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A PLANETARY SCIENCE STRATEGY FOR THE MOON

Lunar Exploration Science Working Group (LExSWG)

July 1992

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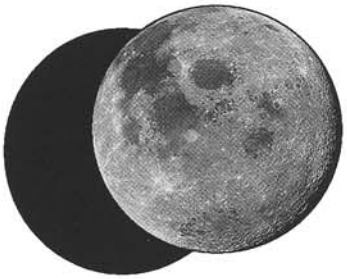

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Solar System Exploration Division
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FOREWORD

For many reasons, the Moon is an important object in space. It is a small planet of rich complexity, one which not only holds secrets of planetary evolution and process, but also preserves a detailed record of the history of our own corner of the Solar System. The lunar soil, or regolith, contains a 4 billion year record of the output of the Sun and the surface craters record the cosmic bombardment history of the Earth-Moon system. Because the Moon is nearby, being only three days away from the Earth, it is an easily accessible body and is a likely destination for missions carrying machines and people into space during the next few decades.

Although we know quite a bit about the Moon from the results of the incredibly successful Apollo program, much of its history and evolution remains mysterious. Understanding exactly how to address the complicated questions that confront us when we contemplate the Moon is a difficult task, one which requires the experience and expertise of a wide spectrum of disciplines. The Lunar Exploration Science Working Group (LExSWG) is a group of active lunar scientists who have considered the strategic approaches necessary for us to read lunar "Rosetta Stone." In this report, the LExSWG presents us with a series of important scientific questions that are addressable on the Moon. The group provides a challenging strategic vision—a series of missions, both robotic and human, that will give us an unprecedented understanding of our nearest planetary neighbor. This planetary science strategy is not only a plan to investigate and exploit the scientific richness of the Moon, but may also serve as a general guide for the exploration of any terrestrial planet.

As humanity moves into the Solar System, the Moon is both a waypoint and a guidepost. This report provides the basis for understanding the Moon as a planetary body with its own fascinating history and as a key to the obscure early segments of terrestrial planetary evolution. The rich harvest of knowledge that awaits us on the Moon will open new intellectual vistas in our inexorable drive into space.

Wesley Huntress
Director, Solar System Exploration Division

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EXECUTIVE SUMMARY

This planetary science strategy for the Moon establishes the essential framework for carrying out a long-term program leading to fundamental improvements in our understanding of the early evolution of terrestrial planets, the formation of the Earth-Moon system, the Solar System environment over time at 1 AU, and the history of the Sun recorded in the lunar regolith. The strategy also recognizes that the Moon offers an ideal locale to study the physics and chemistry of the class of tenuous planetary atmospheres with surface-boundary exospheres and serves as an excellent platform for planetary astronomy.

In the general field of planetary science, the Moon is important because it has preserved its *primordial crust* and is arguably the preeminent location in the Solar System in which to study the evolution of a terrestrial planet immediately following accretion. The Moon has retained a record of its *post-accretional* impact history and its origin is inextricably linked to the *earliest evolution of the Earth.* A small planetary object of surprising complexity, the Moon is a natural laboratory in which general geological processes important in planetary evolution may be studied and understood.

The strategy presented here combines elements of Earth-based observations, lunar orbiting spacecraft missions, geological field work taking advantage of human presence on the Moon, various robotic missions on the lunar surface, the emplacement of a long-lived geophysical network, the emplacement of astronomical facilities on the Moon, and terrestrial laboratory studies of lunar materials and data. It is also evolutionary in the sense that ideas, instruments, equipment, and procedures developed and refined at the Moon can be applied to the exploration of Mars and other Solar System bodies. Major themes of the science strategy are:

1. Formation of the Earth-Moon system
2. Thermal and magmatic evolution of the Moon
3. Bombardment history of the Earth-Moon system and nature of impact processes
4. Regolith formation and evolution of the Sun
5. Nature of the lunar atmosphere
6. Planetary astronomy from the Moon

To implement these themes, six mission elements are defined:

1. Earth-based and Galileo observations
2. Orbital missions
3. Geoscience rovers
4. Geophysical network
5. Reconnaissance sample returns
6. Geological field work

A key to our strategy is flexibility. Different and varying mixtures of mission elements are required to address the different science themes. We emphasize here the distinct contributions to be made by the various mission elements, but without specifying any architectural dependence. As the various lunar exploration architectures become more sharply defined, our strategy will permit a rational and evolutionary selection of mission elements to address a variety of science themes.

Research and analysis is required in a large number of disciplines to carry out the lunar program and to attract and train young lunar scientists. To accomplish the goals in the time frame required, the human infrastructure of trained lunar scientists must be aggressively expanded, technical facilities must be upgraded to provide first-class research capabilities, and a solid interpretative data base of remote measurements must be established. Definition studies must be started for scientific experiments to be carried within the mission elements.

INTRODUCTION

The Moon occupies a pivotal position in attempts to understand the origin and evolution of the inner or terrestrial planets of the Solar System. The terrestrial bodies most likely formed by collisional accretion, the gravitational collection of a vast size range of objects in orbit around the forming Sun. The gravitational potential energy associated with the accretion process was converted, in part, to thermal energy, heating and melting the forming bodies to differing degrees. Because the Moon is a small planet, it quickly evolved to a relatively quiescent state, preserving the effects of the late stages of the accretion process. The evolution of terrestrial planetary bodies immediately following accretion is one of competition between the primary processes associated with the formation event, such as the fractionation of a primordial crust and the bombardment associated with the terminal phases of accretion, and secondary processes, such as crustal recycling and magmatic differentiation of the solid interior. On the Earth, all evidence of the accretion event has been removed by secondary processes. The Moon is the best location in the Solar System to study such primary planetary events; the Moon is thus a keystone for understanding the early evolution of the Solar System.

A planetary science strategy for the Moon establishes the essential framework for carrying out a long-term program leading to fundamental improvements in our understanding of the early evolution of terrestrial planets, the formation of the Earth-Moon system, the Solar System environment over time at 1 AU, and the history of the Sun as recorded in the lunar regolith. The Moon also offers an ideal locale to study the physics and chemistry of the class of tenuous planetary atmospheres with surface-boundary exospheres, and serves as an excellent platform for planetary astronomy.

In the context of planetary evolution, there is a triumvirate of ideas that forms the basis for defining such a science strategy. These are:

1. The Moon has preserved its *primordial crust* and is arguably the preeminent location in the Solar System in which to study the evolution of a terrestrial planet immediately following accretion.
2. The Moon has retained a record of its *near-post-accretional* impact history.
3. The origin of the Moon is inextricably linked to the *earliest evolution of the Earth.*

A planetary science strategy must combine elements of Earth-based observations, lunar orbiting spacecraft missions, geological field work taking advantage of human presence on the Moon, various robotic missions on the lunar surface, the emplacement of a long-lived geophysical network, the emplacement of astronomical facilities on the Moon, and studies of lunar materials and data in terrestrial laboratories. The strategy should be evolutionary in the sense that ideas, instruments, equipment, and procedures developed and refined at the Moon can be applied to the exploration of Mars.

The strategy anticipates a high level of activity at the Moon through the Space Exploration Initiative (SEI), but is not tied to any specific architecture of that program and is able to make significant progress with robotic phases of lunar exploration. The mission elements that are necessary to carry out the various themes of the science strategy can only be integrated into SEI when a better definition of that program is available. This document does not specifically address the science impact on outpost and human landing site selection, nor does it address the role of science in choosing among various exploration architectures. It is implicit, however, that in order to successfully address the major planetary science themes, the mission elements defined here will have to be incorporated into the overall SEI strategy.

In this report, six major science themes are presented, followed by six mission elements required to implement the themes. One theme is then selected to show by example how the mission elements can be used to carry out the science strategy. This report concludes with a discussion of the necessary research and analysis for this program, and points out the synergism between science strategies for the Moon and Mars.

PLANETARY SCIENCE THEMES

— Formation of the Earth-Moon system.

— Thermal and magmatic evolution of the Moon.

— Bombardment history of the Earth-Moon system and nature of impact processes.

— Regolith formation and evolution of the Sun.

— Nature of the lunar atmosphere.

— Planetary astronomy from the Moon.

SCIENTIFIC THEMES AT THE MOON

Formation of the Earth-Moon System

Key scientific questions. The formation of the Moon is intimately connected with the dynamical environment of accretion in the inner Solar System. A fundamental question is whether the inner Solar System was a relatively violent place toward the end of accretion, with a large number of Moon-sized or larger bodies in orbits characterized by significant eccentricities so that giant collisions were common, or whether it was a quiet place characterized by large bodies in almost circular orbits and a dearth of intermediate, lunar-sized bodies. The origin of the Moon, the early thermal state of the Earth, and the development of clement conditions conducive to the origin of self-replicating life at the Earth's surface are direct consequences of this dynamical environment. In the violent accretion case, very large impacts into the Earth may have been responsible for the origin of the Moon and may have repeatedly heated the surface of the Earth to above the boiling point of water; such conditions would have repeatedly extinguished any incipient life. In the quiet accretion case, an origin of the Moon in a giant impact is not tenable and life on Earth may have originated soon after accretion when liquid water became permanently stable.

The bulk composition of the Moon must be determined. If the Moon is enriched in refractory elements such as U, Th, and Al, or is enriched in oxidized Fe compared to the upper mantle of the Earth, as is suggested by data provided by the Apollo missions, an origin of the Moon in a giant impact would be unlikely, with attendant implications for the dynamical environment of the inner Solar System during accretion, as discussed above.

Data to be acquired. The global chemical composition of the surface of the Moon must be determined. Such data, in concert with visual and near-infrared spectra and imaging data taken at higher spatial resolution, will permit estimates of lateral and vertical (through careful study of crater ejecta) compositional variations in the lunar crust. This information, in turn, will permit estimates of minimum global abundances of elements largely extracted into the crust, including the refractory elements U and Th.

The structure and physical properties (e.g., seismic velocities) of the lunar mantle (and core if one exists) will permit estimates of the mineralogy of the mantle as a function of depth. From this mineralogy, the abundances of elements partially retained in the mantle (e.g., Al in garnet and spinel) may be determined. Measurement of surface heat flow at a variety of geologically homogeneous locations on the lunar surface will constrain estimates of global abundances of heat-producing elements, including U and Th.

Samples of the lunar mantle may have been exposed in the ejecta of large impact basins or present as xenoliths in lava flows. The return of such samples to Earth for analysis in terrestrial laboratories will yield direct measurements of the oxidized Fe content of the mantle.

Thermal and Magmatic Evolution of the Moon

Key scientific questions. Apollo results demonstrate that the Moon melted early in its history, forming a relatively low-density crust, a denser mantle, and perhaps a small metallic core. Subsequent geological activity on the Moon was not vigorous enough to erase the record of this important event, so some rocks in the ancient crust contain the record of the Moon's primary differentiation. This record is not preserved on larger planetary bodies; thus, understanding the differentiation of the Moon sheds light on planetary differentiation in general. It is also important to understand the initial thermal state of the Moon as this has important inferences for mechanisms of accretion and hence, for the details of lunar origin.

The evolution of the mantle and core and their current structure tie directly to questions of the thermal evolution of the Moon, its bulk

EARTH-MOON SYSTEM

— Dynamical environment of accretion in inner Solar System.

— Earth & Moon origin are linked; both must be understood.

— Test giant impact hypothesis for origin of Moon.

