JSC-12521

NASA TECHNICAL MEMORANDUM

NASA TM X-58202
March 1977

AN OUTLINE OF PLANETARY GEOSCIENCE

(NASA-TM-X-58202) AN OUTLINE OF PLANETARY GEOSCIENCE (NASA) 41 p HC A03/MF A01 CSCL 03B

N77-19968

Unclas

G3/90 21421

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LYNDON B. JOHNSON SPACE CENTER

HOUSTON, TEXAS 77058

1. Report No. NASA TM X-58202	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle AN OUTLINE OF PLANETARY GEOSCIENCE		5. Report Date 6. Performing Organization Code JSC-12521
7. Author(s) Members of the Lunar and Planetary Sciences Division		8. Performing Organization Report No.
9. Performing Organization Name and Address Lyndon B. Johnson Space Center Houston, Texas 77058		10. Work Unit No. 383-85-00-00-72 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This document outlines key issues in planetary geoscience and is designed to aid in addressing a number of major scientific questions; answers to these questions should constitute the basic geoscientific knowledge of the solar system. However, any compilation of major questions or basic knowledge in planetary geoscience involves compromises and somewhat arbitrary boundaries that reflect the prevalent level of understanding at the time. Previous documents usually have been structured around spacecraft missions or techniques and have not provided a philosophy for planetary geoscience. This document seeks to provide this philosophy.

17. Key Words (Suggested by Author(s)) Planetary geoscience Planetology Planetary evolution Planetary investigation Celestial bodies Solar nebula Fractionation		18. Distribution Statement STAR Subject Category: 42 Geosciences (General)	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 41	22. Price* $4.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

NASA — JSC

NASA TM X-58202

AN OUTLINE OF PLANETARY GEOSCIENCE

By Members of the Lunar and Planetary Sciences Division
Lyndon B. Johnson Space Center
Houston, Texas 77058

From man or angel the great architect
Did wisely to conceal, and not divulge
His secrets to be scanned by them who ought
Rather admire; or, if they list to try
Conjecture, he his fabric of the heavens
Hath left to their disputes, perhaps to move
His laughter at their quaint opinions wide
Hereafter, when they come to model heaven
And calculate the stars, how they will wield
The mighty frame, how build, unbuild, contrive
To save appearances, how gird the sphere
With centric and eccentric scribbled o'er,
Cycle and epicycle, orb in orb:

- Milton: Paradise Lost
(Book VIII)

CONTENTS

Section | Page

AN OUTLINE OF PLANETARY GEOSCIENCE

By Members of the
Lunar and Planetary Sciences Division

1.0 SUMMARY

This document presents a basic approach to planetary geoscience. It outlines key issues and addresses a number of major scientific questions, answers to which should constitute the basic geoscientific knowledge and understanding of the solar system. Important scientific questions are structured in the context of processes that have been active in the formation and evolution of the solid objects in the solar system. Emphasis is placed on the fact that a program of planetary geoscience must be balanced to include observations of a variety of solar system objects; laboratory, theoretical, and modeling studies; and instrument development.

2.0 INTRODUCTION

This is a time of substantial activity in planetary science. Apollo instrumental data and returned samples from the Moon are under intensive study. Mariner data from Mars, Venus, and Mercury are being analyzed. Pioneer observations of Jupiter are being integrated into models, and the first closeup view of Saturn is imminent. Studies of meteorites and new theoretical work are directing renewed attention to the early solar nebula. Earth-based observations of planets, asteroids, satellites, and comets are broadening our data base on the entire solar system.

If planetary science is to develop properly in the context of NASA's charter to explore the solar system, new observational data will be required. New data imply new missions — orbiters, landers, sample returns — as well as continued Earth-based observations, laboratory studies, and theoretical work. At present, long-range goals for this activity appear ill-defined.

The NASA Lyndon B. Johnson Space Center (JSC) has been assigned the role of Lead Center for Lunar and Planetary Geoscience. Because the tasks for this role will be carried out primarily by the JSC Lunar and Planetary Sciences Division, members of the division have prepared this document to provide a scientific framework within which detailed plans for geoscientific exploration of the solar system can be formulated. This document focuses on processes of formation and evolution rather than on individual planets or missions to provide the base for developing strategy for exploration.

The scope of planetary geoscience has been deliberately restricted, partly because of the character of the assigned role and partly because of the need to divide the subject of planetary exploration into manageable areas of study. The term "planetary geoscience" is used throughout this document in explicit recognition of these somewhat arbitrary boundaries on the subject matter. Despite the restriction imposed for the purpose of this document, planetary geoscience (as defined by the Lunar and Planetary Sciences Division) clearly encompasses a broader frame of reference than that usually addressed by the geoscientist. This is particularly true with respect to the formation of the solar system, in recognition that all phenomena of planetary evolution are intimately interwoven with the way in which the solar system formed.

This document is written in general scientific terms rather than in mission-oriented terms. The depth of discussion has been limited to avoid encyclopedic proportions. It is intended to be just specific enough to touch on all first-order geoscientific aspects of origin, evolution, structure, and composition of the solid bodies of the solar system.

The document was prepared by members of the JSC Lunar and Planetary Sciences Division.[1] Several scientists outside the division were asked to review the document and provide suggestions for improvement. Critical reviews by A. Albee, E. Anders, R. Brett, A. Cameron, B. Doe, W. Kaula, M. Langseth, D. Matson, C. Sagan, C. Simonds, S. Solomon, and C. Sonett aided in revision. Their help in meeting a tight schedule and in improving the document is gratefully acknowledged. Additional comments by J. Head, J. Papike, F. Press, and D. Strangway are also appreciated.

3.0 DEFINITION OF PLANETARY GEOSCIENCE

The only planetary system presently recognized and accessible for study is the solar system. Thus, planetary geoscience investigations must approach the origin and evolution of the planetary systems primarily from observations of presently existing objects in the solar system and studies of related laboratory and theoretical problems. Supplemental information on proto stars, stellar dust clouds, and the search for potential extrasolar planetary systems are also used. Planetary geoscience is defined as the study of the nature of the materials, processes, and energy sources that produced the solid

---

[1] Essentially all of the scientific staff of the Lunar and Planetary Sciences Division were involved in this effort. The writing team leaders for each section were as follows: sections 1.0 to 6.0, J. Minear; section 7.0, D. Bogard; section 8.0, N. Hubbard; section 9.0, D. McKay; section 10.0, D. Bogard; sections 11.0 and 12.0, W. Mendell. The editing committee consisted of W. Phinney, G. Lofgren, and R. Morris. Other participants included D. Anderson, L. Bennett, D. Blanchard, W. Chapman, U. Clanton, R. Fruland, E. Gibson, L. Haskin, F. Horz, J. Keith, C. Meyer, D. Morrison, L. Nyquist, E. Schonfeld, J. Warner, and H. Zook.

objects in planetary systems, led to their present state, and are currently active.

Any framework of planetary geoscience must fit within guidelines that must be neither too restrictive to recognize the complexities and interactions with other areas of study nor too broad to provide sufficient detail and guidance. Thus, the following guidelines were adopted.

