of balloon would be designed to perform atmospheric measurements and, perhaps, be optimized for extended operation; the other type would be designed to conduct surface and near-surface studies. In either case, it is likely that the balloons must rise periodically to cloud-top levels in the atmosphere to cool instruments and hardware. This requirement would allow additional measurements at higher levels, which would extend the lower atmosphere profiles and aid in their interpretation. During vertical ascent and descent, the balloons would travel horizontally via the winds, which would greatly expand the observed regions of the planet.

The length of the mission would be determined by the atmospheric rotation rate and the relevant time scales of thermal processes in the dense lower atmosphere. A mission lasting for, say, 30 days would provide measurements covering much if not all of the globe. Geographic coverage is very sensitive to the height to which the balloons must rise in the atmosphere to cool and to the amount of time they spend at high altitudes where the winds are stronger than they are at lower altitudes. Obtaining adequate latitude coverage might require 5 to 10 balloons (i.e., a minimum of one in each of the polar and mid-latitude regions and another at the equator; twice as many would give some degree of redundancy). This is so because the mean north-south winds in the lower atmosphere (probably associated with a Hadley Cell circulation) are likely to be relatively weak (less than ~1 to 2 m/s), and any given balloon is likely to spend its entire lifetime in a rather narrow band of latitudes.

Careful tracking of the balloons will be necessary so that their locations are known with respect to those of gross atmospheric features. A positional accuracy of some 100 km may be sufficient. This could be achieved at least on Venus's Earth-facing hemisphere by using interferometric observations by Earth-based radio telescopes. This technique was successfully used to track the balloons deployed by the former Soviet Union's Vega 1 and 2 missions in 1985 (see Box 3.5 in Chapter 3).

In summary, a small fleet of balloons could obtain the needed measurements, offering major advantages over multiple entry probes and remote sensing from orbiters. In particular, balloons could reveal the full extent of horizontal and vertical variations in composition, structure, and wind velocity, including the important but currently poorly understood planetary boundary layer.

TECTONIC PROCESSES ON VENUS

Importance

A major theme of solar system exploration is to understand how planets work.[10] One of the key processes is the conversion of thermal energy in planetary interiors to the mechanical energy that deforms their surfaces and creates geologic landforms. The geology of Earth is dominated by plate tectonics, a mode of surface deformation apparently unique to our planet. The other solid planets and moons display a variety of tectonic styles that operate to create a diversity of geological landscapes. Just as plate tectonics is probably unique to Earth, certain tectonic styles might also be unique to other bodies. COMPLEX has identified the determination of the nature and sources of stress responsible for the global tectonics of Mars, Venus, and several icy satellites of the outer planets as a primary objective for understanding planets.[11] A specific objective is to determine why the tectonic histories of Venus, Earth, and Mars are so markedly distinct.[12]

With regard to Venus, the major puzzle remaining after exploration by the Magellan spacecraft is the identification of the tectonic process that resurfaced the planet 300 million to 600 million years ago.[13] Can such an event occur again on Venus? Are similar tectonic upheavals possible in Earth's future? While theoretical speculations for the resurfacing of Venus abound, the real answer to what caused it lies in the geologic structures of the planet's surface. The unusual and possibly unique landforms on Venus, such as chasmata and coronae, must be studied thoroughly at sufficiently close range to understand their origin and significance for global-scale tectonics.

The study of global tectonics is relevant to the goals of one of the campaigns, Formation and Dynamics of Earthlike Planets, in NASA's solar system exploration roadmap,[14] because tectonic processes control crustal evolution. Although this campaign is concerned predominantly with atmospheres and climate, Venus's tectonic style and history are also important, because they exercise significant control over interactions between the planet's surface and its atmosphere.

Rift-like features, called chasmata, were first imaged with Earth-based radar.[15] Their dimensions, global extent, and possible tectonic significance became more apparent in Pioneer Venus altimetry data.[16,17] Chasmata are long, narrow troughs; some are many thousands of kilometers long but only about 100 kilometers or less wide, and several to nearly 10 kilometers deep. Some chasmata are associated with major volcanic highlands, such as Atla and Beta Regiones. Many are associated with coronae (Figure 2.1), structures characterized by diverse and complex topography and quasi-circular rings of tectonic deformation. The margins of some very large coronae, such as Artemis and Latona, consist of segments of chasmata. Volcanism is commonly, but not universally, associated with coronae and chasmata.

Key questions about these unique features include these:

- How do chasmata and the associated coronae form?
- Is crustal extension involved, making chasmata similar to rifts on Earth?
- Some chasmata appear to be associated with crustal compression. Are chasmata then more like oceanic trenches on Earth?

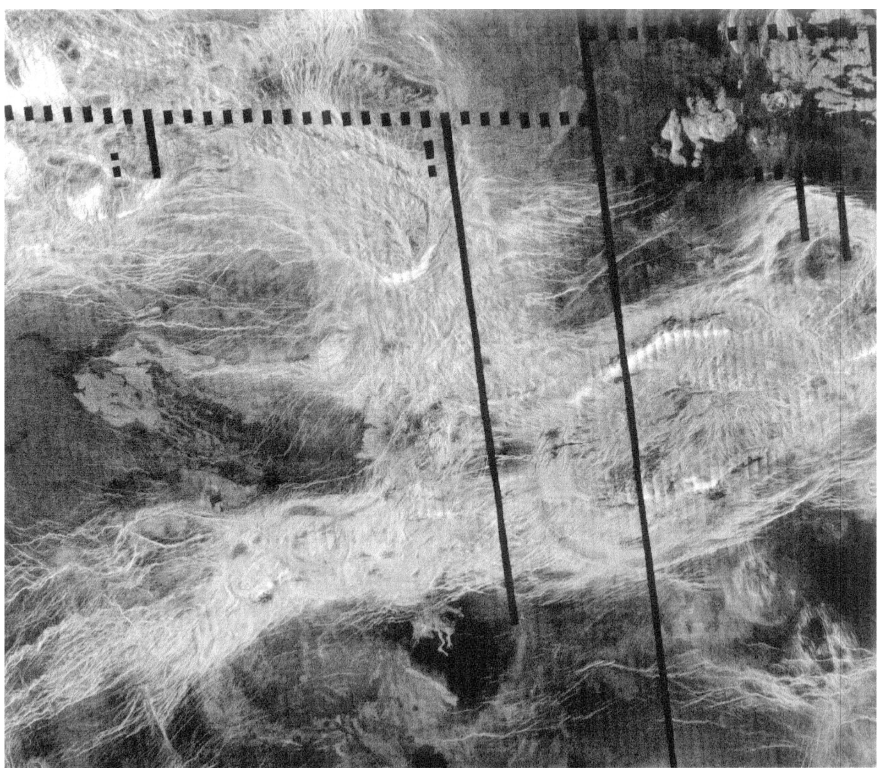

FIGURE 2.1 Part of Diana Chasma (bright band from lower left to center right), Venus. The ovoidal structure along the band at center right is the corona Ceres. Magellan SAR image C1_MIDR15S146; radar-look direction from the left; horizontal dimension about 1,500 km. Courtesy NASA, Jet Propulsion Laboratory.

• Are the mineral and chemical compositions of associated volcanic rocks different from those of the lavas that cover most of the planet, suggesting different mantle sources?
• Is there any correlation between topographic features of chasmata and the mineral and chemical compositions of rocks? For instance, do chasmata expose intrusive rocks of deep origin?

Necessary Observations

An understanding of the nature of chasmata on Venus will require a combination of geological, geochemical, and geophysical observations similar to those required for studies of terrestrial geologic features, including these:

• Determinations of elemental compositions, mineralogy, and physical properties of rocks;
• Measurements of isotopic abundances;
• Identification of deformational features, such as folds and faults, and determination of the motion sense across faults;
• Measurements of seismic velocity to determine parameters such as crustal thickness;
• Measurements of gravity and topography to constrain internal structure and mantle processes; and
• Measurements of remanent magnetization and electrical properties to constrain internal structure and thermal history.

Geological, geochemical, and geophysical studies should be carried out within and near chasmata along transects perpendicular to their trends and extending one or two chasma widths beyond their margins. Moreover, chasmata should be studied at many locations along their lengths because they change character with distance along trend. These observations are achieved only by surface measurements and by low-altitude reconnaissance over horizontal distances of hundreds of kilometers. The many parameters one must measure require the determination of crustal characteristics at scales of 10 km or smaller. This, in turn, implies spacing ground stations 10 km or less apart, and obtaining aerial data at altitudes of 10 km, or at most, a few tens of kilometers. An added benefit of images collected by rovers or by low-altitude balloons is the ability to “calibrate” the radar data that underlie all of our current interpretations of Venus’s structure and crustal history.

Need for Mobility

The global distribution, long-wavelength gravity signatures, and general topographic and structural characteristics of chasmata and coronae have been determined by Pioneer Venus, Venera, and Magellan missions. The Venera and Vega landers provided valuable data concerning rock compositions at specific sites, but none of them landed on a chasma or corona, and each provided only a point datum. High-resolution geophysical data and structural analysis are beyond the resolution currently available from orbit. Moreover, mineralogical and compositional data cannot be obtained by spectroscopy from orbit because Venus is continuously covered by clouds. Thus, collecting the relevant high-resolution geological, geochemical, and geophysical measurements from within and near chasmata will involve highly capable mobile platforms. Specifically:

• Collection of gravity, topography, and mineralogical data will require an aircraft or controllable balloon to fly at low altitude (a few kilometers) along traverses across chasmata for distances greater than 100 km; and
• Deployment of seismic stations, measurements of rock compositions, and sample collection for compositional analysis could be accomplished by rovers capable of traversing tens of kilometers, or by an aircraft or balloon that can touch down at intervals while conducting traverses across chasmata.

These requirements pose significant technical challenges because of the hostile surface environment of Venus (pressures greater than 90 bars and temperatures near 730 K) and the demands for range and controllability imposed on the mobile platforms. These factors suggest that this case study will have to be addressed in an incremental manner, using a sequence of missions. The sequence would, possibly, begin with the use of balloons (perhaps related to those designed for surface and near-surface operations, as discussed in the previous case study).

EXTINCT OR EXTANT LIFE ON MARS

Importance

The possible existence of extraterrestrial life is one of the most fascinating issues being addressed by the scientific community and a topic of great public interest. Given the likely environmental requirements for the origin of life on a planet—access to the necessary biogenic elements, the presence of liquid water, and the availability of a source of energy that can drive chemical disequilibrium—Mars is one of the most plausible places within our own solar system where life might exist or have existed. Mars shows geologic evidence for the existence of liquid water (at the surface early in its history and beneath the surface throughout its history), for the presence of the biogenic elements, and for the availability of abundant geochemical or geothermal energy that can drive chemical reactions.

The search for evidence of past or present life on Mars has become one of the major scientific goals of Mars exploration and of the ongoing Mars Surveyor program. A recent NRC report[18] summarized one of the specific objectives for Mars exploration as "searching . . . [Mars] for extinct or extant life, including evidence of the accumulation of a reservoir of prebiotic organic compounds and the extent of any subsequent prebiotic chemical evolution." This objective is a direct outgrowth of recommendations and conclusions reached in previous reports[19–21] and of the inference that the putative martian meteorite ALH84001 may contain evidence for past life on Mars.[22]

This case study is also directly relevant to one of the campaigns that NASA's solar system exploration roadmap outlines, the Evolution of Earthlike Environments, and is indirectly relevant to another, the Formation and Dynamics of Earthlike Planets. These connections exist because of the sensitivity of life to climate, which is, in turn, controlled by the totality of processes involved in Mars's origin and evolution: atmospheric, surface, and interior.

It is widely accepted that determining whether or not life existed on Mars will require a return of samples to Earth for laboratory analysis. In turn, this will require a careful selection of rocks and other materials from appropriate scientifically relevant sites on the martian surface.

Necessary Observations

Specific observations and measurements that are pertinent to studies of life on Mars include the following:

- Determination of the geologic context of regions to be sampled, including the geologic history of the terrain and the elemental and mineralogical composition of the surface at regional and local scales;
- Determination of the composition (at meter scale) of promising areas to search for minerals that might be indicative of the existence (past or present) of liquid water;
- A search for evidence of organic molecules within specific samples. Of particular interest are biochemicals such as amino acids, purines and pyrimidines, and sugars;
- Determination of stable isotope ratios within individual rocks or mineral components of rocks for signatures thought to be indicative of biological processes;
- Determination of mineral types, abundances, and petrographic relationships within individual samples that can be used to indicate the nature of the environment in which the material has existed and the likelihood of living organisms having been associated with it;
- Analyses of textures and structures of rocks and soils on scales from 1 to 10 microns in order to search for features that would indicate possible fossil biota; and
- Determination of the radiometric ages of samples and/or deposits from sites for which the geological history can be deciphered.

Need for Mobility

Although the global- and regional-scale surveys of mineralogical and elemental compositions that are a prerequisite for any assessment of Mars's potential as an abode of life can be determined from orbit, the detailed characterization of local sites of particular exobiological interest requires in situ measurements.[23] Most researchers do not expect that evidence for past or present life will be so abundant or widespread that it will be available in the immediate vicinity of landing sites. This is particularly true given that landings may occur up to tens of kilometers from the desired aim point. Without the mobility necessary to conduct in situ exploration, it may not be possible to identify a target location uniquely. The required mobility could, potentially, be achieved by use of the following technologies:

- Balloons or aircraft to act as mineralogical "eyes," i.e., obtain compositional information by performing spectroscopic assessments of rock and soil units at spatial scales smaller than can be obtained practically from orbital vehicles;
- Highly capable rovers to traverse from a landing site to sites of specific exobiologic interest and to explore the geologic history and context of the intervening region. These rovers must be capable of both autonomous navigation and real-time traverse planning from Earth. Given the current uncertainties in landing at a specific location, traverses of up to several tens of kilometers over complex terrain will be likely (demonstration of a precision-landing capability may, however, reduce this traverse distance by a considerable factor);
- An articulated arm capable of positioning analytic or imaging devices against rock and soil surfaces, oriented at any angle from the horizontal, to an accuracy and precision of better than 1 cm.
- A device to manipulate and move rocks from the surface, including picking them up, turning them over, or pushing them out of the way, to allow characterization or examination of all sides of a rock and of the underlying surface, or to place samples in a container for eventual return to Earth;
- Devices for crushing, breaking, or abrading rocks in order to expose unweathered surfaces for analysis or to create fragments small enough to be collected for in situ analysis or sample return;
- Devices for digging or coring into the subsurface to depths of at least a meter, and perhaps as much as several tens of meters, to search for evidence of biota or relevant organic chemistry; and
- Techniques to prevent biological or chemical contamination during these activities.

This variety of mobility modes suggests a sequence of missions equipped with more and more sophisticated landers and rovers, augmented by remote-sensing observations from balloons or aircraft. Many of the initial scientific and technological steps necessary to perform these studies have either already taken place or will be accomplished by missions in the near future. The Viking landers demonstrated the use of robotic arms to dig trenches, manipulate surface materials, and deliver samples to analytic instruments. Additional experience in performing such tasks will be gained in the near future with the operation of the robotic arm on the Mars Polar Lander. Sojourner provided initial experience with rover operations on Mars, and subsequent rovers in the Mars Surveyor program will, according to current plans, perform more complex activities, such as extracting core samples from rocks and soil and caching them for later return to Earth.