The currently favored model for lunar origin envisions the collision of a Mars-sized planet with the proto-Earth 4.6 billion years ago. Determining the details of the origin of the Moon is an important task in its scientific exploration. *Painting courtesy of William K. Hartmann.*

composition, and the extent of primordial melting and differentiation. For example, strong discontinuities in seismic velocity in the mantle may indicate the depth of original melting. The compositional density structure of the mantle controls the style of mantle convection. The existence of an iron core constrains the bulk composition, and hence origin, but also has relevance to the question of an ancient geomagnetic dynamo.

There are several crucial scientific problems to address. First and foremost, was the Moon enveloped by a global ocean of magma when it formed? This idea was proposed soon after the return of the first batch of lunar samples over twenty years ago, but it has not been proven. If there was a magma ocean, what processes operated in it? If there was not a global ocean of magma, what was the nature of the earliest lunar differentiation? What were the products of this event? What are the ages of the oldest lunar rocks?

In addition to the formation of the primordial crust, the overall history of melting events inside the Moon is important for several reasons. A planet's igneous history is a powerful recorder of its thermal history. Thus, to understand the thermal history of the Moon, the details of its magmatic evolution must be worked out. Melts formed inside planets also contain quantitative information about the chemical composition and mineralogy of their interiors. Combined with seismic and other geophysical data, such information will provide vital knowledge of the nature of the interior of the Moon, which has bearing on lunar origin. Finally, understanding magmatic evolution and processes on the Moon forms the basis for understanding magmatic processes on other planets.

Our present knowledge of the Moon's igneous history is meager. We do not know how many rock types there are in the lunar highlands or how they relate to each other. We do not know the full range of highland rock or mare basalt compositions or the full range in their ages. We do not know how the depths of melting or the rates of magma production changed with time.

The putative lunar core raises another set of fundamental issues. We need to know the existence, size, and mass of a metallic core. The mass of a possible metallic Fe-Ni core is a missing part of the bulk composition that would impose an important constraint on models of lunar origin. This is because the amount of segregated metal together with the present abundances of siderophile elements (W, Co, Ni, Mo, etc.) can be used to infer the original abundances of these elements in the protomoon prior to differentiation. Comparisons of these abundances with those in other Solar System objects (e.g., carbonaceous meteorites, the terrestrial upper mantle) can help to identify the source of the protolunar material. The composition and structure of the mantle is an important constraint on bulk composition and also directly relates to the depth of initial melting of the protomoon. The global mean heat flow provides the most basic of constraints on thermal history models and also indirectly constrains the total abundance of radioactive elements such as U and Th that supply most of

the present-day internal heat of the Moon. Finally, the origin of lunar paleomagnetism is a question raised by the absence of a global magnetic field and the small size of its metallic core where such a field could have been generated in the past. It is possible that magnetic fields and rapid magnetization may occur in local surface processes such as impacts. Such a phenomenon would have major implications for the interpretation of paleomagnetism on airless silicate bodies in the Solar System.

Data to be acquired. Global surveys from orbit will provide important information, including determining the composition of the uppermost crust and assessing the size of the lunar core. It will also furnish the global geological context in which to place more detailed studies to be made on the lunar surface. To understand the origin of primordial crust, samples must be obtained from the ancient highlands by humans or robots. Simple reconnaissance missions to specific areas identified on the basis of data obtained by orbital reconnaissance will provide important information about crustal composition. A full understanding of early differentiation requires detailed field studies to search for contacts between different rock types and to study layering in complex rock bodies. For example, the Inner Rook Mountain ring of the Orientale basin appears from Earth-based remote sensing data to consist of a rock type called anorthosite, thought to be the major crustal product of the magma ocean. Field studies at sites in this region would collect samples to test the remote observations and would search for layering in the rocks. Layers would record pulses of magma intruding the growing crust, perhaps driven by vigorous convection in the magma ocean. Alternately, the layers might indicate subsequent igneous activity.

Solving the problems of the overall magmatic evolution of the Moon also requires sample returns from areas identified from data returned by orbital remote sensing spacecraft. For example, an important question is, "When did volcanism cease on the Moon?" This can be answered by returning samples from flows that have the lowest abundances of impact craters, which is a measure of their age. The ages of the samples would be determined radiometrically in laboratories on Earth. Such a mission would also help calibrate the cratering rate through time, which also has application to our understanding of when events took place on other planets. In addition to such specific sample return missions, many science investigations will need to be of long duration to allow for detailed field work. The field studies are needed for a variety of reasons. For example, field work is needed to determine the relationships between different types of rocks, to study eruption mechanisms, and to search for inclusions of lower crust or mantle rocks in lava flows.

In order to more accurately determine the internal structure and thermal properties of the Moon, a global network of geophysical instruments including seismometers, heat flow probes, and magnetometers is required. In addition, orbital magnetic field measurements can help to constrain the existence of a metallic core and the origin of lunar paleomagnetism, while orbital microwave radiometer measurements can assist in determining regolith depth and in constraining the true global mean heat flow. An initial technique for constraining the size of a possible metallic core will involve deep magnetic sounding using magnetometers on orbiting spacecraft(s). By improving this technique based on Apollo experience, it is expected that at least an upper limit on the core radius will be obtained. The same magnetometers would map the distribution of crustal magnetic fields allowing correlative studies with surface geology to constrain the origin of the paleomagnetism. Later, surface geophysical stations must be established to determine more definitively the internal structure of the Moon.

THERMAL AND MAGMATIC EVOLUTION

— Primordial crust related to accretion.

— Did a magma ocean exist?

—Extent of primordial melting.

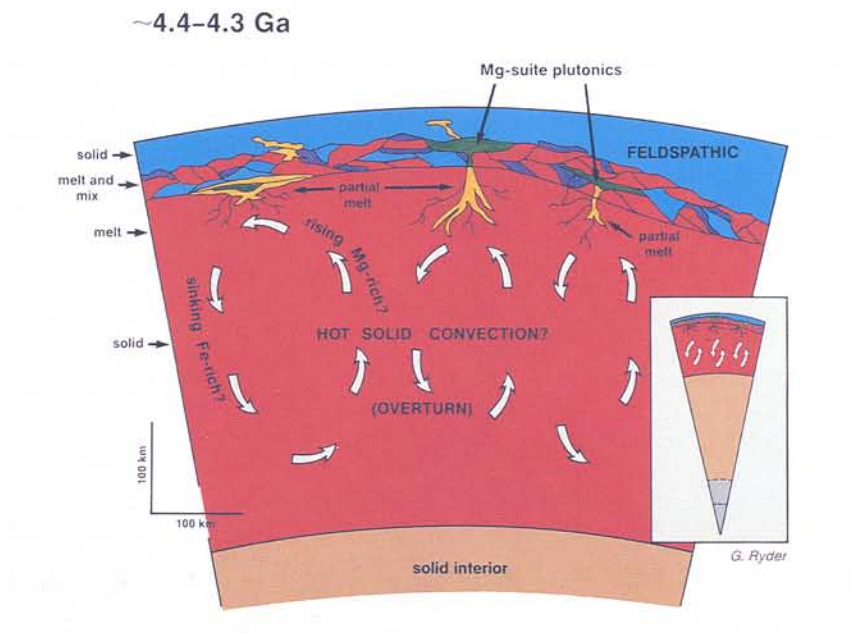
— Igneous history.

— Does a lunar core exist?

Bombardment History of the Earth-Moon System and Nature of Impact Processes

Key scientific questions. Impact is the fundamental process by which planets are assembled and all terrestrial planets display the effects of bombardment by solid objects. The Moon is an ideal natural laboratory in which to decipher impact processes because the lunar surface preserves a more complete record of impact bombardment than does the ever-changing surface of our home planet. Important topics for study in this area include the origin of the Earth-Moon system, its late stage accretional history, and the nature of possible episodicities in the intensity of the impact flux over geological time. Such questions, which cannot be addressed on any other body in the Solar System, can be productively studied on the Moon.

The detailed nature of the flux history of the Moon is an area of intense controversy. Early in lunar history, about 3.9 billion years ago, a substantial increase in the bombardment rate (the "cataclysm") had been proposed, but not proven; if



After the crystallization of the lunar "magma ocean," intrusive activity produced a complex sequence of plutonic rocks, all contributing to the heterogeneity and complexity of the crust of the Moon. *Diagram by Graham Ryder.*

such an increase occurred, it has important consequences for the absolute age of most of the visible features on the Moon and the dating of other planetary surfaces.

The possible link between impact and biological evolution on Earth must be seriously considered. Geochemical and mineralogical evidence of impact has been detected within strata marking abrupt mass extinctions at the Cretaceous-Tertiary (66 million years ago) and upper Eocene (about 37 million years ago) boundaries. Subsequent claims that periodic variations in the record of extinctions may correlate with possible periodic variations in the impact flux on Earth have prompted considerable interest (including skepticism) from the biological and astronomical communities. But the terrestrial record of impact is far too incomplete to allow rigorous testing of the hypotheses of periodicity and correlation. Fortunately, the Moon offers an important opportunity to assess episodicity by sampling the multitudes of pristine impact craters which mark its surface and provide a virtually complete cratering record of the Earth-Moon system spanning the last 3 billion years.

Despite intensive study, our understanding of the impact process itself is far from complete. The exact shape and relative dimensions of the cavity of excavation in large cratering events, a parameter of extreme importance in the determination of sample provenance, is still unknown. Multiple, concentric rings are found around large basins on the Moon; their mechanism of formation remains an area of contention. The Moon also has a relatively simple tectonic style and most lunar tectonic features are ultimately related to the presence of impact landforms (i.e., mascon basins).

Data to be acquired. Orbital data can be used to select crater and basin targets most likely to provide the best data to decipher lunar cratering history. On the basis of current (and inadequate) data, we now suspect that only about 70 million years separate the formation of the lunar Nectaris basin from the Imbrium basin; if so, then a large fraction of landforms currently visible in the lunar highlands formed at about 3.9 billion years ago, i.e., a cataclysm occurred. This vexing question can be answered by carefully sampling the impact melt sheets of several key features, including the Nectaris, Imbrium, and Orientale basins, and several large craters that occur stratigraphically between them. If all formed within a restricted interval of less than 100 million years, the existence of a cataclysm is indicated. This has profound implications not only for the geological history of the Moon, but also the early bombardment history of the Earth.

In the later part of lunar history, we can use the preserved impact record of the Moon to address a problem in the evolution of terrestrial life; viz., the problem of episodic, and possibly periodic, extinctions and its relation to impact flux variations. The approach on the Moon is to obtain impact melt samples of a large population of post-mare (less than 3 billion years old) craters and date these samples radiometrically. A minimum of 100 separate impact events would have to be dated to resolve any periodicity with some statistical confidence.

Study of the physics of impact processes requires a combined approach in the exploration of the Moon. Global remote-sensing data permit coordinated analysis of the

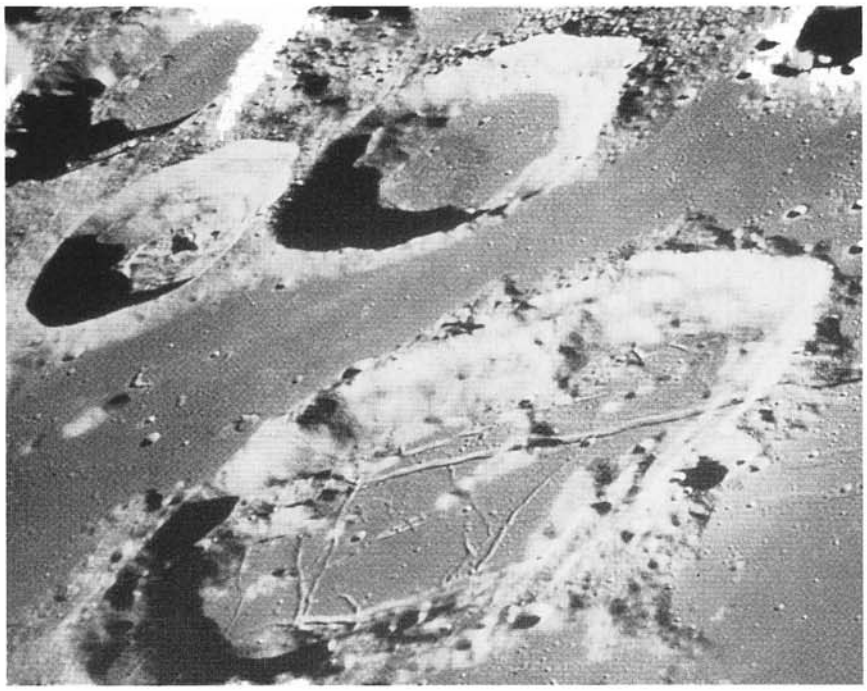
BOMBARDMENT HISTORY AND NATURE OF IMPACTS

— Moon preserves a long impact record.

