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Report of the Terrestrial Bodies Science Working Group

Volume IV. The Moon

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Space Administration

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OVERLEAF: The Moon—Earth's Nearest Neighbor

Studied intensively for hundreds of years and the only extraterrestrial body to be visited by man, the Moon remains enigmatic: the greater our knowledge, the deeper and more challenging the questions concerning the origin and evolution of the planet. Further exploration of the Moon poses two challenges—the scientific challenge to build upon the foundation of knowledge already in hand and the social and economic challenge to utilize the potential of lunar resources for the benefit of all mankind.

(Lick Observatory photomosaic of lunar near-side. Left side illuminated from left, right side from right; JPL photograph M-3273A)

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Science Working Group
Volume IV. The Moon**

September 15, 1977

National Aeronautics and
Space Administration

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PREFACE

This volume is one of a nine-volume series documenting the work of the NASA-sponsored Terrestrial Bodies Science Working Group in developing plans for the exploration of Mercury, Venus, the Moon, Mars, asteroids, Galilean satellites, and comets during the period 1980-1990. Principal recommendations and conclusions are contained in Volume I (Executive Summary); reports and working papers of the study subgroups are presented in Volumes II-IX.

This volume is the report of the Moon subgroup, whose members and contributors are L. A. Haskin (chairman), M. B. Duke, N. Hubbard, T. V. Johnson, M. C. Malin, and J. Minear.

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SECTION I

FURTHER EXPLORATION OF THE MOON

Moon and Earth are a unique binary planet system. More is known about the Moon than about any other planet except Earth. This is a direct consequence of the Apollo program and prior supporting missions. We now know that the Moon is a differentiated planet with its own evolutionary history. Changing ideas about the Moon are significantly affecting our ways of thinking about all planets and the strategies for their exploration (including Earth). The Moon's role in the planetary evolution of Earth is not well understood; for example, its effects, if any, in making Earth capable of harboring life are not known. Only the Moon of all the planets provides an accessible, detailed record of early events in the history of the solar system and in the evolution of planetary bodies. The thick lunar lithosphere and early cessation of major lunar vulcanism may contain lessons about Earth's distant future. The Moon's composition and density do not fit the major theory for condensation of planets from the solar nebula.

In the context of orderly exploration of solid planetary bodies, we are fortunate in already having lunar scientific stations and surface samples from which much of our present knowledge derives. We also have fairly complete orbital photographic coverage and a limited amount of other orbital data. To complete the "first order" data base for the Moon as a planet we must have a global survey of geophysical and geochemical characteristics. Present lunar understanding is such that these data are needed now to constrain and guide our development of hypotheses of the compositional and structural nature of the Moon and its history and thereby affect our views of all terrestrial bodies. Obtaining global data for the Moon will not precede sample return. Knowledge from samples and surface science, however, will greatly enhance our ability to interpret the global data when it becomes available. The experience will improve our ability to interpret global data from other planets. Thus, for the most effective program, a global survey of the Moon should precede such surveys for other bodies.

Because of its proximity to Earth, the Moon is the overwhelming candidate for establishment of man's first planetary base and first use of extraterrestrial resources, in situ or in orbiting space stations. Even before serious planning for such uses of the Moon, a global survey of lunar resources is needed. The nature of a lunar base or the manner in which lunar materials would be used (or even whether they would be used) would be greatly influenced by the discovery of unknown quantities, such as water or some other valuable resource. The survey would determine the distributions of lunar materials of known types and will surely indicate the presence of new types, information essential to determining the optimum site for the multiuse base. In order for results from the global survey to be useful, the survey would need to precede site selection or planning for resource use by approximately five years, to allow time for data reduction, correlations, and overall synthesis of knowledge about the Moon.

Such a resources survey of the Moon for future utilization and the global survey required in the context of scientific exploration of solid bodies are highly compatible: in fact, they are virtually identical. The Lunar Polar Orbiter mission (Section II), which has been formulated in great detail, meets the major requirements of both types of surveys. Because of the timeliness and importance of completing the basic data set on the Moon and its effect on planning for and using data from the other solid bodies (see Section III), we have given this mission our very strong endorsement.

In the context of solid-body geoscience, the data from LPO is needed now. A decision to make use of the Moon and its resources, if it occurs at all, will probably arise suddenly rather than as part of a long-range plan; however, such use can be anticipated by the end of the 1980's. Thus, it is important that the LPO mission be flown in the earliest 1980's.

Other types of missions to the Moon will also be needed (landers, sample returns) either in response to scientific questions raised by LPO or Apollo data or more detailed, local information about proposed base sites. The LPO is a necessary precursor to these missions. In short, further exploration or informed use of the Moon is dependent on study of results of the LPO mission.

In considering a long-range scientific program for the Moon, we have identified four aspects, as listed below:

1. Intensive study of Apollo and lunar samples and ALSEP and Orbiter data, accompanied by theoretical work and data synthesis, should continue for as long as solid scientific results are forthcoming. It is vital to planetary science and to the ultimate use of the Moon that a cadre of planetary scientists with strong interests in the Moon and experience working with lunar data and samples be maintained. This is necessary both for the full use of lunar data and for maintaining the geoscience capability that will be needed for more detailed study of other terrestrial bodies. The lunar samples and Apollo data must be carefully protected for future generations of scientists. It is vital that we continue to acquire material for study from Soviet Luna missions.

2. A global survey of the Moon must be made. This survey is the principal task of the proposed Lunar Polar Orbiter mission and has been discussed extensively above. It is vital that, until LPO is funded for a new start and instrument designs become fixed, adequate funds be provided for continued development of instruments for that mission so they will reflect state-of-the-art technology when the mission is flown.

3. The global survey, future analysis of existing samples and data, and planning for use of the Moon and its resources will bring about needs for further surface landers. These needs cannot be specified now, but some idea of the nature of future scientific missions can be given.

In terms of additional sampling, for example, it must be remembered that Apollo and Luna sampling have, by and large, avoided the areas most characteristic of the lunar surface, i.e., most common types of lunar highlands. No samples have been returned from the lunar far-side, already known from existing geophysical and geochemical information to be somewhat different from nearside terrains. LPO data may indicate sites where deep crustal or upper mantle material might be sampled. Any site of strikingly high or low concentration of a remotely sensed chemical element could be an important target for future sampling. Chemical characterization of a proposed site for a lunar base or acquisition of lunar resources might require additional sampling. It may prove desirable to sample areas of younger mare basalts than obtained so far and to determine compositions and ages of the relatively rare farside mare materials. It may prove desirable to obtain detailed information on volatiles which are hypothesized to be trapped at the lunar poles. For all our present confidence that we have extensive samples of lunar materials and can safely generalize about the nature of the Moon overall, our detailed sampling is from relatively few, somewhat atypical sites within a narrow geographic band on the Moon's nearside. For there to be no important and striking differences in other parts of the Moon would indeed be an anomaly in scientific exploration!

Certain standard classes of measurements could be carried out by hard or soft landers (e.g., chemical composition); a standard package of such instruments might accompany landers sent for more specialized purposes. Some examples of specialized landers are the following: If the presence of volatiles at the lunar poles was indicated by LPO data, a lander could carry instruments similar to the Viking gas chromatograph/mass spectrometer to characterize them. Similar instruments could determine the flux of ^{40}Ar in the lunar atmosphere; that in combination with alpha-particle detectors for Rn would provide information on outgassing and behavior of volatiles absorbed on lunar soil. Soft landers could deploy additional laser ranging reflectors in widely dispersed locations, if needed for improved libration determination and extension of the selenodetic network. They could deploy active seismic experiments for determination of local crustal structure. Currently, no seismically determined crustal information is available for the farside. Hard landers could be deployed to provide a broad seismic net about the Moon with six or more instruments at distances of the order of 1000 km apart. Network lifetimes and data acquisition times of 3-5 years could be achieved. Hard lander seismometer sensitivity would have to be at least that of the Apollo seismic network if significant information beyond that from Apollo were to be obtained.

4. By the late 1980's we anticipate that there will be lunar bases, manned or unmanned or, at least, plans for the establishment of such bases. Additional scientific study (LPO and beyond) will be needed for establishing such bases, and the bases will serve, in part, to support future scientific exploration of the Moon. Planetary geoscientists will contribute substantially to the applied studies pertinent to establishment, habitation, and uses of the bases as well as using them for additional geoscientific exploration. It is imperative for these purposes that

an interested and knowledgeable group of such scientists continue working on lunar problems.

The rationale for establishment of lunar bases is expected to stem principally from programs to use the Moon and near-Earth space for economic purposes. On scientific grounds alone such a base might be justified, however, by the combined opportunities it would afford to the physical, the life, and the social sciences and to engineering research. Planetary science would contribute or be advanced in the following ways: Lunar geoscientific studies will be required for general site selection, local geologic engineering, local exploration for resources, resource geochemistry, and practical understanding of the immediate environment of the base. Planetary science will be an objective of any lunar base program and will provide detailed local geology of a planet very different from Earth. Manned investigations with surface mobility ranging up to 100 km from the base will be needed. A long-term geophysical network could be established and serviced from such a base. Lunar rocks and soils could be collected systematically and with geologic control for detailed analysis on Earth. Excavation and deep drilling programs would vastly improve our knowledge of subsurface composition and structure. The lunar base would be used for investigating present and ancient interactions of the Moon with meteorites, solar radiation, and cosmic radiation.