PHYSICAL AND CHEMICAL HETEROGENEITY WITHIN SMALL BODIES

Importance

Comets and chondritic asteroids are thought to consist of relatively primitive materials and, thus, their study is relevant to addressing issues encompassed by the campaign, Building Blocks and Our Chemical Origins, outlined in NASA's solar system exploration roadmap. However, many of the small bodies in the solar system have apparently been modified by thermal and impact processes. Imaging of asteroids during spacecraft flybys and studies of meteorites derived from asteroidal bodies reveal that asteroids have experienced both internal and external modifications to varying degrees. This includes thermal metamorphism, aqueous alteration, melting, core formation, impact cratering with attendant shock effects, regolith formation, and space weathering. The internal structure and composition, geophysical attributes, and surface geology of such bodies remain largely unknown. Their characterization represents a key objective remaining to be met.[24,25]

Perhaps the best-documented example of an asteroid exhibiting diverse surface properties is 4 Vesta, the third-largest known asteroid. For many years[26] it has been known that Vesta exhibits spectral variations with rotation,[27] and the heterogeneity of Vesta's surface has been confirmed by geologic mapping based on observations performed with the Hubble Space Telescope.[28] The spectral properties of Vesta have long been recognized as being similar to those of HED (howardite, eucrite, diogenite) meteorites, an important class of achondrites. The igneous nature of these samples implies that their parent body was highly differentiated. Geographic variations in Vesta's topography determined from Hubble Space Telescope images[29] reveal the presence of a very large impact crater that apparently excavated to depths of many kilometers into the crust and possibly the mantle, in the process ejecting kilometer-sized fragments that now can be dynamically linked to Vesta through their orbital properties.[30] Reflectance spectra from the floor of this large crater suggest that there are significant mineralogical differences between the surficial crust and deeper units.[31] The small Vesta-like asteroids liberated from the larger parent body also have spectral properties that link them to the HED meteorites and to Vesta itself.[32] Understanding the heterogeneity within individual bodies such as Vesta provides a geologic context for these meteorites.

Documenting the diversity among small solar system bodies, both heavily processed like Vesta and those that may have experienced less severe processing, can address the following objectives previously identified in NRC reports:[33–35]

- Determination of the record of early solar system processes and history retained by small bodies;
- Constraining the nature and composition of planetesimals, such as those that accreted to form the planets; and
- Recognition of relationships among asteroids, comets, and extraterrestrial samples (meteorites and interplanetary dust particles).

COMPLEX cites Vesta as an example because enough is known about it to anticipate the measurements and mobility techniques likely to be required to explore less-well-known small bodies. Many other asteroids and comets would be attractive targets. Judging from the prevalence of metamorphosed chondrites among meteorites, many chondritic asteroids must have experienced significant heating, although not necessarily to the point of melting as in the case of Vesta. Interplanetary dust particles thought to have been derived from comets show minimal thermal processing, but even these objects have been affected by heating during atmospheric transit. Thus, the abundances of volatile elements and organic compounds in their parent objects may only be understood from measurements made in situ on cometary nuclei.

Necessary Observations

The horizontal and vertical variations in mineralogy and mineral abundances can be estimated in a rudimentary way from rotational spectra,[36] but the data may not be interpretable in terms of unique, individual minerals. The following observations are needed:

- Optical measurements at high resolution, essentially equivalent to viewing through a geological hand lens or microscope, to determine the texture of rocks and soils, as well as particle-size distributions in regolith materials (these observations provide a context for interpreting chemical data and for calibrating remote sensing measurements);
- Direct measurements of the mineralogy of surface and subsurface units, using methods such as x-ray diffraction and various spectroscopic techniques (e.g., thermal infrared, Raman, Mössbauer), to help constrain the processes that produce the rocks and soils and the conditions under which they operate;
- Chemical analyses of surface and subsurface units, which can be combined with mineralogy data to estimate mineral relative abundances and provide ground truth for calibrating spectra;

- Determination of isotopic and trace-element abundances to quantify the chronology of various events and to constrain and model petrogenetic processes such as partial melting, fractional crystallization, or impact melting;
- Seismic data to determine the asteroid's interior structure;
- Heat flow measurements, which can be used to estimate the inventory of long-lived radioactive isotopes in the whole body;
- Measurements of the magnetic field to provide information on the body's differentiation and thermal history; and
- Small-scale gravity measurements to help define the moment of inertia of complexly shaped and compositionally diverse objects. Local variations in the gravity field can also be modeled to reveal the existence of subsurface plutons and other heterogeneities.

Need for Mobility

Chemical variations for minor and trace elements that carry much information on interior source regions and on melting and crystallization processes cannot be measured remotely. Remote measurements also cannot determine radiogenic isotope compositions and absolute ages of various units, data that provide essential detailed information on the evolutionary history of the body.[37,38]

A more fundamental understanding of the geologic context for the HED meteorite samples from Vesta's ancient volcanic surface will first require measurements from orbit to identify both ancient flow sites and units exhibiting the most extreme diversity either through a complex volcanic history or from deep impact excavation and mixing. Observations of the context and petrology of rock types at multiple locations will provide a basis for fully tapping the potential of linking in situ measurements with the wealth of laboratory information available from HED meteorites. Through this link, a more fundamental understanding of the geology, stratigraphy, and internal structure of Vesta's preserved ancient planetary surface will be achieved.

The observations identified above require mobility, either for sampling of multiple surface and subsurface units on a heterogeneous asteroid such as Vesta, or for positioning geophysical instruments that must work in tandem. Horizontal mobility also could provide vertical mobility by sampling blocks excavated by impact craters. Whether mobility is provided by rovers, touch-and-go orbiters, or some other platform will depend in large part on the size of the body under study. The specific mobility requirements for this case study are the following:

- Mobility of meters to hundreds of meters for kilometer-sized bodies, and of tens of kilometers for larger objects such as Vesta, to measure the horizontal variations of mineralogy and chemistry of materials, or to collect samples for return to Earth;
- Vertical sampling to depths on the order of tens of meters of regolith on asteroids or devolatilized crust on comets. Although recoverable penetrators might provide a means to sample the subsurface, coring devices are probably superior choices;
- Mobility of meters to hundreds of meters for kilometer-sized bodies, and of tens of kilometers for larger objects such as Vesta, to deploy geophysical instruments; and
- Devices capable of collecting samples for return to Earth. Some important measurements, such as abundances of radiogenic isotopes and trace elements, will likely require sample return to Earth-based laboratories unless future instrument development advances significantly in remote sample handling, processing, and analysis. Returning samples from small asteroids and comets, with escape velocities of less than a few meters per second, may well be technologically easier and involve less cost than performing complex sample manipulation and analysis on the bodies themselves.

As with the other case studies, it is highly unlikely that a single mission will embody all of these mobility modes. A number of current or approved missions will demonstrate how some of the necessary technological challenges will be addressed. If, as currently planned, the Near-Earth Asteroid Rendezvous (NEAR) spacecraft lands successfully on Eros at the end of its mission, it will demonstrate many facets of the precision navigation necessary for the operation of a touch-and-go orbiter.

Other missions under development that are relevant to this case study are Japan's MUSES-C asteroid sample-return mission and NASA's Champollion/Deep Space 4 comet-nucleus lander. MUSES-C will deploy a NASA-developed microrover on 4660 Nereus in 2003. Champollion will land on the nucleus of Comet Tempel 1 in 2005, drill into the surface to the depth of approximately 1 meter, extract some 100 cc of material, and package it for return to Earth.

ZONAL WINDS IN THE JOVIAN ATMOSPHERE

Importance

The recent Galileo mission provided strong evidence that the composition[39,40] and structure[41,42] in some regions of the jovian atmosphere differ greatly from those that exist in the bulk of the planet.[43] The Galileo probe appears to have descended into a "desert"—a region known as a 5-µm hot spot[44]—in which the temperature increases with depth along a dry adiabat (neutral stability). Such regions contain relatively little water or other condensables, such as ammonia (Figure 2.2).

Data from Galileo's Near-Infrared Mapping Spectrometer (NIMS) observations of hot spots and their surroundings show a gradient in water concentration, increasing outward from the dry centers of hot spots to their peripheries.[45] The hot spot sampled by the Galileo probe may be an area in which downward motions associated with convection are occurring.[46] In surrounding areas, rising air loses its minor constituent condensables, such as water, through condensation and cloud formation. Thus, descending air in the hot spot is depleted of condensable species, accounting for the dryness. However, dry air on Jupiter is lighter than wet air, and the mechanism for forcing dry air downward in the 5-µm hot spots is uncertain.

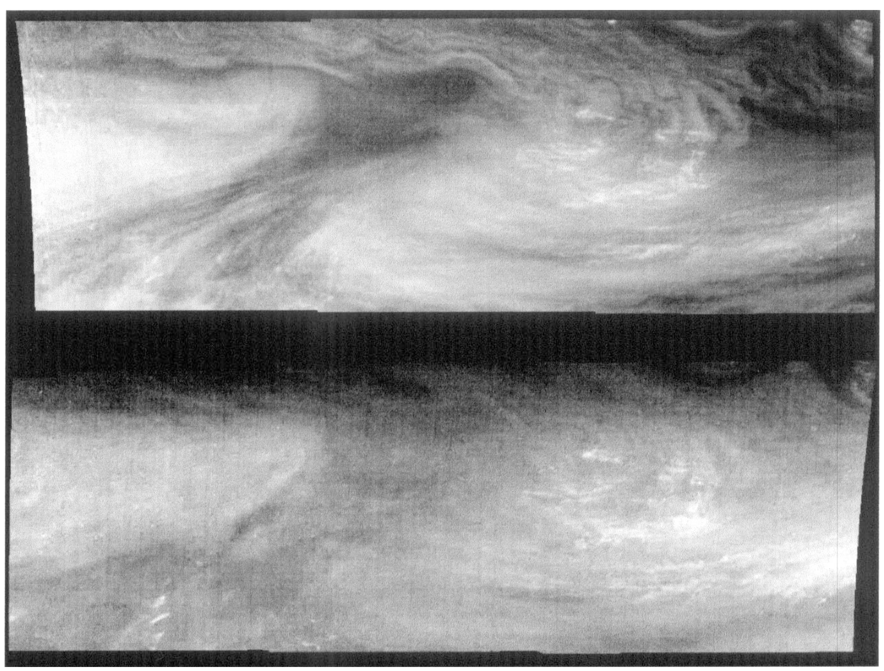

FIGURE 2.2 A near-equatorial hot spot (elongate dark patch) in the atmosphere of Jupiter. The upper image was taken in the 727-nm methane band, and the lower image was taken in the 889-nm methane band. The images cover an area of some 34,000 by 11,000 km and are centered on about 5° North, 336° West. Courtesy NASA, Jet Propulsion Laboratory.

Other Galileo observations have shown that the zonal winds at the probe's entry site increase with depth and approach a constant velocity of about 200 m/s at the largest depths studied.[47–50] The increase of zonal wind speed with depth suggests that these winds are driven by deep-seated dynamical processes, such as the global thermal convection of jovian internal heat.[51–53] If solar energy were driving the zonal winds, their speed should decrease with depth below the solar-energy deposition level in the atmosphere.

The detailed dynamical processes involved in the forcing of the zonal winds at depth are, however, not well understood. Whether or not the zonal winds persist to pressure levels greater than about 20 bars, and whether the special characteristics of 5-μm hot spots (dryness, downflow, neutral stability) continue to similar depths, are questions of vital importance to understanding Jupiter's atmosphere. A better understanding of the dynamics of Jupiter's atmosphere is one of the key elements of NASA's solar system exploration roadmap's campaign, Astrophysical Analogs in the Solar System.

Necessary Observations

To gain an improved understanding of the dynamics and compositional variations of 5-μm hot spots and the dynamics of the zonal winds in the jovian atmosphere, the following measurements are needed:

- Abundances of condensable species (e.g., H_2O, NH_3, NH_4S) as functions of altitude and horizontal location in 5-μm hot spots and in the background atmosphere;
- Compositions, abundances, and altitudes of cloud layers;
- Temperatures, pressures, and winds as a function of depth and horizontal location; and
- Radiative fluxes versus depth and horizontal position.

Need for Mobility

Some of the required measurements could be obtained with multiple, widely separated atmospheric entry probes, but this would provide data at only a handful of particular locations and of short time duration. Remote-sensing by instruments such as Galileo's NIMS could also acquire relevant data, but not below the clouds, and with only limited horizontal and vertical spatial resolution above the clouds. Mobility is required to obtain the structure, composition, and wind velocity data below the clouds with the appropriate spatial and temporal characteristics. Observations from balloons would be extended in time and would include simultaneous (synoptic) measurements, which is very desirable. The requisite measurements could be made by the following:

- The deployment of a number of balloons capable of vertical ascent and descent to probe the atmosphere to great depth. Vertical ascent and descent capability may be limited by communication difficulties and the high temperatures and pressures to be found at depth. If so, very deep levels could be probed with the use of specially designed and equipped dropsondes released from the balloons.
- The deployment of balloons at various latitudes to sample different belts and zones. The balloons would be carried in the prevailing zonal winds and, thus, could sample longitudinal and altitudinal variations in atmospheric conditions within a belt or zone for the duration of their lifetimes.
- The deployment of balloons in special atmospheric locations such as the 5-μm hot spots or selected storm systems.

These mobility requirements may best be addressed by a number of missions specifically designed to deploy different types of balloons in Jupiter's atmosphere. The initial mission would release balloons in a number of different latitude bands. Subsequent missions would emplace more sophisticated balloons capable of descending deep into Jupiter's atmosphere and/or balloons with the ability to release dropsondes. In either case, it is likely that the latter balloons or dropsondes would need to survive to pressure depths of some 100 bars, that is, four to five times that experienced by Galileo's probe.

The primary factors determining the required lifetimes of the balloons are the wind speeds. These vary greatly from place to place on Jupiter but tend to be strong (~50 to 100 m/s). At these speeds, a lifetime of less than a week is probably sufficient to traverse a hot spot. Considerably longer lifetimes would, however, be required to sample a sizable portion of the planet. Knowledge of the locations of the balloons with respect to gross atmospheric features will be required. Radio tracking with interferometric techniques may be sufficient to achieve the requisite accuracy, at least while the balloons are on Jupiter's Earth-facing hemisphere.

In summary, a fleet of balloons could obtain the needed measurements, offering major advantages over multiple entry probes. In particular, balloons could reveal the full extent of horizontal and vertical variations in composition, structure, and wind velocity in the jovian atmosphere.