1. Although other models are possible, the starting point generally assumes the existence of a primitive solar nebula, and processes that relate to chemical fractionation and accretion within the nebula are considered. Information from stellar astronomy on proto stars and on composition, density, heterogeneity, and evolution of stellar dust clouds and on the nature of planetary systems of other stars are useful.

2. Evolutionary processes that modify planetary objects (e.g., plate tectonics, igneous differentiation, meteorite impacts, and orbital dynamical interactions) are of major importance in unraveling their history.

3. Interest in the outer planets centers primarily on their bulk chemical composition and their implications for processes active in the early solar system (e.g., their effect on inner-planet accretion).

4. The satellite systems of planets may provide information on the processes of chemical differentiation in the solar system, dynamical interactions, internal differentiation of bodies having a variety of compositions, and evolution of planetary atmospheres.

5. Although a large body of geoscience data has been accumulated about the Earth, this document considers only those terrestrial investigations that have broader applications to planetary geoscience.

6. Planetary atmospheres are considered only from the point of view of their origins, chemical compositions, and chemical and physical interactions with planetary surfaces.

7. Energetic particles such as cosmic rays, solar flares, and solar wind are considered only in regard to their composition and their interactions with solid objects.

8. Questions concerning organic compounds of nonbiogenic origin (e.g., comets and meteorites) and interactions of organisms with planetary surfaces are considered. The origin and evolution of life are considered outside the realm of planetary geoscience.

4.0 EVOLUTION OF COMPLEXITY

The beginnings of planetary geoscience are ancient. Babylonians perceived that different movements across the sky distinguished the known five planets from the other stars. Throughout most of the timespan from the Babylonians to the present, scientific interest in the planets has been directed primarily on their orbital motions. Remarkable advance was made from the Babylonian version of an Earth mountain to the Herakleidian concept of a heliocentric system. The latter concept grazed the truth and then was lost for two millennia. Copernicus reluctantly resurrected the heliocentric system and thereby laid the groundwork for Kepler and Galileo. With the planets finally settled into their present positions, attention has turned to their formation and subsequent evolution. To the original five objects of interest have been added the four outermost planets, 32 moons, an asteroid belt, meteorites, comets, cosmic dust, and, the birthplace of them all, the solar nebula. These objects have been the catalytic agents for the mingling of many disciplines ranging from solar physics, astronomy, experimental mineralogy and petrology, and volcanology to geophysics, geochemistry, meteorology, and spacecraft engineering.

The early data on planetary motions and brightness have grown to include details of the morphology, temperature, chemical composition, mineralogy, and albedo of the surface of the planets, moons, and asteroids. Flyby spacecraft have contributed data on the surface appearance, magnetic fields, gravity field and mean density, and atmospheric composition of several solid objects. Orbital spacecraft have contributed data on surface chemical composition, surface morphology, gravity fields, magnetic fields, surface thermal properties, and density distribution, all of which are directly related to the internal nature and evolution of solid objects in the solar system. Soft landers on the Moon and Venus and planetary rovers on the Moon have contributed data on soil mechanics and magnetic fields as well as thermal, optical, and physical properties, and morphology and chemical composition of the surface. The analyses of meteoritic and lunar samples have furnished petrologic, geochemical, and chronological data that are intimately related to processes active in the early solar system as well as in the evolution of the planetary objects. Concepts of future missions involving advanced orbiters, penetrators, sophisticated soft landers with rovers, and sample returns forecast an ever-increasing quantity of data.

5.0 OBSERVATIONS OF THE SOLAR SYSTEM

Scientific study of the solar system has only recently begun in detail, and it promises to be as challenging, illuminating, and exciting as the exploration of the Earth during past centuries. What is being learned about the nature and history of objects in the solar system as this exploration proceeds is as astounding as it is complex. For example, there exist volcanoes on Mars larger than any on Earth; a crushing atmosphere of carbon dioxide (CO_2) is present on Venus; intense electromagnetic fields surround Jupiter; there is an atmosphere of neutral sodium about Io; there are possible glaciers of methane and ammonia on some satellites of the outer planets; and giant meteorite impact basins exist on many planets, including the Earth. Many of these discoveries should bring about better understanding and appreciation of the delicate balance of natural forces that has allowed a sophisticated civilization to develop on apparently only one member of the solar system.

To better understand the solar system, many disciplines must be involved, and many experimental techniques must be used. Both selective questions and scientific tools will make significant contributions to this understanding. Selection of the most important questions is made difficult by the complexity and interdependence of the problems and the interaction of the disciplines. The Rosetta Stone for one scientist is only a bit of contributing evidence to another. Thus, the important questions must provide balance and continuity in scientific research without precluding the acquisition of totally unexpected data and knowledge.

The Earth, its Moon, and meteorites will remain strong reference points for comparative studies in planetology for the foreseeable future. The Earth provides a more comprehensive amount of basic data than any other object. As an extremely differentiated object that possesses a core, mantle, and crust and whose internal thermally driven processes are still active, the Earth is a natural laboratory. As such, it offers a new perspective for the study of endogenic processes associated with the evolution of some of the large solid objects in the solar system. The Moon is the only planetary body whose surface has been sampled and studied directly that interacts directly with particles and radiation without the shielding of an intervening atmosphere. The Moon also represents another stage in planetary evolution and a class of objects having similar size and uncompressed density. Meteorites supply the greatest variety of "returned samples" from the solar system and provide important clues to the very early conditions and processes in the solar system, the variations in chemical composition among solid objects in the solar system, and the lifetimes and collision frequency of planetary debris. Experience in studying the Earth, Moon, and meteorites has highlighted the fact that one measurement, or even one set of data, may not yield answers to the major questions associated with the formation and evolution of these objects. Many types of data must be synthesized to understand the important processes active in the formation, evolution, and present state of each object as well as the solar system itself. These include returned sample data, global survey data, Earth-analog studies, theoretical modeling, and laboratory experiments.

6.0 PROCESS APPROACH

The major questions in planetary geoscience may be structured object by object, by chronology, or by process. Although an object-by-object discussion may allow convenient organization of data, it is redundant with respect to basic processes that cut across object boundaries (e.g., igneous differentiation processes may be associated with planets, moons, and perhaps some of the asteroids, and surface modification processes are active on all solar system objects). The chronological categories of (1) formation, (2) evolution, and (3) present state also form a natural and conceptually convenient framework for stating the relatively broad questions of planetary geoscience. Each chronological category, however, embodies a distinctive set of processes that are important in their own right. Processes, therefore, provide an important link between chronological and object-by-object discussions and will be used as the framework to organize the major questions of planetary geoscience.

The next three sections discuss formation processes, planetary differentiation processes, and surface processes, in that order. Processes that were active during the very early stages of the solar nebula left their imprint during a relatively short time and ceased to operate in a significant manner during later developments. These processes embody chemical fractionations of the nebula and accretion of planetesimals and planets and are discussed in the section titled Formation Processes. The postformational period can be viewed as two sets of processes. One is dominated by the internal evolution of the larger objects such as planets, moons, and asteroids and involves core formation, crustal and atmospheric evolution, and igneous activity. These processes of primarily endogenic origin are discussed in the section Planetary Differentiation Processes. The other set of processes involves the interactions of surfaces of objects with atmospheres, meteoroid impacts, and solar and galactic radiation and particles. These processes of primarily exogenic origin are discussed in the section Surface Processes.

