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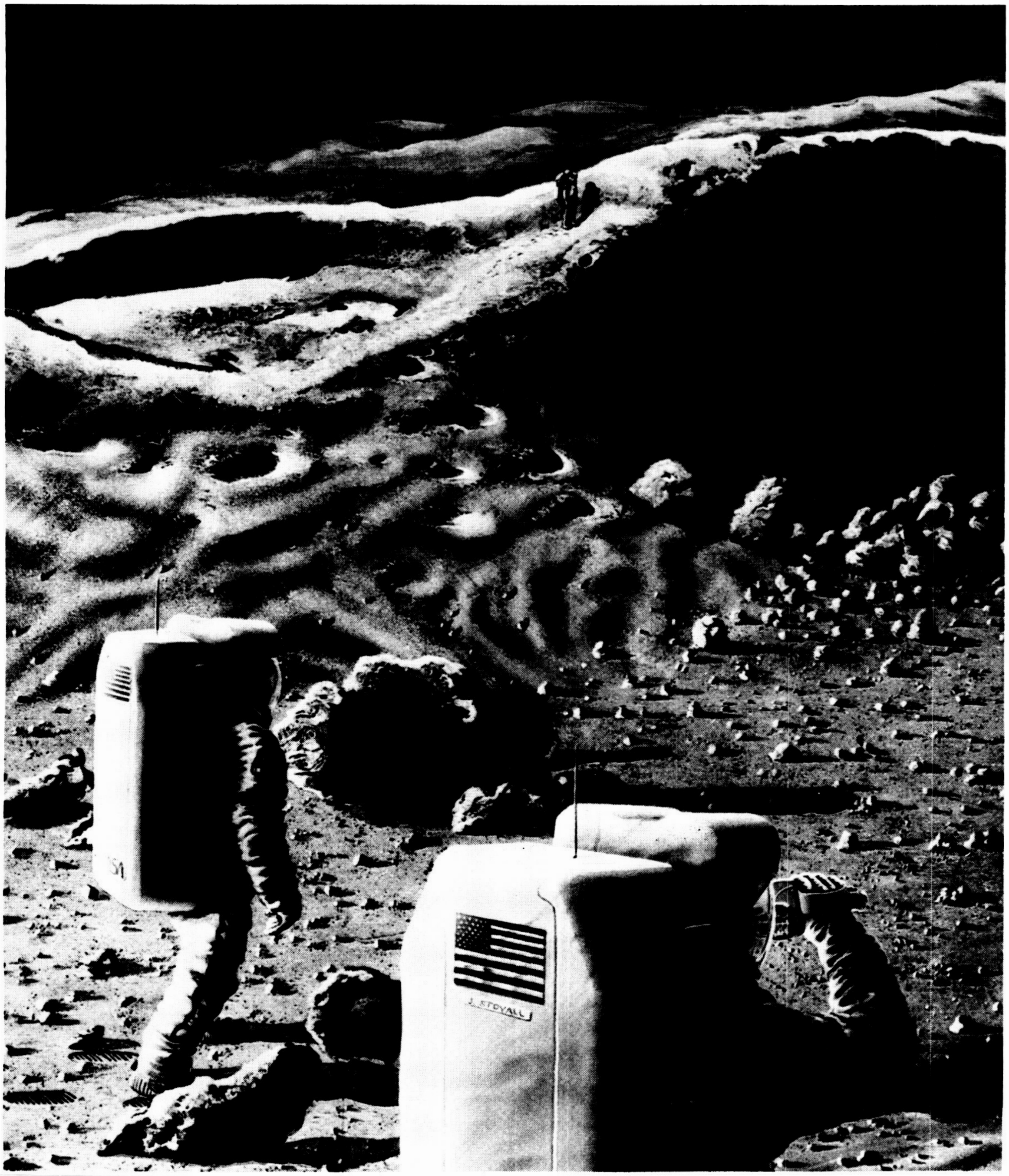
# Science Exploration Opportunities for Manned Missions to the Moon, Mars, Phobos, and an Asteroid



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# Science Exploration Opportunities for Manned Missions to the Moon, Mars, Phobos, and an Asteroid

by

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# Abstract

Scientific exploration opportunities for human missions to the Moon, Mars, Phobos, and an asteroid are addressed. These planetary objects are of prime interest to scientists because they are the accessible, terrestrial-like bodies most likely to be the next destinations for human missions beyond Earth orbit.

Three categories of science opportunities are defined and discussed: Target Science, Platform Science, and Cruise Science. Target science is the study of the planetary object and its surroundings (including geological, biological, atmospheric, and fields and particles sciences) to determine the object's natural physical characteristics, planetological history, mode of origin, relation to possible extant or extinct life forms, surface environmental properties, resource potential, and suitability for human bases or outposts. Platform science takes advantage of the target body, using it as a site for establishing laboratory facilities and observatories; and cruise science consists of studies conducted by the crew during the voyage to and from a target body.

Generic and specific science opportunities for each target are summarized along with listings of strawman payloads, desired or required precursor information, priorities for initial scientific objectives, and candidate landing sites. An appendix details the potential use of the Moon for astronomical observatories and specialized laboratories, and a bibliography compiles recent work on topics relating to human scientific exploration of the Moon, Phobos, Mars, and asteroids.

The report concludes that there are a wide variety of scientific exploration opportunities involving many science disciplines that can be pursued during human missions to planetary targets, but that more detailed planning studies and precursor unmanned missions should be carried out first.

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# Introduction

The advent of human exploration of the planets promises to be an unparalleled opportunity for scientists to play a major role in the planning, execution, and science return of these extraordinary missions, which will expand mankind's frontier. This exploration opportunity will also allow humans to be more directly involved in achieving the goals established by the Space Science Board of the National Academy of Science; namely, to learn and understand how the solar system formed, how planets evolve, and how planetary conditions led to the origin of life.

The NASA Office of Exploration (OEXP) is conducting a series of studies of candidate human exploration missions beyond Earth orbit. One or more of these missions may be chosen as the next major thrust in space by the United States, possibly as a partner in an international cooperative effort.

So far, studies by OEXP have considered operational plans and requirements for manned outposts or bases on Mars and the Moon and manned expeditions to Phobos and an asteroid. In planning for these missions, the OEXP solar system exploration program is focusing on science activities that can be conducted during human-crewed missions. Thus, the search for and definition of scientific, technological, and resource-related investigations that can be conducted on these missions is under way.

The purpose of this report is to describe a wide range of potential opportunities for science activities and resource assessments that can be performed on human missions targeted for the Moon, Mars, Phobos, or an asteroid. These missions are described in the exploration case studies conducted by OEXP (see summary of current case studies in Table 1). The scope of potential science exploration opportunities on the missions described in the case studies is very broad and, at this juncture, somewhat diffuse. However, the focus of these explorations should sharpen as studies continue, future program decisions are made, and mission priorities established. Until then, this report attempts to assemble most of the known possibilities for scientific exploration activities.

The format of the report is intended to facilitate use by mission planners, analysts, and other users. Thus, it has been structured in an expanded-outline format for easy reference to specific mission objectives. This report provides only cursory explanation of the rationale for considering most of the opportunities that are mentioned; the detailed rationale for these opportunities can be found in many of the previous studies listed in the bibliography.

According to current OEXP planning, this "Exploration Opportunities Document" will be used to help define the science elements in a series of follow-on studies that include an engineering analysis by a systems engineering task group (leading to an OEXP Study Requirements Document) and further detailed science plans for individual missions.

Our premises for the science exploration opportunities discussed here are as follows.

(1) The exploration, which will take place beyond low Earth orbit, will be conducted on manned missions. It will emphasize activities that can be uniquely accomplished or significantly enhanced in precision, versatility, and adaptability by the presence and capabilities of humans. These activities include tasks that would be very difficult or impractical to carry out using solely robotic systems directed from Earth;

(2) The eventual decision to go first to Mars or to the Moon will be strongly conditioned by non-scientific reasons. Science, though a factor, will not be the driver. Thus, the real issue here is, if humans are to go to any planetary body, what science and related activities can be performed to take maximum advantage of the presence of humans on these missions?

The information presented in this report was compiled from a wide variety of study reports, workshop proceedings, and other documents by many different individuals and study groups generated over the past few years (see bibliography). These materials were augmented and synthesized during a small workshop of the CEPS group, "Exploration Science Opportunities," held at Caltech on December 15–16, 1988, from which this report evolved.

## OBJECTIVES

This report addresses two key questions:

(1) What are the scientific and related exploration opportunities for human missions beyond low Earth orbit?

(2) What prior knowledge is required or desired to facilitate these exploration opportunities, and what precursor missions or other activities are needed to obtain this knowledge?

The answers to these questions will aid in planning the activities to be conducted in preparation for and implementation of science opportunities during human exploration of the inner solar system.

One problem recognized during the course of this study is the hazy distinction between scientific tasks that can best be performed by humans because of their presence on a solar system mission and those tasks that can perhaps be done sooner, more safely, or less costly by robotic spacecraft. In virtually all the cases discussed, this distinction is somewhat artificial since in all space exploration activities both humans and machines are always involved. In many cases, the presence of humans in the spacecraft can enormously enhance the capabilities of scientific instruments or other robotic devices. In other cases, the presence of humans is unnecessary and may create severe cost or operational constraints. The objective here, however, is to describe scientific and related investigations that can be done *because* of the unique presence, versatility, and capabilities of humans on or close to the target planet. These investigations, however, may greatly depend on machines—including autonomous machines such as sample-collecting rovers—that extend the capabilities of humans during their exploration activities. Also, some scientific investigations such as life-support or reduced-gravity-effects studies are made necessary by the presence of humans or by the intention to support humans for extended periods of time in these new environments. Less important but not excluded are those investigations that can be done simply because humans are present rather than requiring their presence.

## PRECURSOR ROBOTIC MISSIONS BACKGROUND

It has been anticipated and assumed in this study that the human exploration activities discussed in this report will be conducted after the initiation or completion of a series of robotic "precursor" missions by the United States or other nations. Although it is generally thought that precursor missions are not absolutely required prior to manned missions to planets, precursor missions are highly desirable in order to achieve maximum safety and science return. Relevant missions known to be under way or in the planning stages that could be considered precursors to manned missions include missions

### *To Mars*

U.S.S.R. Mars 94 mission—Orbiter, lander, lightweight rover, balloons.

U.S. Mars Observer—Polar orbiter, global surface and atmosphere maps.

U.S. Mars Rover Sample Return—Sample return, geologic reconnaissance.

U.S. Mars Aeronomy Observer—Polar orbiter, detailed atmospheric sounding.

U.S. Mars surface penetrators—Seismicity and meteorology networks.

### *To the Moon*

U.S. Galileo—Two flybys at 400K km range; high latitude images, spectra.

U.S. Lunar Observer or Prospector—Polar orbiter, global mapping.

U.S.S.R. Lunar Orbiter—Polar orbiter, global mapping coverage.

Japan Lunar Orbiter—Polar orbiter, global mapping, surface packages.

### *To an Asteroid*

U.S. Galileo—Flybys of two S-type mainbelt asteroids; images, spectra.

U.S. Comet Rendezvous/Asteroid Flyby—Small body reconnaissance.

Additional precursor missions may also prove necessary prior to human exploration.

# Section 1

# Generic Types of Human Exploration Science Opportunities

Three types of scientific activities that can be carried out on human exploration missions to planetary bodies are target science, platform science, and cruise science.

**Target science** is the study of the target object's fundamental nature, history, mode of origin, resource potential, and natural environmental characteristics;

**Platform science** uses the planetary body's environment either as a laboratory site for conducting various physical science and life-science studies, materials and engineering studies, and other diverse technical activities or as an observing platform for conducting astronomical and other "outward-looking" scientific investigations;

**Cruise science** consists of measurements and investigations made from the spacecraft during the cruise or transit stages of the mission to its planetary target. These activities could be conducted during both the outbound and return legs of the mission. Cruise conditions offer a unique opportunity on manned missions to make long-term, human-tended and continuous observations well away from any planetary body in interplanetary space.

These three categories are used to organize and describe the science and related exploration activities that are discussed in the remainder of this report.

# Target Science

Target science consists of those investigations that elucidate the physical nature of the target body and its immediate surroundings. (Relevant targets include the Moon, Mars, Phobos, and an asteroid.) Clearly, such activities could be carried out by unmanned spacecraft and even ground-based studies from Earth. However, we are primarily concerned with target science activities that can be carried out by humans from bases or outposts on or near the surface of the planetary body.

The objective of target science is to gain an understanding of the planetological, environmental, and possible biological characteristics of the body and its immediate surroundings and of the processes affecting these characteristics. The target body is used essentially as a natural laboratory for the study of planetary processes.

Some target science information may be required prior to human missions, some may be obtained by unmanned missions, and some may require human presence on the planet to obtain it.

***Astronaut collecting rock sample at the Apollo 16 landing site.***

## GEOLOGY AND RELATED STUDIES

*(Targets: Moon, Mars, Phobos, Asteroid)*

Studies of the geology, geochemistry, and geophysics of the target body are important in order to gain a thorough knowledge of the physical properties, processes, and environment on and within the body at varying scales. This geological information is essential in understanding how planets form and evolve, and, specifically, how the study of other planetary objects can provide a better understanding of the Earth—the basis of comparative planetology.

In order for humans to live and work on a planetary surface, to avoid its hazards, and to take advantage of its available resources, its near-surface geologic and atmospheric environment must be well understood. For these purposes, data are required on several scales: (1) on a global scale to place the body and its surface in complete perspective; (2) on regional and local scales to understand detailed processes that have governed its character; and (3) on local scales for selecting specific landing and operational sites.

Geology studies include global reconnaissance surveys, geological and geochemical studies at regional and local scales, and geophysical studies.

**Global Reconnaissance Surveys.** These surveys should be done first from orbit using robotic remote-sensing techniques from unmanned spacecraft, followed by human exploration surveys (long-distance traverses) on the surface. Survey objectives should include

- Broad characterization of geologic and structural relations on the surface including
    - Relative ages of global and regional rock and soil units.
    - Processes and rates of impact, volcanism, tectonism, erosion.
    - Composition of major rock units (mineralogy, petrology, elemental concentration, and spatial distribution).
    - State and distribution of volatiles (near-surface and atmospheric).
- Gravity field and high-resolution topography determination.
- Assessment of potential sites for
    - Unmanned landers, atmospheric probes, or surface penetrators.
    - Landing points for manned spacecraft or cargo craft.
    - Permanent human outposts or bases.
    - Resource-extraction facilities.
    - Observatory and laboratory facilities.

**Detailed Geological and Geochemical Studies at Regional and Local Scales.** After global reconnaissance surveys have been completed, geological and geochemical studies should be conducted, focusing on more limited and scientifically important areas. These detailed studies should be iterative and, as in terrestrial studies, conducted with interspersed field and laboratory work and possibly supported by teleoperated robotic systems to overcome environmental constraints. *In situ* human interaction at this stage of exploration on or near the planetary body significantly enhances, and perhaps enables, such studies.