EUROPA'S INTERNAL STRUCTURE

Importance

The nature of Europa's internal structure and, in particular, the possibility of a liquid water ocean beneath the ice cover are crucial to the past or present existence of life on this satellite of Jupiter.[54] The surface of Europa is composed primarily of water ice, with only a small amount of contaminating material.[55,56] The scarcity of impact craters in many areas implies a relatively young age for the surface and suggests that there must have been active resurfacing in geologically recent epochs. Because the actual age of this relatively recent resurfacing depends on models of the flux of objects striking Europa's surface,[57,58] there is some disagreement about the meaning of "recent." The most likely model, however, predicts surface ages as young as 10 million years, with an uncertainty of a factor of five.[59] In addition, the surface is riven by cracks and faults, suggesting that tectonic movement of the ice has occurred.

Tidal heating similar to that driving the extreme volcanic activity on Io provides some heating of the Europan interior. The deeper parts of the ice cover may have reached the melting point, and thus, the ice may be underlain by a local or global ocean. Recent Doppler measurements from the Galileo spacecraft yield a moment-of-inertia factor indicating that the outer water ice/liquid layer of Europa is at least 125 km thick.[60]

Images of the surface show faulting and movement of the ice at all scales down to a few tens of meters; the physical appearance is similar to that of terrestrial sea ice. The surface ice has broken apart and moved in blocks (Figure 2.3), either on warm, soft ice very near the melting point or on a subsurface ocean.[61] Although not proven, the possibility of liquid water near the surface, perhaps globally distributed and very recent in time, is strong. Because Europa has no appreciable atmosphere, any liquid at the free surface would immediately freeze by evaporative self-cooling and by thermal radiation.

If liquid water is present in the near subsurface, there are substantial ramifications for Europa, as both the ice tectonics and the interior heating change dramatically. Dissipation of tidal energy increases in the presence of a liquid water ocean because the surface ice shell experiences greater deformation. Movement of the ice at the surface and resurfacing of the planet, either by liquid or ice emplacement, are more efficient in the presence of liquid.

The presence of liquid water enhances the possibilities for the origin and evolution of life on Europa because liquid water is generally thought to be required for life. In addition, access to biogenic elements and a usable source of energy to drive chemical reactions are necessary. These may be available at, for example, the interface between the liquid water and the rocky material that underlies the ice/water surface layer. These possibilities imply that Europa is a natural laboratory for studies of the processes leading to the origins of life. As such, this case study is directly relevant to NASA's solar system exploration roadmap campaign, Pre-Biotic Chemistry in the Outer Solar System

The history of the surface and interior of Europa, along with the prebiological and possible biological nature of the interior, may be revealed by determining the structure of the surface layers at scales from global to local (i.e., subkilometer) to establish whether liquid water is present today or has been present in geologically recent epochs. If liquid water is present today, the distribution of liquid throughout the ice layer, the nature of the liquid region, and the potential for biological activity need to be determined.

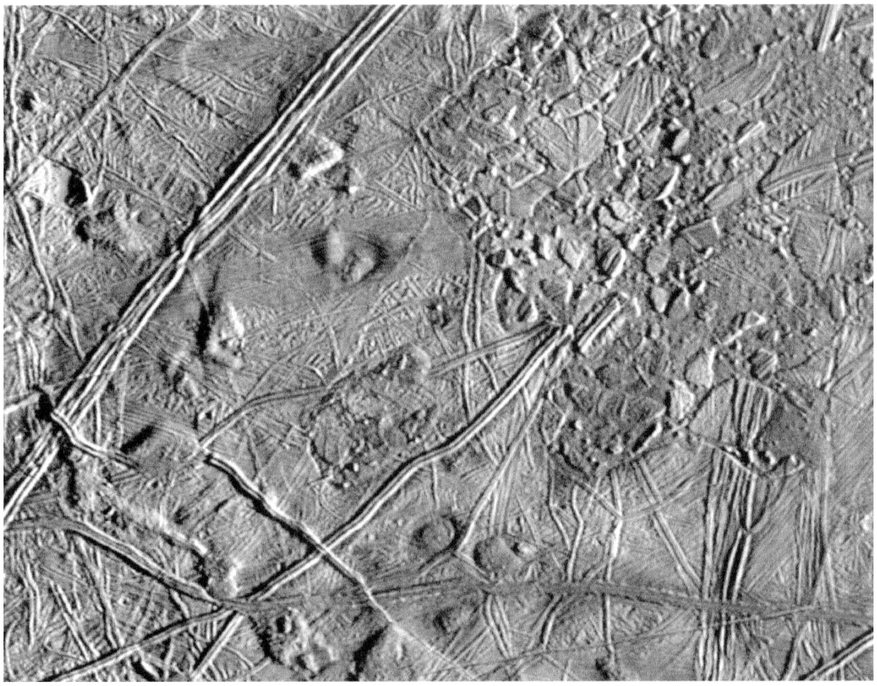

FIGURE 2.3 A portion of the surface of Europa showing prominent deformation bands, a complex fracture pattern, and jumbled blocks of elevated crust. The solar illumination is from the right in this Galileo image, which is centered on 8° North, 275° West. The field of view covers an area 100 by 140 km across. Courtesy NASA, Jet Propulsion Laboratory.

Necessary Observations

The goals outlined above for the characterization of Europa require the following observations:

- Determination of the geologic structure and tectonic history of the ice crust;
- Estimation of the ages of different segments of crust based on differences in impact-crater densities;
- In situ analysis of young, near-surface ice to determine its chemistry, including salts, particulates, organic constituents, and possible isotopic indicators of biological activity;
- Measurements of local and global values of the geothermal gradient in the ice crust within boreholes and by remote sensing using microwave techniques;
- Geodetic measurements of the response of the crust to tidal forces;
- Analysis of the chemical and physical properties of near-surface liquid, if present; and
- Identification of the geological processes occurring at the interface between a liquid layer, if it exists, and the surrounding ice or rock.

Need for Mobility

Detailed measurements of Europa's shape and gravitational field are priority goals of NASA's Europa Orbiter mission.[62] These data should provide the critical evidence needed to determine if a subsurface ocean actually exists. Other, follow-on measurements, such as those pertaining to chemical composition, crustal processes, and detailed internal structure, require in situ measurements and will necessitate substantial mobility on the satellite's surface. In particular, in situ measurements of the composition of the ice or of the non-ice portion of the surface, and measurements that pertain to the possible presence of liquid water and its properties, would need to be made from a variety of locations on and beneath Europa's surface. As these locations cannot be determined a priori, but will require analysis of data from the surface, the ability to move from one place to another is required. Thus, in addition to acquiring global remote-sensing measurements from a low-altitude orbiting spacecraft, the following mobility modes are potentially required:

- A surface rover capable of moving over long distances (perhaps the tens of kilometers necessary to cross the landing-error ellipse and reach areas of interest) to make pertinent geological, geochemical, and geophysical measurements, and to identify regions that might have a locally thin crust;
- A multifunctional arm on a rover or lander to deploy and position instrument detectors or sampling devices;
- Drilling and coring devices capable of penetrating to shallow depths (meters) beneath the surface. Mobility of this form would allow the deployment of instruments to measure subsurface temperature gradients, in situ composition measurement, and the collection of samples for analysis on board a lander or rover;
- Devices for collecting coherent samples, and facilities to maintain them in a pristine thermal environment for eventual return to Earth;
- A cryobot for melting into the ice shell of Europa, to depths on the order of kilometers, to deploy instruments either within the ice or within the underlying water, if it is present; and
- A small submarine, deployed by the cryobot, to explore the subsurface water ocean, if it is present.

The range of mobility modes required suggests a progression of missions that each collect data relevant to the feasibility of later activities. Such a progression could begin with a relatively simple lander equipped with either an arm to collect samples or a similarly equipped rover. Additional surface missions, such as landers capable of performing more complex activities (e.g., drilling to relatively shallow depths), may be required before the deployment of cryobots capable of melting their way through a considerable thickness of ice and, possibly, penetrating the ice/water interface. Even the simplest of these activities is likely to present unique technological challenges due to Europa's extreme radiation environment and low surface temperatures.

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3

Technological Capabilities

The following discussion of the technological status of various mobility systems and their application in past planetary exploration missions is organized according to the specific tasks outlined in the charge given to the Committee on Planetary and Lunar Exploration (COMPLEX) by the Space Studies Board (see preface). These tasks are the following:

- *Achieving mobility*. What are the practical methods, the state of technology, and the key requirements for technology development?
- *Sample acquisition*. What are the associated needs for sample acquisition?
- *Terrestrial field demonstrations*. What terrestrial field demonstrations are required prior to spaceflight missions?

ACHIEVING MOBILITY

Several distinctly different approaches to mobility will be needed to accomplish the science goals outlined in COMPLEX's *Integrated Strategy*[1] and NASA's solar system exploration roadmap,[2] as illustrated through examples described in the previous chapter of this report. Although the need for a variety of devices is dictated somewhat by differences in the mobility requirements among scientific disciplines, the mobility requirements among disciplines overlap more than they differ. The need for a variety of mobile platforms and devices stems primarily from environmental differences among solar system bodies, that is, from small bodies with negligible gravity to large bodies with significant gravity, from bodies with no atmospheres to bodies with dense atmospheres, from bodies with accessible solid surfaces to bodies with no solid surfaces, and, not the least, bodies with a variety of extreme thermal and radiation environments.

The platforms currently under consideration include rovers, hoppers (and their more extreme relatives, the touch-and-go orbiters), balloons (including aerobots), aircraft, and cryobots. Several of these vehicles also require devices for manipulation of instruments and for manipulation or collection of samples. These devices are dealt with in this chapter's section on sample acquisition. Where relevant, a brief summary of past experience with the use of similar devices is summarized in a text box.

Rovers

The first use of an unmanned rover on another solar system body occurred in the early 1970s when the former Soviet Union's Luna 17 and 21 missions landed the Lunokhod rovers on the surface of the Moon (see Box 3.1). Not until the successful deployment of Sojourner on the surface of Mars in 1997 was another unmanned rover used for solar system exploration (see Box 3.2). More attention has been paid to the development of rovers than any other form of mobility.[3–8]

The range of rover types and the technological problems associated with their deployment were well understood by the late 1980s.[9] Many rover types have been discussed to date, ranging in size from nano- and microrovers with total masses of less than 1 kg to large vehicles with masses in excess of 400 kg (Box 3.3).[10] Although many generic science payloads have been proposed for discussion purposes, the overall thrust of much of the work to date has been technological. For much of the 1990s, major development efforts have been directed toward reducing the total size of rovers and increasing their autonomy.[11,12]

Scientific and Technological Requirements

To be most effective, rovers must be able to carry a set of complementary science instruments for a significant range. The extent of this range will depend on mission-specific factors. These include the scientific objectives to be met, the scientific payload carried by the rover, the size of the landing-error ellipse, nature of the site chosen, prelanding knowledge of the site, and the availability of planning materials (e.g., maps based on very high resolution orbital or descent imagery) to facilitate rover operations. Given these caveats, assessments of, for example, various martian landing sites offered by the planetary geoscience community suggest that minimum ranges of 1 to 10 km are required.[13] Longer ranges will be necessary if a rover is to characterize and sample geological units on a more regional scale or if it is to visit more than one specific site. To adequately perform the scientific characterization of a site, a rover requires the following capabilities:[14]

- *Context*—the ability to determine the lander's location in relation to features recognizable from orbit;
- *Vision*—the ability to return recognizable images of the local area to Earth;
- *Mobility*—the ability for significant movement away from the landing site;
- *Manipulation*—the ability to handle samples physically.

Furthermore, the rover must carry an integrated set of science instruments. That is, in the words of a report on a recent workshop on surface instruments, the rover "should not just carry a collection of individual instruments each playing its own tune, but must be an orchestra."[15] Many planetary researchers believe that single-instrument rovers are not likely to be very useful scientifically, because an array of measurements taken by different instruments commonly is necessary to answer even simple questions. For example, adequately defining a rock type requires at least one instrument capable of measuring elemental abundances, visual to infrared spectrometers to determine mineralogy, and a very high resolution (<1 mm/pixel) imager to determine grain size, structure, and texture.

Technological requirements for the command and control of conventional rovers can be stringent. As exemplified by Lunokhod, system and vehicle control can be largely Earth based for lunar rovers because the two-way communication time is short. However, even though Pathfinder was a highly successful mission, the speed and range of Sojourner were limited by the long two-way communication time and by its limited autonomy.

Future rovers designed to conduct long traverses (tens to hundreds of kilometers or more) or to operate on more distant bodies face a significant operational challenge. Such missions will require significant local autonomy, including the ability to perform local navigation, identify or sample sites of potential scientific interest, regulate on-board resources, and schedule activities. But mission scientists want to retain some control over the rover and its operations. If they do, in the words of the Mars 2001 Science Definition Team, "the rover would spend most of its time stationary waiting for instructions from home and so distances traveled would be greatly reduced as would the number of analyses, images . . . ."[16]

BOX 3.1
Lunokhod

The Soviet Luna 17 and 21 missions (launched in 1970 and 1973, respectively) each delivered to the Moon's surface an eight-wheeled, roving vehicle called Lunokhod (Figure 3.1.1). Weighing 756 and 840 kg, respectively, Lunokhods 1 and 2 each carried several instruments, including stereocameras, a survey camera, a laser reflector (for laser ranging), a magnetometer, a cosmic ray detector, an x-ray spectrometer, and a penetrometer.[1] Lunokhod 1 returned data for more than 10 months and traversed 10.54 km, while its successor operated for only 3 months but ranged 37 km over the surface of the Moon.[2]

Lunokhod resembled a teapot, complete with an openable lid that was hinged along one side of the kettle top. Solar panels covered the underside of the lid; during the day, the lid remained open, collecting energy for operation and storage. At night, the lid closed to conserve heat inside the instrument housing. Lunokhod's chassis supported eight independently suspended and powered wheels. Each wheel was constructed of three wire rims, each of which was attached to the hub by sixteen spokes. A wire mesh and lugs covered and connected the wheel rims.[3] Additional characteristics of the Lunokhod vehicles are listed in Table 3.1.1.

The Lunokhods fulfilled both scientific and engineering objectives. Combined, they returned more than 500,000 images and 500 panoramas, performed some 1000 soil property tests and 50 soil chemical analyses, and returned astronomical observations from the surface of the Moon.[4] Despite its shorter life span, Lunokhod 2 took proportionally more measurements than did its predecessor, consistent with the distance it traversed. The Lunokhods successfully negotiated the lunar mare, a surface that is relatively free of large obstacles and for which they were specifically designed. Lunokhod 1 traversed the western section of Mare Imbrium, and Lunokhod 2 traveled over Mare Serenitatis.