Subsequent to the discussion of processes is a section that identifies specific or unique properties of objects in the solar system. The intent of this section is to relate important planetary geoscience questions to specific objects that offer the greatest potential for providing answers. The document concludes with a section on general concepts for future exploration trends in planetary geoscience.

7.0 FORMATION PROCESSES

Although a reasonable outline of formation processes leading to the early solar system may be constructed, most of the important details are lacking. It is generally believed that all planetary objects in the solar system are products of a chain of events that began with a collapsing solar nebula, proceeded through the condensation of gases into solid chemical compounds and minerals, and culminated in the accretion of solid particles into planetary bodies of ever-increasing size. Prevailing concepts of the early solar nebula envision a cloud of interstellar gas and dust that collapsed by gravitational attraction into a spinning, flattened disk. Eventually, gravitational energy and internal opacity sufficiently heated the central portion enough to sustain the first nuclear reactions of the infant Sun. The heated nebula surrounding the early Sun may have comprised a significant fraction of a solar mass and exhibited important gradients in several physical properties, especially temperature and pressure. Although this general scenario of an early solar nebula is widely accepted, other very different models have also been proposed. At least one model even precludes the existence of an early solar nebula as just described.

The physical and chemical characteristics of the early nebula and the relative age of formation of the Sun and planets, though not adequately understood, constitute vital inputs into various models of condensation and accretion of solid objects to form the planetary systems. These formation processes occurred over a relatively short portion of the total age of the solar system. Major chemical fractionations took place during condensation and accretion, producing planetary and minor bodies of diverse chemical compositions that ranged from the solarlike composition of the giant planets to the rocky and metallic terrestrial planets to comets, asteroids, and small planetary satellites. Accretionary processes may account for some of the chemical and physical layering or heterogeneity within individual planetary objects.

Direct information on these early formation processes is difficult to obtain because few unaltered remnants of the early condensed and accreted primitive material remain in the solar system. Many of the inherent characteristics of the formation processes have been lost from the planets and larger satellites. The primitive material was destroyed as it became involved in the subsequent evolutionary processes. Planetary reworking, however, has been partially arrested in some planetary bodies such as comets and asteroids, and surfaces or fragments of these objects may provide the best evidence for the original state of condensed and accreted material. Meteorites have proven to be particularly valuable objects for deciphering events and processes of the formation period.

A large number of major questions concerning the mechanisms and products of formation processes in the early solar system remain unanswered. This section emphasizes the unknown but potentially resolvable aspects of formation processes by listing a number of major questions, each constituting a broad and multidisciplined topic of current scientific investigation. Questions and discussion are grouped into five broad topics: (1) physical and chemical properties of the early solar nebula, (2) condensation of gases into solids, (3) accretion of dust grains into planetary objects, (4) fractionation of elements within the nebula, and (5) surviving physical and chemical evidence of formation processes.

7.1 Physical and Chemical Properties of the Early Solar Nebula

<u>What physical and chemical properties of the hypothesized solar nebula controlled the processes of condensation and accretion?</u>

1. Did a large early solar nebula exist? What was its size? What was the ratio of gas to dust?

2. What magnetic fields existed?

3. At what stage did the embryonic Sun begin to appreciably heat the nebula? What proportion of dust ecaped volatilization?

4. Did strong solar irradiations produce appreciable nuclear reactions?

5. What was the gradient of pressure and temperature as a function of time and radial distance?

6. What chemical and isotopic heterogeneities existed?

7. What turbulence and dynamic instabilities existed?

Formation processes occurred some 4500 million years ago, and very few direct remnants of a solar nebula or of these early processes still exist in the planetary systems. Thus, to obtain direct data on the characteristics of an early solar nebula and on those processes that led to the formation of solid bodies in the solar system is extremely difficult. Much of the information obtained to date has come from the study of meteorites. Among the existing data that help characterize the early solar nebula are (1) the present-day mass and chemical composition of the Sun and planets that place a lower limit on the mass of the solar nebula and constrain its possible chemical composition; (2) spectral observations of other nebulae that give some indication as to possible size, composition, and gas/dust ratio; and (3) isotopic heterogeneities found in meteorites that suggest similar heterogeneities in the nebula may reflect nuclear reactions induced by the embryonic Sun, or they may represent a postcollapse addition of matter.

These data may be used to develop models of condensation and accretion processes by assuming certain initial conditions such as composition, mass, temperature, and pressure. The test of any one model of formation is how accurately and completely it predicts the observable end products, which range from the giant volatile-rich Jupiter, to terrestrial planets, to small bodies such as comets, asteroids, and meteorites. To date, data constraints and modeling have been unable to definitely discern between such possible nebula characteristics as (1) a massive nebula with strong turbulence and dynamic instabilities as opposed to a much smaller, more quiescent nebula that evolved much more slowly, or (2) a relatively cool, dust-rich nebula in which solar heating played a minor role as opposed to a strongly heated and vaporized nebula.

7.2 Condensation of Gases Into Solids

What processes controlled the condensation of gas into solid materials?

1. What was the distribution of matter between gas, liquid, and solid phases as a function of radial distance?

2. What was the chronology of condensation of elements and compounds?

3. Was thermodynamic equilibrium maintained? What important chemical reactions occurred? What was the relative importance of plasma reactions?

4. When and how were gases expelled from the solar system?

The major consideration of condensation processes is the extent to which the distribution of solid species and compounds in the solar nebula accounts for the presently observed distribution. Several detailed models of condensation have been proposed. In a number of these models, the inner portion of the solar system is presumed to have been sufficiently heated by gravitational collapse or by the embryo Sun to vaporize solid material. The equilibrium condensation model uses thermodynamic data, cosmic elemental abundances, a presumed pressure-temperature gradient in the solar nebula, and some assumptions about the most probable chemical phases to calculate the sequence of condensation of chemical compounds as the temperature of the nebula falls. A slow cooling rate is assumed to maintain thermodynamic equilibrium via chemical reactions between gas and solids. In another high-temperature condensation model, equilibrium and chemical reactions are constrained such that a layered, nonequilibrium condensate results. Another thermal disequilibrium model, which is more extreme, assumes slow growth of cooler solids from a high-temperature vapor that has low density and is partially ionized. However, not all formation models invoke high-temperature condensation processes. One class of such models assumes that accretion of solid bodies occurred from a relatively cool, dust-rich, solar nebula in which the oxidation state of the material largely determined the chemical phases.