Key geological and geochemical studies on the target body include

- Mapping the detailed distribution and composition of local and regional surface geologic units to determine
    - Mode of origin of rock and soil units, processes, rates.
    - Geologic structures and surface morphologies.
    - Regolith structure and heterogeneity (lateral and vertical).
    - Resource potential, including
        - Material identification (water, ores, building materials).
        - Location, concentration, and character of mineralogical hosts.
        - Potential for extraction and utilization.
- Collecting and analyzing returned samples including coring and trenching for samples of rock, soil, volatiles, and organics, to determine
    - Chemical and isotopic composition.
    - Texture and fabric of materials.
    - Mineral and petrologic composition.
    - Depth-related (stratigraphic) properties.
    - Radiometric age (rock formation chronology, including age of the impactors and calibration of impact time scale).
    - Rock and soil mechanical properties (bearing strength, cohesiveness, etc.).

- Determining the nature, origin, and significance of
  - Layered polar deposits, aeolian and sublimation deposits and processes.
  - Surface weathering; rock, soil, dust, sunlight, and atmospheric interactions.
  - Seasonal and climate change effects on rock surfaces.
  - Volatile reservoirs and their atmospheric exchange processes and rates.
  - Surface radiation effects (solar ultraviolet, solar wind, cosmic rays).

**Geophysical Studies (Global, Regional, and Local).** There are several types of geophysical studies that should be an integral part of any thorough geologic characterization of a planetary body. Where geologic mapping and rock sampling contribute to knowledge of the surface, geophysical measurements contribute to the knowledge of the subsurface and bulk interior. An understanding of the interior body processes (such as melting, differentiation, faulting, and heat transport) is important because these processes are largely responsible for the development of many of the surface characteristics observed today. Again, as with geological and geochemical studies, the geophysical work should be carried out at a variety of scales (global to local) with corresponding changes in resolution.

Key geophysical studies include

- Seismology:
  - Measure and monitor natural seismic waves to determine
    - Crustal structure.
    - Interior structure (Core-mantle-crust boundaries).
    - Global seismicity levels.
  - Active seismic exploration for
    - Reflection, refraction (to determine near-subsurface layering).
- Heat flow (global, regional, and local scale measurements).
- Surface and near-subsurface electrical conductivity and dielectric studies.
- Magnetic field studies:
  - Induced/remanent fields.
  - Paleomagnetic properties of rocks (ancient magnetic fields).
- Radar and electromagnetic (EM) sounding (e.g., to search for subsurface frozen water).
- Surface irradiation history.
- Ionospheric and magnetospheric interactions.
- Lunar motions and dynamics (internal mass distribution).

## REQUIRED CAPABILITIES FOR GEOLOGICAL/ GEOPHYSICAL EXPLORATION

In order to accomplish the geological investigations already mentioned, certain data, analytical capabilities, and measurement tools are required. These items allow researchers to carry out an effective program of geoscience exploration. Some of the required capabilities involve orbital instruments, others landed systems, and others hand-held equipment and tools. These requirements include

- Capability to map the regional and global distribution of surface rock and soil units accessible to humans. These data provide the framework for more detailed local geological and geophysical investigations and resource surveys and are required for siting of permanent bases.
- Capability to obtain samples of major rock units globally distributed on the surface to determine detailed compositional information (surface chemistry and mineralogy), absolute ages (radiometric) of igneous rock units, engineering data (such as bearing strength and tractability), and potential for resource extraction. Operations that will reach and obtain samples from all longitudes, latitudes, and terrain types will also require global accessibility.

The sampling operations will involve

- Drilling or excavation for subsurface samples to at least 1-meter depths.
- Sample return (from local, regional, and global sites) to base or outpost, then to Earth; these operations will be enhanced by the use of rovers, especially with high mobility.
- Potential sampling sites include
  - Craters (interior floor, central peaks, ejecta blankets).

  - Canyons (walls, floors, landslide deposits).
  - Volcanic units (lava flows, ash deposits).
  - Layered deposits (sediments, interlayered volcanics, ice).
  - Surface material (dust, regolith, weathering products, frost).
  - Subsurface material (interpore ice or frozen volatiles) below the annual (seasonal) skin depth (~1 m).
- Capability for simple, real-time identification of rock type in the field.
  - Petrologic type (texture, mineralogy, density, etc.).
  - Chemical type (elemental, molecular).
- Capability for determining the presence of organic compounds, micro-organisms, or fossil organisms in soil or rock deposits and, thus, identifying rock formations of extreme importance to biological studies.
- Capability to deploy instrument packages on the surface at globally distributed multiple sites, and to establish global networks for
  - Seismic monitoring (natural seismicity, short- and long-period waves).
  - Geophysical measurements (heat flow, magnetic fields, charged particles, subsurface EM and radar-sounding, libration network).
  - Meteorologic/atmospheric monitoring (gas composition, mixing ratios, wind velocity and direction, temperature, pressure, and water vapor).
- Capability to sample and preserve subsurface rock, soil, and frozen volatile samples
  - Beneath surface rind on rocks (to depths of at least several centimeters).
  - Beneath dust layers (to several decimeters).
  - With soil cores to depth of several meters.
  - With regolith cores to depths of tens of meters.
- Capability for long-term stays and continuous human presence.
- Capability for extensive telerobotic geologic field studies.

## ATMOSPHERE STUDIES

*(Targets: Mars, Moon)*

The study, as well as the characterization, of a planetary body's atmosphere is important for four reasons:

- to establish a purely scientific understanding of its fundamental properties, such as composition, density and temperature, structure, weather and climate, history and mode of origin, and its relevance to understanding the Earth's atmosphere;
- to assess its effects on humans who must work in it;
- to determine the atmosphere's effect on spacecraft hardware during high speed flight through it and while operating in it for extended time periods on the surface;
- to assess its practical use as a resource for life support or other needs.

The atmosphere's effects on humans are threefold; first, its possible threat to human life during storm conditions (relevant on Mars); second, its longer term effect on life-support equipment and scientific instruments (relevant to both the Moon and Mars); and third, the possible obscuring opacity of the atmosphere (or exosphere) at various wavelengths, which could interfere with communication or observations.

Atmospheric studies for Mars should be able to

- Determine the present state and circulation of the martian atmosphere in order to understand
  - General circulation patterns and seasonal variations.
  - Effects of topography and surface interaction.
  - Global transport of water vapor and other important gases.
  - Atmospheric chemistry.
  - Dust and aerosol behavior and temporal and seasonal variation.
  - Global energy balance and variability.
  - Clouds, ground fog, and surface frost formation.
  - Interaction with solar wind and possible magnetic field.

- Measure meteorological conditions and long-term variations on Mars using weather- and climate-monitoring stations at multi-latitude sites from north to south (surface and upper atmosphere) to measure
  - Temperature and pressure.
  - Wind speed and direction.
  - Dust content.
  - Compositional variation.
  - Weather and climate changes.
- Determine ancient climate and atmospheric properties on Mars by studying
  - Surface outflow channels and valley network morphology.
  - Sediment compositional variation (especially $CO_2$- and $H_2O$-bearing deposits) and evidence for groundwater/ice deposits.
  - Subsurface frozen or adsorbed volatiles.
  - Layered deposits for indications of periodic phenomena:
    - Obliquity changes in Mars' rotational axis.
    - Solar insolation or solar intensity changes.
- Determine the cause and mechanism for climate change.

Atmospheric studies for the Moon are concerned with its exosphere and should include

- Determining what atmospheric (exospheric) constituents compose the present near-lunar-surface environment:
  - Neutral gas and ion density, composition, and spatial distribution.
  - Diurnal and latitude variation of these species.
- Establishing a network of instrumented stations for continuous long-term monitoring and assessment of the impacts of human activity on the lunar atmosphere.

## FIELDS AND PARTICLES STUDIES

*(Targets: Moon, Mars, Phobos, Asteroids)*

In general, external fields and particles studies are best conducted from free flyers rather than from manned bases. Manned bases do not presently appear to offer enhanced opportunities for direct fields and particles experiments. However, fields and particles investigations could be conducted by rockets, balloons, or orbiting spacecraft launched from the surface of the target body or as part of a study of magnetic induction in the planet's interior (such as that of Mars and the Moon). Induction studies would require placement of magnetometers on the surface or in orbit. Likewise, study of ionospheric currents at Mars would require placement of a network of magnetometers on the surface. Portable magnetometers on the surface of any planetary body might allow field geologists and geophysicists to map the local magnetic field properties for purposes of deducing subsurface structures or compositional heterogeneities that might reveal mineral resources.

Fields and particles information can be obtained by conducting the following activities.

- Map magnetic field properties at the surface; determine surface field line orientation and strength; correlate with subsurface data (such as gravity anomalies and core/mantle boundaries) and global external field properties from orbital data.
- Determine ionosphere and magnetosphere structure with surface and orbiting magnetometers.
- Determine solar-wind- and solar-flare-particle fluxes at exosphere with orbiting sensors; assess interactions with ionosphere.
- Monitor ion and electron energy, fluxes, and variability at the surface; measure the Moon's plasma emissions before, during, and after the Moon passes monthly through the Earth's plasmapause and magnetotail.
- Determine the history of ancient sun activity (via study of solar-ion-implantation record in subsurface soil samples).

## EXOBIOLOGY STUDIES

*(Target: Moon, Mars, Phobos, Asteroids)*

Both Mars and the Moon (and perhaps smaller bodies such as Phobos, Deimos, and asteroids) are likely to yield important information about the early history of the solar system (i.e., the first billion years) at a time when chemical evolution produced the origin of life on the Earth. Because this period of time is cryptic as far as terrestrial geology is concerned, these data are important to exobiology.

The purpose of exobiological studies on the Moon, Phobos, Deimos, and asteroids is to search for evidence of biological systems or components (such as organic compounds, biogenic elements, and volatiles) to gain an understanding of the interaction between developing or evolving biological systems and the physical environment in which this was taking place. These studies can be done by determining the cratering history; the detailed elemental and isotopic analysis of materials; the level of organic chemistry that exists; and the relation of these factors to those on Mars, to meteorites, to interplanetary dust particles (IDP's), to comets, and to known life forms and their chemistry and history on Earth.

Mars target science studies in exobiology should focus on the detailed analysis of martian materials, which might indicate the presence of biogenic elements and compounds; on the search for chemical and morphological indications of past or present life forms; and on determining the course of chemical evolution that took place on Mars throughout its geological history and how that history relates to the question of whether there ever was biological activity there.

It is assumed that any indications of life forms that exist on Mars will be (a) hidden from macroscopic view in protected micro or oasis habitats and (b) more likely present in ancient subsurface sedimentary materials (including ice-covered materials) that were products of water-rich environments. These conditions suggest that *in situ* biological studies on Mars should emphasize the following activities.

- Collect samples and determine composition of existing surface and subsurface soils; search for signs of biogeochemical activity, evidence of living (metabolizing) organisms, and levels of biogenic elements or prebiotic (replicating) organic molecules.
- Search for promising geological environments such as the oldest accessible sedimentary deposits and for evidence therein of morphological fossil organisms such as stromatolites.
- Search for organic or altered organic material, chemical discontinuities that could be associated with life, inorganic mineral deposits associated with biomineralization processes, and evidence of extinct fixation of biological carbon or nitrogen.
- Determine the nitrogen isotope ratios of any nitrate or organic material in martian sediments.
- Determine whether there was liquid water on Mars for an extended period of time during its early history, as well as when and how often this occurred.
- Determine to what extent conditions on Mars are currently hostile to living organisms, and whether Mars' surface conditions were ever conducive to the origin of life.
- Follow measures designed to minimize contamination of Mars by terrestrial organisms and prevent back-contamination to Earth.

## POTENTIAL LANDING SITES FOR MANNED MISSIONS

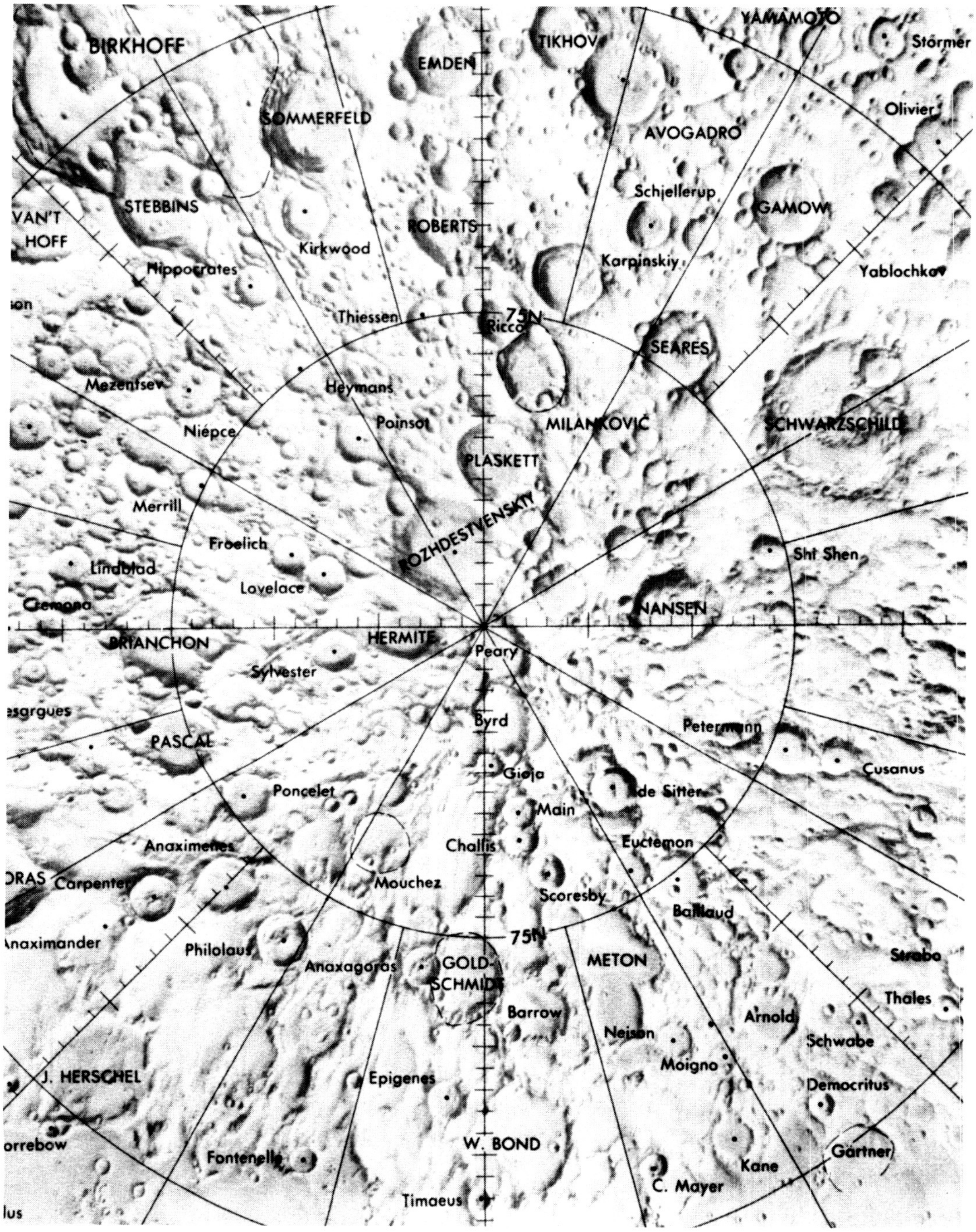
### *(Moon, Mars, Phobos)*

The candidate sites discussed below are sample sites chosen for conducting target science activities. At these sites, detailed field study is necessary to understand the complex properties of the planet that would otherwise not be revealed during preliminary reconnaissance mapping from orbit or through samplings by rovers or other telerobotic systems. (Field study involves extensive and protracted work by humans in which specific scientific questions dealing with geologic and biologic processes and history are addressed.) Other reasons for considering certain sites include the search for resources such as water, building materials, or shelter against weather or radiation hazards (e.g., lava tubes on the Moon).