We note that favorable solar insolation and possible presence of volatiles might result in bases near the lunar poles. Those are now the least well characterized regions of the Moon, and will remain so until a global survey is completed.

SECTION II

MISSION SUMMARY FOR LUNAR POLAR ORBITER MISSION

A. SUMMARY

Lunar Polar Orbiter (LPO) is an important step in the exploration of the solar system. First, the LPO represents excellent planetary science. The Moon provides the most accessible record in the solar system of early planetary evolution, including chemical differentiation, igneous and tectonic activity and the effects of heavy meteorite bombardment. As a representative member of the terrestrial planets and of a number of other solar system objects, the Moon will advance significantly our understanding of the early formation and evolutionary processes of planetary objects. Global geochemical and geophysical data provided by the mission will be timely in their contribution to our present understanding and data base for the Moon, and will allow the testing and extension of hypotheses that are based largely on data from a few lunar sites. The existing absolute chronology, the numerous and varied data from lunar samples and the surface experiment packages will permit the maximum science to be derived from the global LPO data.

Second, LPO represents a new class of spacecraft in instrument complement and in spacecraft evolution. Such spacecraft can provide a high degree of commonality in the types of measurements made on the terrestrial planets. The scientific success of such missions depends on extensive interaction and correlation of the data from different experiments.

Finally, the Moon is a logical way-station in our continued exploration of space, whether as a base for scientific exploration or resource utilization. LPO will provide the global geochemical and topographic survey necessary for such future activities.

 Lunar Polar Orbiter 1980

Launch date:	October 1980
Orbit insertion:	L +115 hr
Orbital lifetime:	1 year
Injected mass:	482 kg
Orbited mass:	297 kg
Subsatellite mass:	28 kg
Instrument mass:	65 kg
Launch vehicle:	Delta 2914, one launch

The objective of the LPO mission is to advance significantly our understanding of the processes of planetary formation and early evolution through global measurements of our most accessible planetary neighbor, the Moon, which retains a relatively undisturbed record of those processes.

1. Science Investigations

Science experiments and mission objectives are given in Table 1. Science payload characteristics are given in Table 2.

2. Mission Description

A polar orbiter spacecraft, (Figure 1) will be inserted into a 118-min, 95-deg inclined circular orbit at 100 km altitude. Nadir pointing instruments will map surface chemical and mineralogical composition using gamma-ray, X-ray, and spectral reflectance spectroscopy and multispectral imagery. Global heat flow will be mapped using microwave and infrared radiometry. Magnetic fields will be mapped using magnetometer and electron reflection techniques. High-resolution images will be obtained in stereo and in six spectral bands. The Moon's gravitational field will be mapped using doppler radio tracking from the orbiter, from a coplanar subsatellite (Figure 2), and via an orbiter-subsatellite signal relay for farside coverage. A radar altimeter will measure the lunar figure. In addition to the major science objectives, other objectives include the search for frozen volatiles (primarily H₂O) in shadowed polar regions and such nonlunar problems as the detection of gamma ray bursts, measurement of solar and stellar spectral fluxes, and measurements of the plasma environment of the Moon.

3. Status

Phase A mission design was completed by Goddard Space Flight Center. The mission was submitted as a candidate new start for FY77. The study was transferred to Jet Propulsion Laboratory in October 1975. Jet Propulsion Laboratory confirmed the Goddard Space Flight Center design except for simplifying the subsatellite to be only a transponding relay, substantially reducing its weight and establishing its orbit to be coplanar with the Orbiter. In June 1976, the Office of Space Science selected a Science Working Team to work with JPL in preparing the mission for the FY78 new start candidate.

B. SCIENCE

In considering the rationale and objectives of any given planetary exploration mission, we should keep in mind that, although we observe and measure the present properties of a planet, the ultimate scientific goals of such exploration are to understand the initial conditions in the solar nebula, the processes of formation and subsequent evolution of planetary bodies, and the presently active processes of the solar

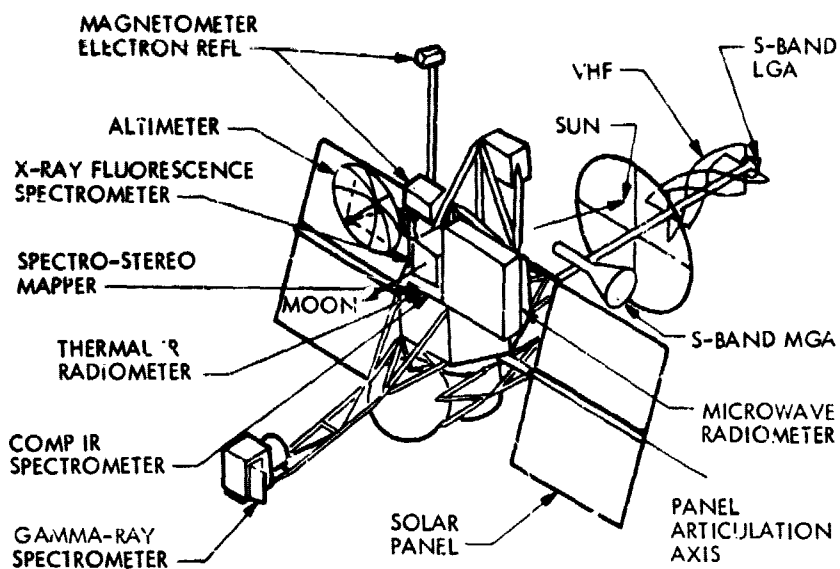


Figure 1. Lunar Polar Orbiter

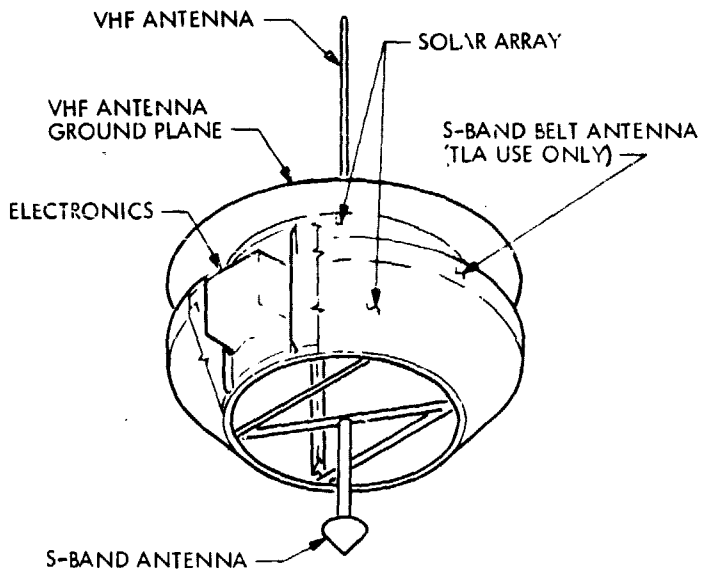


Figure 2. Transponding Subsatellite

Table 1. Science Experiments and Mission Objectives

Experiment	Principal Investigator	Institution	Objectives
Gamma Ray	J. Arnold	UCSD	Global map of elemental composition (including Th, U, K, Fe, Ti, Mg, Al, H) with resolution of ~50-75 km.
X-Ray Fluorescence	J. Trombka	GSFC	Global map of elemental composition for Mg, Al, Si. During high solar activity K, Ca, Ti, and Fe may also be detected. Resolution 5-10 km.
Reflectance Spectroscopy	T. B. McCord	MIT	Global map of mineralogical composition. Resolution ~0.5 km.
Heat Flow/ Infrared Mapping	D. Muhleman	CIT	Global map of internal heat flow with resolution ~50 km, global maps of surface thermal emission.
Spectro-Stereo Imager	M. Davies	RAND	Global multispectral map, high resolution and stereo images of selected areas and moderate resolution ground track images.
Magnetometer	C. Russell	UCLA	Map lunar surface field, determine permanent dipole and multipole moments and sound the deep interior.
Electron Reflection	R. Lin	UCB	Obtain a detailed description of the lunar surface magnetic fields.
Geophysical Altimetry and Gravity Experiment	R. Phillips	JPL	Map the figure and gravity field of the moon. Determine the moment of inertia tensor and the center-of-figure offset.