— Terminal lunar cataclysm?

— Test hypothesis that episodic extinctions of life forms on Earth are related to impact.

— Impact physics and sample provenance.



The cratered surface of the Moon contains information on the bombardment history of the Earth-Moon system and is also a natural laboratory for the study of the impact process. The large, tectonically modified crater in the foreground is Goclenius (72 km), on the southwestern edge of Mare Fecunditatis.

composition and morphology of crater and basin deposits. For example, it will be possible to use orbital data to study the composition of basin ejecta and its distribution around the basin and to reconstruct both the nature of the basin target and the processes responsible for emplacing the ejecta blanket. On the basis of the orbital data, targets can be selected for the return of reconnaissance samples and later, for detailed geological field work. Such work can be used to test models for the formation of basins and will enable a reconstruction of the impact event.

Regolith Formation and Evolution of the Sun

Key scientific questions. Much of the history of the Moon is recorded in or hidden by the lunar regolith, the shroud of broken rock and "soil" that covers the planet. Large and small impact cratering events both produce the materials of the regolith and redistribute them about the lunar surface. The lunar regolith, which is the counterpart of Earth's blanket of sedimentary rocks, is a major feature of the Moon. This alone makes its present nature and the processes that formed it worthy, if difficult, topics of study. Because ions from the solar wind continuously implant themselves into soil grains, and galactic cosmic rays undergo nuclear reactions in the upper meters of the regolith, older layers of lunar soil are expected to carry a detailed record of the ancient history of the sun and cosmic radiations.

If we imagine that beneath the regolith there is an intact crust of igneous origin that carries the record of the Moon's igneous differentiation and evolution, we must learn how to open the window of the regolith to find it. (This is true of all airless planetary bodies that have high crater densities and are, therefore, covered with regolith.) Opening the window does not mean physically sweeping away the layer of broken rocks and soil; in the lunar highlands that layer may be tens of kilometers thick. Rather, it means understanding how regolith materials form and move, so we can relate them accurately to the depths and geographic coordinates of their crustal sources. The regolith is the accessible and principal source of material for resource utilization; we should learn what it has to offer.

All lunar samples collected so far have been part of the regolith. The only in-place igneous rocks sampled by astronauts on the Moon's surface are the mare lava flows in the wall of Hadley Rille near the Apollo 15 landing site. (Mare lava flows are overlain only by shallow regolith since the maria formed after the main bombardment of the Moon had ended, but they overlie ancient highland regolith.) The origin and evolution of the regolith can be described in terms of properties such as the following: its total thickness and state of compaction with depth; the thicknesses and lateral continuity of stratigraphic layers over a broad range of scales; the types and compositions of the contributing igneous materials, their formation ages, and the time when they first entered the regolith; the history of mixing of large batches of regolith with each other, including the ages (as regolith) of these large batches and the time line for their mixing; the relative importance of contributions of local igneous rocks to the regolith as opposed to exotic materials (i.e., the extents of lateral and vertical transport), and contributions of extra-lunar materials. Obtaining this information will be a formidable task of observation, sampling, chemical, isotopic, and mineralogical analysis, and modeling. Much of the necessary data must be "unmixed" from the composite bulk characteristics of the soils. From Apollo and Luna samples, it was learned that mature soils consist mainly of materials so finely pulverized that the identities of their precursor igneous rock types cannot be easily inferred. Additionally, soils do not represent simple mixtures of pulverized igneous rocks of the types and compositions found in association with them.

Understanding the nature of the regolith and the processes that formed it are essential to determining the past

history of the solar wind and galactic cosmic rays. Cosmic rays and the solar wind interact with those portions of the regolith on and near the lunar surface. The solar wind adds volatile elements and produces physical and chemical changes on surfaces of regolith grains, and cosmic ray spallation reactions lead to production of isotopes within the upper meter of the surface. These are essential to understanding the age and state of maturity of individual layers and individual particles of regolith.

Layers of regolith trapped between successive flows of mare basalt of Apollo 11 and Apollo 17 age will contain solar wind and products of cosmic ray bombardment older than 3.8 billion years, the known age of the basalts, because the trapped layers have been protected from solar wind and cosmic ray interactions ever since the surface flows covered them. Similarly, the properties of the trapped solar wind and the cosmic ray bombardment products in regolith found between successive layers of Apollo 12 and Apollo 15 mare basalts will correspond to a maximum age of 3.2 billion years, the ages of those flows. This approach can be extended and generalized to construct a history of solar wind and cosmic ray bombardment onto the lunar surface. Conversely, observed differences in trapped solar wind or cosmic ray bombardment products could then be used to help determine ages of stratigraphic layers in the regolith more generally. One potential stratigraphic marker already observed is the isotopic composition of solar wind nitrogen, which seems to have changed during the last several billion years. No present model of stellar evolution is able to explain this isotopic variation.

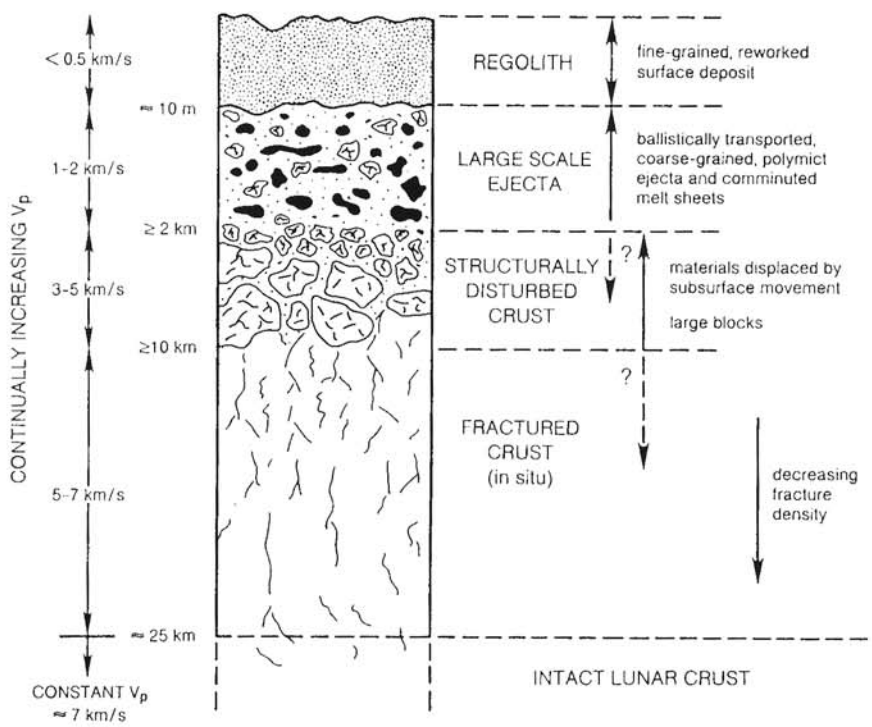
Data to be acquired. Gaining the necessary understanding of the regolith will be a major effort that requires skills in remote sensing, geological field observation, petrographic, geochemical, and isotopic analysis, geophysical interpretation of gravity and magnetic variations, and theoretical modeling of crustal igneous differentiation and regolith-forming processes. Continued study of available lunar samples will yield new insights. Obtaining global "maps" of surface composition and mineralogy, and gravitational and magnetic fields, along with adequate photographic imaging of the lunar surface, is the next step toward understanding the origin and nature of the regolith. These maps will provide information on boundaries among provinces of different composition. To interpret the maps accurately, however, models must be developed for regolith formation that are based on much more detailed study of shallow regolith in a few local regions than could be done with Apollo style observations and sampling; for this we need careful field observation of local and regional stratigraphy and extensive sampling for chemical and isotopic analysis, which will require drilling and trenching. Such an activity is beyond the capability of robotic spacecraft and will require human field study on a long-term basis.

REGOLITH FORMATION; HISTORY OF THE SUN

— Understanding the regolith imperative in fully understanding the nature of the rocks beneath it.

— Regolith traps solar wind isotopes.

— Sampling paleo-regoliths for ancient solar gases constrains history of Sun.



Idealized section of the outer portion of the Moon, showing the relations between regolith, megaregolith, and crust. Note logarithmic scale change at left. *From G. Heiken* et al. *(1991),* Lunar Sourcebook, *Cambridge University Press.*

Nature of the Lunar Atmosphere

Key scientific questions. The lunar atmosphere offers several valuable scientific resources. First, its accessibility gives us the opportunity to study a rich variety of physical phenomena that do not occur in the terrestrial environment. Through similarities with objects such as Mercury, the asteroids, and Io, the Moon provides us with a window on comparative atmospheric processes across the Solar System. Second, the lunar atmosphere is the medium through which orbiting platforms can directly study the weathering and modification of the lunar surface layer and regolith. Third, the atmosphere almost certainly provides the most sensitive means for an orbiting spacecraft to detect the presence of water on the Moon. Finally, when the infrastructure for complex, human-assisted *in situ* research is available, the Moon may even serve to act as the first planetary-scale laboratory for active experiments in the study of tenuous planetary atmospheres.

The Moon belongs to a broad class of bodies with a type of atmosphere known as a *surface-boundary exosphere,* in which energetic atoms and molecules removed from the surface can directly escape to space. Surface boundary exospheres are interesting in part because of the intimate chemical and physical connection between the planetary surface and the atmosphere. As such, the lunar atmosphere is similar to Mercury's, with important analogies to the environments thought to exist on many asteroids and other minor bodies. Given the comparative ease with which we can study and sample the lunar atmosphere, it can serve as a proxy for understanding other, more remote and therefore less accessible environments far across the Solar System.

LUNAR ATMOSPHERE

— Surface boundary exosphere.

— Nature of sources and sinks.

— Detection of surface volatiles by remote sensing.

— Physics of tenuous atmospheres.

— Establish background prior to contamination.

Twenty years after the Apollo program, our knowledge of the lunar atmosphere is still rudimentary. As evidenced by the recent and surprising ground-based discoveries of sodium and potassium vapor, even the composition of the lunar atmosphere is far from known. Prior to these discoveries, only argon and helium were known to populate the lunar atmosphere. It is now thought possible that a host of other species, including molecular hydrogen gas, various metal species such as magnesium and aluminum atoms, and even water vapor and its dissociation products may also exist in the lunar atmosphere, awaiting discovery.