These landing sites were chosen because they pose a number of varied geologic and other scientific problems within a relatively small region. It should be emphasized that numerous other sites of high scientific importance could be listed and that the sites described here are presented only as examples. Furthermore, it is assumed that the crew will have the ability to venture over the terrain out to a few hundred kilometers from the landing site. An inability to move such distances will restrict the potential scientific return from any of these sites and limit the mission objectives to one or two, as opposed to the varied objectives which can be addressed if sufficient mobility is available.

## SITES ON THE MOON

The five candidate lunar sites suggested illustrate the types of target or platform science environments on the Moon that if explored by humans could offer detailed scientific information not obtainable from orbital or ground-based study. All sites are suggested primarily for their geologic diversity except for site L-5, which is favored by radio astronomers for a lunar observatory, and L-6, which is suggested for its proximity to permanently shadowed polar craters, where frozen water or other volatiles may be found and exploited for resources.



***Shaded relief map of the lunar north pole showing possible landing site at Peary Crater.***

### ***Copernicus Crater*** *(Site L-1)*

**Location:** 10° N lat
20° W long

**Geologic context:** Copernicus is a large, relatively recent impact crater (age <1 BY) and serves as the type feature for the system of lunar stratigraphy bearing its name. Determining the absolute age for this crater would aid in quantifying the lunar stratigraphic system and cratering rate. Copernicus is characterized, in remotely sensed data, by rocks rich in Mg, K, P, and rare Earth elements. It displays a central peak, internal terraces, and an extensive ejecta blanket and secondary crater swarms. Radial sampling of the crater's ejecta deposits would allow study of the lunar crust at this location as a function of depth, since material from deeper in the Moon should be found closer to the rim of the crater. Copernicus appears to be located in an area of thin mare material.

**Geologic objectives:**

- Sample the impact melts of the crater for radiometric dating.
- Conduct radial sampling in the ejecta deposits, and sample the mare basalts.
- Determine the nature of crater and basin formation processes.
- Study melt sheet homogenization, clast provenance, and particle motions during cratering flow.
- Study walls, terraces, and slump blocks for structures and compositions.
- Obtain subsurface profiles of the terrain outside of thick ejecta deposits.

### ***Aristarchus Plateau*** *(Site L-2)*

**Location:** 25° N lat
45° W long

**Geologic context:** The Aristarchus Plateau is located in east-central Oceanus Procellarum. It possesses a variety of volcanic features, including the densest concentration of sinuous rilles on the Moon; abundant pyroclastic deposits, vents, and domes; volcanic materials of various ages and apparent compositions; and one of the freshest complex craters (Aristarchus) on the Moon. Orbital-geochemistry information from Apollo indicates that the area is rich in KREEP.

**Geologic objectives:**

- Sample various volcanic units to establish the volcanic history of the area.
- Sample the ejecta deposits, impact melts, and interior of Aristarchus Crater.
- Document stratigraphy of various rilles, volcanic deposits, and the crater.
- Investigate subsurface structure of the plateau with EM and seismic techniques.

### ***Appenine Bench*** *(Site L-3)*

**Location:** 25° N lat
0° long

**Geologic context:** This is an enigmatic formation inside the Imbrium Basin, west of the Apollo 15 landing site. Although it bears resemblance to impact-melt units in the less-degraded Orientale Basin, the most recent interpretations of the formation suggest a volcanic origin. Rocks in the area are rich in KREEP, thus an understanding of the origin of this bench formation is critical to interpretations of the origin of KREEP.

**Geologic objectives:**

- Sample the bench units northwest of the Apollo 15 site, including a deep core.
- Sample the ejecta deposits of Archimedes Crater.
- Document stratigraphy in the nearby Apennine Scarp (sample it laterally).
- Sample nearby Imbrium basalts and those of Palus Putredinis.
- Obtain seismic and EM profiles across Rima Bradley, a linear rille.

### ***Northeast Orientale Basin*** *(Site L-4)*

**Location:** 0° lat
80° W long

**Geologic context:** The Orientale Basin is the youngest of the large impact basins on the Moon, with a diameter of ~930 km. It is the archetypical multiringed basin and used extensively as a model for interpretation of other lunar and planetary multiring basins. Orientale is poorly understood, with no available samples known to have come from this region of the Moon; its formational history is considered one of the most important unsolved problems of lunar geology. Although somewhat constrained, the age of Orientale is unknown; many of the mare deposits inside the basin (Lacus Veris, for example) appear to represent the incipient stages of basalt flooding and, as such, source depths and extrusion mechanisms. If desired, a radio telescope erected to the west of this location would be shielded from interference from the Earth.

**Geologic questions to be addressed:**

- What are the composition and radiometric age of the Orientale impact melts?
- What are the composition and age of mare deposits of Lacus Veris, Knopf Crater, and interior to the Inner Rook Mountains?
- What are the composition and age of the massifs of Inner and Outer Rook mountains?
- What is the subsurface structure profile of the basin in the area around the Lacus Veris, particularly across the Outer Rook Mountains?
- How did the basin form and evolve?
- What was the nature of the impacting body?
- What is the composition of the lower crust and mantle exposed in the basin?
- What is the resource potential of the Orientale Basin region?

### ***Tsiolkovsky Basin*** *(Site L-5)*

**Location:** 20° S lat
130° W long (on lunar far side)

**Geologic context:** Tsiolkovsky is a large, relatively fresh mare-filled impact basin on the far side, with a diameter of ~150 km. It has a relatively smooth crater floor and a rugged central peak offset to the northwest; it is surrounded by high crater-rim mountains outside of which are large ground-surge deposits. Its basalts are some of the relatively few that occur on the lunar far side, and deriving an absolute age for this crater would be a substantial aid in stratigraphic studies of far-side geology. Owing to its location and generally flat floor, this crater would present an ideal site for radio telescope observatories.

**Geologic and other questions to be addressed:**

- What are the age and composition of the mare material filling the basin?
- What are the composition, texture, and age of rocks in the central peak?
- What is the subsurface profile of the mare fill based on EM and seismic data?
- What are the detailed surface topography and structure of the mare crust?
- What is the nature of rocks in the crater walls and outlying surge deposits?
- Would this site be a good location for a major facility such as an observatory?

### ***Peary Crater (North Polar Site)*** *(Site L-6)*

**Location:** 87-90° N lat
30° E long

**Geologic context:** This lunar site is a flat-bottomed crater, ~70 km in diameter, located in ancient, heavily cratered highland terrain. The low sun angle (less than 1.5° from horizontal) means that crater rims will be illuminated and much of the crater floor (containing numerous smaller craters <5 km diameter) will be permanently shadowed from direct sunlight. Little is known about the geologic conditions in the crater bottoms, but typical regolith surface is suspected and possible condensed volatiles (such as water, sodium, etc.) may be present on or beneath the surface because of the extremely cold temperatures there (~40 K or less). The low sun angle and constant illumination conditions on crater rims and the nearby permanently shadowed crater bottoms with cryogenic surface conditions represent a unique environment on the Moon that should be carefully studied and conserved.

**Questions to be addressed at this site:**

- What are the geologic conditions within the permanently shadowed craters?
- Are there accessible deposits of condensed volatiles within the craters?
- Are conditions suitable for establishing observatories or other facilities?

## SITES ON MARS

Six candidate sites are described. These sites are just a few examples of many candidate landing sites that could be explored on Mars. They provide access to a variety of surface exploration locations that range from low elevations to high elevations, from equatorial to polar conditions, from young volcanic terrains to ancient cratered terrains, and from smooth plains to dense valley networks and canyons, where ancient sediments may be found. All elevations given are relative to mean martian datum (the 6.1 mbar level in the atmosphere).

### ***Terra Tyrrhena*** *(Site M-1)*

**Location:** 27° S lat
265° W long
+3 to +4 km elevation

**Geologic context:** This site is located in the southern hemisphere in an area of ancient cratered highlands known as Terra Tyrrhena. Within the region are the Hellas Basin and two old, enigmatic volcanoes—Tyrrhena Patera and Hadriaca Patera. The geologic units within the region include Noachian-age Plateau sequence, which are dissected units of ancient crust with a high density of small channels (valley networks); ridged plains of Hesperian age; smooth plains of Hesperian-age Plateau system; and mountain material, which is the ancient crust uplifted as part of the Hellas Basin rim.

**Questions to be addressed at this site:**

- What are the nature, age, and composition of Mars' ancient cratered terrain?
- What are the nature and origin of the small valley networks common in the ancient terrain?
- What are the composition and geologic history of the volcanoes (Tyrrhena Patera and Hadriaca Patera)?
- What is the nature of the wrinkle ridges, which occur on many plains surfaces?
- What is the age of the Hellas Basin?

***Setting up a martian base.***

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### ***Xanthe Terra*** *(Site M-2)*

| | |
|---|---|
| **Location:** | 15° N lat<br>35° W long<br>0 to -1 km elevation |

**Geologic context:** This site is located in the equatorial area at the point where the large catastrophic channels Simud and Tiu Valles diverge as they flow to the north. Within the region are units of variable age and origin. Geologic units include Noachian crater material (ancient cratered terrain); Noachian-age subdued cratered terrain (ancient cratered terrain covered with plains units presumably formed by lavas); Hesperian-age channel material (the material that makes up the floor of the channels and that exhibits longitudinal scour and tear-drop-shaped island forms); and chaotic material.

**Questions to be addressed at this site:**
- What are the nature, age, and composition of the ancient cratered terrain?
- What is the origin of the smooth intercrater plains?
- Was water responsible for the carving of the large channel systems?
- What is the geologic relation between chaotic terrain and the channel systems?
- Are there sedimentary rocks exposed in the channels?
- Is or was life present in these areas?

### ***Tharsis Montes*** *(Site M-3)*

| | |
|---|---|
| **Location:** | 1° S lat<br>120° W long<br>+9 km elevation |

**Geologic context:** This site lies on the western flank of the Tharsis Montes, the northeast trending ridge on which sit three large shield volcanoes: Arsia Mons, Pavonis Mons, and Ascreaus Mons. Olympus Mons lies to the west. Several smaller, enigmatic volcanoes occur within the immediate area (Ulysses Patera and Biblis Patera). In addition to the large shield volcano structures and these smaller structures, the geologic units include a variety of Amazonian-age volcanic rocks that erupted in the vicinity and lobate-ridged material extending down the slopes of the volcanoes to the west and northwest that have been interpreted as landslide deposits. A small area of older, fractured plains also lies nearby.

**Questions to be addressed at this site:**
- What are the age and composition of the Tharsis Ridge volcanic lava flows?
- What are the nature and age of the small volcanoes (Biblis Patera and Ulysses Patera)?
- What is the nature of the lobate-ridged material (landslides?) extending off the large shields?

### ***Western Daedalia Planum*** *(Site M-4)*

| | |
|---|---|
| **Location:** | 19° S lat<br>144° W long<br>+3 km elevation |

**Geologic context:** Lava flows of the Tharsis province have encroached into the cratered terrain of the martian highlands. The site is located on lava flows, which come in contact with the base of the central peak of a large, nearly buried impact crater (120 km diameter).

**Questions to be addressed at this site:**
- What is the age of the volcanic flows?
- What is the age of the ancient cratered terrain and central peak material of the large buried crater?
- What is the composition of the aeolian (windblown) material composing the wind streaks on the surface in the area?

### ***Planum Boreum*** *(Site M-5)*

| | |
|---|---|
| **Location:** | 82° N lat<br>58° W long<br>elevation uncertain |

**Geologic context:** This north pole site provides a unique geologic environment for exploration. The north polar area is one of the few locations on Mars (the south pole is the only other known location) where water ice is stable at the surface. This site provides the opportunity to address several important questions of martian science. The units exposed within the region include the north polar cap (presumably the bulk of which is carbon dioxide); the residual polar cap (presumably largely water ice); the polar-layered terrain; polar dune fields; and the northern reaches of the northern hemisphere lowlands. These units are all relatively young and, therefore, of Amazonian age; most have no superposed craters (e.g., in the polar deposits, ice caps, and dune fields), suggesting that they are currently active.

**Geologic questions to be addressed:**

- What is the nature (age, composition, origin) of the polar-layered deposits, and how are they formed and sustained?
- Do polar deposits contain evidence of biological or prebiogenic materials?
- What is the composition of the residual (summer) polar cap?
- What is the distribution of subsurface water ice?
- What process causes the arcuate pattern of the layered deposits?
- What type of material forms the polar dunes, and are the dunes active?
- What are the meteorological conditions in this polar region?
- What is the origin of Chasma Boreale?
- What is the nature of the northern plains material?

### ***Candor Chasma (Valles Marineris)*** *(Site M-6)*

**Location:** 6° S lat
76° W long
+2 to +7 km elevation

**Geologic context:** Candor Chasma is a tributary canyon in Valles Marineris and contains layered plateaus rising as high as 5 km above the canyon floor. The canyon walls consist of thick sections of light and dark horizontally layered material thought to have been formed as sediments deposited in ice-covered lakes in the canyons.

**Questions to be addressed at this site:**

- What are the composition and texture of the layered deposits?
- What is the fine-scale layering in the deposits?
- What formed the layers: aqueous sedimentation or subaerial volcanism?
- What is the age span represented by the 5-kilometer-thick layering?
- Do the sediments contain evidence of biological organisms or prebiotic materials?
- Do the sediments contain evidence of past atmospheric or climatic conditions that could have been conducive to biotic chemistry?

### ***Chasma Australe*** *(Site M-7)*

**Location:** 85° S lat
269° W long
elevation uncertain

**Geologic context:** Chasma Australe is a large valley within the layered terrain at the south pole. Valley walls and escarpments range in height from 100 m to 1000 m and have slopes that range as high as 6°. Maximum thickness of the deposits has been estimated at 1 to 2 km. During the summer the area is largely uncovered by winter cap material.

**Questions to be addressed at this site:**

- What is the nature of the layered deposits?
- Were the layered sequences formed by deposition of volatiles and windblown dust?
- Is there evidence of biological material in these deposits?
- What are the composition and detailed dimensions of the fine-scale layering?
- What is the primary mechanism of erosion: wind ablation or sublimation?

## SITES ON PHOBOS

Phobos is a small object (~21 km diameter) but has several distinctive features at various surface sites that should be examined in detail. Presumably many or all of these sites could be visited and examined during a single manned mission.

### ***Stickney Crater*** *(Site P-1)*

**Location:** 0° lat (on leading side)
59° W long

**Geologic context:** This is the largest (~10 km diameter) impact crater on Phobos and offers the best location to obtain samples from depth. The crater is crosscut by several linear grooves and surrounded by hummocky topography containing a higher density of linear radiating grooves and many smaller impacts craters.

**Questions to be addressed at this site:**

- What is the nature of the regolith on Phobos?
- What is the nature of layered material in the crater walls?
- Are there any biologic or prebiogenic components in these materials?
- What are the composition and age of large ejecta blocks around the crater?