Table 2. Science Payload Characteristics

Instrument	Mass, kg	Power, W	Data Rate, bps	Duty Cycle	FOV, deg	Pointing Direction	Size cm	
Gravity/ doppler tracking	-	-	-	-	-	-	-	
Altimeter	7.2	17.5	625	Continuous	2.3° dia (-3 dB)	Nadir	61 dish, 35 x 30 x 13 electronics	
Magnetometer	2.5(1)	4.0	150	Continuous			6 x 6 x 6 detect., 18 x 15 x 13; electronics	
Electron reflection	5.0	5.1	280	Continuous	140 x 5°(3)	Nadir Zenith	8 x 16 x 4 and 8 x 16 x 8	
Microwave radiometer	13.0	12.0	18-158	Continuous	28° dia	Nadir	60 x 60 x 15 Ant. and electronics	
Gamma-ray spectrometer	12.0(2)	6.0	2000	Continuous	-	Nadir	50 x 45 x 40	
X-ray Spectrometer	10.5	10.0	256	Continuous	40°(N) 90°(N)	Nadir and Sun	31 x 21 x 31 (N) 31 x 10 x 15 (S)	
Reflection spectrometer	11.3	9.9	13,312	4 mo/yr	5° dia	Nadir	54 x 20 x 19	
Spectro- stereo imager	3.0	3.5	1274 to 163,000	ø mo/yr	60° dia	Nadir	23 x 10 x 13	
Notes: (1) Does not include boom (assumed 4 kg) Totals: Mass: 64.5 kg								
(2) Does not include boom							Max pwr: 68.0 W (not including peaks)	
(3) Two crossed fans of this FOV each direction							Min pwr: 55.1 (high Sun, darkside)	

system. The LPO mission provides the opportunity to capitalize on our present data and understanding of Earth's Moon for substantial progress toward these fundamental goals.

1. Science Objectives

In order to achieve this progress the following scientific objectives have been defined for LPO:

- (1) To understand the time sequence of lunar differentiation and the compositional heterogeneity.
- (2) To constrain models of lunar origin, thermal history, and bulk composition.
- (3) To determine the extent and basic causes of global asymmetries in composition, morphology, and structure.
- (4) To determine the extent and character of lunar surface magnetic fields and their source.
- (5) To decipher surface aging and modification processes.
- (6) To discover special characteristics of unexplored regions (e.g., the shadowed polar regions).

2. The Moon in Relation to the Solar System

Our present understanding of the Moon is highlighted in Table 3 together with the sources of data most closely associated with each point of understanding. It is emphasized that the knowledge represented by these points is not simply lunar knowledge; our understanding of the Moon is applicable to many planetary objects. This level of lunar understanding is the basis for posing questions appropriate for orbital surveys. Many questions that can be asked about the Moon also relate directly to the formation and evolution of other solid objects in the solar system.

The Moon is now viewed as a representative of a large class of planetary objects. It is one of a number of intermediate-size bodies including Mercury, the Galilean satellites, Titan and probably several others. It is clearly separated from the terrestrial giants Earth and Venus. As shown in Figure 3, the Moon is grouped with intermediate density objects that include Io and Europa but it is clearly separated from denser Mercury and larger Mars. Because density is closely related to bulk composition the Moon is, thus, an important compositional representative of a class of solar system objects. Thus the Moon offers us an accessible laboratory for studying similar planetary processes on a silicate object smaller than Earth and Venus; similar in size but of different bulk composition than Ganymede, Callisto or Titan; similar in size and bulk composition but less volatile rich than Io or Europa.

Table 3. Highlights of Current Lunar Understanding

Points of Understanding	Source of Data
Internal modification; the Moon is not an unaltered original accretion	Sample, Orbital, Lander (Surveyor)
Thick lithosphere	ALSEPa
Deep interior is presently partially molten	ALSEP
Possibility of iron-rich core	Orbital, ALSEP
Nonequilibrium figure; center-of-figure/ center-of-mass offset; local mascom anomalies	Orbital
No planetary dipole magnetic field	Orbital
Surface magnetic fields	Orbital, ALSEP
Samples exhibit remanent magnetism	Sample
Igneous processes active early in lunar history up to about 3 billion years ago	Sample
Present igneous and tectonic activity very low	Sample, ALSEP
Global asymmetry in morphology, surface chemical composition and rock types	Orbital
Three major rock composition types: anorthositic series, mare basalts, nonmare (KREEP and others)	Sample, orbital
Early intense meteorite bombardment ending about 4 billion years ago	Sample, orbital
Impact processes have a dominant role in surface modification	Sample, orbital
Chronology of major crustal formation and modification events	Sample
Samples indicate virtually no contact with water any time in their history	Sample
Surface heat flow is about half that of Earth	ALSEP

^aApollo Lunar Surface Experiment Package.

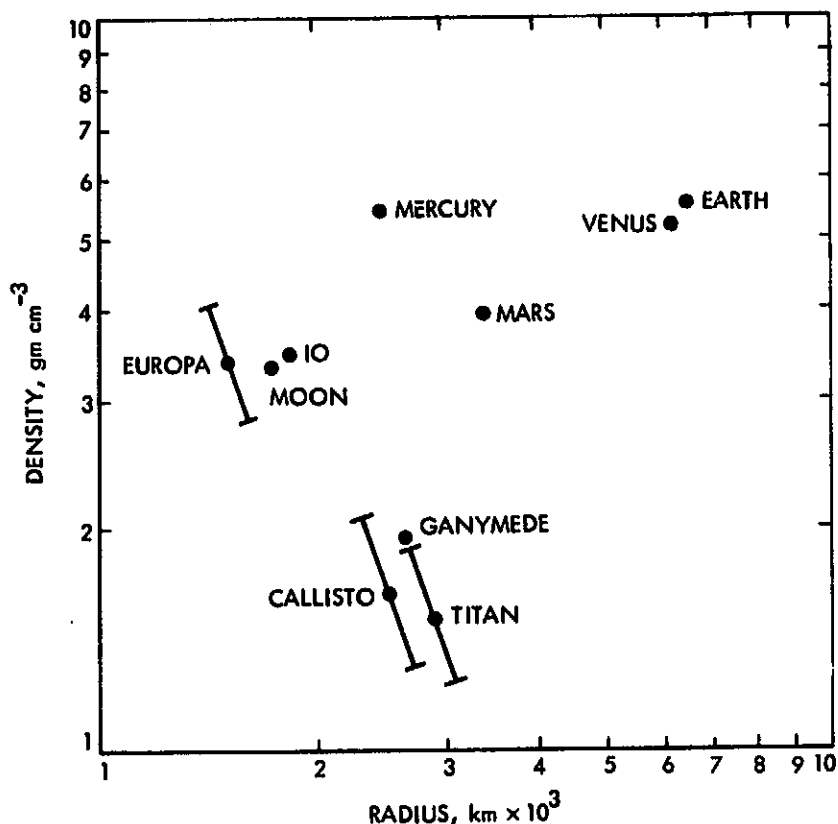


Figure 3. Comparison of Terrestrial Planets and Satellites

The Moon is interesting because of its differences as well as its similarities to other planetary objects. The low-density, volatile-poor, and relatively refractory lunar composition compared to that of the Earth makes it enigmatic to theories that postulate a systematic radial variation in composition in the solar nebula. The ubiquitous remanent magnetism in lunar samples and the absence of any present planetary dipole magnetic field make the source of the remanent magnetism a very significant problem. Its solution bears on the nature of hydromagnetic dynamos, induced planetary fields and the existence of very early magnetic fields.

A basic point in the scientific rationale for a lunar polar orbiter mission is that the Earth-Moon system is, and will remain for the foreseeable future, the tie-point for planetological comparisons. This is true because we have information about these bodies that will be unobtainable for most other planets in anything approaching the depth of that available for the Earth and Moon. Among the most important types of information in this category are: (1) absolute chronology from isotopic studies of samples, (2) internal structure from seismic data, and (3) the many varied and detailed aspects of sample studies: mineralogy, petrology, chemistry, physical properties, etc.

3. The Moon -- A Window on Early Planetary Evolutionary Processes

Two cardinal points of understanding have emerged from post-Apollo lunar science. The first is that the Moon is not an unaltered original accretion, but that it has undergone extensive early chemical differentiation probably related to its formation. This has emphasized the role of formation processes on subsequent evolution and on how small bodies form and evolve. It is now clear that even the smaller terrestrial bodies may have experienced extensive modification. Although some were distinctly different from those on Earth, many processes common to the formation and early evolution of the terrestrial planets and even satellites of the outer planets were active on the Moon. These include the initiation of crustal formation and the effect of large impacts on the course of early crustal formation. Such processes are surely important for setting the stage for later evolution and have been largely obscured by subsequent evolution on larger planets. The second point is that for 2.5 billion years lunar thermal and tectonic activity have been almost nil. Because of this rapid decline in activity, the Moon provides the most accessible record of early planetary evolution anywhere in the solar system.

A class of planetary objects represented by the Moon has surface processes completely different from Earth. Surface processes on the Moon and Mercury are dominated by meteorite impact processes; those on Earth by fluid erosion, transport and deposition. Mars' present surface is a result of both impact and fluid processes. Impact effects are well preserved on the Moon because of its early crustal formation and rapid cooling. Important questions relating to lunar impact processes include the effect of impacts on magnetic fields; meteoritic contamination; effectiveness of material transport; and regolith development. Impact effects may vary considerably depending on the bulk composition of the particular planetary object. For example, crater relaxation may be significantly different for silicate and icy objects (e.g., Callisto and Ganymede).

4. Timeliness of a Lunar Polar Orbiter Mission

Our present understanding of the Moon is based on extensive and detailed sample and photogeologic studies, limited surface (e.g., seismic and magnetic) studies, and limited geochemical and geophysical surveys made from orbit. Important hypotheses about the origin and evolution of the Moon are based heavily on data from the Apollo landing sites; sites that were selected to provide the maximum diversity in observables. We need to be able to view these complex sites in a global context in order to further test and refine these hypotheses. Global data combined with the large body of Apollo data will provide the necessary base for testing and expanding our present lunar understanding, an understanding that is ripe for testing.