One fact about the lunar atmosphere that was established long ago is that it is tenuous indeed. Upper limits derived by Apollo-based instruments indicate that the entire lunar atmosphere weighs less than 25 tons! However, the complexity and importance of this atmosphere cannot be judged by its small mass. In fact, the lunar atmosphere exhibits number densities characteristic of cometary comae, allowing us to study a wholly new atmospheric regime — a gravitationally bound cometary comae! The lunar atmosphere also contains vital information about the location of possible near-surface volatiles (including any water), acts as a reservoir of gases released from the interior, and may even mirror the composition of certain surface-lying mineralogical units.

Models simulating the lunar atmosphere have shown that its composition is likely to be highly time variable, owing to the complex interplay of the various sources and sinks at work. Among the prospective sources are internal outgassing, solar wind capture, water vapor released from cold traps and/or meteoritic bombardment, and impact-induced vaporization and charged particle sputtering of the surface. The relative importance of each of these sources varies as a function of time throughout both the lunar month and the terrestrial year. Like the sources, the range of potential atmospheric sinks is also diverse; included among those suggested or identified are Jeans escape, photo-ionization, and charge exchange. Equally important, chemical reactions between atmospheric species and the surface layer serve to modify the atmospheric composition.

A particularly important point to be made about lunar atmospheric studies is their fundamental connection to studies of the lunar surface, the lunar interior, and the search for volatile resources. By studying the lunar atmosphere, we can also learn about the rate and kind of weathering processes that affect the uppermost regolith. Such weathering is driven by the constant onslaught of charged particle and photon radiations from the Sun; radiation is known to modify the color, albedo, and microphysical structure of the lunar surface. Long-term lunar atmospheric studies may also provide the first-ever opportunity to observe and directly study the complex hydrodynamic processes occurring during planetary impacts. Owing to the high mobility and bright, characteristic spectral features of water vapor and its dissociation products in the lunar environment, atmospheric studies likely provide the best tool for answering long-standing questions about the presence of possible water-ice on the Moon. Therefore, perhaps most importantly, observations of the

lunar atmosphere may be able to reveal the distribution and magnitude of gas releases, whether they be water vapor emanating from cold traps or recent icy meteor impacts, or argon and other decay products resulting from the decay of radionuclear materials in the lunar interior.

An important reason for studying lunar atmosphere now is that any significant degree of human activity or spacecraft traffic associated with future exploration will severely perturb, if not destroy the fragile, native environment that has existed there for several billion years. Indeed, evidence of substantial atmospheric modification was observed even during the relatively brief and limited Apollo exploration era. Although preservation of the pristine environment is not mandatory to lunar science, a complete documentation of the character of that environment must be made before it is destroyed or strongly perturbed, else we will irretrievably lose important information about the history of the Moon and the long-standing space weathering environment.

Data to be acquired. To exploit the lunar atmosphere as a tool to search for volatile resources and for studying processes acting on the lunar surface and in the lunar interior, we must first survey its composition. The complex nature of the time-variable processes at work implies the need for a global survey spanning a period of many months, with access to the polar regions. A critical component in any lunar atmospheric inventory must be the identification of the location and magnitude of any sources of water vapor; as a resource, water offers the potential to greatly reduce the complexity and cost of sustaining a human presence on the Moon. In addition to identifying variations in bulk composition of the lunar atmosphere, such a survey must also determine the relative importance of the various sources and sinks as a function of time, explore the spatial correlations between atmospheric and surface composition, and quantify the role played by varying solar-wind conditions and the passage of the Moon through the terrestrial magnetospheric shadow each month. Additional measurements to determine the vertical temperature structure and ion content of the atmosphere are also needed. The particular advantages of orbiting platforms for such studies are their global coverage, their access to the lunar poles (where volatiles may be more common), and their ability to repeatedly revisit locales on a variety of temporal scales.

Beyond initial orbital surveys, future atmospheric observations should include a network of pressure, composition, and plasma environment monitors strategically placed at a variety of surface sites. Such sites might include locations near peculiar source regions.

Once human activity is established, large-scale experiments should be considered to actively probe the physics at work in the lunar environment. For example, experiments might deliberately bury ice in the regolith to simulate the evolution of lunar polar ice reservoirs or cometary crusts. Other experiments, such as the timed release of tracer species, the simulation of Triton-like or Io-like volcanoes, and the creation of moderate-scale impacts could also be made to take advantage of the lunar environment as a natural laboratory for simulating atmospheric experiments on scales too large for terrestrial laboratories.

Planetary Astronomy from the Moon

Lunar bases offer extraordinary opportunities for astronomy. Ultra-high vacuum allows full spectral coverage and resolving power throughout the electromagnetic spectrum. The stable solid surface of the Moon permits extraordinarily simple and cost-effective telescope mounts and pointing, and especially the ability to construct interferometric systems with very long baselines. The Moon's low gravity permits lighter and less expensive telescope structures; moreover, the absence of wind necessitates consideration of only static and thermal loads for telescopes, in addition to ultra-lightweight and simple "domes." The Moon has a dark, cold sky, free of airflow afflicting terrestrial and near-Earth orbits, and permits telescopes to work efficiently in the thermal infrared. The slow lunar rotation guarantees access to the entire sky visible from the given lunar latitude yet allows very long full-dark-sky exposures. The Moon's proximity to Earth permits real-time control of instruments and direct data transfer back to Earth. Finally, an inexhaustible supply of raw material and solar energy is available on the Moon for shielding and construction of astronomical facilities.

In addition to these and other virtues, the supremely important advantages in operating telescopes from the Moon as opposed to any other space environment lie in the immediate proximity of a support base with common supplies available for power, consumables, and computer facilities and, most important of all, the immediate proximity of skilled people to erect, adjust, and maintain the systems, even though their operations will normally be from Earth.

PLANETARY ASTRONOMY FROM THE MOON

— Ideal observing conditions.

— Mars synoptic weather monitoring.

— Dynamical changes in planetary atmospheres.

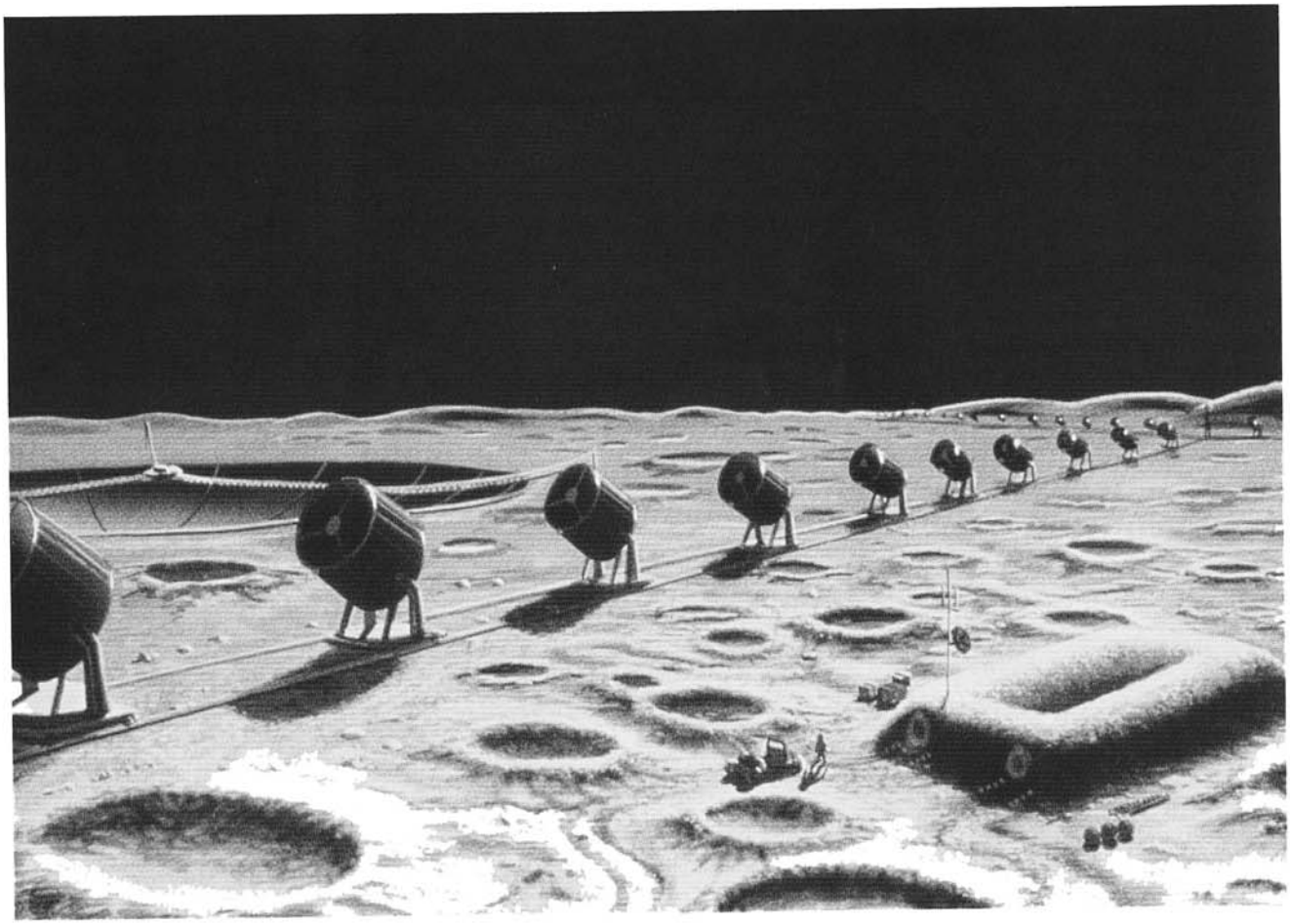
— Extra-Solar System detection.

These factors show why the Moon will surely become, in time, the principal observatory location for the human race. Ultimately, stupendous instruments can be constructed there. If an evolutionary approach is adopted, the initial instruments will be relatively modest, while nevertheless giving extremely valuable scientific results from almost the first days of a lunar outpost. Building on this experience and utilizing the gradually-decreasing cost of transportation and the rapidly increasing sophistication of robotic capabilities, it will become cost-effective to construct very large telescopes on the Moon.

Planetary astronomy has four major areas of interest in lunar-based telescopes. These are: (i) Observations of Mars in preparation for SEI, (ii) High-resolution synoptic and spectroscopic observations of the atmospheres of all the Solar System bodies possessing them, (iii) Study, discovery and characterization of minor bodies (e.g., asteroids and comets) of the Solar System, and (iv) Search for and study of solar systems external to our own.

Planetary data to be acquired from Mars. The atmosphere of Mars is radically different from ours because of its extremely low density and the fact that a substantial fraction of the principal atmospheric constituent precipitates out at each polar cap during the respective seasonal winters. Solar input drives this thin atmosphere into more violent activity than we experience on Earth, including global dust storms. It is possible that the first humans to go to Mars will require aerobraking. If they are not to risk skipping off the atmosphere with no chance of return or plunging into a denser atmosphere than expected with the risk of incineration, the Martian atmosphere should be studied in great detail throughout at least one complete sunspot cycle. Present plans envision the lunar outpost to be functioning at least a dozen years before human landings on Mars. This gives time for the installation of a 1- to 2-meter class high-resolution imaging telescope able to resolve better than 0.1 arcsecond, thus allowing systematic monitoring of the Martian atmosphere and giving a body of detailed synoptic information from which Martian climatology and its effects on atmospheric structure can be determined.