The rovers could operate only under the direction of a team of five (including a vehicle commander, a driver, a navigator, and engineers) who controlled the vehicle remotely based on input from the rover

TABLE 3.1.1 Lunokhod Characteristics

Characteristic	Both Rovers	Lunokhod 1	Lunokhod 2
Rover mass		756 kg	840 kg
Rover length	2.13 m		
Wheel base[a]	1.70 m		
Number of driving wheels[a]	8		
Wheel diameter/width[a]	0.51 m/0.2 m		
Wheel dynamic range[a]	0.1 m		
Maximum surmountable vertical obstacle[a]	0.4 m		
Range traversed[b]		10.54 km	37 km
Length of operations		10 mo	4 mo

[a]A.P. Vinogradov, *Lunokhod 1—Mobile Lunar Laboratory*, translated by Joint Publications Research Service, JPRS#54525, distributed by National Technical Information Service, U.S. Department of Commerce, 1971, p. 73.
[b]Marcia S. Smith, *Space Activities of the United States, CIS, and Other Launching Countries/Organizations: 1957-1994*, Congressional Research Service 95-873 SPR, Library of Congress, Washington, D.C., 1995, p. 90.

cameras and other sensors. This method proved to be extremely challenging and required a crew that had not only "a knowledge of control techniques and skills, but also definite psychophysical qualities: a capacity for prolonged attention, speed in reaction and in processing information, long-term and current memory, acuteness of vision and hearing . . . . [Moreover] no training, even properly formulated, could completely recreate the actual conditions and replace actual control experience."[5] Longer lags in communications make this method of operation highly impractical for use beyond the Moon.

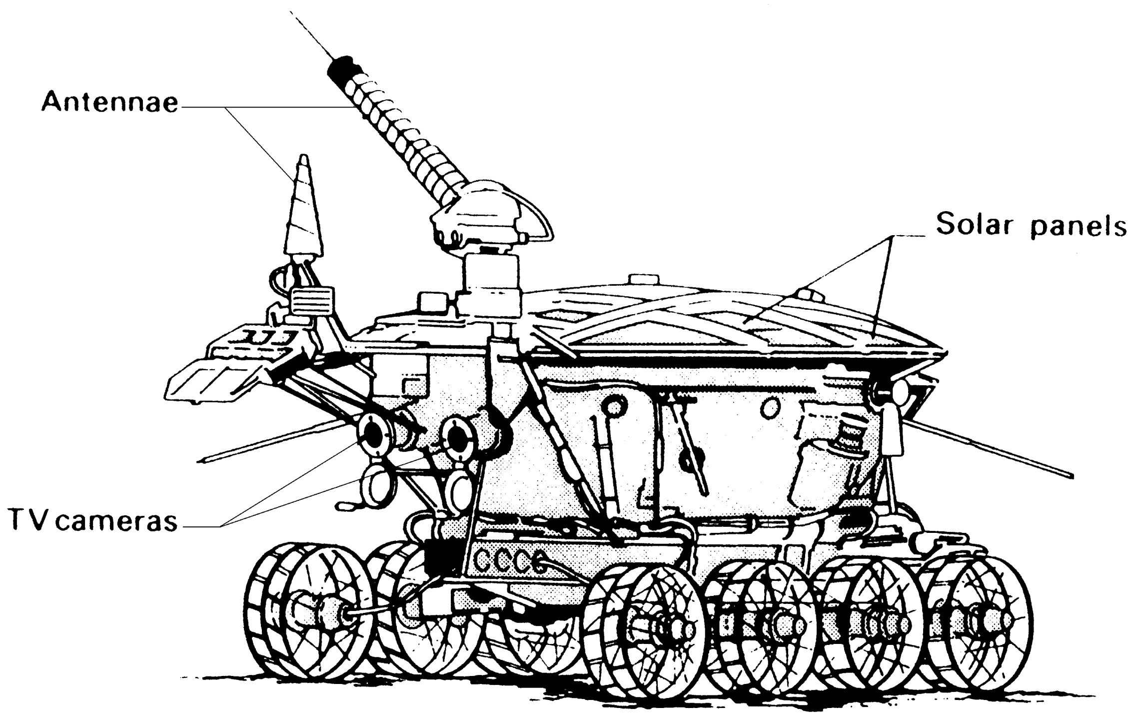

FIGURE 3.1.1 This sketch shows the basic features of the former Soviet Union Lunokhod rover. Two such vehicles were deployed on the Moon in the early 1970s. Illustration adapted from *The Moon—Our Sister Planet*, Cambridge University Press, Cambridge, England, 1981.

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[1]Peter Cadogan, *The Moon—Our Sister Planet*, Cambridge University Press, Cambridge, England, 1981, pp. 139-140.
[2]Marcia S. Smith, *Space Activities of the United States, CIS, and Other Launching Countries/Organizations: 1957-1994*, Congressional Research Service 95-873 SPR, Library of Congress, Washington, D.C., 1995, p. 90.
[3]A.P. Vinogradov, *Lunokhod 1—Mobile Lunar Laboratory*, translated by Joint Publications Research Service, JPRS#54525, distributed by National Technical Information Service, U.S. Department of Commerce, 1971.
[4]Smith, 1995, p. 90.
[5]Vinogradov, 1971, p. 73.

BOX 3.2
Sojourner

Sojourner, the rover on the Mars Pathfinder mission (Figure 3.2.1), was basically a rectangular table on wheels (Table 3.2.1). The "tabletop" was a 0.25 m^2 solar cell array. Navigation was controlled from Earth, but the rover was capable of avoiding obstacles by using laser sensors and a simple avoidance protocol included in its on-board processor (Intel 80C85). Navigation was accomplished with two forward-looking monochromatic cameras that provided a stereoscopic view of the terrain. Sojourner's maximum speed was 1 cm/s for a total possible range of about 60 m/day, assuming continuous driving and no obstacles; actual speeds and distance traveled were much less. The maximum data relay rate was ~ 30 Mbits/day, via the lander.

The suspension system allowed individual wheels to climb over obstacles as high as the wheel diameter (13 cm). In addition, because each wheel was independently driven, Sojourner could use them to dig shallow trenches in the martian soil. A color monoscopic camera was mounted at the back of Sojourner, along with an alpha-proton x-ray spectrometer (APXS). The latter was mounted on an arm that permitted placing its sensor against either rocks or soil. A full elemental analysis of a particular sample required about 10 hours. The color camera imaged the spot where the analysis was carried out. The chemical data returned included some surprises, such as rocks with sufficient SiO_2 that quartz appears in their calculated "normative" mineral compositions, and with higher SiO_2 than any of the known martian meteorites or any martian soils.

Sojourner was originally designed to conduct a 7-day mission on the martian surface. After about 60 days, the batteries were depleted but the rover continued to operate during daylight hours by using solar power. The last contact with Pathfinder was on October 7, 1997. Loss of contact is believed to have been due to extremely low temperatures in the lander. Despite a few communication problems and minor glitches with the positioning of the APXS, Sojourner performed exceptionally well, far exceeding design expectations.

TABLE 3.2.1 Characteristics of Sojourner

Size:
Length = 65 cm
Width = 48 cm
Height = 30 cm (with top raised to full height)
Mass:
Total rover, including instrument payload = 10.5 kg
Instrument payload = 1.5 kg
Support equipment on lander = 5.5 kg
Mobility:
6-wheel rocker-bogie mobility system
Power:
10 W of solar power for basic operations; up to 16 W under optimum conditions
Lithium thionyl chloride D-cell backup batteries

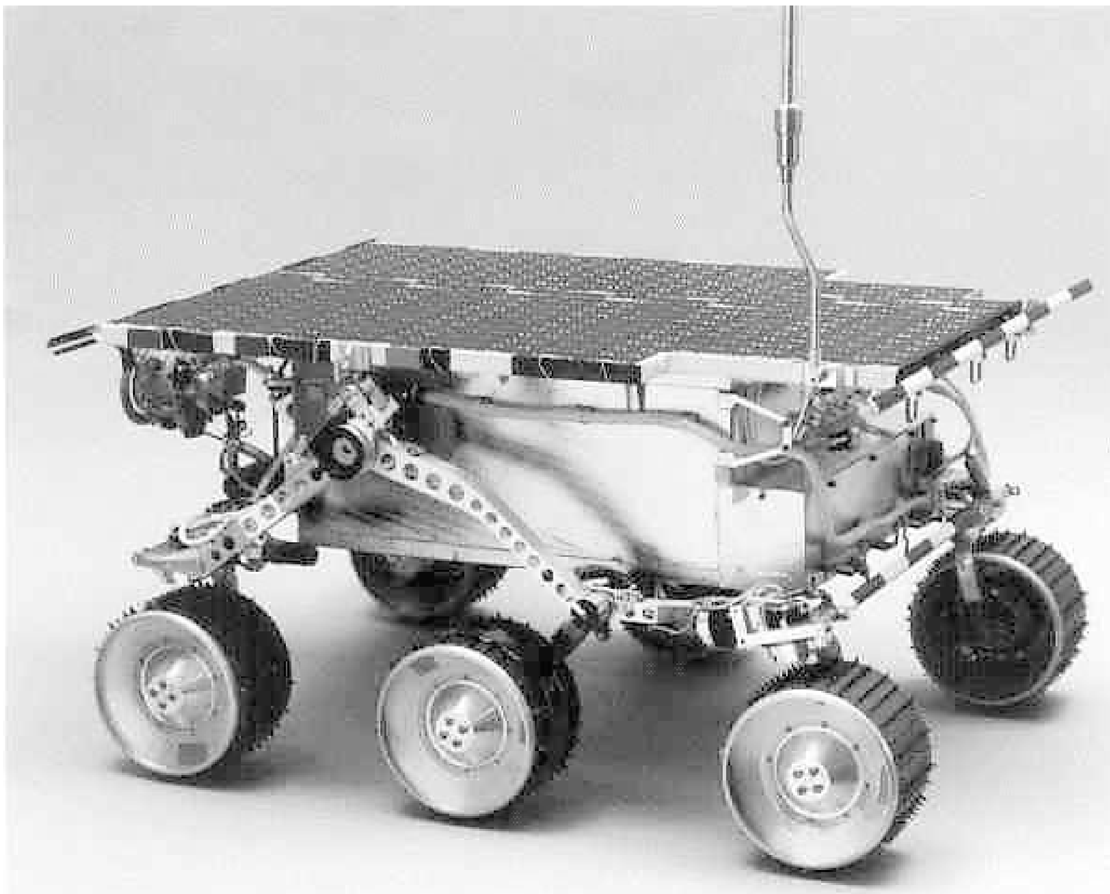

FIGURE 3.2.1 The basic features of Sojourner, the rover deployed by the Mars Pathfinder spacecraft in July 1997, are visible in this photograph. Power was provided by internal batteries and the top-mounted solar array. Sojourner's principal scientific instrument, the rear-mounted alpha-proton x-ray spectrometer, is visible on the extreme left, below the solar array. Photograph courtesy of the Jet Propulsion Laboratory.

BOX 3.3
Rover Characteristics

Large rovers are highly sophisticated vehicles of the type considered in the context of various sample-return and other mission concepts developed in the 1970s and 1980s. They are, in general, conceived as being quasi-autonomous and capable of wide-ranging operations. The only examples of vehicles of this size to be employed were Lunokhod 1 and 2 (see Box 3.1), deployed on the Moon in the 1970s.

- Total mass 100 to 1000 kg
- Payload mass 35 to 150 kg
- Range 0.1 to 10 km per day
- Lifetime months to years

Minirovers are more modest, battery- and solar-powered vehicles developed in the context of the austere Mars mission concepts that were devised in the early 1990s. The smaller vehicles in this class might not, in general, be capable of travel far from their landing sites. Although direct communication with Earth, through an orbital relay, should be feasible for this class of vehicles, for a variety of reasons, some (e.g., Mars Pathfinder's Sojourner) may require their lander to act as a telecommunications relay. Clearly, direct communication is the preferred option. Sojourner (see Box 3.2) and Russia's Marsokhod fall at, respectively, the lower and upper ends of this size category. The Athena rover, originally scheduled to be carried to Mars in 2001 and now deferred until 2003, is of intermediate size, and is designed to have a lifetime of a year.

- Total mass 10 to 100 kg
- Payload mass 2 to 20 kg
- Range tens of meters per day
- Lifetime days to months

Microrovers are vehicles smaller than Sojourner and Athena that might be used to explore low-gravity environments or to deploy an instrument or instruments away from their parent lander. The lifetime and ranges of these vehicles may be severely limited because their small size may render them unable to survive the temperature extremes found on many planetary bodies. A vehicle of this type is being developed by the Jet Propulsion Laboratory as one of NASA's contributions to Japan's MUSES-C asteroid sample-return mission (see Figure 3.2). This particular vehicle is designed to have an extended lifetime and will be able to hop as well as move on its wheels.

- Total mass 0.05 to 2 kg
- Payload mass 0.01 to 0.5 kg
- Range meters per day (not well defined)
- Lifetime days (not well defined)

Nanorovers are the current technological frontier of rover design. Such devices will probably be restricted to operating within view of a lander, and their extremely small size will almost certainly limit their lifetime to less than a day in anything other than the most benign environment.

- Total mass <0.05 kg

Another challenge to rover operations is knowing where the rover is with respect to features visible in orbital surveys. Images with a large range in scales (two or three orders of magnitude total) are required to place the immediate surroundings of the landing site into regional and global geological and geographical context. The most effective way to accomplish this is to collect descent images during landing. Such images may suffer some distortion because they will be taken through the landing-rocket plume. Nevertheless, it should be possible to design descent imagers so that they can collect the most important images prior to the ignition of the landing engines. The inclusion of a descent imager does, however, place technological constraints on the bus transporting the rover. But, these strictures are likely to be less stringent than the financial and programmatic constraints that would be encountered if surface operations required the support of a very high resolution imaging orbiter. The absence of very high resolution surface imagery (either from a descent imager or an orbiter) proved to be a major constraint on the day-to-day operation of the Mars Pathfinder mission, even though Sojourner never traveled more than 10 to 15 meters from its lander.

Future Developments

These technological, scientific, and operational requirements suggest that capable rovers on future missions must be fairly large. Furthermore, the requirement for significant autonomy is likely to be a major mass driver, suggesting the need for major development in four areas. These are the following:

1. Reducing the total mass of the rover's mechanical systems to achieve a higher payload mass fraction;
2. Designing autonomous navigation and control systems that require minimum mass;
3. Designing scientific instruments that are both more capable and smaller than those currently in existence; and
4. Devising and thorough field testing of operational procedures that integrate autonomous control with the scientific community's need to remain in the loop.

The Athena rover, scheduled to be deployed by a future Mars Surveyor mission, represents a significant step in achieving some of these objectives. Although it is similar in its mobility design to Sojourner, it is much larger and some 50 percent more massive (Figure 3.1). It is designed to have a lifetime of approximately 1 year (compared with 1 week) during which it will be able to traverse some 10 km (compared with 100 m). Athena's instrument complement is significantly more ambitious than that equipping Sojourner. According to current plans, Athena will have a 2-m-tall vertical boom carrying a panoramic camera and a thermal-emission spectrometer, and its robotic arm will be equipped with Mössbauer and Raman spectrometers, an alpha-proton x-ray spectrometer (APXS), and a microscope. The rover is also equipped with a drill to collect core samples up to 5 cm long from rocks and soils. Some 91 rock cores and 13 soil samples can be collected and cached for possible retrieval by a sample-return mission currently scheduled for the 2005 launch opportunity.

Rovers very much smaller than Sojourner and Athena have been considered.[17–19] Although they are interesting design concepts, many researchers are skeptical and have argued that their payload capabilities, ranges, and lifetimes are likely to be limited and that such rovers, thus, are of less scientific value in the near term than their larger brethren.