It should be emphasized that polar orbiting spacecraft missions are essential for comprehensive geophysical and geochemical surveys. This global information is complementary to but distinct from sample information. Consider that we have had samples from the Earth

for some years but still need global and regional surveys, made from orbiting spacecraft, for geophysical, meteorological and resources information. The global data sets (topographic and geological maps, for example) for Earth have been built up piecemeal over a long period of time. Such a piecemeal approach to acquiring global planetary data is not practical. A single polar orbiter mission must achieve the maximum in scientific measurements. This requires careful consideration of science objectives and experiment complement. This consideration is reflected in the payload defined for LPO, which is more sophisticated and comprehensive than those of current Mariners or individual Earth-resources satellites.

In addition to this survey aspect of the mission, which is designed to address known problems and expand our current level of lunar understanding, there is an unknown, but very real, exploratory aspect. A year-long, detailed study of an entire planet with such comprehensive geochemical and geophysical techniques will surely produce some unexpected results which may well be as important as the returns we can anticipate based on our current knowledge.

It is vital to recognize the limitations as well as the strengths of polar orbiters. Only certain problems can be approached, e.g., distribution of mare basalts but not absolute chronology. The approachability of problems will depend to some degree on other available data and the current level of understanding of a particular planetary object. For example, interpretations of gravity data are better constrained if information is available on layering (e.g., seismic or magnetic sounding). The theme of constraining the solutions to problems rather than promising clear, unique answers to such questions as "What is the origin of the Moon?" is basic to our concept of the proper objectives for the LPO mission in particular and for orbiting spacecraft in general. Orbiters can provide few simple answers or single measurements that will uniquely solve a problem. In general, data from several sensors must be combined to provide a clear, although perhaps model-dependent, description of a planetary feature. Data from landers or samples will generally be required to further constrain the answers to the problems.

5. Important Lunar Questions

Significant lunar questions that illustrate the nature and breadth of questions approachable by LPO are summarized in Table 4 and discussed in some detail below.

a. How Does the Chemical and Mineralogical Composition of the Crust Vary? The average chemical composition, volume and regional variations in composition, and structure of the crust place constraints on the way in which the Moon and its crust formed and on the bulk chemistry of the Moon. Knowing the crustal volume and average composition, the volume of material involved in crustal formation and hence the extent of chemical differentiation may be estimated. For example, the estimate of a 300 to 500-km initially molten outer zone of the Moon is based on the assumption of a uniform thickness of plagioclase-rich crust and estimates

of the lunar bulk composition. The volume of the Moon that melted to form the crust has implications for the rate and mode of accretion. An initially molten ocean of magma several hundred kilometers thick covering the entire Moon implies a large source of energy to melt this outer zone. If this energy was supplied by accretional energy, then accretion times may have been extremely short. Longer and dynamically more probable accretion times may produce much less melting. Large bodies impacting near the end of lunar formation may have produced relatively localized melting and lateral chemical heterogeneities. The chemical differentiation of a global magma ocean will produce its own pattern of lateral and vertical heterogeneities in chemical and mineralogical compositions. Thus the chemical, mineralogical and structural variations of the crust are important clues to its formation, clues that can best be obtained by a global survey. Finally, the mass of the crustal volume affects the implications of the moment of inertia of the object; a lighter crustal mass has the same effect as a denser core.

One of the major areas where LPO will contribute to lunar science is in the study of the premare (i.e., before the outpouring of the dark, Fe-rich mare basalts) crust because the Apollo and Luna samples are from very complex areas that are perhaps seriously unrepresentative of the crust, and the existing orbital data are only for two near-equatorial bands. The major rock types that make up the premare crust are inferred from the study of lunar samples and the limited coverage by orbiting γ -ray and X-ray fluorescence spectrometers. Broadly speaking, the premare crust is considered to consist of a broad range of plagioclase-rich (anorthositic) and related rocks and a broad spectrum of nonmare basaltic rocks (KREEP and related basaltic rocks of lesser trace element concentrations). Existing orbital X-ray and γ -ray data indicate that considerable chemical variation exists in the premare crust. Much of at least the upper few kilometers of the crust is composed of rocks with greater than 50% plagioclase. Seismic data allow estimation of its thickness and structure for one region of the Moon. Gravity data can extend our knowledge of crustal thickness over the entire Moon. Little is known of its vertical chemical and mineralogical homogeneity, uniformity in thickness and lateral continuity. However, a great deal has been learned about understanding the chemistry and structure of the lunar crust. Large unfilled craters provide windows through which vertical variations in crustal chemical composition and mineralogy can be directly observed. Large-scale lateral variations of surface chemical composition and mineralogy can easily be measured by the X-ray fluorescence, γ -ray and reflectance spectrometers and for much of the crust probably reflect the underlying crustal composition to several kilometers.

Table 4. Important Scientific Problems That Can Be Studied
by Lunar Polar Orbiter

(a) How does the chemical and mineralogical composition of the crust vary?

Does the premare crust have a uniform chemical and mineralogical composition laterally and vertically?

What are the major rock types that make up the premare crust?

How are the heat-producing elements K, U and Th distributed in the crust? Are variations in the concentrations of these elements correlated with surface heat flow values?

Is isostatic compensation in the premare crust related to differences in chemical compositions?

What fraction of the crust consists of mare basalts?

Are volatiles - especially water - trapped in the polar regions?

(b) How did the crust evolve?

Was the crust produced by fractional crystallization of a global "lava ocean" or of large ponds of "impact melt?"

What was the role of extrusive volcanism in crustal evolution?

What role did the large basins have in crustal evolution?

How far back in time were the Fe-rich mare basalts erupted?

How did the Ti concentration of mare basalts vary with time? With location?

What is the physical setting in which mare basalts were generated? What forces erupted mare basalts?

How did crustal rheology vary with time?

Table 4. Important Scientific Problems That Can Be Studied by Lunar Polar Orbiter (Continuation 1)

(c) Does the Moon have a core? If so.

How large is the core?

What is its physical state?

What is its composition?

Was it the source of the magnetic field that magnetized lunar rocks?

(d) What is the thermal history of the Moon?

What was the original temperature profile of the Moon?

What fraction of the Moon was originally above the melting point?

What is the present temperature profile of the lunar interior?

Is the deep lunar interior presently heating or cooling?

What is the relationship of thermal evolution to the crustal stress environment?

What is the global surface heat flow? What are the regional variations? Do regional variations correlate with crustal structure or surface K, U and Th concentrations?

(e) What is the origin of lunar remanent magnetism?

To what extent do the surface magnetic fields of the Moon exhibit patterns that are related to surface features, crustal structure, etc.?

To what extent are the surface fields induced, as well as remanent?

Are the sources of lunar remanent magnetism shallow (<10 km) or deep (a few 100 km)?

Table 4. Important Scientific Problems That Can Be Studied
by Lunar Polar Orbiter (Continuation 2)

(f) What is the origin of lunar light plains?

Are they the ejecta deposits of a few basin-forming events?

Are they the ejecta and mass wasted deposits of many craters?

Are they volcanic?

The distribution of the heat-producing elements K, U and Th in the lunar crust is readily measured by the γ -ray spectrometer and is essential to understanding the differentiation processes related to the lunar crust and to a fuller understanding of the surface heat flow data. Conversely, surface heat flow depends on the strength of heat sources in the underlying crust, and thus provides an important constraint on the depth into the crust that a given surface concentration of K, U, and Th may extend. For example, KREEP basalts are the probable cause of the areas of high natural radioactivity (K, U, Th) on the lunar frontside, but the depth to which they extend is unknown.

Any volatiles - especially water -- cold-trapped at the poles may be evidence that the lunar rocks were not always so devoid of water as those returned by Apollo. Alternatively, the volatiles may be from impacting comets or volatile-rich meteorites. In any case, finding cold-trapped volatiles at the poles would be an exciting scientific discovery.

Much of the lunar frontside, the maria, is flooded by dark, Fe-rich (and sometimes Ti-rich) mare basalts. The volume of mare basalts is small (<1.0% of the crust), but they are very important in deciphering the thermal and internal history of the Moon because they trace a long period of thermal history (about 1 billion years) and they originate in the subcrustal interior and thus provide information about interior composition, physical environment and igneous processes. These basalts and their genesis are more thoroughly studied than any other type of lunar rocks. Their frequent association with topographically low areas, large impact basins on the frontside, areas of high surface radioactivity (not from mare basalts) and mascons further increases their importance in studying the Moon. Global survey information is essential so that the wealth of existing knowledge about mare basalts and related features can be placed in a global context.

b. How Did the Crust Evolve? The importance of this problem has already been stated earlier in Section II.B.3. If our present understanding of lunar differentiation is basically correct, then the lunar crust was produced by differentiating only the outer, initially molten part of the Moon. If so, the Moon is representative of those objects for which crustal evolution may be essentially decoupled from the rest of the planet. Perhaps only mare basalts represent material derived from the interior portion of the planet that was not initially molten.