Planetary data to be acquired from other planets. Synoptic studies of planetary atmospheres do not need to be continuous. Intervals of an hour are normally quite adequate to follow the kinds of changes which can be resolved efficiently at 0.1 arcsecond



An interferometric array of telescopes on the lunar surface would possess resolving power in the range of a micro-arcsecond (i.e., ~10^{-10} degrees of arc), permitting unprecedented views of planets orbiting nearby stars as well as members of our own Solar System.

resolution. Accordingly, a single planetary imaging telescope should be able to follow the dynamical changes in the atmospheres of every planet having visible atmospheric structures. Each of these bodies is substantially different from the Earth in its dynamic meteorology. Such studies are not only interesting in their own right, but are also essential to fully understand Earth's atmosphere and its dynamics; a wide variety of atmospheres must be studied if we are to be sure of understanding our own.

Planetary data to be acquired from minor bodies of the Solar System. The continuous discovery, characterization, and monitoring of minor bodies of the Solar System is an activity ideally suited for lunar astronomical observatories. Discovery of very small asteroidal bodies will be possible with the superior optical conditions prevailing on the Moon. Objects in difficult to observe orbits (e.g., near the Sun) may be cataloged and studied. The larger asteroids can have detailed spectral studies performed by large aperture telescopes and their surface morphologies mapped by interferometers. Comets may be inventoried to a much more comprehensive degree than is presently possible. In addition to these efforts, study and monitoring of small satellites of the Jovian planets will be possible (e.g., compositional studies of Jupiter's moon Almathea or monitoring the volcanic eruptions of Io). Thus, a lunar-based astronomical observatory will greatly benefit ongoing efforts in the study of the minor objects of the Solar System.

Planetary data to be acquired from other solar systems. Finally, the surface of the Moon should also become the best place from which to operate ever larger instruments of higher resolving power, including for example, coronagraphic telescopes able to see directly disks of proto-solar system material, and even to detect the larger planets orbiting nearby stars. Most particularly, the perfect seeing conditions and ultra-stable baselines available on the lunar surface will allow the eventual construction of optical-wavelength interferometers with baselines up to many tens of kilometers, giving micro-arcsecond resolution. Such fantastic resolution would, in principle, allow one even to resolve the continents on an Earth-like planet around a nearby star. Although it will be many decades before such an instrument can be achieved, planetary studies will have a bright future from the very beginning and an ultimate goal truly worth the effort.

MISSION ELEMENTS

Introduction

Experience in the geological exploration of the Moon and planets, including two centuries of intensive study of the Earth, allows us to develop a logical and comprehensive plan to continue the exploration of the Moon. The plan presented here is both scientifically rigorous and operationally flexible. In order to carry out the themes of the scientific strategy, mission elements are defined. The plan then becomes the orderly execution of a mix of the mission elements, the exact nature of which is dependent on the architecture adopted for SEI. Six mission elements are described: (i) Earth-based and Galileo flyby observations, (ii) orbiting spacecraft, (iii) geoscience rovers, (iv) global geophysical network, (v) return of reconnaissance samples to Earth, and (vi) geological field investigations. The explicit relationship of the science themes to the mission elements is shown in Table 1.

Earth-Based and Galileo Observations

Prior to the lunar orbital survey missions, Earth-based and Galileo observations can provide new data that will start to address the science themes discussed here, as well as to help identify and characterize potential human landing and lunar outpost sites. There is an immediacy to initiating science activities from the Earth if the planetary science strategy for the Moon outlined here is to be implemented and seriously underway by the turn of the century. During the 20 years since Apollo, when activity shifted to other parts of the Solar System, the once robust lunar science community has been greatly diminished in all areas and comes close to disappearing in some. With the exception of a reduced but active program in planetary materials, only a small number of scientists and technical personnel are actively involved in or trained to deal with the kind of science (and engineering) questions that must be faced during the next decade as a serious return to the Moon is undertaken.

Important science between now and lunar orbital survey missions. Earth-based telescopic observations of the Moon, using available instrumentation, should be enhanced. Tasks include establishing a baseline on lunar atmosphere, testing promising remote sensing techniques and instrumentation (thermal infrared, optical polarimetry, etc.), and expanding science applications with proven techniques (near-infrared spectroscopy, multispectral imaging, radar, etc.) to strengthen our base of strategic scientific knowledge.

Aggressive advanced sensor development and utilization should be undertaken for use with Earth-based optical and radar telescopes. An integrated data acquisition and analysis program could provide an early assessment of regional and regolith compositional properties of potential lunar base sites.

Galileo, launched in 1989, provides the first return to the Moon with an array of spaceborne sensors. A Galileo Lunar Data Analysis program should be initiated to maximize the return from the two encounters with the Moon: (1) December, 1990 - unique perspective on Mare Orientale, the youngest and hence most well preserved large basin on the lunar surface, and on the South Pole-Aitken Basin, now the largest documented basin on the Moon; (2) December, 1992 - unique perspective over the north pole and high latitudes of the Moon.

Other spacecraft, such as the Hubble Space Telescope and the Gamma Ray Observatory, offer potential opportunities for new remote sensing observations of the Moon.

Laboratory experiments and modeling of analogue, simulated, and real surfaces should be expanded explicitly for lunar applications. Careful documentation and characterization of the interaction of electromagnetic radiation with surface materials is necessary to provide the solid base for accurate interpretation of remotely sensed data obtained with sensors on Earth-based telescopes, lunar orbiting sensors, and more advanced teleoperated sensors on the surface of the Moon.

Orbital Missions

Orbital missions will provide crucial data for the scientific elements described above as well as carry out detailed site surveys and resource surveys to aid in the selection of human landing and outpost sites. The information to be acquired in orbit is critical in both regards: Global geochemical and petrological surveys, global and high-resolution imaging, surveys of the lunar atmosphere, global gravity and magnetic surveys, microwave radiometry to estimate heat flow and regolith thickness, and global altimetry.

Table 1. Planetary Science Themes and Primary Mission Element Requirements

	Earth-Based/ Galileo Obs.	Orbital Missions	Geo-science Rovers	Geo-physical Network	Recon. Sample Returns	Geologi-cal Field Work
Formation Earth-Moon System		■		■	■	■
Thermal/Magmatic Evolution		■		■	■	■
Impact Processes & Bombardment History	■	■	■		■	■
Regolith Formation and Evolution of Sun		■	■		■	■
Lunar Atmosphere		■	■	■	■	
Planetary Astronomy*	■	■			■	■

*Planetary astronomy is a technique that might require some of the mission elements for observatory emplacement.

The science objectives of lunar orbital missions are: (i) Estimate the composition and structure of the lunar crust in order to determine its origin and evolution. (ii) Determine the origin and nature of the lunar magnetic field and estimate the size of the lunar core, if it exists. (iii) Estimate the refractory element content of the bulk Moon by measuring the mean global heat flow and using the refractory content of the crust as a constraint. (iv) Determine the nature of impact processes over geological time and how they have modified the structure of the crust. (v) Determine the nature of the lunar atmosphere and the physical basis for its sources and sinks.

To meet the science objectives, the following set of measurement requirements have been determined and are shown on the following page.

Much of the basic global compositional data obtained to satisfy the goals of lunar science are directly applicable to the assessment and quantification of resources on the Moon. Lunar resources provide useful materials for use on the Moon and in space. Such materials include bulk regolith and metals for shielding, oxygen and hydrogen for propellant and life support, energy resources, construction materials such as glasses, ceramics, and metals, and other life supporting elements including carbon, nitrogen, and sulfur. The ultimate success of a program to explore the Moon in some detail may well rest on our ability to assess the location and nature of usable materials on the Moon.

The planetary science strategy depends on the accomplishment of the full measurement objectives shown here. It is essential that the entire lunar surface be mapped to implement this strategy; this should include geochemical, mineralogical, geophysical, and photographic maps. Besides addressing the science themes, orbital science missions will provide critical information about regions containing potential resources, sites for robotic reconnaissance surface missions and intensive field work, and placement of the stations of a geophysical network.

Geoscience Rovers

The extent to which human presence can be substituted, or at least supplemented, by robotic means is uncertain. Certainly, robotic techniques will play a role in sample gathering and remote sensing/geophysical surveys, particularly at great distances from a human landing or outpost site. Teleoperated robotic vehicles hold the promise of creating human presence remotely at a field site. The strategy for determining the mix of human operations, robotic operations, and

ORBITAL MISSIONS: MEASUREMENT REQUIREMENTS

— Determine globally the elemental and mineralogical composition of the surface.

— Determine globally the surface topography and gravitational field.

— Map globally the distribution of surface magnetic anomalies and measure the magnitude of the induced dipole moment.

— Obtain a global image data base along with selected coverage in stereo and color.

— Measure the microwave brightness temperature as a function of wavelength.

— Measure globally the composition, structure, and temporal variability of the lunar atmosphere.

teleoperated robotics has yet to be worked out and depends on the pace of technology development.

An unpiloted roving vehicle could be used to address a variety of scientific problems. Some reconnaissance studies can be made by making *in situ* analyses of the lunar surface. Such measurements are especially needed for studying time-dependent phenomena (e.g., gas migration driven by diurnal temperature variations) and in making measurements of undisturbed soils and rocks in the natural lunar environment. A semi-autonomous rover could be equipped with a geophysics package, including ground-penetrating radar to obtain data about the depth and blockiness of the regolith and bedrock layers beneath. The rover could also be equipped with stereo imaging, both for ease of teleoperation and for making scientific observations. It also needs to have sampling capabilities and the means to do chemical analyses of the samples. Sample selection would be aided by inclusion of a visual-infrared imaging spectrometer. A rover so equipped could be used to collect reconnaissance samples for return to the lunar outpost/landing site for initial processing and ultimately, to Earth. Alternatively, lunar soft landers could be used to return rover collected samples to Earth. Rovers could also be used to deploy geophysical stations as part of a global network. Semi-autonomous rovers will be essential tools in the detailed exploration of the Moon and can provide a test of the concept of doing field work by teleoperations. Development of autonomous or semi-autonomous rovers will also provide essential experience in payload design and operational strategies for using roving vehicles on Mars.

Geophysical Network

Geophysical measurements on the lunar surface are required for most of the scientific elements of the program. Geophysical techniques fall into two categories: regional exploration and global networks. Regional geophysical surveys could be carried out robotically or by humans. They involve measurements along baselines up to about 100 km in length. The measurements may be repetitive along the baseline (e.g., gravity surveys) or may involve laying down an array of sensors with an active source of energy (seismic surveys).

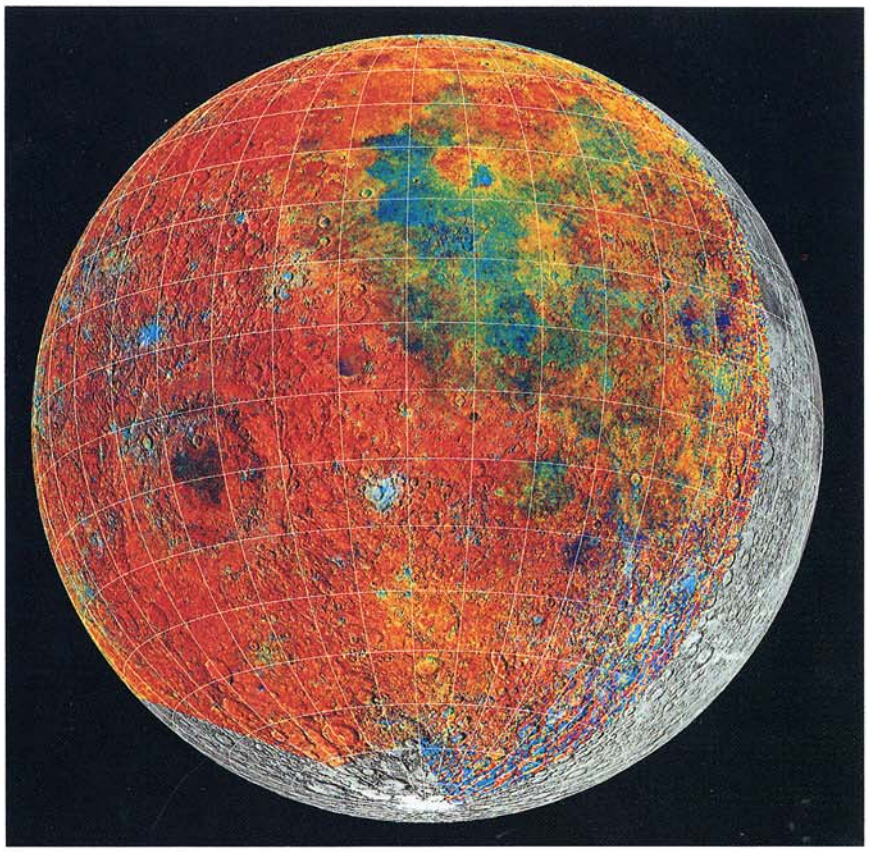
Global access to emplace a geophysical network is also required. A thorough understanding of the Moon will be impossible without knowledge of its interior. The mission activities required to achieve this element involve setting out geophysical stations on a global basis. Such stations would include 3-axis broadband seismometers, heat flow probes, magnetometers, and possibly atmospheric monitoring experiments.