The ultimate test of all such models is how well they explain the growing body of observational data. These data fall into two major categories: (1) Density variations among the planets indicate an appreciable difference in bulk chemical composition, particularly in the relative proportions of volatiles, silicates, and iron. Additional knowledge of the chemical composition of several planetary bodies should permit selection of a particular model because the various condensation models generally differ in specific predictions. These predictions include the values of the ratios iron sulfide/iron and iron oxide/iron for Earth and Venus, iron sulfide/iron oxide for Mars, and iron/silicate for Mercury; (2) laboratory studies of meteorites have shown that these objects represent a wide variation of chemical types and extent of differentiation. Two products of the condensation process may be preserved in some carbonaceous chondrites: the low-temperature, volatile-rich condensates and the high-temperature, refractory condensates. The existence of isotopic variations among meteorite types suggests that appreciable quantities of presolar dust also survived the early formation period. Continued analyses of meteorites offer considerable potential in characterizing early formation processes.

7.3 Accretion of Dust Grains Into Planetary Objects

<u>What processes controlled the accretion of dust grains into larger objects and then eventually into planetary bodies?</u>

1. What was the interrelationship between the processes of condensation and accretion?

2. What effects contributed to the agglomeration of dust grains?

3. What agencies caused the formation of kilometer-sized objects?

4. How did a relatively small number of planetary bodies come to exist? What accounts for the sizes and spacing of planets? How did satellite systems form?

5. What are the time intervals between element synthesis, condensation, and accretion? How rapidly did planetary bodies accrete? What differences in accretion times exist?

6. In what ways did the fluid dynamics (and magnetohydrodynamics) of the nebula drive the accretion of entrained particles? What were the roles of mutual collisions, gravitational interactions, and magnetic fields in accretional processes?

By definition, accretional processes led to the accumulation of dust and gas into planetary bodies. When the proper conditions of gas density, temperature, and particle motion existed, as yet undetermined mechanisms caused condensed materials to first "stick" together and eventually to "clump" into objects of increasing size. When such objects grew large enough, their gravitational fields began attracting solid materials and, possibly, gas. A relatively small number of such objects grew at the expense of others and eventually survived as planets. Although certain systematic variations in properties such as planetary mass, orbital spacing, and rotation rate may be clues to gross properties of the primordial system, the exceptions to every rule evidence the importance of timing and statistical fluctuations in the accretion process. Basic observations include the existence of the asteroid belt, the stunted size of Mars relative to neighboring Jupiter, the anomalous obliquities of Uranus and Venus, and the presence of satellite systems around some planets but not others.

The processes that led to agglomeration of grains are largely speculative because of the large uncertainty about conditions in the nebula. In later stages, the observed predominance of accretion by gravitational attraction over comminution by collision has been extensively modeled, but hard data are limited. In all models, the times and energetics of the accretion mechanisms are critical but largely unknown. Rapid accretion of a planetary object, significant concentrations of short-lived radionuclides, or satellite capture — all liberate appreciable quantities of energy that can play a major role in determining the course of planetary evolution. Similarly, the gravitational dominance of a large growing planet apparently can retard the accretion of a neighboring system, as may have occurred with the asteroid belt. Accurate modeling of the accretional processes must be based on a data base of the physical and chemical characteristics of the present solar system. Key observations include (1) arrangement and dynamics of the planets and of their satellite systems; (2) characteristics of the unusual and well-studied Earth-Moon system; (3) properties of the smaller, more primitive bodies including asteroids and comets; (4) evidence in planets and meteorites for the presence of strong energy sources (e.g., gravitational, radioactive, magnetic) during accretion; and (5) direct evidence, chemical and chronological, for heterogeneous accretion and for late-stage bombardment. Meteorites, and the Earth and the Moon to a lesser extent, also contain isotopic information (decay products of extinct radionuclides, long-lived radionuclides, stable isotope systematics) about the chronology of various formation processes ranging from the production of elements in nucleosynthetic events to differences in formation times for various meteorite types and other bodies.

7.4 Fractionation of Elements Within the Nebula

What processes during condensation and accretion caused physical fractionation of material types?

1. What caused the differences in bulk chemical composition among planets? Did planetary objects accrete heterogeneously; i.e., was chemical layering caused by formational processes? What was the variation in oxidation state among accreting planetary objects?

2. Did planetary objects accrete hot or cold? What were the roles of gravitational energy, short-lived radionuclides, and electromagnetic fields in heating accreting objects?

3. Among the meteorites and asteroids, why do some appear primitive and some differentiated? What caused the variation in oxidation state and the ratio of iron to silicate among chondritic meteorites? Why does Mercury have an apparently high ratio of iron to silicate?

4. What happened to the volatile elements that should have been associated with the terrestrial planets? Why does the Earth have oceans of water?

Fractionation processes have produced a wide variety of material types. Condensation of gas into solids and separation of solids from gases by accretion or by solar expulsion of nebula gas are fractionation mechanisms that are related to formational processes. Some fractionation mechanisms directly concern planetary accretion (e.g., they may determine whether a planet grows homogeneously or heterogeneously). Heterogeneous growth of a planetary object could conceivably explain metallic cores, volatile-rich outer layers, or variations in the values of the ratio of iron to silicate among meteorite types. Other fractionation mechanisms, such as core formation within an initially homogeneous planet, are endogenic processes and are discussed in the next section. Evidence of fractionation mechanisms that may have operated in producing the planetary bodies during the formation period is substantial and includes (1) the existence of distinct chemical types among meteorites and apparently among asteroids, (2) the differences in proportions of volatiles, silicates, and metals (i.e., bulk chemistry) among the planets, (3) the compositional gradient among the four largest Jovian satellites, (4) the large compositional variations among planetary atmospheres, and (5) the fact that compositional differences between the Earth and Moon cannot be readily explained by models of systematic fractionation gradients in the solar system. The energy regime during planetary growth, as controlled by release of gravitational energy or possibly by decay of short-lived radionuclides or by electromagnetic coupling to solar fields, could also cause internal fractionation. Thus, the chemical variation among some meteorites may have occurred by differentiation that was caused by radioactive or solar electric heating of planetesimals during late stages of formation. Planetary fractionation may also have been produced by variation of oxidation states during accretion, by selective depletion of the local nebula of solid materials, or by a lengthy late-stage bombardment of planetary surfaces that added material of different composition. All of these possible fractionation mechanisms, and more, are currently being considered. A large amount of additional data on various planetary bodies, as well as more detailed models, are needed to predict which fractionation mechanisms did occur in a particular circumstance.

7.5 Surviving Physical and Chemical Evidence

What physical and chemical evidence of the formation processes has survived?

1. Do comets and carbonaceous chondrites represent primitive condensates? Where and when did comets form? What is the source of cosmic dust? What is the origin of complex organic compounds in carbonaceous chondrites?

2. How many parent bodies originally existed in the asteroid belt? What selection biases exist in fallen meteorites?

3. What was the source of objects that bombarded the planets during late stages of accretion? What was their radial and time flux distribution? Were these objects the source of surface layers and surface asymmetries on the terrestrial planets?

4. What chemical and isotopic variations of the solar nebula have been recorded in solar system objects? Are presolar grains preserved in meteorites? What chemical evidence of condensation exists?