### ***Grooves*** *(Site P-2)*

**Location:** Widespread on surface, except near antipode of Stickney (~270 W)

**Geologic context:** Grooves predominantly radiate in all directions from Stickney and converge on the opposite side of the body near the Stickney antipodal point, where the surface is largely groove free. They are up to 700 m wide and 90 m deep but average 150 m wide and 15 m deep. Most of the grooves have a pitted appearance and resemble crater chains.

**Questions to be addressed at this type of site:**

- What is the nature of the grooves and pits?
- Are these linear features the result of impact fracturing?
- Are the pits the result of drainage or eruption processes?
- What is the composition of material in and around the pits and grooves?

### ***Kepler Ridge*** *(Site P-3)*

**Location:** 28-30° S lat
330-60° W long

**Geologic context:** This ridge is the top of the largest major slope on Phobos. Areas of degraded crater rims are the most likely spots to find bedrock exposures and will be the source of downslope regolith material.

**Questions to be addressed at this site:**

- Are there any "bedrock" exposures, and what are their composition and age?
- What are the texture, composition, and thickness of the regolith materials?
- How does the regolith material on Phobos migrate across the surface?
- What exogenic processes (e.g., solar radiation) have affected the regolith?

# Platform Science

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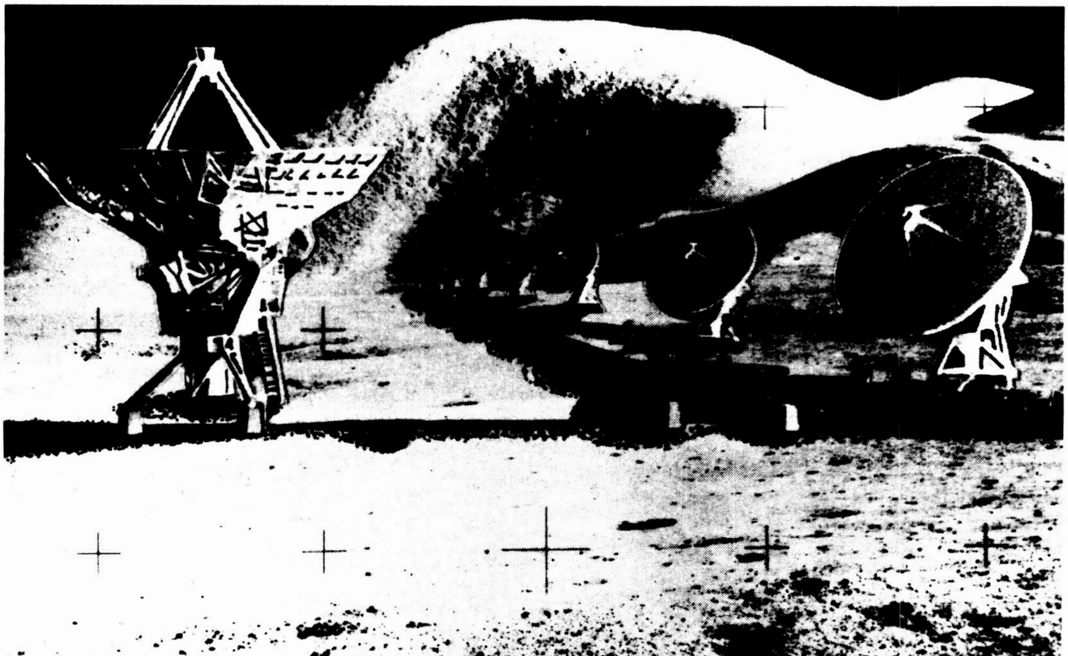
Platform science consists of scientific activities carried out on a planetary body, using the unique aspects of the body's environment for siting laboratory facilities or using the body's surface as a location for establishing observatory facilities.

## OBSERVATORIES

These are observing facilities located beyond low Earth orbit for operating outward-looking instruments that are used for astronomical techniques and for studying solar system or extrasolar system objects and phenomena. A primary location for such facilities is the Moon's surface, especially the far side and perhaps the polar regions. The Moon's absence of an atmosphere, its slow rotation rate, and its vast stable platform would open up vast new observing frequencies and allow the use of new techniques, such as long-baseline interferometers with extremely high spatial resolving power.

### Possible Types of Instruments

- Optical telescopes (EUV, UV, Vis, IR), single or arrayed.
- Imagers with high-resolution spectrometric, photometric, and polarimetric focal-plane detector systems.
- Radio telescopes (wavelengths from sub-millimetric to kilometric).
- Radar telescopes (for planetary surface mapping).
- Gamma-ray spectrometers and telescopes.
- Long-baseline interferometers (radio, optical).
- Particle detectors (cosmic rays, solar wind, solar flare particles).
- Gravity-wave detectors.
- Vector magnetograph.



***A radio astronomy facility depicted on the back side of the Moon.***

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- Soft X-ray telescope.
- Automated telescopes (for remote teleoperation).
- Micrometeorite-flux detectors.
- Laser retroreflectors (multi-site trilateration).
- Beacons (for precise ranging for planetary dynamics studies).

### Targets of Interest

- *Planetary objects:* (a) Where wavelength intervals were not previously available due to Earth-atmosphere interference, and (b) where long-term synoptic observations of time-variable phenomena are meaningful. Examples of the latter are
  - Jupiter — atmosphere, magnetosphere, torus dynamics.
  - Io — frost deposits, thermal emissions, volcanic activity level.
  - Mars — dust storm activity, cloud formation, surface frost.
  - Earth — global albedo variation, auroral activity, RF noise.
- *Sun:* high-resolution multi-wavelength, extended-duration observations to measure the onset and evolution of time-variable solar phenomena such as
  - Flares.
  - Prominences.
  - Magnetic structure.
  - Solar constant.
- *Stellar/galactic sources:*
  - Astrophysics and cosmology studies.
  - Search for extraterrestrial intelligence (SETI) (exobiology).

### Criteria for an Ideally Suitable Platform Body

- Little or no atmosphere or magnetosphere.
- No dust movement on or near the surface.
- Seismically quiet, stable ground surface.
- Radio, optical, magnetic, and plasma environments are quiet.
- Accessible and nearby.

The far side of the Moon meets all of these criteria and, as a result, has been considered to be the logical and desirable location for establishing a wide range of astronomical observatories (see appendix). The most desirable site currently identified for locating a major astronomical observatory is on the floor of Tsiolkovsky basin, a large relatively smooth-floored crater on the lunar far side.

## LABORATORIES

These are facilities on the target body that house instruments, equipment, and other operations necessary in conducting research on scientific and technical issues related to the target body and to human and robotic exploration of space. These studies will provide an understanding of space and planetary environments—particularly how to use the planet's resources—so that humans can survive and operate there. These laboratories can provide conditions that might be unavailable on the Earth or in orbit, such as reduced gravity, lack of (or reduced) atmosphere, passive radiative cooling, solar heating, availability of "unlimited" vacuum, and seismic stability. These laboratories would be part of a manned base and would be located at sites chosen for their accessibility, proximity to resources, or suitability for scientific observations or astronomical observatory facilities.

Types of laboratory investigations that could be carried out include

- Life-science experiments:
  - Radiation tolerance of animals and plants in the target environment.
  - Radiation shielding techniques using local materials.
  - Reduced-gravity effects, adaptation to fractional-g.
  - Advanced closed life-support systems.
  - Isolation endurance.
  - Work usefulness.
  - Health and safety.
  - Physical, psychological, emotional conditions.

- Studies of the effects of space environment on life-support and other equipment:
  - Space weathering and vacuum weathering.
  - Microgravity and reduced gravity.
  - Radiation.
  - Thermal variation and extremes.
- Biological laboratory studies:
  - Quarantine facilities.
  - Processing and "cleaning" of samples for return to Earth.
  - Medical and human bioscience.
  - Bioscience of self-sufficiency.
- Fields and particles research:
  - Solar flare monitoring and prediction.
  - Photochemical and photophysical effects on ionosphere and atmosphere properties.
  - Ion/plasma interactions of the Moon with Earth's magnetosphere.
- Lunar and martian materials science and engineering studies:
  - Shelter design and life-support systems research.
  - Controlled ecology systems studies.
  - Resource beneficiation and utilization (also on Phobos/asteroid).
  - Crystal growth and materials processing.
  - Dust mobility and contamination studies (also on Phobos/asteroid).
  - *In situ* rock, soil, and regolith mechanics (also on Phobos/asteroid).
  - Power system research.
  - Atmospheric modification studies.
- Physics and astrophysics research:
  - Gravity waves and relativity.
  - Proton decay.
  - Fluid mechanics.
  - Fifth force.
  - Sputtering and electrostatics.
  - Neutrino studies.

# Cruise Science *(En route to the Moon, Mars, Phobos, and an Asteroid)*

Cruise science consists of human scientific activity carried out on board a spacecraft during the cruise or transit phases of a mission—on both the outbound leg from and return leg to Earth. Cruise science could also include observations made during orbital stages of the mission. The presence of humans during these observations either enhances or enables the scientific investigations, ensuring that measurements are made properly and are analyzed and interpreted, to a great extent, in real time.

## TELESCOPIC OBSERVATIONS

Observations of various phenomena will be made at gamma ray, X-ray, UV, Vis, IR, and radio wavelengths. Targets of interest include

- Solar observations:
  - Flares (brightness, location, duration, particle flux and radio energy).
  - Prominences (structure, stability, size, and plasma temperature).
- Magnetic structure and fluxes.
- Planetary objects (where extended-duration observation is meaningful).
  - Surface activity (e.g., dust clouds on Mars, volcanism on Io).
  - Atmospheric dynamics (cloud structure, wind patterns).
  - Ionosphere structure.
  - Magnetosphere structure (planetary rotation dynamics).
  - Extended atmospheres (e.g., Na and K clouds at Io, the Moon, and Mercury).
  - Rings (structure, dynamics).
- Extrasolar system (galactic and extragalactic) objects.

***A manned-mission spacecraft conducting scientific observations en route to Mars.***

## FIELDS AND PARTICLES STUDIES

A study of the radiation environment along the cruise route would include

- Magnetic fields (strength, orientation).
- Solar wind (velocity, direction, composition).
- Cosmic-rays and gamma-ray bursts, X-ray bursts (energy, flux, direction).
- Dust particles (flux, composition, mass, size).

## HUMAN FACTORS STUDIES

- Radiation events and dose monitoring (solar flares, cosmic rays).
- Microgravity and artificial gravity effects.
- Physiology, psychology, and health maintenance.
- Life-support systems.

# Primary Precursor Science Requirements

Many of the detailed precursor requirements for human scientific activities have been outlined in the corresponding sections. The principal unmanned precursor missions that would be useful in safely planning and carrying out subsequent human missions to the target bodies are summarized below.

**Global and Regional Surface Maps for the Moon and Mars.** These surveys provide fundamental data that can be used to plan missions and further scientific work in areas with expected human accessibility; they also provide a coherent context in which the local and regional data can be understood. Types of data needed include

- Imagery (broadband at optimal sun angles, resolution of <1m/pixel).
- Multispectral data (VIMS; high sun angle, resolution of ~50–100 m/pixel).
- Elemental (GRS or XGRS) to spatial resolution of <100 km.
- Topography (vertical resolution of <1 m).
- Global gravity field (especially lunar far side, accuracy to 1 mgal).
- Magnetic field strength and lateral variation (accuracy to <0.1 nT).
- Radiation flux at all energies at surface and various atmosphere levels.
- Near-subsurface structure and regolith properties.

**Martian Surface Sample Return.** This is primarily a safety and hazards-mitigation requirement. The possible short- and long-term effects that martian soil might have on both humans and materials need to be understood. The martian surface would be studied for its toxicity, corrosive potential, possible biological organisms and back-contamination issues, and soil character (assessing potential plant growth and agriculture uses at a martian base).

Return samples would also have great scientific value in providing timely ground-truth information on chemical and mineralogical composition of surface materials that would allow calibration of remote-sensing data sets obtained from Earth and from Viking and Mars Observer missions. Radiometric ages of returned rocks would peg the age scale of the stratigraphic relations of the martian surface and allow much more accurate interpretation of global geologic and climatic history. This information would aid in choosing the safest and most scientifically fruitful landing sites for human-crewed missions to explore the martian surface.

**Better Knowledge of Ionospheric Properties Near the Lunar Surface.** This information is needed to assess and certify the lunar surface environment (sky) as a location for low-frequency radio telescope observatories. Measurements needed are

- Global and near-surface values of electron and proton density: monthly temporal variations.
- Dayside/nightside variations; near side/far side variations.
- Low frequency all-sky survey of planetary or other radio sources.

**Pre-lunar Base or Outpost Measurements of Lunar Atmosphere.** An understanding of the present (post-Apollo) natural lunar atmosphere should be acquired before future human activities alter its mass and composition. These measurements will provide basic data necessary for scientific work, will provide a baseline of information for considering the effects of this very tenuous atmosphere on instrumentation and equipment, will allow study of global-to-local composition, structure, temporal variations, and will provide contingency samples of the pre-human, pristine condition of the lunar environment.

**Martian Atmosphere.** A precise characterization and an understanding of the martian atmosphere are necessary primarily as precursors to human missions—not just for scientific purposes. This information is needed in order to design safe surface human operations and to carry out powered (descent) and unpowered (aerobraking) flight through the atmosphere. Although the two Viking landers provided atmospheric data, those data sets represent only two surface stations which operated for only a few years.

Data for the upper atmosphere are limited to information collected during the two Viking lander descents. Additional data should be collected using weather-monitoring stations, which consist of surface stations at a range of latitudes from north to south and orbital-imaging spacecraft for cloud motion and IR-radiometer sounding. These stations should operate for at least two martian years prior to arrival of human missions.

Specific measurements to be taken include vertical profiles of temperature, pressure, dust, and winds for diurnal, seasonal, and multi-year time scales.

**Asteroid Studies.** Prior to human expeditions, a detailed assessment of the target asteroid's environment must be made in order to plan the mission (in terms of safety and operations) and to enhance the scientific return. Additionally, if asteroids are considered potential resources, it is important to obtain by remote-sensing means as much information as possible on their composition before sending humans to one of these bodies.

The fact that an asteroid is a small body does not decrease the level of scientific understanding necessary to carry out a successful science mission vis-à-vis a full-size planet, such as the Moon or Mars. However, the engineering and other systems requirements for human exploration missions to either small bodies or large bodies may be quite different for each case.

Precursor studies of asteroids should include investigations that are designed to assess the mass, shape, topography, compositional heterogeneity, and surface activity level of the body. These studies should also determine the characteristics of a regolith and whether dust clouds are associated with these bodies. It is hoped that there will also be unmanned reconnaissance surveys of at least one mainbelt or Earth-crossing asteroid prior to any manned mission (e.g., as is planned for the Galileo flybys of Gaspra and Ida—two S-type mainbelt asteroids—in 1991 and 1993).

**Phobos or Deimos.** An unmanned reconnaissance mission should be conducted at the two martian satellites in order to obtain global surface maps of composition and structures (like those data sets for the Moon and Mars) and to determine properties of the surface regolith, or dust layer, and interior structure.