In principle, these stations may be deployed by unmanned soft landers, humans (as in the case of the Apollo stations), or teleoperated robots. The deployment of at least six regional seismic arrays around the Moon would yield data markedly superior to the Apollo data for the purpose of establishing the structure of the crust and lower mantle and for the characterization of a metallic core. Similarly, heat flow measurements at a variety of highland and mare sites would provide a definitive measure of the global mean heat flow. Heat flow probes would most conveniently be deployed in the course of establishing a global seismic network. Other geophysical instruments would allow further deep magnetic sounding studies and characterization of the tenuous lunar atmosphere as a function of time.

At least eighteen geophysical stations (six three-station arrays) are required for a full-up network, along with an orbital communications relay satellite carrying a magnetometer. The full network must be operational for at least a decade.

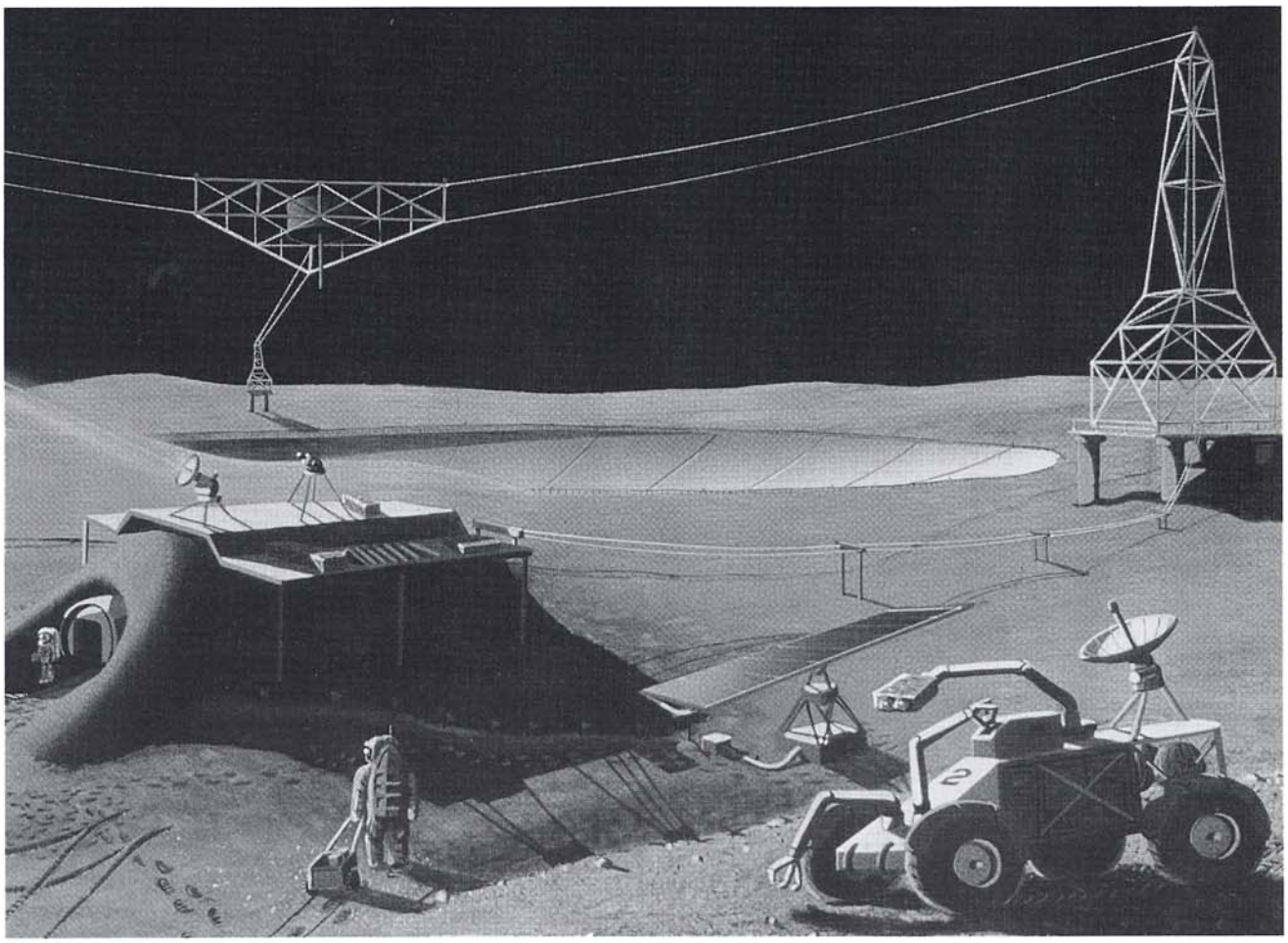
Reconnaissance Sample Returns

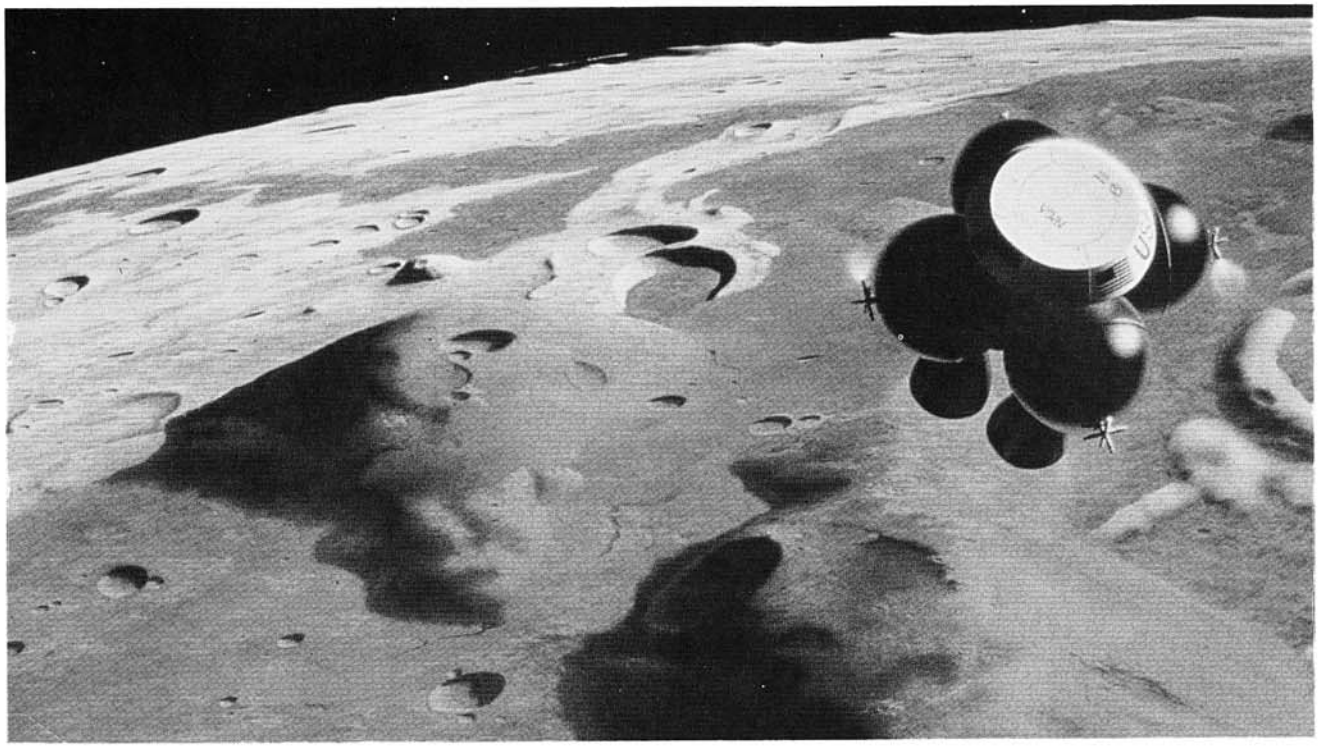
Many significant scientific questions can be answered through the study of samples returned by relatively unsophisticated, automated spacecraft. Automated roving vehicles or landers operationally similar to Soviet Luna spacecraft could be sent to numerous sites over a period of many years. Simple reconnaissance samples are valuable for broad, regional units, whose geological contexts are clear and uncomplicated. Such sample-return missions are an important part of the general scientific exploration of the Moon and may or may not be related to a human exploration program. Development of the technology to collect reconnaissance samples from specific locations will



Left: A false-color composite of data showing surface compositional differences obtained during the Galileo spacecraft flyby of the Moon in December, 1990. In this rendition, red reflects the presence of highlands materials with low iron content, similar to those at the Apollo 16 site while yellow indicates highlands areas of moderately high iron content, possibly reflecting the presence of ancient mare basalts. The maria are portrayed in orange (low-Ti) and blue (high-Ti) colors.

Below: The geological reconnaissance of the Moon is an ongoing scientific requirement, even after the return of people to the Moon. For example, the taking of reconnaissance samples could be combined with automated rover traverses that are conducted primarily for other reasons, such as routine maintenance of a remote telescope facility. *Artwork by Eagle Engineering for NASA.*





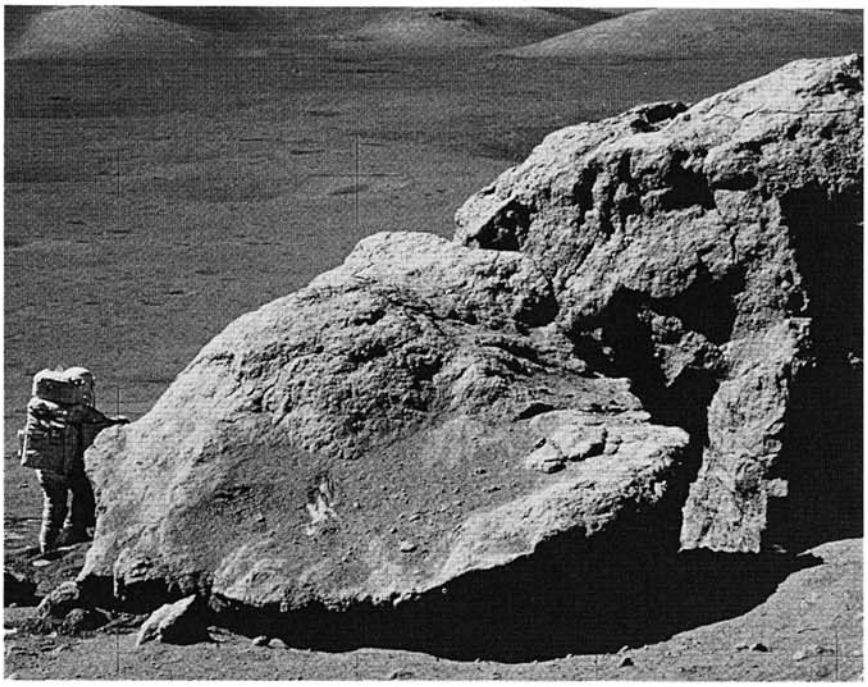
The return of reconnaissance samples is an integral part of our scientific exploration strategy. Here an automated sample return spacecraft lifts off the Moon on an Earth-return trajectory, having collected a surface sample of the enigmatic Gruithuisen domes area of the Moon. *Artwork by Eagle Engineering for NASA.*

offer a cost-effective technique to sample other planetary surfaces as well.