5. What is the significance of paleomagnetism in meteorites?

Most large planetary bodies probably possess considerable internal differentiation as a result of endogenic processes (see next section) and, as a consequence, many of the inherent characteristics of the formation processes have been destroyed. In the smaller bodies, however, endogenic processes have been largely arrested and surfaces or fragments of these objects offer the best evidence for the original state of nebular material and the actual formational mechanisms. Meteorites presently furnish the largest amount of constraining data because they constitute a wide variety of chemical types, they usually show formation ages of approximately 4500 million years, and they are available in sufficient quantity for detailed laboratory examination. Different meteorite types may represent collisional fragments of a relatively few planetary objects, some of which underwent internal differentiation. Other meteorite types apparently experienced little or moderate heating and may represent inhomogeneous accretion products. In either case, they furnish essentially unique information. For example, carbonaceous chondrites are probably essentially unaltered low-temperature condensates, some high-temperature phases in certain meteorites may represent early condensation products, and isotopic variations found in some meteorites suggest heterogeneities in the early solar nebula. A better understanding of the source regions and selection processes that determine the types of meteorites that strike Earth would provide even more insight into processes that led to compositional variations during formation.

Comets probably also contain primitive condensates that have remained relatively unaltered since the formation period. Spectral observations of the easily volatilized species in cometary tails and compositional measurements of their cores should give significant information on low-temperature condensation and accretion products in the outermost parts of the solar system (e.g., the atmospheres of Uranus and Neptune). Cosmic dust and micrometeoroids are thought to be largely derived from comets and may offer comparable information. Micrometeoroids offer the advantage that they may be studied in near-Earth environment, including spectral observations of their passage through the upper atmosphere.

Some asteroids are probably primitive accretionary products; other asteroids and the surfaces of some satellites of the outer planets may also contain primitive accretionary products. These products range from cores of high-temperature condensates, which in the case of asteroids may have been exposed by collisional breakup, to surfaces of low-temperature condensates. A large proportion of both asteroids and satellites are believed to have volatile-rich surface layers that may not have been appreciably altered from the original condensates.

8.0 PLANETARY DIFFERENTIATION PROCESSES

The original chemical and physical structure of a planetary body may be modified by processes that differentiate its interior, alter the composition and structure of its surface, and determine the composition of its atmosphere. Although this postformational modification may be affected by other objects, such as the Moon in the case of Earth and the Jovian satellites in the case of Jupiter, it is largely intrinsic to the planetary body. These modification processes range from those that produced the overall planetary differentiation into core, mantle, crust, and atmosphere to those that are presently active, including volcanism and tectonism. Variations of these processes in time, rate, fraction of a given object involved, and tectonic or volcanic style among solar system objects are of major geoscientific interest.

The course of planetary differentiation is determined by a complex interplay of several processes that are regulated by such major factors as the size of the planet and its chemical composition, initial thermal state, and content of short-lived isotopes such as aluminum-26 and long-lived isotopes of potassium (K), uranium (U), and thorium (Th) (i.e., intrinsic heat sources). The size of a planet controls the rate at which heat can be lost. The chemical composition of a planet and particularly the presence or absence of water determine the temperature at which differentiation can occur. The initial thermal state and short-lived radioactive isotopes have the greatest effect on differentiation of a planet early in its history. For small bodies such as asteroids and small moons, the initial thermal state may provide the only energy source for differentiation because small bodies lose their radiogenic heat without reaching temperatures high enough to cause differentiation. The long-lived radioactive isotopes of K, U, and Th are the most general and widespread energy source for later differentiation because of the slow rise in temperatures generated by their decay.

The composition and structure of a planetary surface are modified by a variety of processes that may have little effect on the course of nature of planetary differentiation. These processes are related either to the interaction of atmospheres and hydrospheres with the surface or to the impacting of the surface by extraplanetary objects such as planetesimals, meteorites, and cosmic dust. Impacts by large objects early in planetary history may significantly affect the nature of crustal evolution.

The major subdivisions of this section are (1) deep planetary interiors/core-mantle processes, (2) shallow planetary processes/crust-lithosphere processes, and (3) atmospheric processes. Atmospheres are considered primarily as a measure of a planet's chemical and isotopic composition and of the extent and chronology of outgassing. The role of atmospheres is developed as it relates to crustal differentiation; the role of atmospheres in erosion and chemical alteration of a planetary surface is discussed more extensively in the section on surface processes.

8.1 Deep Planetary Interiors/Core-Mantle Processes

1. If a core exists, what is its size, composition, and physical state? How do these features contrast with the rest of the planet?

2. What processes produced the core? Was it produced during planetary formation as an integral part of the processes of condensation and accretion?

3. What fraction of the planetary object was involved in core formation?

4. When was the core formed? What was the rate (gradual or catastrophic) of formation? Did core formation contribute significantly to the internal energy of the object?

5. What are the interplanet variations in core-mantle processes?

A core is defined as the central part of a planetary body differing from the remainder in chemical composition and thus suggests major planetary differentiation. In terrestrial planets and the Moon, the core would be iron-enriched; in icy objects such as Ganymede and Callisto, it may be composed of silicates.

Planetary cores may have formed by heterogeneous accretion or during subsequent differentiation of a planet. It seems likely that, if cores exist in all of the terrestrial planets, they formed early in the planets' histories. Heating by compression, release of accretional kinetic energy, solar induction, and short-lived radioactive isotopes would have been sufficient to initiate the melting of iron and iron sulfide to form the cores. Core formation, once initiated, is thought to be catastrophic for large objects such as Earth and Venus, releasing enough energy to melt all or a major fraction of the object. However, man's understanding of the mechanics of core formation is meager. Its significance for smaller objects such as the Moon, and even Mercury, may be quite different than for Earth and Venus. Core formation in smaller objects with low concentrations of intrinsic heat souces may be delayed significantly. The conditions, rates, and effects of core separation on planetary differentiation for a terrestrial object may be quite different than those for a rock-and-ice satellite of Jupiter or Saturn.

Core formation is intimately associated with the mantle (causing depletion of siderophile and the enrichment of lithophile elements in the mantle) and may affect considerably the crustal and atmospheric formation and evolution. Thus, it may leave as its imprint certain observable features, including the following. (1) The existence of remanent magnetization (paleomagnetism) in young rocks and its absence in similar older ricks may signal the onset of a planetary magnetic field and give a minimum age of the core. This relationship presumes an accurate knowledge of the interrelationship of planetary magnetic fields and cores. (2) In a large terrestrial planet, the complete eradication of the geologic record by a large thermal pulse due to core formation may provide a date if the rocks that formed immediately after can be recognized and dated. (3) A lesser thermal pulse that sharply altered the geologic record could be used if the effects can be recognized and dated. Outgassing events related to core formation may conceivably be recognized in this record. (4) If the crust was chemically involved in formation of an iron-rich core, then the fractionation of lead (Pb) from U by partitioning of Pb into the core would be observable in the ratio of U to Pb in crustal rocks.