Practical experience with the operation of such a vehicle will come with the deployment of a 1-kg microrover on asteroid 4660 Nereus in 2003. This vehicle (Figure 3.2), one of NASA's contributions to Japan's MUSES-C asteroid sample-return mission, is intended to carry a camera, an infrared spectrometer, and an alpha x-ray spectrometer derived from Sojourner's APXS. The microrover will use these instruments to conduct a number of investigations, including studies of the texture, composition, morphology, and lateral heterogeneity of Nereus's surface on scales smaller than 1 cm and investigations of the mechanical and thermal properties of the surface material. Although primary communications with Earth will be by a radio link to the MUSES-C orbiter, the microrover will also attempt to communicate directly to Earth by an optical system that makes use of the vehicle's laser range finder. Since the microrover is solar powered, its lifetime is, in principle, unlimited. In practice, its operational life will probably be set by effects of the thermal environment.

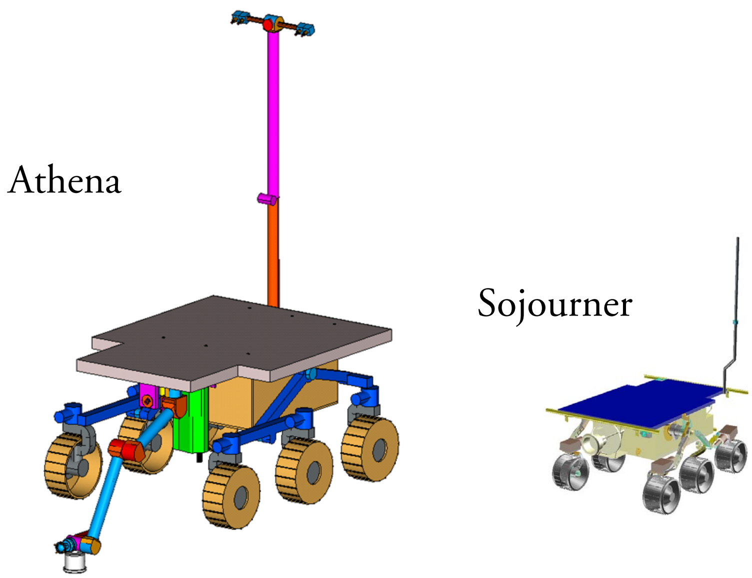

FIGURE 3.1 A size comparison between the Sojourner rover carried by Mars Pathfinder and the Athena rover originally scheduled to be carried by the Mars Surveyor 2001 lander. Athena has now been deferred to 2003. Courtesy of Daniel McCleese, Jet Propulsion Laboratory.

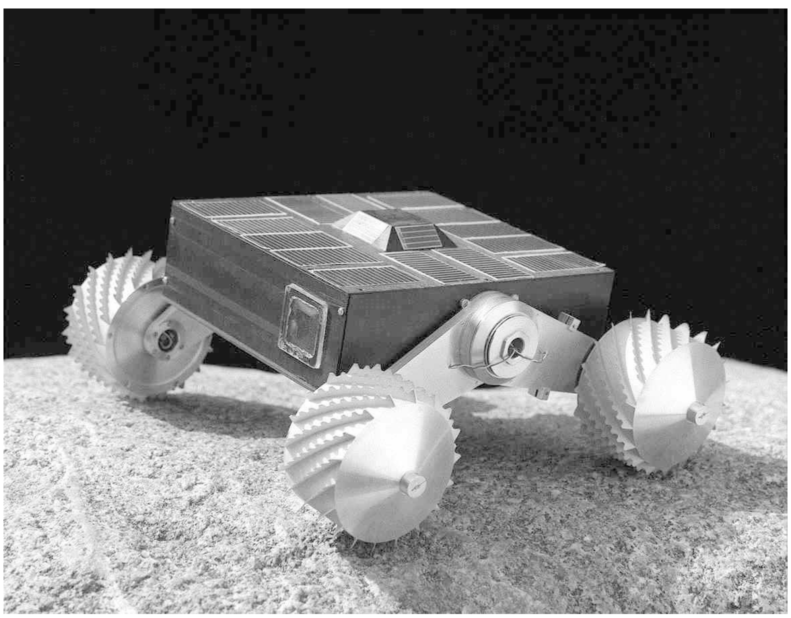

FIGURE 3.2 Recent advances in microtechnology and robotics have made it feasible to create extremely small rovers capable of operating on a variety of planetary bodies. This particular vehicle is designed to operate in a low-gravity environment and is scheduled to be deployed on asteroid 4660 Nereus by Japan's MUSES-C sample-return mission. This rover has a mass of approximately 1 kg and is highly maneuverable. By articulating its wheel struts, it can operate upside down, intentionally flip over and recover, place the body faces in contact with or parallel to the ground, lift the wheels and set them on top of obstacles, and reorient the body during ballistic "hops" in an asteroid's feeble gravitational field. Courtesy of Brian Wilcox, Jet Propulsion Laboratory.

Hoppers

The former Soviet Union's Phobos 1 and 2 missions included unique hopping devices designed to provide mobility on the surface of the martian moon Phobos (see Box 3.4). Because both missions failed before these devices were deployed, their utility was never tested in situ. Hopping is practical on virtually any planetary body. Indeed, Surveyor 6 reignited its descent engines and hopped a distance of some 3 m across the lunar surface to enable pseudostereo imaging. A similar maneuver was also considered as part of a tentative plan to fly a spare Viking lander to Mars in the late 1970s. The technique is, however, most likely to be useful on small bodies with weak gravitational fields where hopping can cover large distances and thus provide significant mobility.

The MUSES-C microrover will have the ability to hop. This will be achieved by articulating the struts on which its four wheels are mounted. Surface inhomogeneities and uncertainties in the regolith's physical properties will result in uncertainties in the rover's point of impact and roving-hopping path. Nevertheless, the technology looks promising for the exploration of a range of low-gravity environments.

Touch-and-Go Orbiters

Another approach, resulting in a similar hopping motion, is the so-called touch-and-go orbiter. This technology has great potential for the exploration of low-gravity environments. For missions to bodies such as small satellites, asteroids, and comets, there is little distinction between orbiters, landers, and rovers. Once in orbit about such a body, it is energetically easy to land once or many times and thus, in a sense, to "rove" over its surface.

The Near-Earth Asteroid Rendezvous (NEAR) mission[20] will conduct maneuvers essential to the success of more ambitious future missions that might employ the touch-and-go concept. In particular, it will use data obtained during a close flyby of asteroid Eros to estimate its gravity field and then take advantage of this information to go into orbit about Eros and probably land on the asteroid at the end of the mission. Although NEAR does not include sampling capability, it will collect valuable data while in orbit about Eros. Furthermore, the experience gained placing a spacecraft into orbit around a small body that most likely has a complex gravitational field will be valuable in the future. Additional important experience will be gained by Japan's MUSES-C asteroid sample-return mission, which envisions touching down more than once from orbit and effectively blasting fragments off the surface to be caught in collection bins on the orbiter-lander.

The science return from multiple landing or sample-return missions to one or more asteroids, small satellites, or comets is potentially very great. Thus, development of the touch-and-go concept is important.

Balloons

The former Soviet Union's Vega 1 and 2 spacecraft deployed balloons in Venus's atmosphere in 1985 (see Box 3.5). These drifted with the prevailing winds at fixed altitude in the atmosphere, surviving for almost two Earth days. The Soviet Union and later Russia, in cooperation with France, developed plans to deploy balloons on Mars as a part of the ambitious, but ultimately ill-fated, Mars 94-96 program. Indeed NASA's own ill-fated Mars mission, Mars Observer, and its successor, Mars Global Surveyor, were specially equipped to relay data from the balloons to Earth. Although the French-Russian balloon experiment was canceled for budgetary reasons, interest in planetary applications of balloons, as exemplified by workshops and ongoing studies, is second only to that for rovers.[21–25] Although balloons are traditionally viewed as platforms for remote sensing and in situ atmospheric studies, their potential for new applications, such as surface sampling, is high, provided that a number of technological challenges can be overcome.

Buoyancy Technologies

Balloons are potentially valuable devices for study of the atmospheres of the four giant planets, and also for studies of the atmospheres and surfaces of Venus, Mars, and Titan. The two basic techniques for providing lift that are under consideration are these:

BOX 3.4
The Phobos Hopper

The Phobos mission, launched by the Soviet Union in 1988, consisted of two identical spacecraft equipped to carry out detailed investigations of Mars and its small moon, Phobos. Although both spacecraft suffered failures before they could begin close-up studies of Phobos, the low-gravity environment of the small, asteroid-like moon enabled a unique lander architecture and approach to mobility. Each craft was equipped with a "hopper" lander that was to be jettisoned toward Phobos from a cruising height above it of ~50 m. The relative free-fall approach velocity of the 50-kg, semispherically shaped lander was designed to be a few meters per second.[1] Upon touchdown on the surface of the moon, two mechanical rods, or levers, would release and work to position the lander so that its instruments faced Phobos's surface (Figure 3.4.1). Each hopper carried several instruments, including an x-ray fluorescence spectrometer, a magnetometer, a gravimeter, and a penetrometer.[2,3] After measurements were made at one location, two spring-loaded "legs" would extend and the hopper would literally jump to a new location up to 20 m away, using no chemical propulsion. With each hop, the position control levers would correct the hopper's attitude after landing. The hopper was designed to sample 10 sites during its 4-hour, battery-powered lifetime.[4]

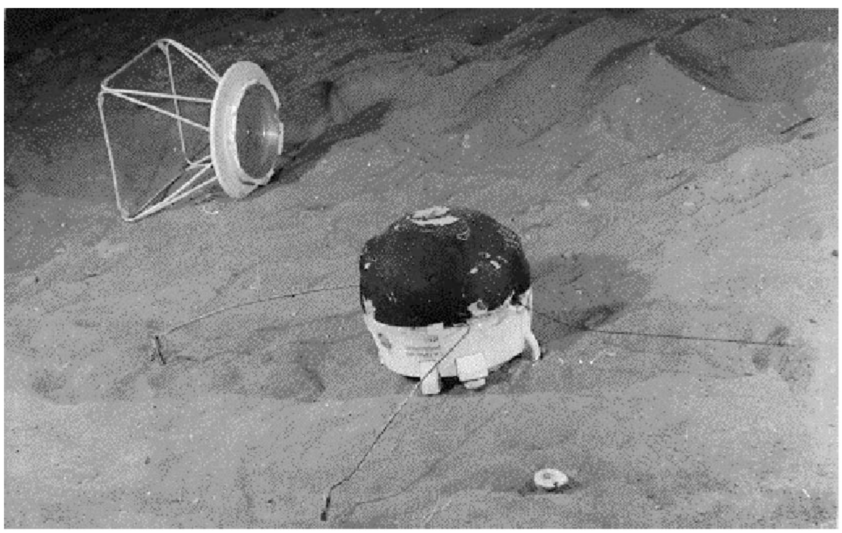

FIGURE 3.4.1 Hopping is an appealing means of providing mobility in a low-gravity environment. The former Soviet Union planned to use hoppers to undertake multipoint measurements on the martian moon, Phobos, in the late 1980s as part of the ambitious, but unsuccessful, Phobos program. Although their parent spacecraft failed before they could be released, these 60-cm-by-90-cm (approximate) hoppers were designed to leap from one site to another up to 20 m away and were outfitted with an array of scientific instruments, including an x-ray fluorescence spectrometer, a magnetometer, and a gravimeter. The two mechanical rods used to position the device are visible to the left of the semispherical hopper. This photograph of one of the engineering test models and its mounting adaptor (upper left) is courtesy of Valery Gromov and Alexander Zakharov.

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[1]Space Research Institute, *Phobos: Exploration of Phobos, Mars, Sun and Interplanetary Space*, Academy of Science of the USSR, Moscow, 1987, p. 7.
[2]Space Research Institute, 1987, p. 12.
[3]"Soviets Will Use Venera Follow-on in Mars Mission," *Aviation Week and Space Technology*, April 14, 1997, p. 125.
[4]Space Research Institute, 1987, p. 12.

BOX 3.5
The Vega Balloons

Both Soviet Vega spacecraft carried payloads dropped at Venus en route to Halley's comet. Arriving at Venus in June 1985, Vegas 1 and 2 each released a spherical capsule that descended into the planet's atmosphere to deploy a surface lander and an atmospheric balloon. The balloons were fully deployed at an altitude of 50 km and floated to their equilibrium altitude of 53.6 km.

The Vega balloons are the only meteorological balloons used thus far in solar system exploration. Constructed of Teflon fabric, the balloons were 3.4 m in diameter and weighed 12 kg. When filled, each Vega balloon carried 2.1 kg of helium and a payload of 6.9 kg on an instrument gondola suspended below the balloon by a 13-m tether. The gondola carried pressure, light, and temperature sensors, a nephelometer cloud sensor, and an anemometer (Figure 3.5.1). Both the anemometer and the temperature sensors

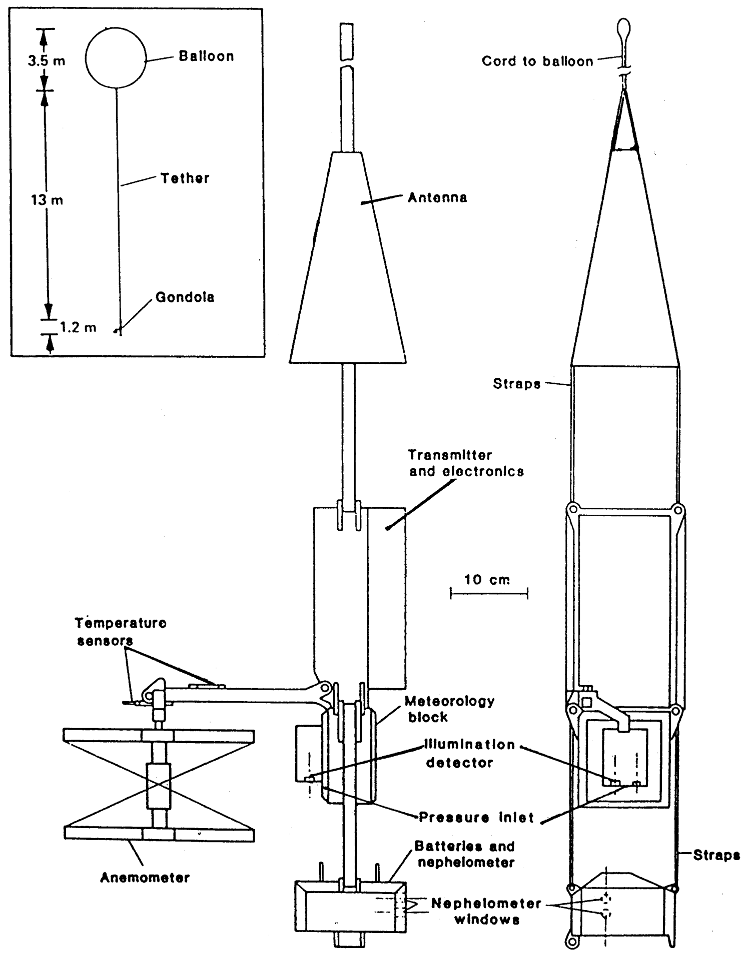

FIGURE 3.5.1 This diagram illustrates the general arrangement of the instruments carried by the balloons released into Venus's atmosphere by the former Soviet Union's Vega spacecraft in 1985. Illustration reprinted, adapted, from R.S. Kemnev et al., "Vega Balloon System and Instrumentation," *Science* 231: 1409, 1986. Copyright © 1986 by the American Association for the Advancement of Science.