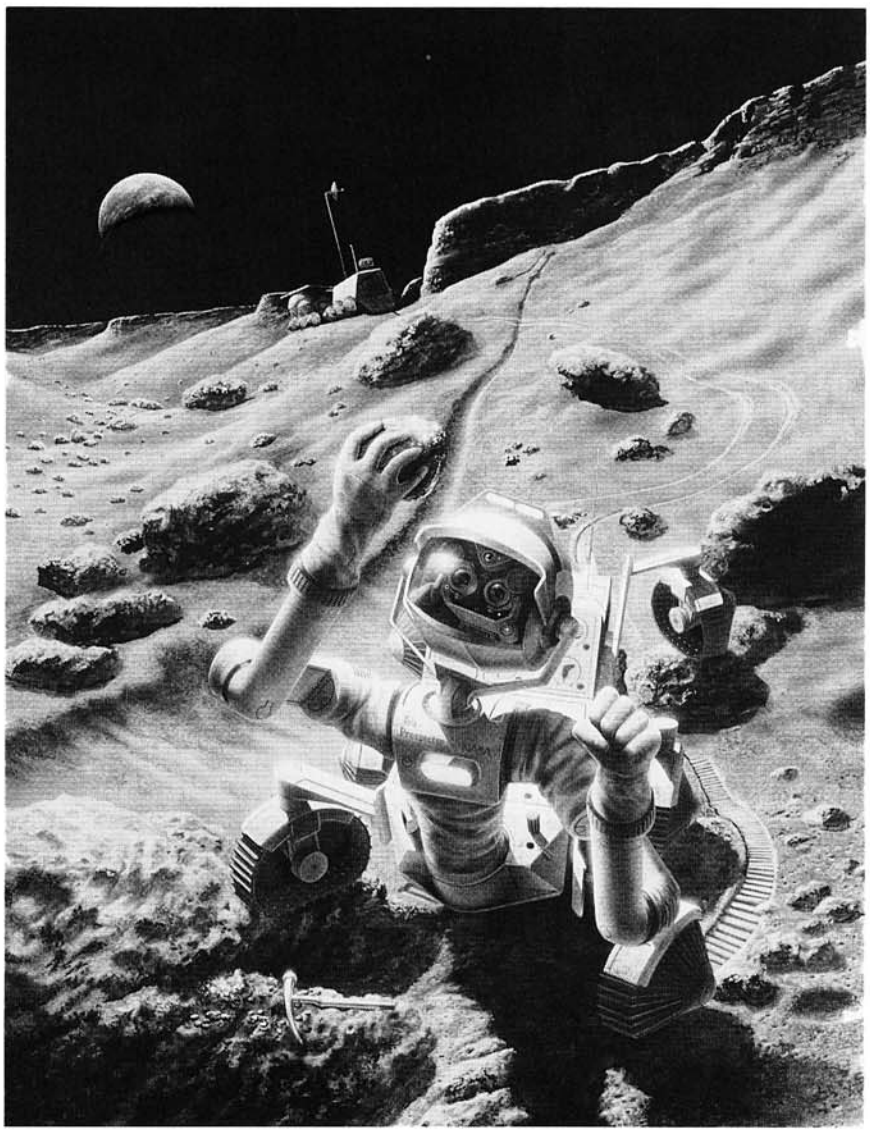
Geological Field Work

A crucial component in addressing scientific goals is the ability to take advantage of the human presence on the Moon. Specifically, field work is required to understand the geological context of specific rock types before they are sampled. Knowledge of the field relationships of one rock type to another and the local tectonic setting of any given rock type is required to intelligently address the issues involved with crustal formation, for example. Additionally, both the cognitive powers and dexterity unique to humans are necessary to recover certain rock samples such as small xenoliths from the lunar mantle embedded in a basalt flow. Global access for field work is ultimately required.

Geological field work is a complex, work-intensive activity that requires the presence and guiding influence of human intelligence. Field work requires long-duration missions, so it clearly requires the capabilities that accompany a lunar outpost. These capabilities will expand with time. Initial human field work might be restricted to within 10 to 20 km of an outpost site. This range could be increased by development of pressurized roving vehicles, but significant advancement will come with the development of telepresence robotic systems, which will greatly extend the range of field operations. As the outpost is being constructed, astronaut time will be devoted to construction, near-outpost field work, and deployment of geophysical and astronomical equipment, but once this first phase of activity is completed, the technology for the teleoperated field geologist needs to be available.



Geological field work is a complex, labor-intensive activity that requires human intelligence and interaction. One way that we know that it can be accomplished is through the use of human field geologists. The large amounts of time available to the people who will inhabit the Lunar Outpost (relative to the short-lived expeditions of the Apollo era) will permit the conduct of true field science and should be planned for in any lunar base architecture.



One way to extend human reach is through the techniques of robotic telepresence. In this concept, a machine actually traverses the Moon, making observations and collecting samples while under the complete control of a human operator who, because of high fidelity sensory data, feels to be physically "present" within the robot. It is not certain if this operator must be on the Moon (for example, in the lunar habitat module) or whether field investigations can be conducted from the Earth (in which the operator experiences a 2.6 second round-trip time delay). *NASA artwork by Pat Rawlings.*

IMPLEMENTATION OF EXPLORATION STRATEGY

Introduction

It is by no means clear what the final architecture for the lunar phase of the Space Exploration Initiative will be, and with that comes uncertainty in the phasing of the mission elements necessary to carry out the planetary science strategy. However, this strategy is flexible. Except for the immediate need for polar orbiting missions to map the Moon, the timing of other types of investigations is open. Reconnaissance and network science can begin before or after a lunar outpost is established or the first human landings take place, or even if an outpost is not established; science activities must continue for years after humans first return to the Moon. Field work can begin modestly near the outpost or landing site, but then can take place anywhere on the Moon through the use of pressurized roving vehicles carrying human geologists, and through the use of robotic field geologists.

Implementation Example: Solar History as Recorded in the Regolith

To help explain how the strategy described above could be implemented, we discuss here how a specific scientific problem, the history of the Sun, will be addressed during hypothetical phases of lunar exploration. This process entails investigating the problem at increasingly greater levels of sophistication and detail as exploration capabilities grow.

Early robotic phase. During this period the lunar regolith will be studied using orbital missions and possibly semi-autonomous rovers. Specific tasks are to understand and characterize regolith blockiness, soil maturity, and thickness variations in an attempt to more completely understand regolith growth. Electromagnetic sounding and ground-penetrating radar carried aboard an automated rover would provide specific information on the bedrock-regolith interface, block distribution, and thickness variations of the regolith at the site.

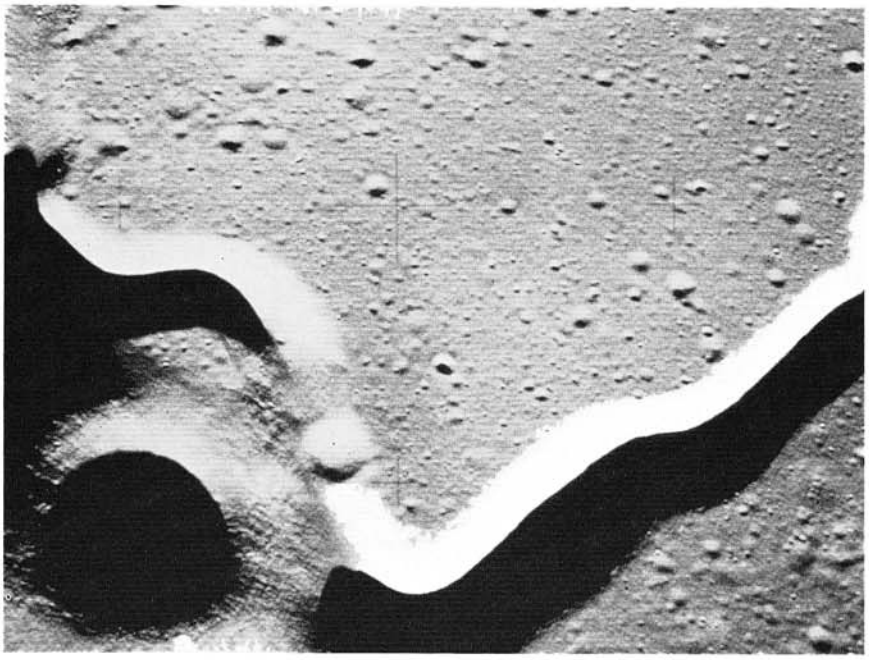
Early human phase. With the return of humans to the Moon, regolith investigations become much more sophisticated. One of the first steps will be to comprehensively sample and analyze the regolith in the area near the outpost/landing site to characterize it for more detailed study. Initial analyses might be simple (e.g., major-element chemical composition) and could be used to prioritize the selection of samples to be shipped to Earth for detailed analysis. Pits into the local regolith will be dug and each one will present a scientific opportunity to study the regolith at depth. Specific tasks for pit study are to identify any site-wide stratigraphic layers (e.g., a crater ray deposit), sample and analyze specific regolith columns, and determine the nature of the regolith/bedrock interface (at a mare site). On a smaller scale, shallow (2-3 m) drill cores collected over a wider area will yield information on regolith variability around the site.

Intermediate phase. During this stage, the crew will have more time to address regolith problems. Moreover, results from sophisticated Earth-based laboratory analyses will be available from the samples collected previously. Such data will include information on major and trace-element chemistry, isotopic data (including cosmic-ray exposure ages of specific rocks and argon degassing ages for impact glasses), and abundances of implanted solar-wind elements and isotopes. These data will permit an initial attempt to model the growth dynamics and history of the regolith at the site. Additional investigations will be performed, collecting and analyzing regolith samples from both additional sites nearby and selected sites farther afield during traverses devoted to regional field geology.

Full lunar exploration phase. With the advent of global access and virtually unlimited time to study lunar problems, regolith and solar history studies could enter a new phase. Sophisticated and complex studies would be aimed at completely understanding regolith growth and evolution and the history of the Sun. For example, regolith developed on an entire mare basalt flow of known age could be mapped, studied, sampled, and analyzed, thus detailing solar-wind output over the last four billion years. Such a solar history could be finely time calibrated through correlation with ages of specific impact craters that formed after the flow (the ages would be obtained by argon dating of melt rocks and glasses and by measuring cosmic ray exposure ages). In addition to information about the history of the Sun, such research would also provide information on the controversial question of cratering flux episodicity.

During extended geological traverses, specific attempts should be made to identify and explore lunar paleoregoliths (e.g., regoliths developed between two lava flows of known age). Sampling such a paleoregolith would allow analysis of implanted solar-wind constituents, yielding a snapshot of solar

output from a known, limited interval in the geological past. A number of lunar paleoregolith samples would provide valuable calibration points to understand the detailed solar history discussed above and to assess the long-term (order of one-billion years) variability of solar output.