The spatial relationships of lunar rocks to crustal structure and major events (large impacts, for example) are crucial to providing a better definition of the physical setting in which lunar rocks were generated. The anorthositic series of rocks was apparently generated so early in lunar history that the conditions of their genesis were directly inherited from the conditions of lunar formation. The origin of these rocks is very poorly understood; the origin of similar rocks on Earth is also a mystery. For lunar rocks that were generated later (primarily KREEP basalts and mare basalts) a major unknown is the interplay of the igneous processes that occurred. On Earth, certain igneous rock types are commonly related to certain tectonic environments - tholeiitic basalts with mid-ocean ridges, andesites with subduction zones and granitic intrusives with stable continental areas. Are there analogous relationships between lunar KREEP and mare basalts and the types of basins they fill or the local crustal structure? Were mare basalt flows triggered by large impacts? Were they released by tensional fractures due to cooling and merely fill the lower elevations of the Moon? What aspects of crustal evolution result in the asymmetrical distribution of mare basalts?

c. Does the Moon Have a Core? A chemically distinct core implies chemical differentiation or inhomogeneous accretion. Both the existence and present state of a core place strong constraints on the thermal history and evolution of the Moon. The existence of an iron or iron-sulfide lunar core would have important implications for the origin of remanent magnetism observed in all returned samples, especially if the core existed early in lunar history. Seismic and electrical conductivity data (derived from magnetic sounding) indicate that the Moon's deep interior may be partially molten. The magnetic permeability and moment-of-inertia suggest that a small iron or iron sulfide core may exist. However, present data are not conclusive.

Determining the definite existence of a chemically distinct lunar core, its size, and its probable composition is one of the most important lunar problems with a high probability of solution with LPO data. Comparison of observed and model magnetic responses should provide a tightly constrained estimate of the size of the core. The moment of inertia determined more precisely from the gravity experiment used in conjunction with the magnetically determined core size would provide a strong constraint on core composition through its density. Density of the mantle would also be constrained. These constraints on core size and composition would be complemented by present seismic velocity and attenuation data that suggest a partially molten core.

d. What Is the Thermal History of the Moon? An extremely useful vehicle for discussing the variables affecting planetary differentiation is the thermal history. It provides a framework for understanding the implications of present-day observables for past processes of planetary differentiation. Major lunar observables having direct thermal implications are (1) the present thermal state of the interior (magnetic sounding and seismic data), (2) the present surface heat flow, (3) the surface concentrations of heat-producing elements (K, U and Th), (4) the duration of mare volcanism, and (5) gravity anomalies. LPO should also be able to refine our understanding of a major and immensely important aspect of the lunar thermal history, i.e., the extent to which the Moon was initially molten as a consequence of its mode of formation. Studies of lunar remanent magnetization are also expected to lead to inferences about the thermal history.

e. What Is the Origin of Lunar Remanent Magnetism? The origin of the remanent magnetism observed in all lunar samples is one of the major lunar problems to which LPO is likely to contribute substantially. On Earth, remanent magnetism may be attributed to dynamo action in the Earth's core. However, no lunar core-associated field exists today. Is lunar remanent magnetism due to past dynamo action in a lunar core or subsurface Fe-FeS melts or to early permanent internal magnetization that was later lost by heating? Could shock magnetization due to meteorites or comets account for the observations? Can the observations be explained by thermoelectric currents in a molten crust?

Present observations by magnetometers and the electron reflection technique show that numerous regions of localized magnetization ranging from several hundred to ~ 10 kilometers (present limit of resolution) scale size are present on the lunar surface. The present data base is insufficient to determine whether large regional areas of magnetization typically occur, but there is some indication that large areas are magnetized to an unknown depth. Some correlations with craters, crater peaks, and linear rilles have been established. In some cases surface fields may be due to gaps (linear rilles, etc.) in a uniformly magnetized crust where field lines can escape.

A global map of lunar remanent fields will allow the uniformity and direction of ancient magnetizing fields to be determined; correlations with crustal thickness and surface features will characterize the gross subsurface magnetization properties. The delineation of the detailed history of early lunar magnetism, utilizing the established chronology of the surface geology, will constrain models of early lunar crustal temperature and variation with time of the source fields. Electron mirroring observations will remotely measure the surface field with high sensitivity ($< 10^{-2}\gamma$) and spatial resolution (< 3 km). The magnetometer will observe broad ($\sim 10^2$ km) areas of regional magnetism and provide measurements of the height dependence and direction of the field. The global coverage provided by LPO is crucial to determining the origin of lunar remanent magnetism.

A study of the lunar dipole moment induced by external magnetic fields is also possible. The strength of the induced dipole

depends upon lunar magnetic permeability and the size of a possible core. LPO measurements could resolve the discrepancy between present measurements and detect a possible Fe-FeS core; this investigation, although degraded by the lack of a second magnetometer in a high orbit, has the advantage of improved plasma diagnostics by the electron mirroring detector.

f. What Is the Origin of the Lunar Light Plains? A major geologic unit occupying approximately 10% of the lunar frontside is represented by the so-called "light plains." These plains are characterized by subdued topography, intermediate albedo, and occupy (fill?) topographic lows, particularly in heavily cratered highland terrains. Identical formations are observed on Mercury and similar deposits occur on Mars. Consequently, the formation of such plains appears to be a fundamental planetary process. At present their origin is not known. The major hypotheses are (1) that they are volcanic deposits representing early endogenetic activity, (2) that they are the product of crater ejecta from a few large basin-forming impacts, e.g., Mare Orientale or Imbrium, and (3) that they are the ejecta and erosional products of both large and small meteorite impacts, including secondary craters.

Chemical and mineralogical data for the light plains deposits, neighboring regions and suspected source regions are needed to resolve these hypotheses. Reflectance and X-ray fluorescence spectrometry and multispectral imaging will provide these data.

6. Non-Lunar Science Contributions

In addition to contributing to the solution of major lunar problems, several of the LPO experiments may contribute significant non-lunar information. The electron reflection and magnetometer experiments together will provide substantially more sensitive measurements of magnetotail field line dynamics because of the lower energy range of the particle measurements and the more favorable polar orbit of the LPO spacecraft. The continuous data over the anticipated minimum one-year lifetime will permit detailed studies of substorms and reconnection events.

The electron reflection experiment will also be one of the most sensitive flown for the measurement of the energy spectrum and angular distribution of solar, interplanetary and terrestrial ions and electrons in the transition energy range between thermal plasma and nonthermal particles (10 eV to 20 keV). Thus this experiment should provide substantial new information on particle acceleration, storage and propagation processes. It and the magnetometer may provide possibly the only near-Earth interplanetary low-energy particles and fields measurements in the post ISEE-C (heliocentric) period.

The spectral fluxes for celestial objects are not known very well because of the effects of the Earth's atmosphere on ground-based measurements and because the proper instruments have not been flown or cannot be flown on existing or planned space telescopes. Direct information

about the state of these objects, as well as valuable calibration information for use in ground-based observations will result from improved measurements. For solar system astronomers the solar spectral flux and solar/star spectral flux ratios are especially useful. During the nominal mission the reflection spectrometer can provide measurements of the solar flux at 256 wavelengths between 0.35 and 2.5 μm with an intensity precision of 0.1 to 0.5% and an absolute accuracy of up to 0.5% depending on the accuracy of the reference standard. With repointing of the spacecraft to bright extra-lunar objects during a very small portion of the mission, stellar and solar/star spectral ratios could also be obtained.

The intrinsic germanium crystal gamma-ray spectrometer provides the excellent energy resolution required to detect discrete line spectra above the high continua associated with nonthermal processes of interest in solar physics and astrophysics. The sensitivity of the instrument to cosmic and solar gamma-ray burst fluxes will be about $0.2\gamma/\text{cm}^2\text{s}$. The instrument has a fast data-gathering mode for obtaining high temporal resolution observations of cosmic gamma-ray bursts. The long duration of this mission relative to Apollo or a balloon flight provides an excellent opportunity to gather statistics on their frequency distribution vs both intensity and time. Such data bear on their location and mechanism. It can be reasonably assumed that other gamma-ray burst detection experiments will be flying at the same time as LPO. By matching the time of arrival of a burst at two or more locations using spacecraft at the Moon and near the Earth, the baseline distance and hence the accuracy of the direction determinations are greatly increased over previous measurements.

The heat flow and IR mapping experiments can provide indirect measurements of the solar flux in the range 25 to 70 μm by measuring the lunar albedo and the conductive heat flow into the Moon from the lunar surface. The estimated absolute accuracy of these measurements is 5-10% and the relative accuracy $\sim 2\%$.