A hydromagnetic core dynamo is the source of Earth's magnetic field. Jupiter has a very large, dipolar magnetic field probably caused by convective processes in a metallic hydrogen core. Are hydromagnetic dynamos the only source of intrinsic magnetic fields in solar system objects? What is the source of the ubiquitous remanent magnetism in lunar samples and the weak magnetic fields of Mars and Mercury? What is the critical size of a dynamo? Can they exist in planetary crusts? Do any of the rock-and-ice satellites of Jupiter or Saturn possess a magnetic field? Is the weak magnetic field of Mercury induced or intrinsic?

The thermal history of a solar system object is a major influence on the physical regime in which chemical differentiation occurs. Thermal history models, although nonunique, provide an important unifying framework for integrating a wide range of constraints and for understanding the interactions of energy input, bulk composition, and energy transfer modes. Mantle convection is both an important heat transfer mechanism and a process that may influence chemical differentiation. There appears little doubt that molten silicate layers convect vigorously. However, the extent of solid-state convection, an equally important energy transfer agent, in solar system objects of differing sizes, rheologies, and bulk compositions is unknown. The ice and rock-ice outer-planet satellites may exhibit active convection and tectonism even though their complement of intrinsic heat sources is less than the terrestrial planets. Mantle convective processes exert a major influence on the evolution of a planetary object, including the style of crustal tectonics and igneous activity. Such effects include (1) changes in the figure of the body caused by convection, (2) additions to the energy budget caused by the release of gravitational potential energy during core formation, (3) continued crustal and upper mantle differentiation or recycling driven by convection, (4) crustal tectonics related to convection, (5) changes in orbital parameters, especially rotation periods, caused by changes in the figure, and (6) expansion or contraction forces in the shallow regions of the body. These effects must also play an important role in chemical differentiation. As yet, there is meager understanding of this role. Does convection homogenize or differentiate, and under what sets of conditions? How does it affect the distribution of radioactive elements that are a major source of the driving energy for convection?

8.2 Shallow Planetary Interiors/Crust-Lithosphere Processes

1. If a crust exists, what is its thickness, composition, and physical state? How does its composition differ from the rest of the planet?

2. What are the processes that produced the crust? When was the crust produced? Was it produced during planetary formation as an integral part of the processes of condensation and accretion? Was it produced by the process of planetary differentiation of the whole planet or only part? Was the energy for crustal formation produced from within the planet or from without?

3. What are the processes that have modified the crust? How have igneous, metamorphic, and weathering processes altered the composition of the crust? How have tectonic processes rearranged the physical structure of the crust or affected the igneous and metamorphic processes? Is the crust modified by processes occurring in the mantle or in the core? Have extraplanetary processes, such as bombardment by large meteoroids or induction heating, significantly affected the course of crustal evolution?

4. What tectonic and igneous processes are presently active in the solar system? How do they differ from object to object?

Processes operative in the crust and lithosphere of a planetary object produce many of the observable features of a planetary surface. The crust is the outer layer of a planetary object that is chemically distinct from the mantle. The lithosphere is the outer layer of a planetary object that is stronger mechanically than the underlying material. The lower boundary of the lithosphere is represented by the relative softening of the outer material and is thus mainly determined by the temperature profile, bulk composition, and volatile content, especially water.

Seismically determined structure and the distribution of quakes yield the best information about the existence and nature of the crust and lithosphere. Other techniques rely on estimating the mass of crustal material so that determinations of thickness and chemical composition of the crust are closely interrelated. Both are important in estimating the degree of differentiation of an object and its bulk chemistry. A crust can be shown to exist if the density of the observed surface composition when extrapolated to depth cannot account for the bulk density or moment of inertia of a planet. An isostatically compensated surface layer implies the existence of a crust. The offset of the center of figure from the center of mass of planetary objects may be interpreted to yield a minimum crustal thickness. A weak constraint on crustal thickness is obtained by estimating the crustal volume (of observed surface composition) that would differentiate from an assumed initial bulk composition of the entire planet.

A major objective in studies of the shallow interior is elucidation of the degree of mechanical interaction between the mantle and lithosphere and of material mixing between the crust, lithosphere, and mantle. These interactions have influenced and continue to influence the style of tectonics (e.g., lithosphere-mantle interaction in plate tectonics), the patterns of igneous activity (e.g., the distribution of volcanoes), and the composition of crustal rocks. Seismic information from seismographic networks and laboratory experiments yield information about the nature of such structural or chemical boundaries as that between the crust and mantle. Seismic networks provide the spatial distribution of quake hypocenters, which in turn provide information about tectonic units. Photographic data provide information about stratigraphy, the extent and distribution of volcanic activity, and fault systems. High-resolution gravity data can indicate regions of strong interactions including those between the lithosphere and mantle. Specifically, large negative anomalies may be associated with zones of extensive dynamic intrusion of low-density crustal materials into the mantle (subduction zones); large positive anomalies may be associated with zones where dense mantle material has been thrust up into less-dense crustal material (mantle plugs) and with areas where a strong crust has been loaded by deep-seated volcanic activity (lunar mascons). The present extent and style of tectonic and igneous activity and their variation among planets are extremely important aspects of out geoscientific understanding of the solar system. How do the tectonic styles of Earth and Venus compare? Can differences be explained by different water content? How does the "igneous" activity of principally icy objects differ from silicate objects? Is Mars tectonically or volcanically active? Why do both differentiated and undifferentiated asteroids of approximately the same size exist?

Crusts produced by planetary differentiation, as opposed to condensation or accretion processes, result from igneous processes. Igneous processes produce chemical differentiation by separation of low-temperature liquids from refractory residues. Development of a crust by igneous differentiation requires large inputs of energy to partially or wholly melt large volumes of the planet. The timing of the igneous processes that result in crustal formation has implications about the source of this energy. Early crustal formation requires large heat sources early in planetary history, perhaps linked to the formation of the planet. Intermediate or later stages of crustal formation imply slow-acting heat sources or major thermal events.

Rapid formation of a planet can result in melting of its outer shell by the conversion of kinetic and potential energy of the accreting masses to heat. Less rapid accretion, featuring large impacts during the late stages, may focus the intrinsic effects of planetary differentiation around the large physical, thermal, and possibly chemical inhomogeneities that are produced by large impacts. If the formation of planets occurs near the time of nucleosynthesis, short-lived radioisotopes may be an important early heat source when incorporated early into objects of sufficient size to retain heat. During early solar evolution, the Sun may have produced a very intense solar wind, whose strong electrical and magnetic fields induced electrical currents and high temperatures in planetary objects. The relative chronology of these three sources of early heat is unknown. The interaction of intrinsic planetary differentiation with such impacts may cause the hemispherical differences that are known to exist on Mars and the Moon. Hemispherical asymmetries may also result from continuing tectonic activity, as in the case of Earth.

Once an early crust forms, igneous processes further alter the crust by injecting magma into and erupting it onto the crust along fractures or other weak zones. Global tectonic patterns and associated volcanism are major sources of information about crustal evolution. This information may relate to global convection patterns driven by deep-seated heat sources, which cause long-lived planetary differentiation. Examination of the associations of oceanic ridge basaltic volcanism with midoceanic ridges, calc-alkaline circum-Pacific volcanism with subduction zones, or Martian volcanoes with the Tharsis plateau indicate the interplay of large-scale convection, global tectonism, and volcanism in long-term differentation.