**Human Factors Research.** It is essential to know how to establish and maintain proper human-machine interactions in order to exploit exploration opportunities on extended human-crewed missions. We must know how to maintain human health and strength during long missions to Mars, Phobos, or the Moon, and we must know how to enable scientists to function effectively in target or cruise environments with the requisite habitats, tools, and equipment.

# Section 2

# Specific Science for Designated Planetary Bodies

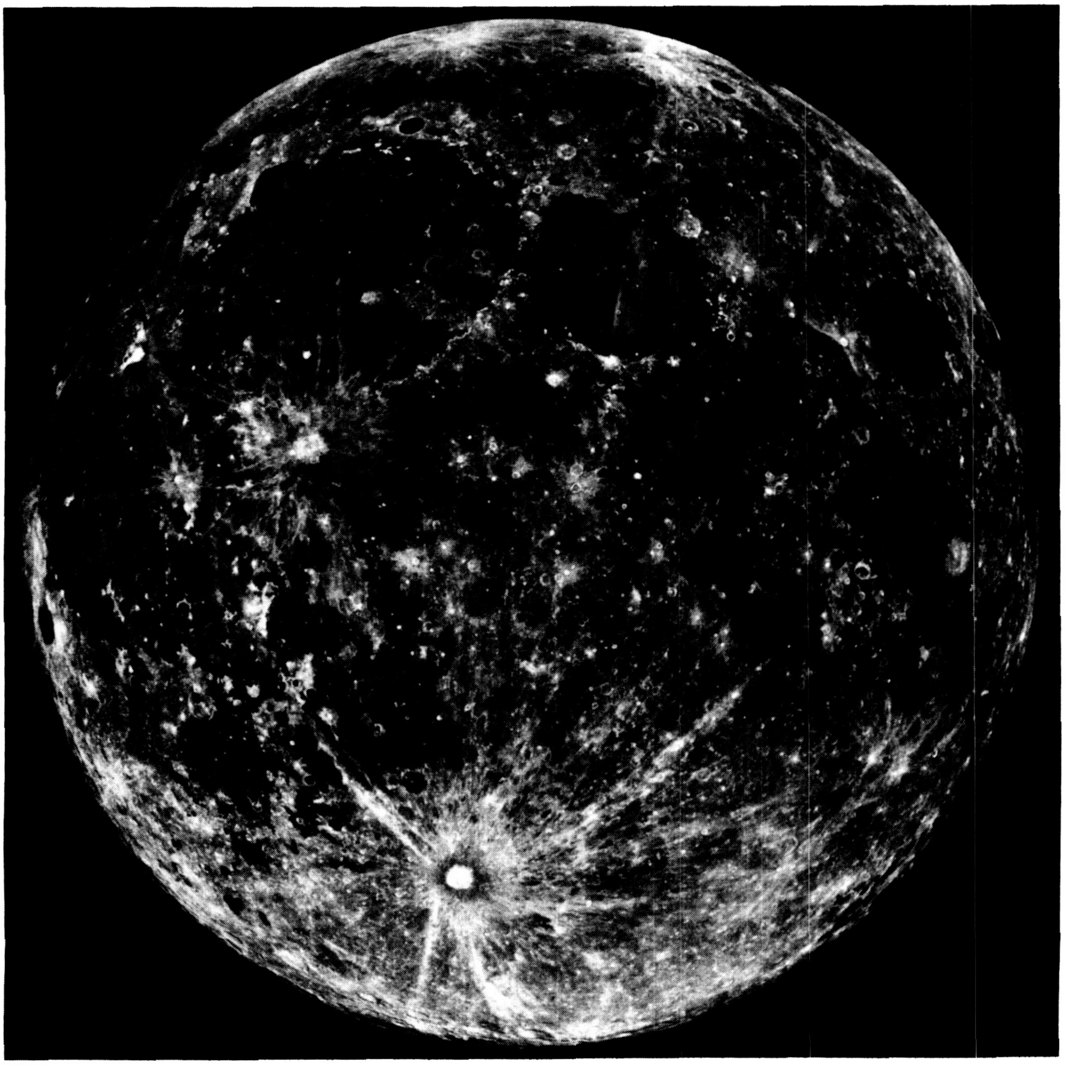
# Moon

## LUNAR SCIENCE OPPORTUNITIES SUMMARY

The tasks summarized below are investigations that are enabled or enhanced by the presence of humans and that should be carried out by humans in the early post-Apollo missions to the Moon. In many cases, it is not merely the ability of a human to carry out a task that makes it desirable, but rather the versatility, rapidity, and interactive ability of a human that significantly increases the potential scientific return. Depending on the specific mission profile chosen, the following task recommendations would be subject to change.

### Lunar Target Science Investigations

- Lunar geological/geophysical studies:
  - Carry out site-intensive science investigations to study
    - Soil, rock, regolith particle-size distribution, structural relations, and rock mechanics.
    - Composition and age of collected samples.
    - Subsurface properties; composition, stratigraphy.
    - Surface physical properties.



*Telescopic photograph of a full Moon.*

    - Erosion phenomena (micrometeorites, sputtering).
    - Dust mobility (electrostatic, ballistic).
    - Cosmic-ray penetration (profiles with depth).
  - Conduct traverse science to provide regional ground truth for orbital data by
    - Sampling at local sites on traverse route (coring and trenching).
    - Mapping (detailed rock unit boundaries and structure).
    - Carrying out geophysical surveys (magnetic, gravity, seismic, radar, and EM).
  - Set up network science system (installation of surface-monitoring stations) to determine
    - Seismicity (short- and long-period event sensitivity).
    - Heat flow.
    - Atmospheric volatiles.
    - Solar wind flux (incident at surface).
  - Investigate impact cratering history for
    - Age distribution of lunar craters.
    - Relation to mass extinctions on Earth.
- Lunar atmosphere studies of neutral atoms and ions (density and distribution):
  - Diurnal or other short-term variations.
  - Long-term temporal variations (effects of human activity).
- Lunar fields and particles studies:
  - Surface magnetic field measurements and spatial variation.
  - Solar wind and electron impact flux (spatial and temporal variation).
- Candidate landing sites for manned science exploration on the Moon (see details on pages 11-13):
  - Copernicus crater (L-1).
  - Aristarchus Plateau (L-2).
  - Appenine Bench (L-3).
  - Northeast Orientale Basin (L-4).
  - Tsiolkovsky basin (L-5).
  - Peary Crater (north polar site) (L-6).

### Lunar Platform Science Investigations

- Lunar laboratory studies:
  - Biological effects of radiation and dust in the long-term lunar environment.
  - Human performance factors associated with reduced-gravity environment (physiological effects and human-machine interactions).
  - Geological materials studies (e.g., low-g, high P-T petrology) in support of target science.
  - Geological engineering:
    - Materials processing test bed.
    - Mining operations demonstrations (for oxygen, helium extraction) and environmental impact assessments (e.g., atmosphere and dust effects on optical equipment).
    - Lunar materials science.
    - History of ancient sun (from soil and regolith core samples).
  - Physics laboratories to study
    - Proton decay.
    - Relativity.
    - Fluid mechanics.
    - Fifth force.
- Lunar observatory activities:
  - Astronomical/astrophysical (gamma ray to radio wavelengths)
    - Site selection and certification
      - for single telescopes and detectors.
      - for arrayed telescopes.
      - for long-baseline interferometer arrays.
  - Earth observations (hemispherical contemporaneous data sets):
    - Albedo, global energy balance.
    - Meteorology.
    - Atmosphere.
    - Oceanography.
    - Aurorae.
    - Global magnetosphere.

### Lunar Cruise Science Investigations

None are recommended here due to short trip times (2-3 days), but solar flare particle warning measures should be taken during cruise.

## LUNAR STRAWMAN PAYLOADS
*(For Manned Missions)*

The strawman payload list provides a comprehensive suite of instruments and tools that would be necessary to carry out the scientific objectives noted above. It is presumed, however, that these objectives could not all be achieved on a single mission at a single site but would be accomplished during a long-range exploration program at several sites. Depending on the landing site and the mission objectives, the list of payload items for that mission would have to be modified to accomplish the relevant studies planned for the mission. The scientific payload would generally include instruments, tools, vehicles, self-contained laboratory modules, and related apparatus. The following list of payload items includes equipment necessary to address the scientific objectives (listed above) from a manned outpost or base.

### Lunar Target Science Payloads

- Geological and geophysical field science equipment:
  - Sampling tools for dislodging, acquiring, and stowing rock and soil samples (grabbers or tongs for handling solid rocks, rakes for 1- to 4-cm rock fragments, shovel or scoop for soil and bulk regolith samples).
  - Coring tools to obtain cores 5 cm diameter, 10 m deep in regolith; 2 cm diameter, 1 m deep in solid rock.
  - Trenching rig for digging trenches and burying equipment.
  - Major sieving operation system to prepare separated samples of loose material.
  - Vehicle:
    - Range ≥ 500 km.
    - Pressurized.
    - Holds 3 to 4 people.
    - Adaptable arm (backhoe, crane, sample stowage, etc.).
  - Portable geophysical instrument packages containing magnetometer, gravimeter, active seismic array, radar/EM sounder, corner-cube retroflectors.
  - Multispectral imager with close-up and telescopic capability.
  - Elemental analysis spectrometers (X-ray, gamma ray, neutron activation).
- Base science equipment:
  - Seismometer (pier mounted, short- and long-period sensitivity).
  - Local vehicles for excavation and transport.
  - Soil mechanics testers.
  - Electrical/thermal properties analyzers.
  - Dust collectors and mobility analyzers.
  - Sample packaging equipment for transporting samples to Earth.
  - Radiation counters.
  - Cameras.
  - Telescope (small, with accessories for image and spectra observations in the visible and infrared).
  - Computers for equipment control and data processing.
  - Analytical lab (elemental, mineralogical, particle/grain size).
    - Electron microscopes (SEM, TEM, microprobe).
    - Optical microscopes (petrographic, binocular).
    - Thin-sectioning equipment.
    - X-ray diffractometer.
    - X-ray fluorescence spectrometer.
    - UV/Vis/IR spectrometer.
  - Network (e.g., charged particle detectors, heat flow) central node.
- Atmospheric studies payload:
  - Mass spectrometer.
  - Ion detector.
  - Microwave and radiowave radiometers.
- Fields and particles studies equipment:
  - Solar wind spectrometer.
  - Magnetometer.
  - Electron reflectometer.

### Lunar Platform Science Payloads

- Laboratories:
  - Self-contained laboratory modules (selected from lunar platform science investigations; see page 30).
- Observatories:
  - UV/Visible telescope, modest aperture, high resolution.

- IR telescope, aperture >2 m, with surface dust and solar radiation shields.
- Vis interferometer array, >9 apertures on 10-km circle, 2-m mirrors.
- Radio telescope array; interferometric, laid wire form.
- Vector magnetograph.
- Soft X-ray telescope.

### Lunar Cruise Science Payload

- Flare monitoring detectors and particle arrival warnings.

## LUNAR PRECURSORS

*(To Human Missions)*

Prior to embarking on a human mission to the Moon (to establish a base, an outpost, or an observatory), precursor scientific data would greatly enhance the planning and successful operation of the mission. Although a simple return to the Moon (like an Apollo mission) would not require additional information, the establishment of a long-term base or observatory there would require additional data to ensure an optimum location.

Depending on the nature of the mission, the following types of precursor data would be required.

### To Enhance Lunar Target Science

- Global surface maps of imaging, topography, gravity, and composition data.
- Geophysical net installation data from landed probes or surface penetrators.
- Teleoperated rover(s) to survey local sites and recover samples.

### To Enhance Lunar Platform Science

- Seismic stability assessment data.
- Surface and atmospheric dust and ionospheric plasma levels assessment.

## LUNAR PRIORITIES

The following list prioritizes the possible lunar scientific objectives for the first or early (post-Apollo) human exploration activities on the Moon.

### For Lunar Target Science

- Surface traverses (EVA's) with sampling, local site analysis, and sample return.
- Resource assessment survey and mining and oxygen extraction tests.
- Installation of global geophysical network to assess global geophysical properties.

### For Lunar Platform Science

- *In situ* human performance and instrument functionality tests; certification for extended staytimes.
- Lunar environment protection measures.
- Astronomical/astrophysical observatory environment assessment (optical, radio) and initial equipment installation and operation for certifying Moon as an observatory site.
- Determine lunar support requirements for transition between zero and 1/6 g.

### For Lunar Cruise Science

- Solar flare monitoring.

***Depiction of astronauts exploring lunar surface using long-range mobile vehicle system.***

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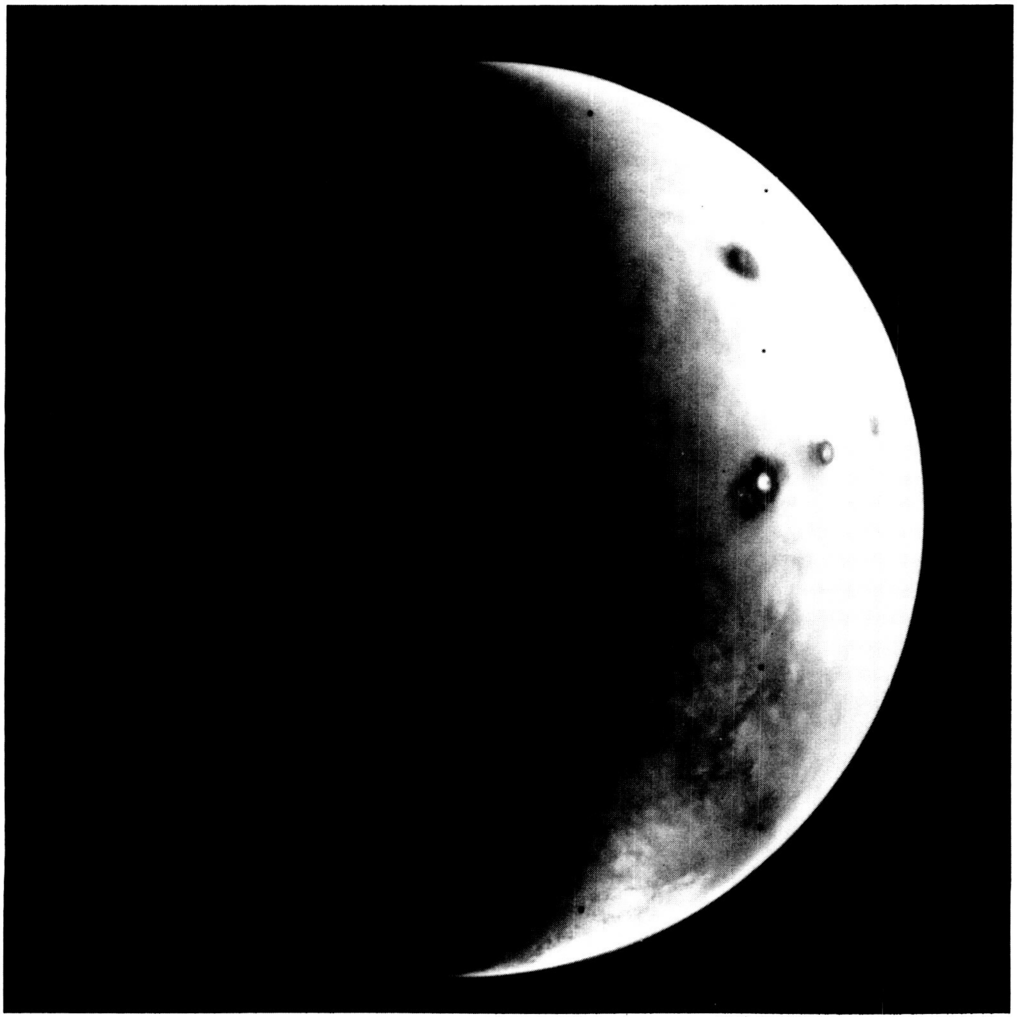
# Mars

## MARS SCIENCE OPPORTUNITIES SUMMARY

The activities summarized in this section are potential scientific investigations on Mars that would be enabled or significantly enhanced by the presence of humans. In most of the investigation cases, it is not merely the ability of a human to carry out the science tasks with the aid of robotic instruments that makes human involvement desirable but rather the versatility, rapidity, and interactive ability of a human that significantly increases the potential scientific return. Human explorers, for example, can take advantage of scientific or environmental surprises and adapt to them; they can also ensure that instruments operate successfully under unanticipated conditions.