BOX 3.5 Continued

were mounted on a deployable arm that extended perpendicular to the vertically hung gondola to minimize the influence of the radiant heat from the gondola and to provide the best vantage for the anemometer.[1]

The equilibrium altitude was chosen in part for its benign temperature during the night on Venus, which averages 305 K. The balloons began their trek at 180 degrees longitude, 7 degrees north and south of Venus's equator, respectively. Both balloons operated for 46.5 hours, passing into the day side of the planet 33 hours after deployment. They traveled more than 11,000 km, with Vega 1 going slightly farther, covering 109 degrees of longitude, just 4 more degrees than its successor, Vega 2.[2] The balloons alternated between 25 minutes of data gathering (often taking measurements every 90 seconds in order to conserve power) and 5 minutes of Earth-relay.[3] The Vega balloons were tracked interferometrically by an international array of antennae that included NASA's Deep Space Network.[4]

Both balloons fulfilled nearly all of their planned science objectives. Engineering data indicated that at the end of the mission only 5 percent of the helium had been lost, consistent with estimated diffusion through the Teflon. Although the balloons were expected to fail once they passed into the planet's day side, they proved more robust. Signal loss is attributed to battery exhaustion (the batteries were designed for a nominal 50-hour operating lifetime).

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[1]R.S. Kemnev et al., "Vega Balloon System and Instrumentation," *Science* 231: 1408, 1986.
[2]"Vegas at Venus—1," *Sky and Telescope*, September 1986, p. 231.
[3]J. Kelly Beatty, "A Soviet Space Odyssey," *Sky and Telescope*, October 1985, p. 310.
[4]R.S. Kemnev et al., "Vega Balloon System and Instrumentation," *Science* 231: 1408, 1986.

1. Use of gases inherently less dense than the ambient atmosphere (primarily for application on Venus, Mars, and Titan); and
2. Heating of the ambient atmosphere (primarily for application on Jupiter, Saturn, Uranus, and Neptune).

Current development efforts in the United States are focused primarily on the first technique and, in particular, on the use of so-called reversible fluids as a means to provide elevation control. This technique makes use of the buoyancy provided by two fluids. One fluid remains in the gaseous state at all ambient temperatures. The other alternates between gas at low altitudes and relatively high temperatures and liquid at high altitudes and relatively low temperatures. By providing a container for the reversible fluid that can be closed or opened on command, it is possible to control the equilibrium altitude of the balloon.[26]

A series of some eight Altitude Control Experiment (ALICE) flights, conducted by NASA between July 1993 and September 1997, validated the basic concept of the reversible-fluid balloon. Interest in this technology is not confined to the United States; relevant work has also been conducted in France and Japan. An alternate solution to the problem of elevation control is to use a single-medium, superpressure balloon that maintains a constant-density altitude.

The second lifting technique is embodied in the infrared Montgolfiere balloon. This concept involves the use of the upward infrared radiation from the planet's surface or lower atmosphere to heat ambient gas within the balloon.[27] This requires that the top of the balloon consist of an infrared-reflective outer surface and an infrared-absorbing inner surface.

Extensive terrestrial testing of this concept has been conducted by France's Centre National d'Études Spatiales, with some 30 test flights flown between the late 1970s and the early 1990s. Altitudes greater than 30 km were attained, and the longest flight lasted more than 65 days.[28] A series of test flights conducted in the United States in 1997 demonstrated an altitude-control mechanism that will allow this type of balloon to conduct repeated precision soft landings. Although planetary application of this technology has focused on the outer planets, it has some potential for use on Mars. While flights in the mid-latitudes would be limited to daylight hours because of the low nighttime temperatures on Mars, flights in the polar summers could be of extended duration.

Aerobots

A balloon with one or more of the following characteristics is termed an "aerobot":[29]

- Autonomous position, altitude, and velocity determination without ground intervention;
- Altitude control capability;
- Ability to execute a designated flight path in a planetary atmosphere using altitude change and global wind patterns; and
- Landing capability at designated surface sites.

Such characteristics mean that aerobots are to entry probes as orbiters are to flyby spacecraft.

Scientific and Technological Requirements

Conceptual development for the placement of an aerobot in the atmosphere of Venus is fairly mature, and relevant test flights have been carried out on Earth. At present, it appears necessary to provide for significant (as much as 60 kilometers) repeated vertical motion of the balloon to provide for adequate cooling of the avionics and instruments if the aerobot is to descend into the lower atmosphere or to the surface of Venus. This vertical movement is an asset for many science objectives, such as vertical sampling of atmospheric composition, thermal structure, and dynamics. A balloon operating at a range of altitudes also allows for the gathering of optical and near-infrared images and spectra of the planet's surface at a variety of spatial resolutions.

In addition to altitude control, other desirable characteristics that would enhance the efficient operation of balloons and aerobots include these:

- *Navigation.* Knowing the three-dimensional position of the balloon at any given time is crucial for many observations. The Vega balloons were, for example, tracked by Earth-based radio telescopes using techniques of very long baseline interferometry.
- *Horizontal control.* The ability to predict and, preferably control, horizontal movement of the balloon would be highly desirable, because selected sites are generally of greater scientific interest than random sites. Some control over the traverse route could be attainable by taking advantage of different wind speeds and directions at different altitudes.[30] However, even if the desired diversity exists in an atmosphere, it could require several exploratory balloon missions to understand atmospheric dynamics sufficiently well to use this technique. Political problems aside, recent unsuccessful attempts to circle Earth in balloons highlight how difficult it is to control balloon flight paths even with the relatively greater knowledge of atmospheric dynamics available for this planet. Thus, for the foreseeable future, balloon traverses on other planets will not be controllable.
- *Touchdown.* The ability to touch down is important because it would allow study of the atmospheric boundary layer structure, permit sample collection, and provide for soft deployment of geophysical or atmospheric surface stations.
- *Long lifetimes*. Balloons that can survive for weeks rather than the Vegas's 2 days are important for sampling the atmosphere and the surface over a wide geographic range. Longer balloon lives also provide a synoptic view that is important for many studies, particularly those of planetary atmospheres.

These attributes are as applicable to a Mars balloon as to a Venus balloon, except that there is no technology-driven need to move vertically for cooling and communication. However, Mars presents its own technological challenges because of its thin atmosphere. It is not clear at present that a Mars balloon with a significant payload can attain altitudes necessary to clear the highest volcanoes on the planet. This would restrict a balloon mission to latitudes selected to avoid these volcanoes or to a short lifetime.

Advantages and Disadvantages

In addition to their use for studying atmospheric composition, structure, and dynamics, balloons also provide a means to obtain images and spectra of planetary surfaces at resolutions greater than those readily obtainable from orbit. Aerobots almost certainly provide the only platform capable of obtaining images at visible wavelengths of any substantial fraction of the surfaces of Venus and, in the more distant future, Titan. Other advantages are the long travel distances that are possible, the ability to control elevation (and perhaps even to touch down), and propulsion without the need to transport fuel from Earth.

Although balloons have many attractive features, they also have a number of important disadvantages. Some, such as navigation and the difficulty in controlling flight path, are discussed above. An important issue to be faced in the planetary application of balloons is that their size is proportional to their payload mass. Thus, the ability to carry a significant complement of scientific instruments will necessarily be constrained to keep the balloon's size within reasonable limits. Size is likely to be a particularly important factor for those balloons designed to be deployed in low-density atmospheres (e.g., Mars) or at high elevations on other bodies. Another disadvantage is, ironically, a consequence of the balloon's inherent advantages as a platform for high-resolution imagery and spectroscopy, which generate such large volumes of information that necessary data rates may stress the uplink capabilities to, and on-board memory of, a relay orbiter.

Future Developments

Several development thrusts are clearly called for, which include the following:

- Studying the use of reversible fluids for altitude control of balloons on Venus and Titan;
- Studying methods to attain altitude control with an infrared-heated balloon in the atmospheres of the giant planets;
- Designing science instruments that are of significantly smaller mass than those currently available; and
- Devising techniques to increase data rates by at least an order of magnitude.

Aircraft

An alternative to balloons for use on Mars in the mid-term future is lightweight aircraft.[31] Small, unmanned aircraft are used for high-altitude (20 to 30 km) research in Earth's atmosphere. Indeed, there is currently great interest in the potential application of remotely piloted vehicles (RPV) for a host of commercial and military applications on Earth. Much of the current activity in this area is centered on the development of technologies such as autonomous control systems, high-energy-density batteries, and lightweight propulsion systems. Conceptual studies for planetary aircraft to date have been directed at adapting terrestrial RPV technology for use on Mars, where the aircraft would fly at low elevations. Present models envision aircraft of 35 to 200 kg with wingspans of 6 to 15 m. These aircraft are potentially capable of carrying payloads of 3 to 10 kg for thousands of kilometers.[32] In order to do this, the aircraft must travel at relatively high speeds (~100 m/sec).

Advantages and Disadvantages

Planetary aircraft could provide multiband spectral data and images of the surface at higher resolutions than those currently attainable from orbit around Mars. They would be particularly effective for collecting oblique images of volcanic features, layering in canyon walls, and the laminated terrain found in Mars's polar regions.[33] In the distant future, aircraft could obtain similar data for Titan, where atmospheric opacity severely limits collecting such data from orbit. In addition to these advantages, which are shared with aerobots, an aircraft's traverse route is controllable. Aircraft are comparable to balloons in ability to collect useful atmospheric data, but because of high speed and short flight duration, extended synoptic measurements will be much more difficult. However, an aircraft can also be flown to features of particular interest (e.g., the poles or canyons), if desired.

The practical application of aircraft to planetary exploration faces a number of technical challenges. It is not clear, for example, what propulsion system is best. A variety of power sources, including liquid fuels (hydrazine), solar cells, and radioisotope thermoelectric generators, have been investigated,[34,35] but batteries are now favored.[36] Because the vehicle must enter the martian atmosphere in an aeroshell with a shape completely unlike that of an aircraft, it will be necessary to design a collapsible structure (at least the wings must fold). Studies performed in the late 1970s centered on aircraft that could be folded to fit inside a 4-m-diameter Viking aeroshell. More recent studies have involved aircraft that could fold up inside 2-m-diameter Mars Pathfinder aeroshells and even 0.2-m aeroshells designed for the Deep Space 2 microprobes.

Navigation and control systems capable of dealing with high-speed flight must be developed. Finally, it is essentially impossible for the data to be relayed directly to Earth during flight. Thus, a relay satellite would be needed. Even then, the volume of data that can be collected by a low-flying aircraft might be a problem. If data rates of a megabit per second are achievable, as is likely, then data storage on the relay satellite may become a significant limiting factor (although memory technology is advancing at a rapid rate). Both aircraft and balloons will suffer from this potential technological shortfall.

Future Developments

The potential value of an aircraft capable of flying in the martian atmosphere makes further development of this concept desirable. In addition, in common with balloon development, a major effort is needed to increase data rates substantially and, in common with virtually all other modes for attaining mobility, it is essential that a major effort be undertaken to increase the efficiency and decrease the mass of payload instruments. COMPLEX notes that the issue of data rates is not unique to missions using mobility or to solar system exploration missions. Other branches of the space-science enterprise (particularly the Earth sciences), as well as military and commercial communications and remote-sensing communities, are facing similar operational limitations due to restricted data rates. Synergistic cooperation between these various groups is encouraged.

Cryobots

Current interest in the possibility of a liquid water ocean beneath the icy crust of Europa has spawned early conceptual models for devices capable of penetrating through several kilometers of ice. The basic concept of such a vehicle, a cryobot, is relatively simple: a small device containing a heating element is placed on the surface and allowed to melt passively through the ice.

Cryobots are conceptually similar to the so-called thermal or Philberth probes developed more than 30 years ago for polar and glacial studies on Earth.[37,38] By the late-1960s, a thermal probe developed at the U.S. Army's Cold Regions Research and Engineering Laboratory had penetrated more than 1000 meters into Greenland's ice cap before additional progress was prevented by the length of the available tether.[39] Although further development of the concept was conducted in the 1980s,[40] it has fallen out of favor as the technology for deep drilling has been perfected.

Interest in the possible use of thermal probes in extraterrestrial environments has prompted some limited experimental studies of the applicability of this technology with and without a vacuum to cryogenic ice. The application of this technology for the exploration of the martian polar caps has been considered. The Mars Polar Pathfinder Discovery mission concept envisages the use of a 22-cm-long thermal probe to measure the thermal profile and conduct optical measurements of the ice to a depth of some 150 m in Mars's northern polar cap.[41]

An exciting analog for Europa exists on Earth; about 4 km beneath the surface of the antarctic ice cap is a large body of water, Lake Vostok, that is about the size of Lake Ontario. It is likely that both the ice above Lake Vostok and the lake itself harbor microorganisms that have been isolated from the active Earth's atmosphere and hydrosphere for a very long time, perhaps for as long as 10^5 to 10^6 years.[42,43] Whether the ice and the putative water mantle on Europa also harbor life is one of the primary questions to be answered by a cryobot mission. However, these devices require significant development, both in the purely technical area and in dealing with problems of contamination.

Advantages and Disadvantages

The cryobot may be simple in concept, but there are a host of practical problems. Holes melted in the ice will, of course, freeze behind the cryobot, raising the important technical issue of communication: by tether or by acoustic waves? For Lake Vostok, a tether will probably be best, but for the much colder and probably thicker ice crust on Europa the choice is less straightforward. Technical difficulties for both tethers and acoustic communication devices on Europa will not easily be overcome.

The intense radiation environment on and near Europa requires that the electronic components of instruments on the cryobot be radiation hardened and possibly shielded as well. It also is a technical challenge to position the cryobot and initiate the melting process. This is a serious issue for Europa, because the cryobot cannot remain in the hostile surface radiation environment for very long. One possible way to minimize the cryobot's exposure to radiation on Europa's surface is to deploy it by a penetrator rather than a conventional lander. Even so, some form of communications infrastructure will have to remain on the surface. Overall, the technical challenge of a cryobot designed to penetrate to Lake Vostok is significantly less than that for the Europa cryobot.

The issue of biological contamination is essentially the same for both Lake Vostok and Europa. It is critical that neither cryobot transport Earth-surface microorganisms into the ice or into the water below the ice. If these devices contaminate the ice and water, the primary purpose of these efforts will be compromised. It is not clear that significant progress has been made toward a solution to this problem.