7. Experiment Descriptions

The LPO science payload consists of eight experiment packages. Several of the experiments are dependent on other experiments for information that enhances, or is essential to, the basic data reductions. Synthesis of data from several experiments is essential to answering most of the important lunar questions discussed earlier. Because of this, an individual experiment's value to the total mission is much greater than its value as an isolated experiment.

a. Gamma-Ray Spectrometer. The gamma-ray experiment will map the chemical composition of the Moon's surface. The radioactive elements Th, K, and U emit characteristic gamma-rays spontaneously, while major elements such as Fe, Mg, Ti, Al, Si, and O emit gamma-rays because of cosmic ray bombardment of the surface. The areal resolution of the mapping will be on the order of 50 km. Areal resolution and analytical precision are best near the poles, where time spent per unit area is greatest, and for the elements (Th, U, K and Fe) which show the

strongest lines and largest variations over the lunar surface. Si and O give intense lines, but seem to vary little over the lunar surface; Mg, Al, and Ti can be measured somewhat less precisely. There are other elements, about which the experiment can tell us something, with much poorer areal resolution. These include Ca, Na, Mn, and possibly one or more rare earths.

If, as suggested by Watson, Murray and Brown, volatiles are condensed in the permanently shadowed regions near the poles, the 2.22-MeV line of H can be seen there. The presence of trapped volatiles (ice) in the permanently shadowed lunar polar regions would be a discovery with major scientific and technical implications. These regions make up at least 0.5% of the lunar surface and are very well covered by the LPO ground track.

The instrument consists of an intrinsic Ge gamma-ray detector of the order of 100 cm³ active volume, cooled to its operating temperature of ≤ 125 K by a passive radiative cooler pointed to space and mounted on a boom to decrease interactions with the spacecraft mass. Gamma rays stopped in the crystal give rise to electron pulses which are collected, amplified, and converted to digital form. These digital events are relayed to the ground, where they are accumulated into spectra showing the sharp lines characteristic of each element. Background subtraction is necessary because of strong continua from various sources. Data must be accumulated from many successive passes to provide adequate statistics. The line intensities for Th, K and U can be converted to concentrations directly; those derived from our model for other elements require "ground truth" normalization using the soil analyses from surface landing sites. About nine months of counting data are needed to achieve the nominal objective of the experiment; more would be very useful in improving areal resolution and analytical precision.

b. X-Ray Fluorescence. The X-ray fluorescence experiment will map the chemical composition of the surface of the moon for the elements Mg, Al, Si and possibly K and Ca. The outstanding features of this experiment are the high precision of the concentrations measured, the excellent spatial resolution, the simplicity of conversion from X-ray flux to elemental composition, and the capability of determining the elemental composition over the entire range of expected concentrations of Mg, Al and Si. This experiment utilizes the solar X-radiation as the exciting flux and measures the secondary X-ray flux that is produced when the solar flux interacts with the lunar surface. The secondary X-rays are characteristic of the elements and the intensity of the X-radiation of an element is proportional to that element's abundance at the lunar surface. During periods of increased solar activity the solar X-ray flux increases in intensity and maximum spectral energy such that the abundances in K, Ca and elements of higher atomic number may also be determined.

The identification and analysis of geochemical units in the lunar crust has profound significance for understanding global compositional variations owing possibly to primary accretion but certainly to the results of early melting and crystallization phenomena, which are closely

related to the formation conditions of the Moon, and to the results of mare volcanism, which is more closely related to later stages of lunar evolution. Nearside/farside/polar, etc., compositional differences will be determined and a better estimate obtained of the regional and local variations in the composition of the highland regions and of the lavas produced by mare volcanism. The elements Mg, Al and K are particularly suited to studying compositional variations in the lunar crust.

The X-ray fluorescence experiment is also well-suited to the positive identification of any extensive occurrence of previously unsampled regolith, for example, one composed largely of dunitic, pyroxenitic, granitic or spinel peridotite rocks.

Three proportional counters will be used to monitor the lunar X-ray flux. Each counter will have a 0.0025-cm-thick Be window with approximately 50 cm² unobstructed area. The total field of view planned is 40 deg with a full width at half maximum of approximately 20 deg and a nearly circular response pattern. This will give areal resolution as good as 10 km on the lunar surface. Al and Mg filters on the second and third detectors, respectively, will be used to discriminate between the elements Mg, Al, and Si. The energy range will extend to approximately 8 keV to allow measurement of the heavier elements by pulse height analysis. The Sun will be monitored via an irradiated standard target in order to make corrections for solar variations. This will make it possible to combine data from repeated orbits in order to increase the data precision.

c. Reflectance Spectroscopy. The reflectance spectroscopy experiment will characterize the lunar surface materials in terms of mineralogy and soil maturity and will provide some information about chemical composition. The 0.5-km spatial resolution of this experiment permits use of the abundant small, fresh craters to study the mineralogy of surface lunar materials. The majority of the lunar surface has been vitrified (agglutinated) by micrometeorite bombardment such that the mineralogy is largely destroyed. The percentage of agglutinates is proportional to the length of time that the material has been exposed on the lunar surface, that is the degree of soil maturity. For fully mature soils the slope of the nearly featureless reflectance spectra has been calibrated in terms of Ti and Fe concentrations using the Apollo samples.

The reflectance spectroscopy experiment will measure the fraction of sunlight that is reflected from the surface as a function of wavelength. Reflectance spectra contain absorption bands that are diagnostic of the type and amount of minerals that contain transition element ions such as Fe²⁺. These minerals include the major minerals pyroxene, olivine, plagioclase, and ilmenite, as well as lunar glasses and agglutinates. The data will be presented in the form of point compositional analysis as well as geochemical and multispectral maps, and they will be analyzed in terms of regional geology, and for the constraints that they place on bulk lunar composition and on models of thermal history and lunar origin.

The reflectance spectrometer consists of entrance optics, dispersive devices, a series of detectors and an interface to the spacecraft data and control systems. A field stop located in the focal plane of the down-looking telescope selects light from a subspacecraft lunar surface area 0.5 km in diameter. A cross-dispersion Echelle spectrograph provides a dispersed spectrum of this light in a two-dimensional format to several linear arrays of passively cooled (-50°C) lead sulfide and ambient temperature silicon diode detectors. All 256 spectral channels, covering the spectral range 0.35 to 2.5 μm , are sampled at a maximum of 4 sec^{-1} with 10 bits precision for signal magnitudes and three bits used as a scale factor. Intensity precision is 0.1 to 0.5%. Maximum data rate is $13,312 \text{ sec}^{-1}$.

d. Gravity Field and Altimetry. The gravity field and altimetry experiment will map the detailed figure of the Moon with a Ku-band radar altimeter and map the gravity field of the Moon with doppler tracking data. Gravity information will be derived by modeling doppler tracking data. A subsatellite in a highly elliptical orbit will be used for acquiring doppler data on the lunar farside via a relay link to the orbiter. The subsatellite will also provide unique information for the low-order gravity harmonics, which are required to determine the moment of inertia tensor. Spatial resolution is related to approximately twice the spacecraft altitude (e.g., 100-km features are resolved at 50-km altitude.) Anomalies of 5 milligals at spacecraft altitude will be resolvable.

The primary purpose of the altimeter is to provide topographic data for Bouguer corrections of the gravity data and to determine the center-of-figure offset vector to within 100 m. A secondary purpose of acquiring topographic information is for geomorphology studies. The precision required for Bouguer corrections is about 100 m in range and not less than several kilometers in horizontal positioning. The altimeter has a 20-m range resolution and a maximum footprint radius of approximately 2 km, which is more than sufficient for the Bouguer corrections as well as the center-of-figure offset determination. Topography and gravity data will be used to construct internal density models, address the question of isostasy, attempt to reconstruct the rheological history, investigate the nature and origin of the center-of-figure offset, and assess the composition and present thermal state of the interior. Such results will be used to investigate the origin and thermal evolution of the Moon.

e. Electron Reflection. The electron reflection experiment will map magnetic features over the entire lunar surface to a previously unattainable spatial resolution of $<3 \text{ km}$ and sensitivity of $\sim 10^{-2}\gamma$ and also will obtain the direction of the field. This experiment remotely senses regions of lunar surface remanent magnetic fields by comparing solar and terrestrial electrons coming toward and magnetically reflected from those regions. Detailed correlations of these measurements of remanent magnetism with lunar surface geologic structures will contribute to the identification of the processes which produce crustal magnetization and an assessment of their relative importance and the delineation of the detailed history of lunar magnetism, utilizing the established

chronology of the surface geology. Studies of the height dependence of the lunar surface fields in conjunction with the orbiting magnetometer will aid in the characterization of the gross subsurface structure of the magnetization, i.e., its depth and strength. The strength of the magnetization provides constraints on the subsurface composition. In addition, the experiment will make highly sensitive measurements of 2.5-e V to 20-ke V ions and electrons in the cis-lunar environment, including lunar charged particle emission. It may also obtain information on lunar surface electric fields.

The instrumentation consists of four 90 deg wedge triple spherical plate electrostatic analyzers which identify the direction of arrival of 12.5-e V to 20-ke V charged particles both incident on and reflected from the lunar surface. Particles entering the analyzers at different angles are mapped to different locations at the analyzer exit, where they are counted by a spatially resolved detector consisting of a chevron microchannel plate continuous dynode electron multiplier followed by a resistive anode and appropriate electronics.

f. Magnetometer. The magnetometer measures the magnetic field at the location of the polar orbiter. The objective of these measurements is to determine the source of the ancient lunar magnetizing field and to determine the existence and size of a highly conducting lunar core.