### Mars Target Science Investigations

- Geological and geophysical studies, including mapping and sample collection:
  - Reconnaissance surveys, traverse mode, network installation, resource assessments.
  - Site-intensive studies, detailed rock chemistry and mineralogy; age and structure analysis with *in situ* lab support.
- Exobiological studies:
  - Search for oldest exposed sedimentary deposits.
  - Search for evidence of present or past life.
  - Search for organic compounds.



***Mars as seen during the approach to the planet. The four large Tharsis volcanoes are the dark spots visible on the lighted face.***

  - Elucidation of oxidants in martian soil or rocks.
  - Surveys for biogenic elements (C, N, P, O, S, H).
- Atmosphere and ionosphere studies:
  - Composition and structure of atmosphere.
  - Diurnal and seasonal variations.
  - Weather, clouds, and dust storms monitoring at multi-latitude sites.
  - Surface/atmosphere interactions.
  - Ionosphere composition and structure; interactions with magnetic field and solar wind.
- Resource acquisition and utilization studies.
- Candidate landing sites for target science (see details on pages 14-16):
  - Terra Tyrrhena (mid-south latitude, moderate elevation) (M-1).
  - Xanthe Terra (low northern equatorial latitude, low elevation) (M-2).
  - Tharsis Montes (equator, high elevation) (M-3).
  - Western Daedalia Planum (mid-south latitude, moderate elevation) (M-4).
  - Planum Boreum (north pole) (M-5).
  - Candor Chasma (Valles Marineris) (M-6).
  - Chasma Australe (south pole) (M-7).

### Mars Platform Science

- Surface environmental studies:
  - Weather and climate effects on human activities and facilities.
  - Human performance research.
  - Resource-utilization studies.
- Observations of Phobos and Deimos:
  - Orbital dynamics.
  - Librations (for moment of inertia and internal mass distribution).

### Mars Cruise Science

- Solar observations (solar wind plasma, solar magnetography).
- Interplanetary dust detection, collection, and analysis.
- Cosmic-ray detection; gamma-ray and X-ray burst detection.
- Optical, IR, UV astronomy, astrophysics.
- Biomedical studies:
  - Radiation effects.
  - Microgravity effects.
  - Physiological/psychological studies.

## MARS STRAWMAN PAYLOADS

*(For Manned Missions)*

The strawman payload list provides a complete suite of instruments and tools that would be needed to carry out all of the scientific objectives noted above. As in the case for the Moon (depending on the landing site and mission profile for a given Mars mission profile), the payload list would be modified to accomplish the intended studies. A possible sequence of three missions to Mars and corresponding science payloads are shown in Table 2 (page 56). A more detailed list of payload items for any major Mars mission is given below.

### Mars Target Science Payloads

- For exobiological studies:
  - Subsurface sampling equipment.
  - Gas Chromatograph/mass Spectrometer.
  - Scanning electron microscope.
  - Microbiology lab.
  - Chemistry lab.
  - Differential scanning calorimeter and evolved gas analyzer.
- For geological studies (see lunar payload, page 31, for more details):
  - Cameras.
  - Navigation equipment.
  - Subsurface drilling and sampling equipment.
  - Geophysical traverse sounding and network equipment.
  - Vehicles, hand tools, and sample containers.
  - Elemental and molecular analysis equipment (XRD, XRF).
- For atmosphere studies:
  - GCMS, LIDAR, IR radiometer.
  - Weather station (plus mini-stations deployable at multiple sites).
  - Water-vapor detector.
  - Dust collection array.

- For fields and particles studies:
    - Energetic particle detector and mass spectrometer.
    - Magnetometer.
    - X-ray monitor.
    - Cosmic-ray detector.
    - Ionospheric sounder.
- For material science studies:
    - Material stability test equipment.
    - Soil testing and agricultural experiment equipment.

### Mars Platform Science Payloads

- Microbiological laboratory.
- Contamination, sterilization, and sample preparation laboratory.
- Geological laboratory (see lunar payloads, page 31, for more details).
- Weather-monitoring equipment.
- Human safety/toxicity lab equipment.

### Mars Cruise Science Payloads

- X-ray, ultraviolet, visible, and infrared telescopes.
- Magnetometer.
- Particle detectors and mass spectrometers (solar wind, flares, cosmic rays).
- Gamma-ray and X-ray burst detector.
- Radio interferometer.
- Cosmic dust detector and collector.
- Biomedical studies equipment (physiology/ psychology laboratory).

## MARS PRECURSORS

*(To Human Missions)*

Prior to embarking on a human mission to Mars (for establishing either a manned base or an outpost), the acquisition of certain priority knowledge and data would significantly enhance the planning and successful operation of the mission and might decrease the overall cost. Even a simple Apollo-style mission to Mars would require information beyond what can be obtained by the unmanned missions currently planned such as the Mars Observer. Placing a long-term base or outpost on Mars would certainly require additional data (especially high-resolution imaging) if an optimum location is desired. Therefore, depending on the nature of the Mars mission, the following types of precursor data would be required.

### To Enable a Safe Manned Mission to Mars

- Quarantine and analysis confidence to relieve back-contamination issue.
- Sample return for toxicity assessment.
- Radiation environment assessment.

### To Enable or Enhance Mars Surface Science

- High-resolution imaging of candidate landing sites.
- Global maps of surface composition.
- Surface sampling and sample return.
- Global, regional, and local weather data.
- Global seismicity level.

### To Enhance Mars Platform Science

- Global weather information (from orbiting satellites).
- Surface weather stations at multi-latitude sites (north and south).
- Earth-based Mars exobiology studies.
- Mars and lunar resource utilization studies.

### To Enhance Mars Cruise Science

- Lunar and space station studies on human-performance factors (including psychological, behavioral, and biomedical issues) and life-support systems.
- Instrument development for long-term, human-tended measurements and observations from a manned spacecraft in interplanetary space.

## MARS PRIORITIES

The following list identifies the priorities for initial Mars human exploration science objectives.

### For Mars Target Science

- Detailed surface regolith and rock compositions and radiometric ages studies.
- Exobiology studies (search for present or extinct life forms, prebiotic organic chemistry; characterization of current and ancient surface conditions).
- Laboratory for detailed paleontology (ancient life) studies.
- Resource assessment for self-sufficiency in life-support items, (fuel, etc.).
- Global geophysical assessment.
- Atmosphere/meteorological assessment.
- Radiation environment assessment.

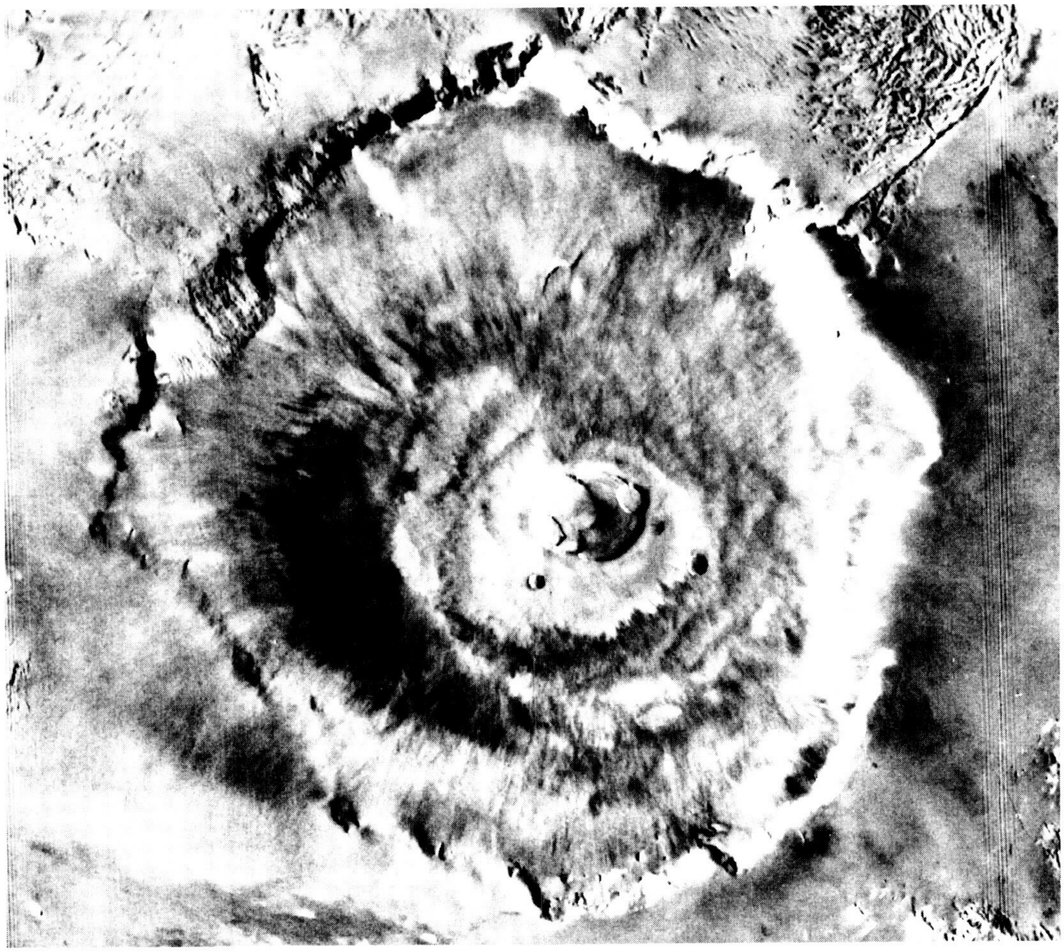
### For Mars Platform Science

- Environmental protection measures.
- Facilities on Mars to eliminate fore- or back-contamination of organisms.

### For Mars Cruise Science

- Long-term continuous observations (select objectives from generic list, pages 23-24).
- Maximum observing sensitivity and monitoring of time-variable phenomena.

*Olympus Mons, the largest volcano in the solar system.*



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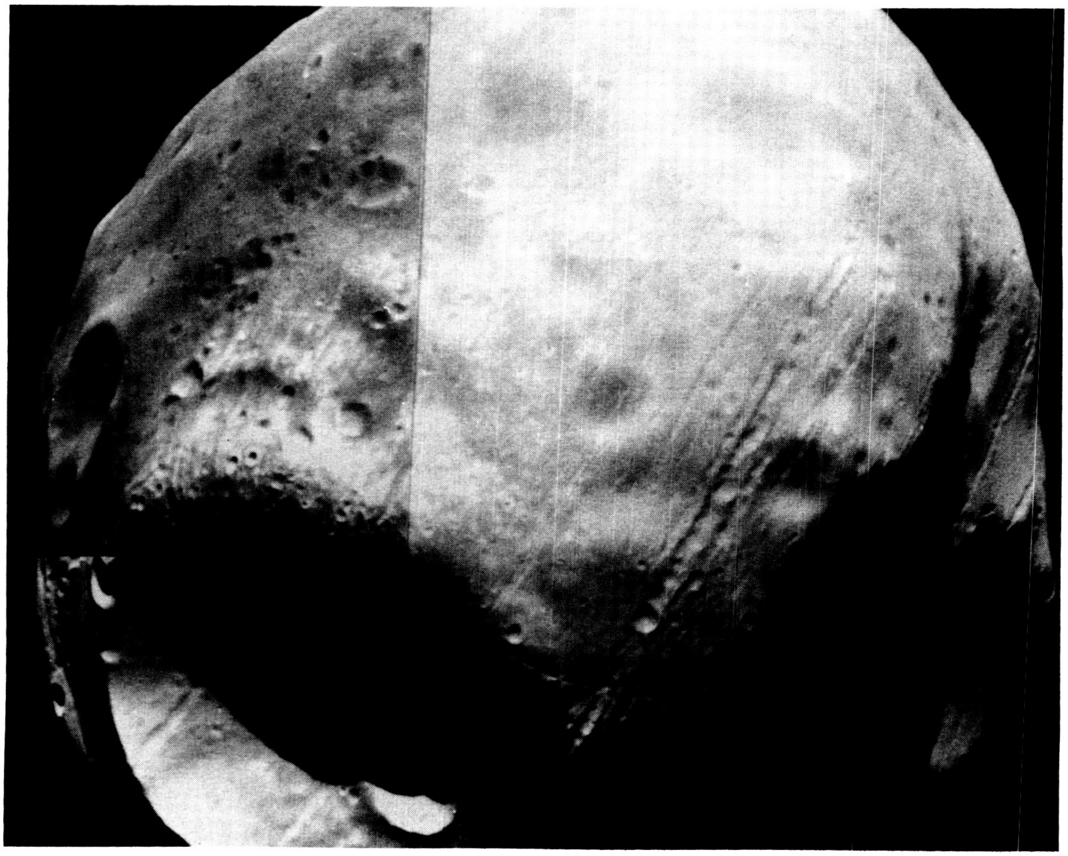
# Small Bodies *(Phobos, Deimos, and an Asteroid)*

## SMALL BODIES SCIENCE OPPORTUNITIES SUMMARY

In this study the martian satellites Phobos and Deimos are considered similar in characteristics to asteroids, especially the C-class mainbelt asteroids, which are thought to be compositionally like carbonaceous chondrite meteorites. The less-abundant Earth-crossing asteroids are more similar in size and mass to the Mars moons and are likely to be the target of any plausible human exploration mission to an asteroid because they are more accessible. The martian moons and typical asteroids are small, rocky bodies that have very low gravity (~0.01 g) and no atmosphere, are irregular in shape, have a low albedo surface layer composed of fragmental regolith material, and may have fine-scale (centimeter to decimeter) roughness smoother than that of the Moon.

### Target Science Investigations

- Geological studies (details are the same as for the Moon).
- Atmosphere studies:
  - Water-vapor flux from interior of body.
  - Solar wind equilibration atmosphere (exosphere) at surface.
- Fields and particles studies (solar wind interaction).
- Resource assessment studies (especially water or organic molecules).
- Exobiologic studies (search for organics, biogenic elements, volatiles).
- Candidate sites for surface examination (example for Phobos):
  - Large impact crater and ejecta blanket (Stickney Crater).
  - Grooves and pits terrain.
  - Ridges (Kepler Ridge).