Future Developments

Despite these serious problems, the potential science returns of successful cryobot missions to both Lake Vostok and to Europa are so great that development of the cryobot concept should continue. Areas to be studied include modification of the thermal-probe technology to accept a radioactive heat source, radiation hardening of electronics, the development of techniques to reduce biological and chemical contamination, and improving communicating over distances of tens of kilometers with and without tethers. These studies should be carried out by a consortium of scientists and engineers, many of whom will not be directly associated with NASA.

SAMPLE ACQUISITION

A review of the various documents outlining plans for future space exploration is sufficient to gain a sense of the importance of sample acquisition.[44] These sample-acquisition plans cannot succeed unless devices capable of collecting samples are present on landers and, even more importantly, on mobile platforms.

A variety of techniques for sample acquisition have been pioneered in the last 30 years of planetary exploration. The first such device was employed by Surveyor 3 in 1967. It was equipped with a robotic arm, which dug trenches in the lunar regolith and carried out tests on the regolith's physical properties. The first robotic sample collection was accomplished in 1970 by the Soviet spacecraft Luna 16, which collected and returned samples from Mare Fecunditatis on the Moon. Luna 20 returned samples from the Apollonius highlands in 1972, and Luna 24 returned a core sample of regolith from Mare Crisium in 1976. Also in 1976, Viking 1 and 2 landers used jawed scoops on the ends of booms to collect samples of martian soil and deliver them to instruments mounted on the lander. In 1981, the Soviet spacecraft Venera 13 and 14 successfully collected samples from the surface of Venus for in situ x-ray fluorescence analysis, using drills mounted on the base of the landers.[45] Also worthy of mention are the 3-m rotary-percussive coring drills used on the Apollo missions. Although they were hand-operated by the Apollo astronauts, the technology was fully amenable to robotic control.

The sample acquisition devices employed to date can be divided into the three following categories:

1. Robotic arms for positioning other devices;
2. Tools for both chipping and scraping; and
3. Devices for trenching, drilling, or coring.

All of these devices contribute to the overall purpose of collecting samples for delivery to the lander or mobile platform carrying them, or to a cache for future collection.

Robotic Arms

Robotic arms, such as were present on the Viking landers (see Box 3.6), serve a variety of purposes. At a minimum, these devices permit placing instruments on or adjacent to selected soils or rocks. The Mars Polar Lander, scheduled to touch down on the northern edge of Mars's southern polar cap in 1999, for example, will be equipped with a 2-m robotic arm with a microscope camera at its tip. Similarly, the Mars Surveyor 2001 lander may be equipped with an arm designed to collect soil samples and deliver them to instruments for analysis.

With claws or scoops attached, robotic arms become capable of collecting soil samples or small rocks for delivery to instruments on the lander or rover. An arm of some sort is almost certainly needed for positioning other sample acquisition devices. It is difficult to imagine how many of the objectives of future missions could be accomplished unless robotic arms are included.

Chipping and Scraping Tools

For many objectives of space exploration, it will be necessary to remove the thin rind of weathered material that commonly is present on rocks. These rinds can exist on bodies with atmospheres, where they are due to chemical weathering, but also on bodies without atmospheres, where they are due to various processes of space weathering. Most analytical instruments, such as the alpha-proton x-ray spectrometer (APXS) on Sojourner, are capable of penetrating only to depths of a few micrometers.[46] Although the compositions of these weathered rinds are of great interest, they will not, in general, provide a reliable inventory of the elements present in the fresh material. This problem is common to efforts to determine compositions of solid materials on terrestrial planets, asteroids, rocky and icy satellites, and comets. Thus, the development of satisfactory devices for removing the rinds is extremely important. A coring drill is one possibility, but this will not, in general, produce a fresh surface against which a robotic arm can readily place an instrument such as an APXS or a "hand lens." Thus, chipping or scraping tools may be necessary even if a coring device is available.

The simplest devices for removing a weathered rind would be either hammers or chisels that can break chips off the rock, or a hardened device that can grind or scrape the rind away. Of the two approaches, the chippers seem best because they can also be used to obtain small samples from large rocks or exposed rocky or icy crust for which much other information can be obtained by in situ visual and multispectral analysis. However, chippers will jar the lander or rover, and for this reason a scraper may be the safer alternative.

Trenching, Drilling, and Coring Devices

Trenching implies the use of some sort of scraper or jawed scoop capable of digging into unconsolidated or loosely consolidated surface materials. Drilling involves rotary devices that cut or auger into rock, ice, or regolith. Coring involves collecting a cylindrical sample of material by means of a rotary coring drill or, for regolith, a driven coring tube. All three of these technologies have been used in past space missions; trenching by the Viking landers, coring by Luna 24, and drilling by Venera 13 and 14.

Trenching and coring are useful for obtaining samples of regolith from below the surface and for gaining knowledge of shallow regolith stratigraphy. Coring has the potential for collecting samples from greater depth than digging and has the great advantage of collecting a sample with its stratigraphy preserved. Trenching, on the other hand, produces a cross section of the surface layers that can be readily seen using cameras, and thus potentially permits the collection of in situ visual stratigraphic data without the need to return the sample to Earth.

BOX 3.6
The Viking Arm

Several planetary spacecraft have employed sampling arms during surface operations. The Soviet Luna missions, for example, used a drill on the end of an arm to collect core samples for return to Earth, and Surveyor 3 used a trenching device on a telescopic arm to test the physical characteristics of the lunar regolith. The Soviet Venera and Vega landers on Venus also made use of an arm and drill apparatus to collect material for analysis. However, so far the most elaborate and sophisticated arm and sample collection device used in robotic exploration flew on the U.S. Viking landers.

The Viking landers were stationary science stations on the surface of Mars.[1] Touching down on Mars on July 20th and September 3rd, 1976, respectively, each lander was equipped with an assembly that could collect samples from around the lander for delivery to science experiments on the lander. The nominal sample acquisition area was a 15-m^2 sector in front of the lander.

The Viking sample collection assembly consisted of a head attached to a 3-m furlable boom (Figure 3.6.1). The boom was constructed of two thin sheets of metal fused at the edges that became stiff when

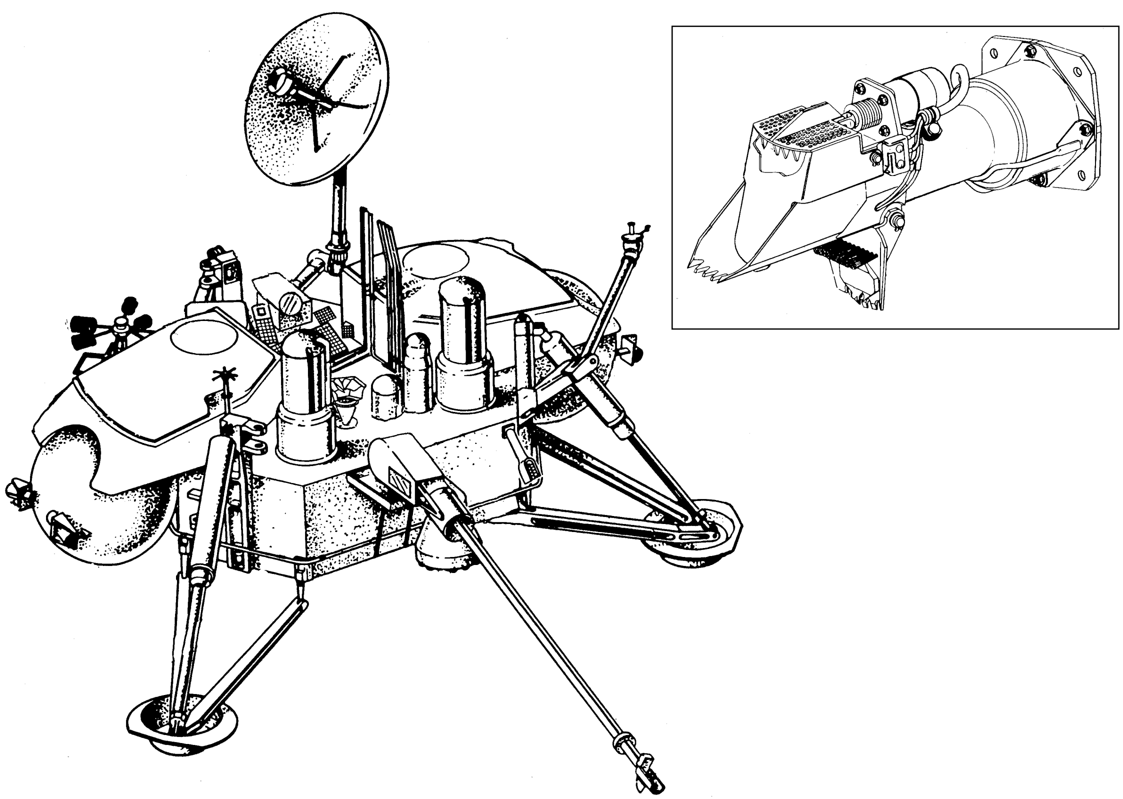

FIGURE 3.6.1 Both of the Viking landers were equipped with a 3-m boom terminating in a collection head (*inset*) used to gather soil samples. Rather than being a rigid rod, the boom was constructed of two thin sheets of metal fused at the edges in such a way that they became stiff when extended. The arm was free to move in azimuth and elevation, and its extension could be varied by rolling up excess boom material inside the housing it its base. The collector head was connected to the boom by a wrist joint that could rotate through 180 degrees. The collector's 4.45-cm-wide jawed scoop was equipped with a movable upper lid and a backhoe attached to the bottom. The hoe was used to excavate shallow trenches and the upper lid served as a sieve. Illustrations courtesy of the Jet Propulsion Laboratory.

extended. When the full extension of the boom was not required, the unnecessary length would roll up inside the arm housing at the base of the boom. The arm housing had two degrees of freedom in addition to boom extension: it could swing in azimuth (yaw), and it could vary its elevation angle (pitch). The collector head was connected to the boom by a "wrist" that was flexible in pitch and could rotate 180 degrees to turn the collection head upside down.

The collector head consisted of a jawed scoop 4.45 cm wide[2] with a movable upper lid and a backhoe attached to the bottom. The hoe enabled the excavation of shallow trenches from which subsurface samples could be taken, and it served as a tool for attempting to chip rocks. The lid top was a metal sieve with 2-mm-diameter holes, designed to deliver sifted samples to the instruments.

The Viking sample collection assembly successfully:

- Collected soil from a variety of locations within the sample collection area around the landing site,
- Pushed a moderately sized rock approximately 12 to 15 cm away from the lander,[3] and
- Rolled over a moderately sized rock and collected soil from beneath it.

Despite efforts to the contrary, Viking did not:

- Dig a trench deeper than ~23 cm;
- Collect a sample from a rock itself (chip it);
- Manage to scratch the surface of a rock; or
- Deliver any pebbles to the experiment housings, despite repeated attempts to do so. What were believed to be pebbles were determined to be samples of cemented soil (duricrust).

The forward scoop motion of the Viking arm, in combination with its limited force (approximately 210 N through boom extension), most likely limited its ability to scratch or chip a rock for a sample. Additionally, the sensitivity of the arm to the slope of the collecting area constrained the limits of trench depth. Because the Vikings landed in an above-average rocky area of the martian surface, the inability of the sampling arm to deliver pebbles to the lander housing for analysis is not fully understood;[4] however, the problem is believed to have been rooted in some combination of the actual landing sites (the local versus the general area) and the collector design. It should be noted, however, that there was never any requirement for the arm to collect pebbles or to chip rocks. Its only requirement was to collect soil samples. The fact that it was able to roll rocks, dig trenches, and collect duricrust clods was due purely to the clever operation of the arm and the flexibility in commanding that the engineering design enabled.

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[1]Henry J. Moore et al., "Surface Materials of the Viking Landing Sites," *Journal of Geophysical Research* 82: 4497, 1977.
[2]Moore, 1977, p. 4504.
[3]Moore, 1977, p. 4509.
[4]Michael H. Carr (U.S. Geological Survey), "Mars Surveyor Program," a presentation at the Workshop on Mobility, NASA Ames Research Center, July 19-20, 1995.

A trenching device can also transfer samples of unconsolidated material to instruments for analysis. Both technologies are important for sampling regoliths on planets, asteroids, and satellites, and possibly for sampling comet cores.

Drilling and coring into hard rock or ice is a difficult technology, especially if the goal is to obtain relatively undisturbed core samples from the holes. Coring maintains the petrologic and stratigraphic context of samples, whereas drilling produces a locally mixed sample. Mixtures are, however, easier to manipulate autonomously than cores, and some oven-based, in situ instrumentation works better with locally mixed materials. On Earth, drilling with sample return, either as chips or as complete cores, is a highly developed technology, but it generally involves the use of large volumes of water and heavy drilling mud. The technology for shallow drilling and coring from landers or rovers currently exists. Indeed, the Athena rover will, according to current plans, be equipped with a drill capable of extracting core samples up to 5 cm long from boulders or bedrock. However, given the present volume, power, and reliability constraints, drilling can acquire samples from greater depths than can coring. Indeed, the drill for the Champollion/Deep Space 4 comet nucleus mission is designed to collect samples from depths 20 times greater than Athena's coring drill. Moreover, Champollion's drill is designed to carry an optical fiber to permit in situ examination of the bore hole.

It is not at present clear how drilling to depths much greater than a few meters can be accomplished. Some NASA-supported research is being performed to automate a small oil-well-type, deep-drilling rig. Other approaches under development include a small, tethered boring device that pulls itself into regolith, a miniature inchworm drill, and a pile-driver concept.[47]

Penetrating to depths of meters or perhaps tens of meters is a critically important technology if we wish to address one of the primary objectives of solar system exploration—the evaluation of Mars as a site for extant or fossil life. It is necessary to sample below Mars's highly oxidized surface layers to have any chance of finding extant life, and this may require the capability of drilling through regolith to depths of at least several meters.[48] Similarly, deep drilling may be important if we wish to search for evidence of extant or past life at a depth comparable to that associated with known terrestrial ecosystems, e.g., hydrothermal vents. Another prime environment for seeking evidence of past life on Mars will be a site believed to be underlain by deposits of an extinct lake.[49] Although it is possible to collect subsurface samples from such a site in the ejecta of impact craters formed since the lake disappeared, drill-core samples would be much more satisfactory because the material collected will come from known depths and will preserve local stratigraphy.

Three-dimensional sampling is important for a number of additional objectives. If the rock or ice being drilled preserves a stratigraphic record, then a drill-core sample will reveal changes in composition and other properties as a function of time. Furthermore, if weathering is an important process, then a drill sample will permit detailed chemical analysis of the weathering processes because effects of these processes will gradually disappear with distance from the present surface.