Both the permanent and induced magnetic moments of the Moon will be measured. The induced moment is determined by the crustal permeability and the exclusion of the interplanetary magnetic field from a highly conducting core. Determination of the induced magnetic moment will thus allow the size of the core to be estimated. Measurements of the permanent moment are obtained by a fit of magnetic data to obtain the spherical harmonic dipole term. The induced moment is found by comparing magnetometer measurements obtained in the north and south geomagnetic tail lobes in which the inducing external magnetic fields are oppositely directed.

Present estimates of the lunar permanent magnetic moment are extremely small. However, even the small moment would be evidence for an ancient global magnetic field. LPO magnetometer measurements will allow a much better determination of the dipole and higher magnetic moments and thus have important consequences for the existence of an ancient field.

Permanent magnetic fields as measured in the geomagnetic tail at the altitude of the satellite will be mapped, in conjunction with the electron reflection experiment, to delineate the dimensions and regional and global field direction patterns of these magnetized regions.

g. Microwave Heat Flow and IR Mappings. The microwave heat flow experiment will measure the temperature gradient in the upper 10 meters of the lunar regolith in resolution cells of about 50 x 50 km over the entire Moon except for small caps at the poles excluded by

the orbit's inclination. The observations will be interpreted in terms of heat flow due to radiogenic sources beneath the regolith. The measurements consist of radio brightness temperatures at three wavelengths: 3.6, 10.7, 20 cm, and two infrared channels for each resolution cell over the full range of solar illumination (a lunation). Heat flow is associated with an increase of temperature with depth which will be observed as an increase in brightness temperature with wavelength since the effective emitting depth increases with wavelength. Observable diurnal-like variations during the lunation yield sufficient information on the thermal and electrical parameters of the soil to interpret the increase with wavelength of the lunation-averaged brightness temperatures for each cell in terms of heat flow to an accuracy of $\pm 0.2 \mu\text{W}/\text{cm}^2$. The heat flow will be determined for all cells which have a regolith thickness greater than 10 meters. The infrared mapping experiment will utilize infrared horizon sensors in the spacecraft attitude control system as mapping radiometers. The scanning horizon sensors will be capable of mapping surface thermal emission globally at all phases of a lunation. (The polar regions may be excluded if surface temperatures are too low.) The resultant global set of lunation temperatures can be used for modeling the surface thermal regime in support of the heat flow measurement. Nighttime thermal maps have been shown to contain significant geological information. The instrumentation consists of three antennas with identical beams pointed along the nadir, three radiometers sharing a common calibration system which will yield brightness temperature measurements with a channel-to-channel stability of $\pm 0.1 \text{ K}$, and an infrared radiometer system which is sufficiently sensitive to measure the surface temperature to $\pm 2.0 \text{ K}$ during the lunar night.

h. Spectro-Stereo Imaging. The spectro-stereo imager operates in different modes to provide large-area mapping, multispectral, stereoscopic, and high spatial resolution pictures. The instrument has been designed to be easily adapted to mission requirements and to acquire a variety of forms of data. These include low-resolution (1- to 1.5-km) pictures of the spacecraft groundtrack, high-resolution (65- to 90-m and 125- to 175-m) images of selected areas, spectroscopic maps of spectral reflectivity and composition with an average spatial resolution of 500 m.

Low-resolution images will be used to identify terrain and topography along the spacecraft groundtrack. These images, provided in near-real-time, will be provided to other experimenters for use in interpretation of measurements made by different instruments.

High-resolution images will complement and supplement the Apollo data particularly in the polar regions and greatly increase the coverage of low-Sun-illumination pictures over the entire Moon. They can be used for topical studies of morphology, stratigraphy, and crater distributions. Stereoscopic images will allow estimates of the volume of crater ejecta, thickness of mare flows and the thickness of lunar light plains deposits. They will also allow extension of the Apollo control net over much of the lunar surface so that surface features may be specified by improved selenographic coordinates.

Multispectral imagery will provide data on the Fe and Ti content of soils and will be used in identifying the boundaries between different geological units. The instrument consists of an optical system with six 1000-element line arrays in the focal plane; each line array is covered by a filter with a specific bandpass. There is no shutter, and the spacecraft motion sweeps out six images simultaneously. The filters have been chosen to provide information on the location and depth of absorption bands characteristic of certain mineral and glass phases within the lunar surface materials.

C. MISSION DESCRIPTION

The Lunar Polar Orbiter will be launched on a Delta 2914 vehicle which has a 510-kg gross payload capability. LPO is a dual spacecraft consisting of an orbiter, carrying all of the science instrumentation, and a subsatellite. Following a 115-h flight, the spinning dual assembly is inserted into a 95 deg inclined, 100 x 3424-km orbit by a solid rocket motor. After two weeks of tracking to determine the lunar gravitational harmonics, the still-spinning subsatellite is separated. The orbiter's orbit is then circularized to 100 km by successive applications of retro thrust from four 5-lb hydrazine engines. The orbiter is despun and becomes a 3-axis-oriented, nadir-pointing spacecraft with continuous yawing to track the Sun. Key mission parameters are given in Table 5.

A view of the trajectory geometry is shown in Figure 4. The functions of the subsatellite are to provide doppler tracking coverage for the gravity experiment on the far side of the Moon, and to provide unique information on the low-order gravity harmonics. Placing the subsatellite in a coplanar orbit significantly increases the number of farside passes (about 75/month) and permits taking vertical doppler at the poles. Communication between orbiter and subsatellite is via a VHF link. Both craft communicate with Earth (2-way) via separate S-band links. Tracking is by the Deep Space Network's 26-meter stations. By taking advantage of inserting the subsatellite at a prescribed value of the argument of perilune, its orbital lifetime can be as long as 2-5 years without propulsive corrections. Thus it has no propulsion or attitude control subsystems. Conversely the Orbiter's orbit requires periodic correction to raise the perilune to avoid crashing. Present models of the lunar gravity field differ drastically and yield wide differences in the frequency of correction.

Table 5. Key Mission Parameters

Launch period	October 1980
Launch energy	-2.1 to -1.9 km ² /sec ²
Separated spacecraft mass	482 kg
Translunar flight time	115 hr
Total ΔV available	948 m/s
Separated subsatellite mass	28 kg
Subsatellite orbital period	5.3 hr
Subsatellite orbit altitudes	100 x 3424 km
Orbiter and subsatellite inclinations	95°
Orbiter orbit altitude (circular)	100 km
Orbiter period	118 min
Mission duration	1 yr

Science operations fall into two classes -- continuous and lighting angle dependent. The gamma-ray spectroscopy, magnetic mapping, heat flow, doppler tracking, and altimetry are conducted continuously. The reflectance spectroscopy, spectro-stereo mapping, and X-ray fluorescence observe only on the lighted side within 30 to 60 deg of the high Sun point. The ground track of the orbiter advances west by 1.1 deg/rev, thus repeating every 14 days. Repetition of the same orbit/lighting/terrain geometry occurs every six months. Science data are recorded on a tape recorder and played back for about 8 min near the polar region to the DSN 26-m stations via a 1-ft-dia medium-gain antenna. Selected science data are transmitted in real-time at 4000 bps continuously over an omniantenna except when the Moon occults the orbiter from the Earth.

D. GENERAL SPACECRAFT CHARACTERISTICS

The orbiter spacecraft (Figure 1) design is the first of a series of Terrestrial Bodies Orbiters sharing common properties and equipments to effect substantial cost savings. The subsatellite (Figure 2) sits atop the orbiter during launch. It is passive until separated from the orbiter into its 5.3-hour orbit. It contains no battery, attitude

control, or propulsion, thus acting only as a transponding relay. Solar power is provided by 2480 body-mounted silicon cells which deliver 33 and 57 watts when the Sun is perpendicular or parallel to the spin axis, respectively. Radio transmission to orbiter is via a 2.0-W VHF transmitter. Transmission to earth is via a 3.5-W NASA standard S-band transponder. Total subsatellite weight is 28 kg.

Principal features of the orbiter spacecraft are a hexagonal bus with two 14-ft single-degree-of-freedom solar paddles providing 232 watts. A 11000-N (2500-lbf) solid rocket engine with 70-kg propellant is augmented with a monopropellant hydrazine propulsion system consisting of four 22-N (5 lbf) axial thrusters and two 0.9-N (0.21 lbf) tangential thrusters. Two 22-in-diameter tanks carry 87 kg of hydrazine. The liquid system provides for circularization of the orbit to nominal 100 km altitude, trajectory correction maneuvers, altitude maneuvers, and orbit sustenance trims. A ΔV budget is given in Table 6.

Communication with earth is via 1.4/3.5-W NASA standard transponder. A VHF transponder with 2 W output at 150-MHz communicates with the subsatellite.