Igneous rocks, both extrusive and intrusive, are the major source of chronological information about the course of planetary evolution because they can be dated by radiometric methods. The chemical and isotopic compositions of these rocks are used to deduce information about the composition of the subcrustal regions, the conditions of magma genesis, and the past evolution of the planet. Mineralogy and texture are used primarily to infer the conditions under which the magmas crystallized. In the special case where crystalline material is brought to the surface, it can supply direct information about planetary interiors. Some types of igneous rocks such as granites and the calc-alkaline suites may be produced from material that passed through the surface processes of erosion and weathering and then were carried back into the shallow planetary interior by tectonic processes, where melting occurred to produce a new generation of igneous rocks. These igneous rocks must be distinguished from those derived from the basic processes of planetary differentiation.

The two other major classes of rocks, sedimentary and metamorphic, can provide important information about near-surface aspects of planetary evolution. These rocks provide information about large-scale physical movements of surficial material by tectonism.

Planetary igneous activity is one area where laboratory studies are indispensible. Remote measurements of chemical and mineralogic compositions cannot provide the wealth of isotopic, chemical, chronological, and mineralogical data supplied by laboratory studies of terrestrial, lunar, and meteoritic samples. A full understanding of igneous activity must also include information from global geophysical and geological studies. Knowledge and understanding of igneous processes and the formation and evolution of crusts and cores are major inputs into studies of planetary evolution using thermal models that provide a conceptual framework for studying planetary differentiation. Thermal models allow a means of testing interpretations of diverse data sets by converting the interpretations into thermal constraints and attempting to construct a physically and chemically valid model that meets those constraints.

8.3 Atmospheric Evolution

1. How and when did atmospheres form?

2. What was the initial composition of the atmosphere? How is the composition of the atmosphere related to that of the planet?

3. Has the composition of the atmosphere changed with time? If so, what processes modified the composition? When did the modifications occur? How are the modification processes related to planetary differentiation?

A planetary atmosphere is a mixture of gases and aerosols retained by the planet's gravitational field. Within the context of planetary geoscience, atmospheres are studied for information about the composition, origin, and evolution of a planetary body.

Planetary atmospheres vary considerably. The giant planets, Jupiter and Saturn, have extensive atmospheres; the terrestrial planets, Venus, Earth, and Mars and some large satellites, such as Titan, have appreciable atmospheres; and Mercury, the Moon, asteroids, and the smaller moons of the outer planets have virtually no atmosphere. The atmospheres of the giant planets must have been acquired by protoplanetary "cores" that were large enough to attract even the light gases, hydrogen (H_2) and helium (He). These atmospheres have remained the most primitive because the intense gravitational fields do not allow the escape of even such light gases as H_2 and He. Such atmospheres have evolved essentially by internal rearrangement and are perhaps our best samples of the solar nebula. The terrestrial planets have weaker gravitational fields and cannot retain the light gases. Even if these planets once had atmospheres of primitive solar nebula composition, they would have soon been modified by loss of the light gases. The weak gravitational fields of the smaller bodies may retain only the denser gases such as argon, xenon, krypton. These gases, however, may also be derived from radioactive decay, nuclear interactions, and the solar wind.

The nature of the initial atmospheres of the terrestrial planets is related to the mode and timing of planetary formation and differentiation. If these planets formed cold before the solar nebula dissipated, then their primitive atmospheres would consist of only the noncondensed solar nebula minus the light gases. If the planets formed hot, then the products of outgassing from the condensed solar nebula materials must be added to the primitive atmosphere. If the planet formed after the solar nebula was dissipated, then the initial atmosphere would consist only of the products of outgassing from the condenced solar nebula materials minus the light gases. If the early Sun went through a T-Tauri phase, then a part of the primitive atmospheres may have been lost from the terrestrial planets.

Processes that change the composition of a planetary atmosphere must be recognized. Processes that add material include capture from a primitive solar nebula, capture from the solar wind, acquisition during late-stage accretion, acquisition during collisions with comets and meteorites, accumulation from outgassing of the planetary interior, accumulation from biological activity, and accumulation from chemical reactions with surface materials. Processes that subtract material include evaporative escape from a gravitational field, consumption by chemical reactions with surface materials, and escape by ionization and subsequent electromagnetic field acceleration by the solar wind. In the presence of a sufficiently strong planetary magnetic field, the upper atmosphere is protected from ionization and subsequent removal by the charged particles of the normal solar wind. The subtraction processes are most active on the terrestrial planets and probably have eliminated virtually all traces of their primitive atmospheres.

The most important data for a planetary atmosphere include its mass, composition, temperature distribution, and variability with time and location. The most important and satisfactory determinations of these properties result from analyses done in situ. The atmospheres of Earth and Venus have been sampled directly. The Viking landers may provide our first in situ analysis of the Martian atmosphere.

A sample of planetary atmosphere returned with a surface sample would provide constraints on the bulk elemental and isotopic composition of the atmosphere and atmospheric/crustal interactions. Martian surface materials may provide evidence for a previous "wet" regime on Mars when the atmosphere contained greater abundances of water and oxygen. Samples from the Venusian surface which include calcium (Ca), magnesium (Mg) and carbon (C) should provide information on such reactions as $CaMgSi_2O_6 + CO_2 = MgSiO_3 + CaCO_3 + SiO_2$. The CO_2 partial pressure in the atmosphere should be buffered with respect to the crust by reactions similar to the one specified.

9.0 SURFACE PROCESSES

Surface processes are important for several reasons. The surface of a body is the most easily studied by either remote sensing or direct examination. Much internal constitution and evolution of a planetary body must be inferred from data collected on surface materials. These data provide information about the composition and density of an atmosphere, if present, and about the Sun, meteorites, and extrasolar system. These data, however, will be influenced by the effects of surface processes that must be understood before the data can be properly interpreted. Surface processes are of direct importance to man because they provide the environment in which he lives or may wish to explore or colonize. Finally, surface processes have been the principle agents that concentrate many of the economically important natural resources that have played a major role in the development of civilization on Earth.

Surface processes such as weathering, erosion, transportation, deposition, and lithification are universal to all planetary bodies. The differences are in the form each process takes in response to its energy source, and they may be either destructive or constructive. For planets with atmospheres, the prime energy source is the secondary dissipation of electromagnetic radiation that arrives at the surface and heats the atmosphere. For planets with virtually no atmosphere, the prime energy source is the direct transmission of energy in the form of meteorites, radiation, and atomic and nuclear particles. The Earth and possibly Venus, having appreciable atmospheres, form one end-member. The dominant exogenetic surface processes on these planets are chemical weathering; wind- and/or liquid-driven erosion, transportation, and deposition; lithification; and chemical precipitation. The Moon and Mercury, having virtually no atmosphere, form the other end-member and are subject to direct bombardment of energy and material. The dominant exogenetic surface processes on these bodies are mechanical-weathering and impact-driven erosion, transportation, deposition, and lithification. Mars and Titan, having thin atmospheres, are intermediate members and may show a complex mixture of the processes from both end-members. In the rest of this section, discussion and questions are grouped under the two headings: (1) surface processes for planetary bodies that have atmospheres and (2) surface processes for planetary bodies that have virtually no atmospheres.