Hadley Rille, an example of a site where the composition of the ancient solar wind could be addressed. Right: Orbital view of the rille. Average width is about 2 km. Below: Surface view showing layering in the west wall of Hadley Rille near the Apollo 15 landing site. Ancient regolith may be present between the basalt layers, providing us with a "snapshot" of the solar output over 3 billion years ago.

RESEARCH AND ANALYSIS

Introduction

Research and analysis is required in a large number of disciplines as a precursor to carrying out the lunar program and to attract and train young lunar scientists. To accomplish the goals in the time frame required, the human infrastructure of trained lunar scientists must be aggressively expanded, technical facilities must be upgraded to provide first class research capabilities, and a solid interpretative data base of remote measurements must be established. Definition studies must be started for scientific experiments to be carried within the mission elements. Examples of the kind of technological research needed are development of teleoperation techniques and miniaturization and packaging techniques for scientific instruments.

Need for Solid Science Activities During Robotic Phase and Later

Specially funded interdisciplinary lunar science research programs should be initiated, similar to the Mars Data Analysis Program. These would be focused research and analysis programs developed to stimulate activity and scientific thinking about unresolved problems in lunar science. They are very important to expand the community of knowledgeable lunar scientists and prepare them to efficiently use global lunar data.

U.S. education in science and technology needs to be revitalized to meet the challenge of space science. The human infrastructure for lunar science depends on people who have been technically trained with advanced instruments and techniques and who are familiar with the major scientific advances made during the last several decades. It is recommended that a significant NASA graduate trainee program for lunar science be implemented, as well as a program for post-doctoral research fellows in lunar science.

Similarly, U.S. laboratories must be maintained at the highest level of technical capabilities in order for U.S. researchers to participate as leaders in international space science during the next decade. A significant expansion and upgrade of scientific instrumentation in university and federal laboratories must occur over the next decade. Analytical, experimental and computational capabilities must compete at the technical level where significant science now proceeds.

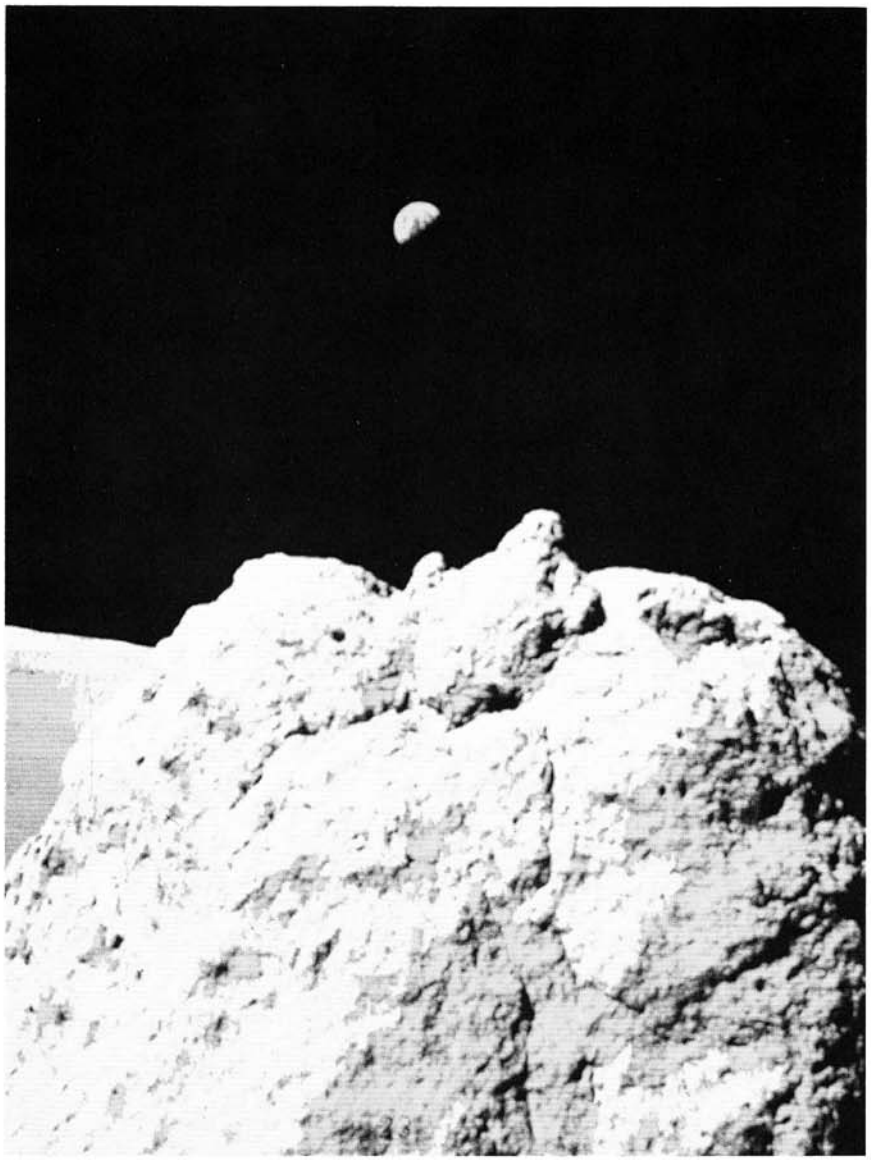
Since technology has advanced significantly since the Apollo and pre-Apollo data for the Moon were obtained, there are areas where retrospective science can optimize use of available data and produce new information. Examples include: creation of digital images from Lunar Orbiter and Apollo photographs, and re-analysis of Apollo tracking data with new algorithms to improve current lunar gravity information.

There are major instrument development requirements that affect the science output. Instrument definition studies should be initiated for surface experiments (geophysics, atmospheric monitoring, etc.). Teleoperated techniques for efficient geological field work at remote sites need to be developed and tested. Similarly, teleoperated techniques will have to be developed to identify and select specific kinds of samples that are exceptionally valuable (e.g., mantle xenoliths). In addition, definition studies need to be initiated for experiments using the unique solar and galactic environment of the lunar surface.

The extraordinary merit of using the lunar surface for astronomical observations is well recognized. To realize its promise for planetary science (monitoring transient events and weather on Mars, Jupiter, Io; search for extra solar systems) requires that telescope design begin immediately and that prototype telescopes be built. There is no reason why the first emplacement of the lunar outpost would not contain a dedicated planetary science telescope that would usher in this stimulating new era.

MOON-MARS SYNERGISM

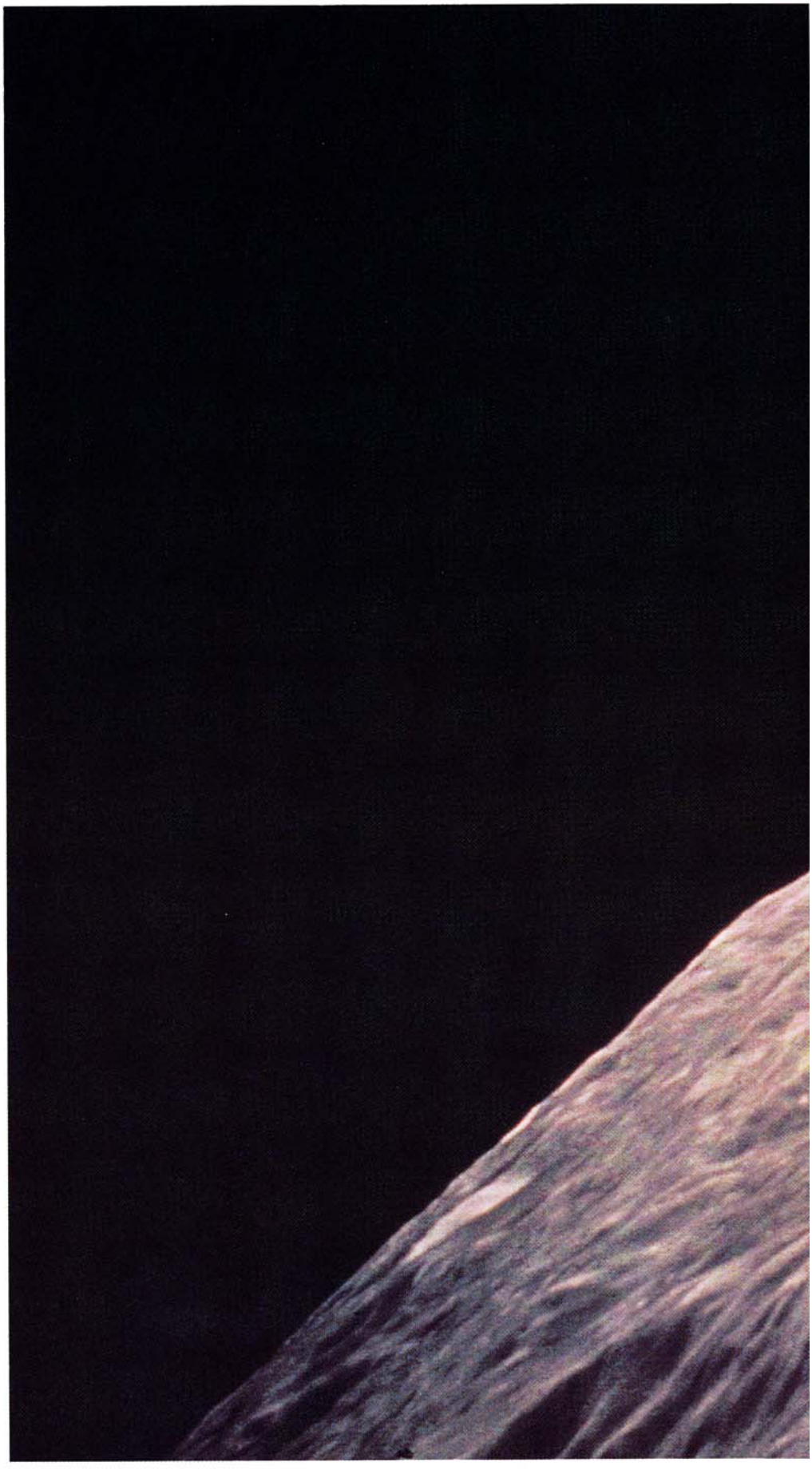
Exploration at a lunar outpost will dramatically increase our understanding of both lunar history and processes. This knowledge will facilitate understanding of the geological processes of Mars. For example, our vastly improved knowledge of how large impact craters and basins form will help us decide where to sample such structures on Mars. The lunar experience will have provided technologically advanced robotic tools for use in geological studies, including experience in doing field work by teleoperation. Lunar exploration will have provided experience in defining the proper mix of human operations, teleoperations, and autonomous robotic operations. By the time we reach Mars, we will have increased capabilities in our use of pressurized rovers and have vast experience in doing field work wearing pressure suits. Finally, exploration from the lunar outpost will have given us years of experience in geological exploration in sites remote from both the outpost and the Earth, essential experience for planning excursions on Mars.



SUMMARY

We have set out six science themes to be carried out at the Moon, addressing fundamental planetary science issues such as origin of the Earth-Moon system, history of the Sun, early impact and magmatic history of a planet, and possible episodic extinctions of life on Earth.

Our approach to implementing the science strategy has been an exploration-architecture-independent matrix of mission elements and science themes. This scheme emphasizes increasing confidence in scientific models with increasing implementation of mission elements. This approach also emphasizes flexibility and adaptability as the Space Exploration Initiative architecture becomes better defined for the Moon.



LExSWG

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