***Phobos, one of the martian moons.***

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### Platform Science

- Use small body as parent-body or as interplanetary gravity-dynamics probe and fields and particles probe.
- Implant or install scientific beacons, transponders, radiation or charged particle detectors, and dust detectors on the body.
- Use small body as a site for piggybacking instruments to distant parts of the solar system for long-term exposure to low-g, zero-atmosphere conditions.

### Cruise Science

Same objectives as for Mars case (page 36).

## SMALL BODY MISSION STRAWMAN PAYLOADS

*(For Human Crews)*

### Target Science Payloads

- Remote activities:
  - Telerobotic surface lander and sampler.
  - Elemental and chemical analytical equipment (XRF, alpha-scatter spectrometer, VIMS, DSC/EGA).
  - Penetrometer, acoustic probe, and radar/EM sounder.
- Lander and crew EVA activity:
  - Cameras.
  - Hand-held compositional spectrometers (Vis/IR, XRF).
  - Sample acquisition and storage equipment.

### Platform Science Payloads

- Beacons or transponders for mounting on body in at least two points.
- Fields and particles detector package.
- Automated solar telescope (for extended duration solar flare monitor).

### Cruise Science Payloads

Same as for Mars case (page 37).

## PRECURSORS TO SMALL BODY MISSIONS

*(By Human Crews)*

### To Enhance Target Science

- Extensive ground-based study of Earth-crossing asteroids to
  - Determine size, composition, and heterogeneity.
  - Assess resource potential.
  - Determine orbital elements.
  - Assess thermophysical properties (to estimate surface roughness and bearing strength).
  - Determine radar scattering properties.
- Unmanned flyby/rendezvous/lander survey (by Soviet or U.S. Galileo and CRAF missions).
- Robotic probe to surface of the body.

### To Enhance Platform Science

None.

### To Enhance Cruise Science

Same as for Mars (page 37).

## PRIORITIES FOR FIRST SMALL BODY MISSIONS

### For Target Science

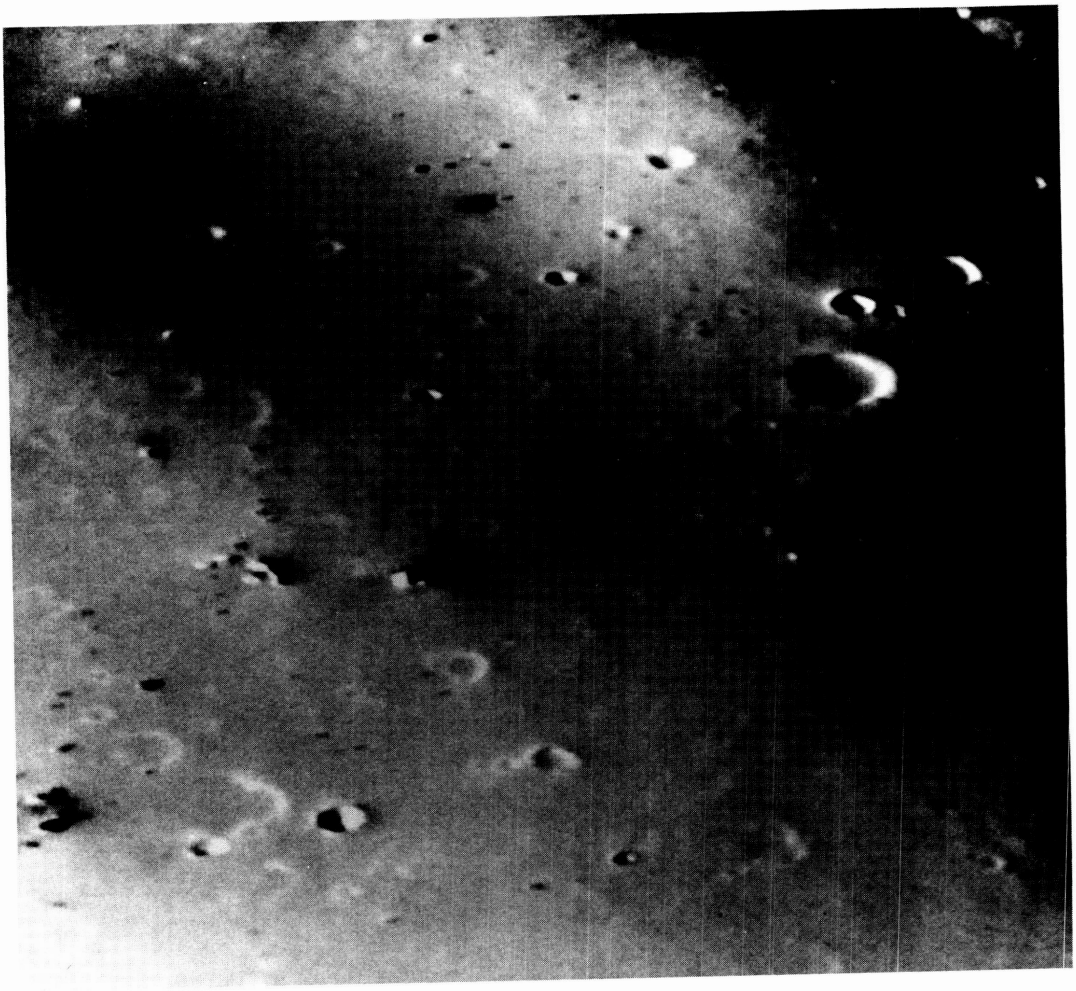
- Surface composition and heterogeneity.
- Resource assessment.
- Bulk geophysical properties.

### For Platform Science

- Install scientific beacon(s) or transponder(s) for precise ranging.
- Install fields and particles detectors.

### For Cruise Science

Same as for Mars (page 38).



*The rock-strewn surface of Deimos.*

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# Conclusions

As a result of conducting this study and preparing this report, we draw the following conclusions:

1. There are a wide variety of exploration opportunities for humans working in virtually all physical and biological science disciplines (see Table 3). If these explorations are carried out, they can contribute greatly to the success of manned missions to planetary targets in the solar system beyond Earth orbit.

2. The arrangement of dividing potential science exploration activities into the categories of *target science*, *platform science*, and *cruise science* has provided an effective and comprehensive framework for organizing these activities, and it covers virtually all possibilities for exploration opportunities in science and related technical areas.

3. Most target science objectives and payloads for all target bodies are identical, with some variation required for bodies having atmospheres, possible exobiology attributes, and differences in resource potential.

4. Cruise science objectives are, likewise, similar for various missions with differences only in the duration of the cruise periods and perhaps the number of persons in the transit crew.

5. Platform science activities will vary considerably due to the proximity and size (and thus surface gravity) of the planetary target body. The principal site (other than Earth orbit) for major platform science activities, such as astronomical observatories, is the surface of the Moon.

6. Most instruments and techniques for planetary science exploration have general application to all planetary targets. They are virtually identical in principle and objectives to those used for unmanned planetary and manned Earth-science investigations, with variations due only to a need for the instruments to be operable and serviceable *in situ* by humans.

7. It is essential that additional, detailed science planning studies be conducted for each target body in order to refine the exploration opportunity information presented here (and summarized in Table 3). In future studies, emphasis should be on determining more focused exploration priorities, specific mission sequences, specific landing sites and traverse routes, detailed payloads, and operational objectives. In addition, the cruise science and platform science activities should be delineated in greater detail with priorities and exploration objectives firmly established. Future studies should also include separate treatments of target resource exploration and assessments and technology development issues.

8. Precursor robotic missions, including Mars sample return and lunar global compositional and structural mapping, are essential in paving the way for human exploration missions that could establish and accommodate permanent human presence on a target body. These robotic precursors are important in order (a) to reduce the chance of missing major scientific, environmental, or resource discoveries because pre-mission preparation was incomplete and landing site selection was not optimum; (b) to minimize dangerous or hazardous situations for the human crew; (c) to alleviate concerns over possible harmful effects of back-contamination of Earth; and (d) to maximize the exploration opportunities and efficiency of the human-crewed missions.

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# Appendix. The Moon as a Scientific Platform

## LUNAR OBSERVATORY SITES

The Moon has long been recognized as an ideal place to conduct certain astronomical and astrophysical observations in order to avoid problems created by various natural and man-made noise phenomena on Earth.

### *Characteristics of the Moon as an observatory platform:*

- Proximity to Earth.
- Ease of access.
- Ease of communication.
- Possible resources available (shelter, shielding, water, oxygen, hydrogen).
- Clear, dark skies.
- No atmosphere ($<10^{-12}$ torr).
- No winds (collisionless gas, ~ $10^5$ molecules/ $cm^3$).
- No dust in sky (except possibly at sunset and sunrise).
- No scattered light (?).
- No plasma except solar wind (unknown at surface?).
- No global magnetic field; only local remanent fields.
- Transits Earth magnetotail periodically (monthly).
- Seismically quiet (magnitude 1-2 quakes), stable point platform.
- Radio quiet (on far side and in polar craters).
- Cold (passive cooling) (100 K nights, <70 K polar craters).
- Long observation times without sunlight (lunar night = 14 Earth days).
    - Radio – continuous on far side and in polar crater.
    - Optical – 14 days on near and far side; continuous in polar crater.
    - Solar shields – no limit on observing times.
- Thermal extremes in non-polar regions (100 to 400 K).
- Significant micrometeoritic flux.
- Costly installation and operation compared to that on Earth.

### *Requirements (to implement lunar observatories):*

- Capability to erect single and multiple large-area antennas or detectors over baselines tens of kilometers in length.
- Capability to erect medium- and large-aperture optical telescopes (with photometric and spectrometric detector focal-plane systems).
- Capability to reach (and return from) virtually any selected point on surface (polar and equatorial) with crews, habitation facility, observatory components, and operational equipment and supplies.
- Capability to communicate (via satellite net?) between observatory and base or outpost site and among site, main base or outpost, and Earth. Broad bandwidth capability required (up to gigahertz).

### *Plausible stages of development of lunar observatory:*

- Pioneering—survival facilities, simple instruments and equipment for site testing, instrument installation, and certification. Install and leave robotic stations. Example facilities:
    - Large, very-low-frequency radio interferometer; tiny wire elements laid on surface and connected to computer and telecommunication system.
    - Small telescopes for long-term stellar seismology observations.
    - 3-meter-diameter IR cryogenic (cooled) antenna system.
    - UV/optical interferometer with kilometer scale baseline.
- Settlement—install relatively substantial facility with all components brought from Earth. *In situ* operation. Example facility:
    - Multiple telescope sites remote from base.
- Mature base—large facilities, some local manufacturing using local resources such as

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glass for mirrors, rocks for foundations and shielding. Example facilities:
  - Radio interferometers (large, partially filled aperture arrays) with 100 km baseline.
  - Optical interferometers with 10 km baseline.
- Permanent observatory—substantial facilities and near self-sufficiency. Example facilities:
  - Multiple Arecibo-type antennas in natural craters or canyons.
  - Low-noise radio telescope for scientific observations or search for extraterrestrial intelligence (SETI).

### *Summary of suggested observatories on the Moon:*

- Very large, very-low-frequency radio interferometers; 10–100 km baselines, using short-wires-array antenna, 10–100 m wavelength.
- Small, lightweight optical telescopes for stellar seismology.
- 3-meter-class cryogenic IR/submillimeter antenna system.
- UV/optical interferometer with kilometer-scale baseline.
- X-ray (0.2 – 100 keV) and gamma ray ($10^{-1}$–$10^4$ GeV);
  - Large aperture (~$10^5$ cm$^2$).
  - Long focal length, high resolution.
  - Broad sky coverage.
- Cosmic-ray detectors (>1 TeV).
- Astrometric telescopes.
- All-sky UV optical survey telescopes.
- Solar/stellar monitors, long term.
- Very large interferometric array optical facilities (optical VLA);
  - Net collecting areas of 20–30 m$^2$.
  - Array size ~10 km.
  - Angular resolution of 1–10 microarcsec.
  - Wavelength range 121 nm (Ly-alpha) to 5 mm.
  - Total of 27 telescopes, ~200 kg each.
- IR telescope(s), single and arrayed.
- Very large Arecibo-type radio telescope arrays using crater or valley wall as structure.
- Ultra-long-baseline Moon-Earth radio interferometer.
  - Baseline ~5 x $10^5$ km, 10-300 GHz.
  - Angular resolution of 12 to 0.4 microarcsec.
- High-energy neutrino detector.

### *Observatory Site Locations*

*(Candidate sites)*

- Northeast Orientale Basin (0° lat, 80° W long, on east limb of Moon as viewed from Earth).

- Tsiolkovsky basin (on far side of Moon).

## LUNAR LABORATORIES

Laboratory facilities would be a natural adjunct to a lunar outpost or base. A wide range of scientific and technical research activities could be conducted in a unique environment. A principal function of these lab facilities—in addition to the intrinsic lunar science studies—would be to test and demonstrate human systems and programs for the long haul to Mars and other solar system objects.

### *Laboratories for* in situ *studies of*

- Effects of local environment (reduced gravity, high vacuum, temperature extremes, radiation, micrometeorites, etc.) on
  - Human performance, health and safety, and food and waste management.
  - Engineering materials and structures—mechanical and chemical.
  - Surface mobility—foot, rovers, copters, rocket hoppers (for a lab on Mars: aircraft or balloons).
- Scientific analysis of Moon materials (including lunar meteoritic in-fall):
  - Geologic samples—detailed composition, petrogenesis, and assaying.
  - Biologic samples—tests for life or past life and organic or biogenic components.
  - Sample quarantine and processing for return to Earth.

- Resource assessment, processing, and beneficiation:
  - Extraction and storage of vital materials.
  - Water, oxygen, hydrogen, metals, and $^3$He.
  - Glass and composites for structure and shields.
- Raw materials exploration and development:
  - For use on planet body.
  - For export to space or Earth orbit.
- Earth atmosphere, weather, and climate monitoring.
- One planet (e.g., the Moon) serving as test bed for developing exploration, operational, and contruction techniques for use on another planet (e.g., Mars).
- Communications systems testing for local or global sites and interplanet links.

### *Table 1. SUMMARY OF OEXP FY 89 EXPLORATION PROGRAM CASE STUDIES*

| Case Study | Objectives | Major Program Phases | Number of Flights | Constraint (MT)* |
|---|---|---|---|---|
| Lunar Evolution | First flights by 2003 | Emplacement | 5 | 170 |
| | Permanent habitation by 2007 | Consolidation | 13 | 325+ |
| | Self-sufficient base by 2012 | Utilization | 5+ | 155+ |
| Mars Expedition | Flags and footprints as early as possible | To Mars and back, no Phobos stop | 1** | TBD |
| Mars Evolution | First Flight by 2004<br>One-year Mars surface stay by 2009 | Manned to Mars, robotic to Phobos (emplacement) | 3 (Mars)<br>1 (Phobos) | 85+ (each) |
| | Propellant production at Phobos | Consolidation | 2 (Mars)<br>1 (Phobos) | 60+ |
| | Permanent Mars settlement by 2017; *in situ* propellant used for return flights | Utilization | 3+ (Mars) | TBD |
| Asteroid Expedition | Exploration by 2003-2006 | To asteroid and return | 1 | TBD |

* Metric tons to the surface per phase [1 metric ton = 1000 kg].

** One cargo flight and one manned flight [20 days on surface].

Source: Study Requirements Document, No. Z-2.-1-002, March 1989, plus revisions.