Although not yet used on a mission, penetrators have potential as a low-cost means of acquiring samples. Traditional penetrators are designed to be dropped by an orbiter or by a lander during descent and deliver impact-resistant instruments to the shallow subsurface. Penetrators, such as the Deep Space 2 microprobes to be deployed by the Mars Polar Lander, are designed to orient themselves such that a reinforced tip strikes the surface as nearly vertically as possible, so that the lower part of the device penetrates the surface but the upper part does not. A sample-collecting penetrator could be deployed by a rover or lander. In this application, a pyrotechnic device shoots a tethered projectile into the ground. A sampling device is then pulled out of the projectile and collects material as it is reeled back to the surface. Once emptied, the sampling device could, in principle, be reloaded into another projectile and armed with a new pyrotechnic charge, and then could collect another sample at a new location.[50]

TERRESTRIAL FIELD DEMONSTRATIONS

It is essential that spacecraft systems be thoroughly tested before being sent into space. Rovers, balloons, and aircraft (and their complements of manipulative devices) must be tested to be certain that they will function as desired under stressful conditions. Likewise, the instruments carried by these platforms need to be tested both before and after they are mounted on their platforms. Finally, the total systems, including human operators, must undergo testing under conditions as similar as possible to those to be experienced on other solar system bodies.

Various balloon and aerobot concepts have undergone field testing on Earth in anticipation of deployment on Venus, Mars, or Titan.[51] Rovers have been tested extensively for many years; important recent examples include tests of the Mars Pathfinder Sojourner rover using a simulated Mars surface environment, and the field tests of Rocky 7 at Lavic Lake, California,[52] and of Nomad in the Atacama Desert of Chile.[53]

Marsokhod Field Tests

An instructive series of tests involved the use of the Russian Marsokhod rover. Three field trials have been completed: at Amboy Lava Field, California, in 1994,[54] on Kilauea volcano, Hawaii, in 1995,[55] and near Tuba City, Arizona, in 1996.[56] For the first of these, the operations were centered in the Los Angeles area, and for the other two, at NASA Ames Research Center, Moffett Field, California.

The Marsokhod field demonstrations were full operational tests designed to determine all aspects of the rover's operations and the interactions between its operators and a team of scientists attempting to interpret the data collected. As such:

- The localities and traverses were selected to determine the physical ability of the rover to negotiate terrains believed to be good analogs of conditions on Mars.
- The instruments and peripheral devices carried by the rover were evaluated.
- The ability of science teams to interpret correctly the geology of a site was tested because the specifics of the sites were not known by these teams in advance.
- The ability of the various individuals and teams to coordinate activities and communicate with each other was tested.

In general, the Marsokhod proved able to negotiate the terrain at each of the three test sites. The science teams did reasonably well in interpreting the local geology, but all of them missed some specific features that were present. Much was learned with each day of testing that resulted in significant improvements in operations during the next day. On the other hand, communication and coordination problems significantly hampered operations during some of these demonstrations. This problem is discussed in the report of the first demonstration, in which it is stated that science, engineering, and operations objectives were competing for time and resources. The same problem still existed during the third test. In short, many of the same things were "learned" over and over again.

Some of the recommendations from the first demonstration were put into effect for later demonstrations. For example, the terrain types were different for each test, as recommended. Additional science instruments and capabilities were added, such as the ability to obtain color and close-up images and the placement of a "hand lens" (a microcamera) on the manipulator arm. These devices were used during the third test but, unfortunately, not all of them functioned satisfactorily. True multispectral images could not be obtained because the camera was out of focus in many wavelengths. Moreover, the depth of field of the hand lens was so limited that it was not possible to interpret the pictures with any confidence. This experience highlights the need to test thoroughly the payload instruments and peripheral devices before they are placed on a mobile platform for a full field test or, more critically, before launch of a space mission.

Lessons Learned from Sojourner Operations

Operation of the Sojourner rover on the Mars Pathfinder mission also provided opportunities for field testing, both on Earth (operational readiness tests) and in the martian environment. The insights and lessons from these exercises are important. During the mission, the rover traversed a total distance of approximately 100 m in the immediate vicinity of the lander over a period of 82 martian days.

Mars Pathfinder was not equipped with a descent imager, and it quickly became apparent that a birds-eye view of the landing site was needed. Various teams attempted to construct rectified contour maps and virtual-reality displays for rover navigation purposes, with mixed success. Autonomous navigation involving point-to-point traverses, and techniques for finding and avoiding rocks, were tested. These techniques, however, did not always operate successfully because of software and communications link problems, errors in uplinked commands, and difficulties encountered in moving across loose soil and sand. Moreover, the cameras mounted on Sojourner did not have sufficient resolution for navigational purposes.

The lessons learned from Pathfinder emphasize the difficulties in operating rovers without benefit of real-time observation and execution of commands. Future rovers that operate outside the line of sight of a lander (which can provide images from an elevated perspective, plus a fixed frame of reference) will encounter considerable problems if they do not have rapidly produced maps and flexible navigation tools. Capable imaging systems (both descent and rover-mounted) are necessary, as are improvements in autonomous navigation systems and communications. Scientific goals that require ranging over tens or hundreds of kilometers may be difficult to accomplish except in cases of relatively unchallenging geologic terrains. These views are echoed by the Mars Surveyor 2001 Science Definition Team (SDT), whose report comments that the lack of a satisfactory robotic field capability, even when the vehicle is under the full control of mission scientists, is "somewhat sobering."[57] The SDT ascribes the limitations not to the rover hardware, but to the following:

1. Lack of experience;
2. Limitations in imaging resolution and in the coverage that low-bandwidth communications permit; and
3. Lack of software to allow scientists to quickly and fully visualize the data that are returned.

Future Need for Field Demonstrations

It is clear that field demonstrations are essential. One area of particular importance is the operational integration of autonomous and direct control systems. A sophisticated rover should, in principle, be able to make observations while traversing from one predetermined location to another and use the results of the observations to select the most scientifically interesting route to take. Recent field tests have demonstrated that this capacity does not yet exist even when scientists have full control of the rover.[58] Limited communications windows and available bandwidth will, necessarily, limit the degree to which mission scientists can have direct control over the planning of the rover's operations. Without some degree of autonomous control during the periods when it is not in communication with Earth, the rover is likely to spend a significant fraction of its operational life waiting for instructions. With the twice-daily communications sessions scheduled for future Mars Surveyor missions, this downtime could amount to 90 percent. Field demonstrations offer a ready means to develop and validate schemes for autonomous operations and to develop techniques for their harmonious integration with the limited periods when mission scientists will be in the control loop.

What also is clear is that the usefulness of field demonstrations will be greatly enhanced if better continuity exists between tests so that problems exposed in one test are not "forgotten" during the planning of subsequent tests. Many of the problems of this type that arose in the various rover tests conducted to date were related to people and operational systems rather than to the rovers themselves. These problems are, therefore, likely to be universal with respect to mobile platforms or mission objectives. Operational problems experienced by the Sojourner team (e.g., the fact that it took them much longer than planned to maneuver the rover from one rock to the next) could have been anticipated and planned for had there been better communication of field-test results. A mechanism needs to be devised to ensure that important operational problems are known and acted on by all groups. Adequate peer review of proposed operational tests and the prompt publication of the results of those tests in peer-reviewed journals are essential.

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4

Conclusions and Recommendations

The most important conclusion from this study is that mobility is not just important for solar system exploration—it is essential. Many of the most significant and exciting goals spelled out in numerous NASA and NRC documents simply cannot be met without mobile platforms of some type. To what degree is this basic conclusion dependent on the selection of the six case studies? To gauge this, COMPLEX considered an independent set of case studies, the portrait missions addressing the campaigns described in NASA's *Mission to the Solar System: Exploration and Discovery*[1] (Table 4.1). Achievement of four of the five campaigns contained in the NASA report depended critically on the use of mobility in the form of rovers, balloons, and robotic arms. Given the results of this independent check, COMPLEX is confident in the robustness of the conclusion that the use of some form of mobility is an essential feature of future solar system exploration missions.

A second conclusion is that the diversity of planetary environments that must be explored to address priority scientific questions requires more than one type of mobile platform. Thus, the simultaneous development of some combination of wheeled rovers, aerobots, aircraft, touch-and-go orbiters, and cryobots is not only justified but is also necessary, as long as there is a scientific justification for the development of each mobile platform. Technology development funds are likely to be scarce and so should be allocated only after a vigorous peer review of the proposed mobility device's technical feasibility and the scientific applications for which it will be used. As the Space Studies Board has previously recommended, technology development activities should be undertaken by the best-qualified individuals and teams within NASA, industry, and academia, as determined by peer review.[2]

With some exceptions, the current technical development efforts are appropriate and well focused. However, it is instructive to compare the tenor of recommendations in science-oriented presentations and of science-centered working groups with the thrust of technical development efforts. The science sources emphasize the need for very capable mobile platforms with the following characteristics:

- Synergy of instruments, that is, a suite of mutually complementary instruments rather than either a small number of instruments or many instruments that are independently conceived and developed;
- Extensive range and long lifetime; and
- One or more manipulative devices, such as claws, drills, and the like, some of which are likely to be complex and difficult to develop.

These characteristics define a mobile platform that is fairly large and potentially rather complex. In contrast,

TABLE 4.1 Mobility Needs in the Solar System Exploration Roadmap's Campaigns and Portrait Missions

Campaign	Portrait Mission	Mission Type	Mobility Needs*
Building Blocks and Our Chemical Origins			
	Pluto/Kuiper Express	Flyby	Low
	Multi-Body Visitors	Flyby	Low
	Large Asteroid Orbiter	Orbiter	Low
	Small Body Sample Return	Sample Return	Medium
	Giant Planet Deep Probes	Entry Probe	Low
Prebiotic Chemistry in the Outer Solar System			
	Europa Ocean Explorer	Orbiter	Low
	Europa Lander	Lander	Medium
	Titan Biologic Explorer	Aerobot	High
Formation and Dynamics of Earth-like Planets			
	Lunar Giant Basin Sample Return	Sample Return	Medium
	Mars Surface Network	Landers	Low
	Venus Surface Mission	Landers/Aerobots	High
	Io Volcanic Observer	Orbiter	Low
	Mercury Orbiter	Orbiter	Low
Evolution of Earth-like Environments			
	Mars Water-Mineralogy Mapper	Orbiter	Low
	Mars Mobile Sciences Lab	Lander/Rover	High
	First Mars Sample Return	Sample Return	High
	Advanced Mars Sample Return	Sample Return/Rover	High
	Mars Geosciences Aerobot	Aerobot	High
	Venus Geosciences Aerobot	Aerobot	High
Astrophysical Analogs in the Solar System			
	Outer Planet Multiprobes	Entry Probe	Low
	Jupiter Polar Orbiter	Orbiter	Low
	Neptune Orbiter/Triton Flyby	Orbiter	Low
	Saturn Ring Observer	Orbiter	Low
	Mercury Magnetospheric Multi-Satellites	Orbiter	Low

*Low, little or no mobility required; medium, robotic arms or other types of sample collection devices needed; high, mobile platform equipped with sophisticated instrumentation required.

the main thrusts of technical development, especially of rovers, are directed at reducing their size and increasing their autonomy. If size reduction also results in a corresponding reduction in range or other capabilities, it will, potentially, have a significant scientific impact. This is so because it creates a capability to make scientific measurements on a scale size that is not necessarily optimal for addressing the scientific questions to be answered.

The pattern of planetary exploration to date has been to make basic observations of planetary surfaces from orbiters and to establish hypotheses for interpreting these observations. These hypotheses are then tested by more directed observations and measurements. Because the hypotheses are based on orbital images with a relatively low characteristic resolution, this suggests that long-range traverses are required to test the relevant hypotheses. However, the focus of technical developments appears to be to create mobility systems capable of producing very detailed, but limited, data sets about very small areas. Thus, we run the danger of creating a technical capability to address scientific issues that might not, necessarily, relate to the framework of scientific questions and issues developed as a result of prior studies. Reconciling these apparently contradictory priorities and minimizing their impact on the scientific productivity of mobility missions will require close cooperation between engineers and scientists.

Most science objectives defined for future solar system missions call for mobile platforms, manipulative devices, and instruments with significant capabilities. Attaining this level of capability will require reducing the total mass of mobile platforms *while maintaining acceptable functional capabilities*. The size of a mobile platform needs to be considered as part of a systems optimization based on scientific needs and mission constraints. Although very small mobile systems, such as the micro- and nanorovers currently under development, involve a significant reduction in mass, their payload capacity may be too limited for widespread application unless particular attention is paid to the development of appropriate micro- and nano-instrumentation.

Long-range mobility, whether with rovers, aerobots, or other devices, poses significant navigational challenges. This is in part due to the constraints imposed by long, two-way communication times and in part to the limited data downlink capacity available. The more time and downlink capacity are used for navigation, the less available they will be for returning scientific data. Lessons learned in the Marsokhod field tests and during the operation of Sojourner suggest that descent imagers should be included on lander and rover missions to provide critical information on the context of the landing site for use in rover navigation and science-operations planning. Navigational tools for long-range mobility should be available in as near real time as feasible. The hardware and software for intelligent autonomous operation and efficient operational planning should be actively developed.

Many planned and possible future missions will require spacecraft and mobility devices to operate in hostile environments. An environment can be hostile because of the high levels of radiation (e.g., the surface of Europa), high pressure (e.g., the atmospheres of the giant planets), high temperatures (e.g., the lower atmosphere of Venus), low temperatures (e.g., the surface of Titan), and very low gravity (e.g., the surfaces of comets and asteroids). Such environments place unusual constraints on spacecraft and instruments, indicating the need for long-range advanced planning and development.

These conclusions suggest two fundamental recommendations:

- Technological development of mobile platforms must be science driven. Available funds will never be adequate to develop all possible types and variants of platforms, and these scarce funds should not be wasted on devices of limited scientific utility no matter how technologically intriguing they may be. Thus, there should be science input into technology development from the very beginning.
- Mobile platforms, ancillary devices, instruments, and operational procedures must be thoroughly tested on Earth. This involves laboratory tests of instruments, field trials of individual components of space missions, and field trials of complete systems (mobile platform and instruments) and all relevant personnel (operators, design engineers, and scientists). To be fully effective, such field trials require thorough testing and calibration of instruments in the laboratory before they are mounted on a mobile platform, extensive field testing of mobile platforms both with and without instruments aboard, and full operational field testing of total systems. Proposals to conduct field tests should be peer reviewed in advance, and the test results should be promptly published in peer-reviewed journals.

In addition, several more-specific recommendations derive from the six case studies:

- Data downlink rates must be significantly increased, perhaps through the use of new technologies, such as the ongoing efforts to upgrade the Deep Space Network to operate in the Ka band or an eventual transition to optical communications. This is a problem that is not unique to mobile platforms.
- A means to *control* aerobot motion, both vertically and horizontally, needs to be developed.
- The capability to obtain descent images should be included on *all* lander and rover missions to provide critical context for navigation and science.
- Navigation tools and operational plans should be developed so that the impact of navigational needs on science return can be minimized.

In summary, the various disciplines interested in solar system exploration and research have many common needs for mobility and, thus, generally need not consider themselves as competitors for payload mass. For example, a rover carrying a suite of instruments designed to carry out a predominantly exobiology mission will differ very little from one designed to carry out a geology/geochemistry mission. Likewise, an aircraft or balloon mission designed to measure important atmospheric parameters at various altitudes can also collect surface spectral data important to geologists, geochemists, and exobiologists. Obviously, not all missions will satisfy all persons, but it seems clear that differences in mobile platform type and design are linked more to the target of the mission than to the interests of the scientists involved.

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