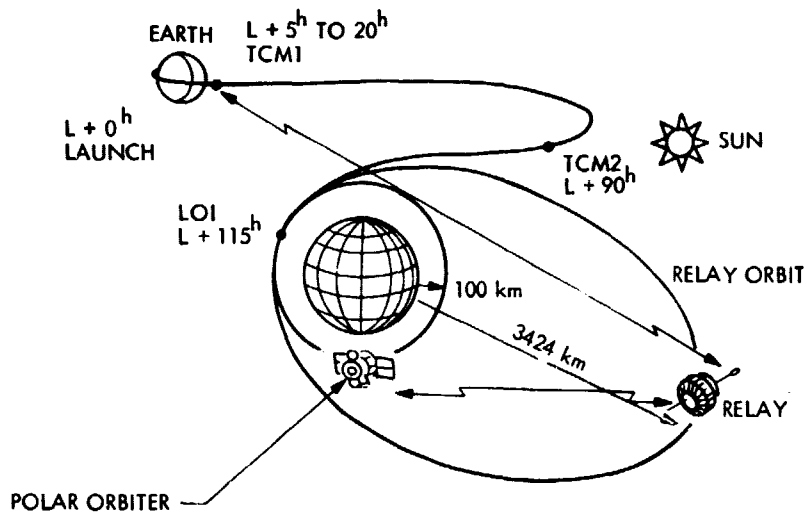


Figure 4. Trajectory Geometry

Table 6. ΔV Budget

Item	ΔV , m/sec
Translunar trajectory correction	83
Initial orbit correction	458
Orbiter circularization	357
Orbiter sustenance	<u>50</u>
	948

S-band transmission is sent via either a 15.8-dB medium gain 12-in-dia horn antenna which articulates in one-degree-of-freedom or a -1.0-dB omni-antenna. VHF is transmitted via a 4.0-dB quadrifilar helix antenna.

The data system employs a new "distributed" concept in which all subsystems (except power and propulsion) and all science instruments have microprocessor terminal modules which interact with a control processor and data handler microprocessors over a bus network. Both command and telemetry data are transmitted over the bus. All data are stored on the 4.5×10^8 bits NASA standard tape recorder and played back to Earth at high rate (approx. 180 kbps) after being convolutionally coded with a rate 1/2, constraint length 7 code. Low-rate data (up to 1000 bps engineering, 2000 bps memory readout, and 4000 bps selected science) are transmitted using the same code. Bit error rate is 10^{-5} for all data modes. Command bit rates to orbiter are 125, 250, and 500 bps.

The attitude control system provides for a spin mode from launch through insertion of orbiter into its circular orbit. In this mode it uses the propulsion thrusters for precession control, a panoramic aspect sensor (PAS), a sun angle sensor (SAS), rate gyro, and accelerometer for nutation control. A 3-axis stabilized mode is used in orbiter's 100-km altitude circular orbit. Its function is to align the orbiter and thus the body-fixed science instruments continuously to the nadir while simultaneously yawing the craft about the nadir direction to keep the solar paddles normal to the Sun. For this purpose three reaction wheels, a yaw gyro, two horizon scanners, and the sun angle sensor are used. The articulation section of the attitude control electronics provides steering signals to the actuators of the single-degree-of-freedom medium gain antenna and each solar paddle. The orbiter's power system is a 28V direct energy system providing 62 to 121 watts of power for engineering functions, depending on what phase the orbiter is executing, and 45 to 72 watts for science instruments for high Sun or terminator

orbits, respectively. A 9 ampere-hour battery is used during Sun occultations. Temperature control is effected by blankets, heaters, shields, and four sets of louvers.

A mass summary for Orbiter is given in Table 7.

Table 7. Mass Summary

Item	Mass, kg
Orbiter (total mass)	<u>454</u>
Science	65
Engineering Mechanics	108
Communications	13
Data system	16
Attitude control	20
Power	22
Propulsion	32
Contingency	21
Other dry	297
Hydrazine and pressurant	87.5
Solid fuel	69.5
Total fuel	157
Subsatellite	<u>28</u>
Launch adapter	<u>28</u>
Launch weight	<u>510</u>

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SECTION III

LETTERS TO NASA

DEPARTMENT OF EARTH AND PLANETARY SCIENCES
54-518
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

1 June 1976

Dr. Edward A. Flinn
Lunar Programs Office
NASA Headquarters, Code SM
Washington, D.C. 20546

Dear Ted:

Enclosed are:

1. A slightly revised version of the charter of the Terrestrial Bodies Science Working Group.
2. A statement of the Terrestrial Bodies Science Working Group regarding the Lunar Polar Orbiter. The TBSWG discussed the Lunar Polar Orbiter mission during its April 1976 meeting, and it strongly supports the LPO.

Sincerely,

*Nafi*₁₆
M. Nafi Toksöz

MNT/sb

cc: TBSWG

Statement of Terrestrial Bodies Science Working Group
Regarding Lunar Polar Orbiter
23 April 1976

The Terrestrial Bodies Science Working Group (TBSWG) strongly recommends the proposed Lunar Polar Orbiter (LPO) mission for a fiscal 1978 new start.

We are convinced that the LPO will provide important new insights in lunar science with respect to composition, internal structure, crustal properties, and magnetic fields. We note that the information expected from the LPO is an essential complement to existing and anticipated future information from the Apollo samples and ALSEP and orbiter data. In this context the LPO mission is timely. Global data are needed to constrain and improve concepts of the nature and history of the moon based on the information from Apollo. The Apollo information will, in turn, enhance our ability to interpret the LPO data and improve our capability to interpret such data from other planets.

We view LPO as part of a broad program of studies of terrestrial bodies of the solar system including the inner planets, satellites of inner and major planets, asteroids, and comets with respect to their compositions, internal structures, and evolutionary histories. Acquisition of parallel sets of data from several of these bodies is an

important new thrust in planetary science. Several of the missions in this program will be orbiters which share common science objectives and whose payloads will vary somewhat according to the body under study. A global survey of the moon is an essential part of this program. The LPO mission is highly feasible and in a unique state of readiness.

Each individual mission in the series will provide important new insights into the major riddles of the planets. However, the depth of our understanding of any one body, as well as of the early history of the solar system in general, will be strongly dependent on having a broad base of information from a group of bodies.

Finally, we mention the importance of the Earth-moon system as a tie-point in studies of all solid bodies, and the potential importance of global coverage of the moon in preparation for its proposed exploitation.

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA 91125

DIVISION OF GEOLOGICAL
AND PLANETARY SCIENCES

TELEPHONE (813) 795-6811

February 7, 1977

Dr. Noel Hinners
Associate Administrator for Space Science
Code S NASA Hdq.
Washington, D. C. 20546

Dear Noel:

At its meeting on January 12-15 the Terrestrial Bodies Science Working Group discussed in some detail the statements of G. Stever regarding the fiscal 1978 budget. As planetary scientists we are heartened that the fiscal 1978 budget includes a new start for the Jupiter Orbiter with Probe mission and for a serious study toward further exploration of Mars. We congratulate NASA for its success so far with these programs and wish for further success in seeing them through.

However, we regret the omission of the Lunar Polar Orbiter mission, which we have strongly endorsed for an early new start. Data from LPO are an integral part of the information base required for comparative planetology of the terrestrial planets and other solid bodies of the solar system. This broad data base will be needed if we are to understand general patterns for evolution of such bodies (as, for example, a broad base of terrestrial data was required before the unifying theory of plate tectonics could be developed). Moon is unique in being small, having no atmosphere, not fitting the models for planetary compositions, being part of a binary planet system, and having known chronology for its early differentiation and lithospheric thickening. The data from LPO are also essential as a survey of resources in anticipation of any serious planning for lunar bases or use of lunar resources. Thus, we believe that LPO must fly sooner or later, and we urge that it be soon for the reasons given below. Also, we urge that funding be continued for development of orbital instruments for LPO and other such missions.

1) LPO data are needed now to complete the first-order data base for Moon and to constrain and guide theories being derived from Apollo data. These theories are the base for much of our planning for exploration of other solid bodies.

2) Interpretation of global survey data for Moon will be greatly enhanced by the extensive information from Apollo, an advantage that will not be available for any other planet. Moreover our ability to interpret global data for other solid bodies would be substantially improved by prior experience with LPO data. Thus, LPO should logically precede global surveys of other bodies.

3) We anticipate that by the late 1980's there will be manned or unmanned lunar bases for the purpose of using lunar resources or, at least, firm and detailed plans for such bases. If so, at least 5 years of planning based on interpreted LPO results will be needed. On this basis, a new start for LPO within the next couple of years seems imperative. The opportunity to establish a lunar base is likely to evolve rapidly and independently of scientific considerations. The necessary base of scientific data should be on hand.

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Dr. Noel Hinners

2/7/77

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4) The community of planetary geoscientists needs an influx of new data in order to maintain a satisfactory rate of progress in planetary studies. The proposed studies of Mars will provide substantial new data but not before 1985. We are concerned about the effects on the strength of this community and loss of momentum that may occur if hard work and planning do not yield a mission in a reasonable length of time and if there is a gap of 8 more years before new data are received.

The LPO mission has been well conceived and planned and high-quality, enthusiastic experiment teams have been selected. It has high regard and support from the general community of planetary and space scientists (e.g., PSC, IAU). We urge that NASA make every effort to obtain a new start for LPO in fiscal 1979.

Sincerely,



Arden L. Albee
for Terrestrial Bodies Science
Working Group

ALA:lc

cc: TBSWG
T. Young - Code SL
E. Flinn - Code SL

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