***Table 2.*** ***A STRAWMAN PAYLOADS SEQUENCE (for a series of three Mars missions)— MARS EVOLUTION CASE***

**TARGET SCIENCE**

| **Mission 1 (to Mars — site M-2) Initial science outpost** | **Mission 2 (to Mars — site M-3) Human-tended base** | **Mission 3 (to Mars — site M-5) Operational base** |
|---|---|---|
| Long-lived geophysics station<br>• Seismometer<br>• Magnetometer<br>• Heat flow<br>• Weather station<br>Automated rover<br>Sample selection facility<br>Binocular microscope<br>Sample analysis kit<br>• Petrographic microscopes<br>• SEM, XRF<br>• Organic analyzer<br>Rock chipper and packager<br>Local geology EVA kit<br>• Imagers<br>• Tools (hammer, rake)<br>• 3–10 m core drill rig<br>Soil preparation, plant growth experiments<br>Local geophysics (EM sounding)<br>Microbiology test kit | Long-lived geophysics station<br>Automated rover<br>Sample selection facility<br>Local geology EVA kit<br>Soil preparation plant growth experiments<br>Local geophysics (EM sounding)<br>Microbiology test kit<br>Phobos resource exploration equipment<br>• Sample collection kit<br>• Sample analysis kit<br>• Microscope<br>• Thin section kit<br>• DSC/EGA<br>• GCMS<br>• SEM<br>Atmospheric science kit<br>Meteorology monitoring kits | Permanent geophysics station<br>Automated and manned rovers<br>Sample preparation facility<br>Regional geology EVA kits<br>Layered terrain drilling kits<br>Regional geophysics (EM sounding)<br>Microbiology test kits<br>Resources production equipment<br>Sample analysis lab<br>Fields and particles kit |

**CRUISE SCIENCE**

| **Mission 1** | **Mission 2** | **Mission 3** |
|---|---|---|
| Solar observatory<br>Neutral ion mass spectrometer<br>Magnetometer<br>Heavy ion detectors<br>Radiation biology experiment<br>Heavy-ion human perception experiments<br>Solar system telescope<br>UV-Vis-IR spectrometer and imager<br>Human factors test kits | (same as mission 1)<br>plus<br>Planetary observatory | (same as mission 1)<br>plus<br>Extrasolar observatory |

***Table 3. MATRIX SUMMARY OF SCIENCE EXPLORATION OPPORTUNITIES, PRECURSORS, STRAWMAN PAYLOADS, AND PRIORITIES FOR HUMAN MISSIONS***

| TARGETS | APPLICABLE SCIENCE DISCIPLINES | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Planetary Science | Geology and Geophysics | Atmosphere Science | Human Factors | Exobiology | Earth Science | Astronomy | Astro-physics | Fields & Particles |
| **MOON**<br>Target science | X | X | X | | X | | | | X |
| Platform science | X | | | X | X | X | X | X | X |
| Cruise science | X | | | X | | X | X | X | X |
| **MARS**<br>Target science | X | X | X | | X | | | | X |
| Platform science | | | | X | X | | | | |
| Cruise science | X | | | X | | X | X | X | X |
| **SMALL BODIES: ASTEROIDS, PHOBOS/DEIMOS**<br>Target science | X | X | | | X | | | | X |
| Platform science | X | | | | X | | | | X |
| Cruise science | X | | | X | | X | X | X | X |
| **PRECURSORS** (Summary) **ROBOTIC SPACECRAFT** | | | | | | | | | |
| **ENABLING AND ENHANCING TECHNOLOGY AND INFORMATION** | | | | | | | | | |
| **PRIORITIES** (Summary) | | | | | | | | | |
| **STRAWMAN PAYLOADS** (Summary) | | | | | | | | | |

***Table 3. (CONTINUED)***

| TARGETS | SCIENCE OPPORTUNITIES |
|---|---|
| **MOON**<br>Target science | Traverse science (surface mapping, sampling, geophysical surveys).<br>Site-intensive science (deep drilling, trenching, stratigraphy, subsurface physical properties, resource delineation).<br>Network science (global seismic, heat flow, atmospheric measurements).<br>Atmospheric studies, effect of human activity on lunar atmosphere. |
| Platform science | Observatories (astronomy, Earth monitoring).<br>Laboratories (biology, human factors, physics, resource development). |
| Cruise science | Relatively few due to short duration of cruise. |
| **MARS**<br>Target science | Exobiology studies (search for prebiotic organic compounds, living organisms, fossils, paleoclimate conditions).<br>Geoscience studies (detailed surface mapping, sampling, analysis, rock dating, geophysical networks).<br>Atmospheric/ionospheric studies (properties, variations, weather).<br>Resource assessment studies (field exploration, sampling, analysis). |
| Platform science | Mars environmental studies (weather, human factors, resource analysis)<br>Observe Phobos and Deimos |
| Cruise science | Solar observations (radiations, particles, solar wind and flares, magnetography).<br>Cosmic dust studies (distribution, composition).<br>Astrophysical studies (stellar source studies; cosmic rays, X-rays, gamma rays).<br>Biomedical studies (radiation, microgravity effects, zero-g countermeasures, physiology/psychology). |
| **SMALL BODIES: ASTEROIDS, PHOBOS/DEIMOS**<br>Target science | Sample small planetary body; determine surface composition, structure, texture, and age.<br>Determine bulk geophysical properties; determine internal mass distribution.<br>Resources assessment and utilization.<br>Search for exobiology materials. |
| Platform science | Use body as a solar system probe (gravity, dynamics, fields and particles). |
| Cruise science | Same as Mars or Phobos mission cruise science. |
| **PRECURSORS (Summary)**<br>**ROBOTIC SPACECRAFT** | |
| **ENABLING AND ENHANCING TECHNOLOGY AND INFORMATION** | |
| **PRIORITIES (Summary)** | |
| **STRAWMAN PAYLOADS (Summary)** | |

***Table 3. (CONTINUED)***

| STRAWMAN PAYLOADS | PRECURSORS | PRIORITIES |
|---|---|---|
| Active seismic survey equipment<br>Deep drilling/sampler equipment<br>Vehicles, tools, analytical equipment | Global orbital mapping (LO)<br>Geophysics net (probes)<br>Teleoperated rovers | Long traverse with/sampling<br>Resource assessment<br>Global geophysical property certification |
| Long-baseline optical observation<br>He-3 benefitiation lab<br>Analytical lab (rock analyses) | Seismic stability certification<br>Atmosphere dust, ionosphere certification (LGO with limb sounder) | *In situ* instrument functionality<br>Lunar environmental protection |
| None | None | None |
| Biology — subsurface sample, micro-organisms or processes.<br>GCMS, DSC, SEM, microscopes<br>Geology — subsurface drill sample, geophysical net equipment | Global mapping (MO); Mars big eye orbiter<br>Surface survey/sample return (MRSR) | Exobiology tests<br>Resource assessments<br>Atmosphere/meteorology certification<br>Global geophysic certification |
| Microbiologic lab<br>CELSS lab<br>Climate lab<br>Weather station | Surface weather stations<br>Orbiting weather satellite | Environment protection<br>No fore- or back-contamination |
| EUV/UV telescopes<br>VIS/IR telescope<br>Fields and particles detectors<br>X-Ray telescope<br>Solar magnetometer<br>Solar wind plasma detector<br>Gamma-ray and X-ray burst detector<br>Radio Interferometer<br>Dust detector<br>Biomed studies equipment | Bare Cathode Instrument Development<br>Improved Detectors | Long-term continuous observations<br>Maximum observing sensitivity |
| IVA — high resolution imaging, telerobotic surface lander<br>EVA — camera, spectrometers sampler | Ground-based spectra, radar<br>Rendezvous survey (Galileo, CRAF)<br>Robotic probe to surface | Resource assessment<br>Bulk geophysical properties |
| Beacon or pair of beacons<br>Solar wind detector<br>Magnetometer | None | Install beacon for ranging.<br>Install fields and particle equipment |
| Same as Mars mission | Same as for Mars mission | Same as Mars mission |
|  | MO, MRSR, LO, CRAF<br>Small body probe, surveyor |  |
|  | Lunar limb particle sounder |  |
|  | Global mappers<br>Surface probes<br>Rover/sampler | Resource assessment<br>Global geophysical certification<br>Environment protection<br>Long-term continuous observation |
| Seismic nets equipment, deep-drilling equipment, high-resolution imaging, portable labs, uncovered detectors, rock and soil sampling equipment, portable spectrometers |  |  |

# Glossary of Terms

| | |
|---|---|
| Alpha scatterer | – Analytical device that uses back-scattered alpha-particles for elemental analysis of surfaces. |
| Biogenic elements | – Hydrogen, carbon, oxygen, nitrogen, sulfur, and phosphorus; elements that play the dominant role in the chemistry of life forms and living systems. |
| BY | – Billion years. |
| CEPS | – NASA Center Exploration Program Scientist(s). |
| Code EL | – NASA Solar System Exploration Division. |
| Code Z | – NASA Office of Exploration. |
| CRAF | – Comet Rendezvous Asteroid Flyby mission. |
| DSC | – Differential Scanning Calorimeter. |
| EM | – Electromagnetic. Usually refers to the technique of electromagnetic sounding, which by convention implies use of frequencies below ~1 MHz (whereas the term radar sounding implies using frequencies above 1 MHz). |
| EGA | – Evolved Gas Analyzer. |
| EUV | – Extreme ultraviolet (wavelengths ~100–200 nm). |
| EVA | – Extravehicular Activity (activity outside the spacecraft). |
| Exobiology | – Life that originated outside the Earth. A field of study that seeks to understand interactions between a biological system and its physical environment. |
| Exosphere | – Outer, or very thin portion, of an atmosphere where lighter, fast-moving atoms have a high probability of escape into space. |
| EXSWG | – Exploration Science Working Group. |
| g | – Acceleration of gravity at surface of Earth (980 cm $s^{-2}$ at sea level). |
| Galileo | – Outer-planet mission to Jupiter, consisting of an orbiter and an atmospheric probe. |
| GCMS | – Gas Chromatograph Mass Spectrometer. |
| GeV | – Gigavolt ($10^9$ volts). |
| GHz | – Gigahertz ($10^9$ Hertz, a frequency of $10^9$ cps). |

| | |
|---|---|
| GRS | Gamma Ray Spectrometer. |
| Human-crewed | A mission with male or female crewmember(s). |
| Ionosphere | Ionized region in the outermost tenuous portion of a thick atmosphere, or a very thin, completely ionized atmosphere. |
| IR | Infrared. |
| IVA | Intravehicle activity (activity inside the spacecraft). |
| KeV | Kilovolt. |
| km | Kilometer. |
| KREEP | Rocks that are rich in Potassium (K), Rare Earth elements, and Phosphorus. |
| LEXSWG | Lunar Exploration Science Working Group. |
| Libration | Oscillation in rotation rate of a planetary body. Physical librations are angular motions about the center of mass due to gravitational torques on the body. Libration of the Moon results in 59 percent of its surface being visible from the Earth at one time or another. |
| LIDAR | Light Detection and Ranging system for the study of atmospheric dust and aerosols ("laser radar"). |
| LO | Lunar Observer mission or spacecraft. |
| Ly-alpha | Lyman-alpha radiation, emission line in the spectrum of hydrogen at 121.567 nm in the extreme ultraviolet. |
| m | Meter. |
| Magnetotail | The extended tail region of a magnetosphere, where the magnetic field lines are parallel to the ecliptic plane due to the streaming action of the solar wind. |
| Mainbelt | Regular asteroid belt located between orbits of Mars and Jupiter. Distinguished from Earth-crossing asteroids whose orbits bring them relatively close to the Earth or its orbit. |
| Manned mission | A mission with male or female crewmember(s). |
| Mare | Large basins on the Moon composed of basalt flows that flooded the basin. |
| mgal | Milligal; unit of gravitational field strength. |
| Mixing ratio | Concentration of gaseous constituents in an atmosphere. |
| MO | Mars Observer mission or spacecraft. |
| MOC | Mars Observer Camera. |

MOLA – Mars Observer Laser Altimeter.

MRSR – Mars Rover Sample Return mission (under study).

MT – Metric ton (equivalent to 1000 kg).

nm – Nanometer (1000 nm = 1 micron); unit of wavelength.

nT – nanotesla. (1 nT = 1 gamma); unit of magnetic field strength.

Petrology – Study of mineralogical relationships within a rock to understand its composition, texture, and mode of origin.

Piloted mission – A manned mission with male or female crewmember(s).

pixel – Picture element.

Plasmapause – Transition region between the solar wind flowfront (bowshock) and the ions in the outer portion of a magnetosphere.

Radar – Radio Detection And Ranging (when term is applied to radar sounding, it implies frequencies >1 MHz).

Regolith – Fragmental surface layer composed of both fine powder and coarse rock or boulder material, with depths up to tens of hundreds of meters.

RF – Radio frequency.

Soil – Fine powder and sand-sized particulate material at the uppermost surface of a planet; a mantle with typical layer depths from a few centimeters to a few meters. It may be weathered by mechanical, radiation, vacuum, or chemical effects.

Solar wind – A radial outflow of plasma from the solar corona that streams out through the solar system and beyond. Composed mostly of hydrogen and helium ions.

Strawman – An example that illustrates what will actually be used.

S-type asteroid – Mainbelt asteroids with moderate albedo and reddish spectral reflectance that occur predominantly in the inner regions of the belt and are thought to be composed of moderate temperature iron-bearing siliceous condensates.

Teleoperated – Remotely operated by radio (telecommunications) linkage.

Terrestrial – Related to the Earth; a planet with a hard surface and generally composed of silicate rocks; it may have an atmosphere.

TeV – Teravolt ($10^{12}$ volts).

Unmanned mission – No humans aboard.

UV – Ultraviolet.

VIMS – Visible Infrared Mapping Spectrometer.

Vis – Visible portion of the electromagnetic spectrum.

XGRS – A combined X-ray and Gamma-ray spectrometer.

XRD – X-ray Diffractometer.

XRF – X-ray Fluorescence spectrometer.

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**16. Abstract**

Scientific exploration opportunities for human missions to the Moon, Phobos, Mars, and an asteroid are addressed. These planetary objects are of prime interest to scientists because they are the accessible, terresterial-like bodies most likely to be the next destinations for human missions beyond Earth orbit. Three categories of science opportunities are defined and discussed: Target science, Platform science, and Cruise Science. Target science is the study of the planetary object and its surroundings (including geological, biological, atmospheric, and fields and particle sciences) to determine the object's natural physical characteristics, planetological history, mode of origin, relation to possible extant or extinct life forms, surface environmental properties, resource potential, and suitability for human bases or outposts. Platform science takes advantage of the target body using it as a site for establishing laboratory facilities and observatories; and cruise science consists of studies conducted by the crew during the voyage to and from a target body. Generic and specific science opportunities for each target are summarized along with listings of strawman payloads, desired or required precursor information, priorities for initial scientific objectives, and candidate landing sites. An appendix details the potential use of the Moon for astronomical observatories and specialized observatories, and a bibliography compiles recent work on topics relating to human scientific exploration of the Moon, Phobos, Mars, and asteroids. The report concludes that there are a wide variety of scientific exploration opportunities involving many science disciplines that can be pursued during human missions to planetary targets but that more detailed studies and pre-

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