9.1 Planetary Bodies Having an Atmosphere

1. To what extent does the atmosphere shield the surface from direct bombardment by external material? How have the effects of impacts been modified by surface processes?

2. What is the nature and extent of physical and chemical weathering?

3. How is material eroded, transported, deposited, and lithified? What agents are available? What is the composition, temperature, and density of agents? What morphological evidence is present?

4. What is the effect of gravity?

5. How does the interaction of electromagnetic radiation with the atmosphere affect surface processes?

Weathering of surface materials may result from both chemical and physical interactions with the gases and liquids of the atmosphere and, if present, the hydrosphere and biosphere. The net result of chemical weathering is to modify the original surface material to produce secondary materials that are the product of equilibrium between the atmosphere and the solid body. Physical weathering modifies the original surface material primarily by fragmentation processes that increase the fraction of fine-grained relative to coarse-grained material. The interaction of chemical and physical processes is complex; e.g., fragmentation processes increase the surface-to-volume ratio of an assemblage of particles, rendering them more susceptible to chemical reaction; physical separation of light from heavy minerals may allow the preferential chemical or physical destruction of one in favor of the other. The physical and chemical processes operating on a given planetary surface can be understood and evaluated only if the composition, pressure, temperature, and dynamic processes of the atmosphere, as well as the composition of the surface materials and the crustal processes acting on these materials, are reasonably well known.

On Earth, most erosion and transportation is caused by running water although wind and glaciers are important locally. On Mars, photogeologic evidence suggests that moving liquids have played some part in the erosion and transportation process, although present-day processes appear to be dominated by wind. On Venus, the dense atmosphere and lack of hydrosphere may favor wind erosion and transportation and may facilitate fluidized surface flow regimes similar to landslides on Earth. The high surface temperature may favor the existence of more exotic erosion and transportation agents, such as molten salts. Chemical weathering may be very important because strong acids are present in dilute proportions in the atmosphere. On some outer planetary bodies, glaciers of water, methane, or ammonia may be effective agents of erosion and transportation. Differences in gravity among the solid bodies will affect the rates at which these processes occur. For example, the lower Martian gravity should produce differences in these mechanisms as compared to Earth.

Material that is eroded and transported is eventually deposited. Depositional features are varied and complex on Earth and include marine sediments, chemical precipitates, sand dunes, alluvial fans, and glacial moraines. Sand dunes are seen in Mariner photographs of Mars, but their grain size, sorting, and other features may differ from those on Earth because of the rarefied atmosphere. Depositional features that may be caused by running water also appear to be present. Glacial deposits may be major depositional features on some of the outer planetary bodies. The effects of differing gravity among the solid bodies must influence the nature of these features.

When products of weathering, erosion, transportation, deposition, and lithification are preserved, they contain a historical record of a planet's climate, atmosphere, volcanism, and tectonism. Before these records can be deciphered, an adequate description and understanding of surface processes is of prime importance for the exploration of the solar system. Finally, surface processes have been of major importance on Earth in forming economically valuable material such as placer, limestone, and gypsum deposits; sand and gravel concentrations; iron, aluminum, and uranium ores; and oil, gas, and coal. Consequently, one of the side benefits of understanding planetary surface processes may be the discovery of new deposits of economic importance.

All planetary objects are continuously bombarded by electromagnetic radiation, solar wind ions, and high energetic galactic cosmic rays that energize atmospheres. A large fraction of this energy heats the atmosphere and is the major driving force for atmospheric circulation producing erosion by wind. The amount of energy that enters the atmosphere determines the state of the liquids or ices and thus their interaction with gravity to further erode the surface.

The interaction products of solar and galactic particles with planetary atmospheres and surfaces may also be utilized to characterize various planetary processes ranging from atmospheric circulation to mixing and deposition rates of surface materials. For example, tritium and carbon-14 may prove useful monitors of vapor-solid transformations of water (H_2O) and CO_2 on Mars.

All planetary bodies are also subject to meteoritic bombardment. The presence of an atmosphere modifies the dynamical behavior and places a lower limit on the size of a meteorite that can impact the surface. In general, the lower limit varies inversely with atmospheric density, which, in turn, may vary with time. At present atmospheric densities, for example, a meteorite initially weighing 1 kilogram will not impact the surface of the Earth but can impact the surface of Mars. The effect of meteoritic impact on planetary bodies with atmospheres can be difficult to recognize because other surface processes such as weathering by running water tend to obliterate them. Meteorite bombardment more severely affects planetary bodies having virtually no atmosphere and will be discussed in the next section.

9.2 Planetary Bodies Having Virtually No Atmosphere

1. What is the temporal and spatial evolution of the meteorite flux? What are the distributions of masses and/or energies that have impacted the planetary surfaces?

2. What are the mechanics of cratering? Did the impact bombardment affect crustal evolution?

3. What is the extent of weathering, erosion, transportation, deposition, and lithification; i.e., constructional and destructional effects caused by meteorite impacts?

4. What are the effects of gravitational forces on different planetary objects on surface processes?

5. How do electromagnetic radiation and energetic particles interact with the planetary surface? What is the dependence of their flux on distance from the Sun?

6. How can electromagnetic interactions with planetary atmospheres be utilized to determine atmospheric circulation, composition, and temperature? How may radiation and particle interactions with planets having virtually no atmosphere be utilized to determine surface chemistry and mineralogy? What effects do weak magnetic fields have on these interactions?

Clearly, from the study of the Moon, meteorite impact is known to have the potential for weathering, erosion, transportation, deposition, and lithification on a planetary body with virtually no atmosphere. All terrestrial planets demonstrate the ubiquitous presence of impact processes, and evidence is mounting for the widespread occurrence of multiple impacts in the asteroidal belt. Meteorite impact processes have apparently been active throughout the entire history of the solar system.

To better understand the effects of meteorite impacts, their flux, mass, and energy distribution must be known in space and time. The present-day spatial- and mass-frequency distributions of interplanetary bodies and the relation of those distributions to the early bombardment history of planets must be determined. It is important to establish whether the meteorite flux varies in an orderly or sporadic fashion and how the bombardment histories differ among planetary bodies. Although the approaches to these problems must be in large part theoretical, they must be consistent with observational constraints derived from the preserved planetary cratering record, the study of lunar materials and meteorites, remote-sensing studies, and direct satellite measurements of the present meteorite environment. Once understood in detail, the meteorite flux may provide a basis for accurate dating of planetary surfaces.

Meteorite impact is capable of excavating and transporting materials leading to a spatial redistribution of planetary surface materials. Meteorite impact also has profound effects on the physical, chemical, and petrographic characteristics of planetary surfaces because the target materials are fractured, shock metamorphosed, melted, vaporized, or ionized. Moreover, large-scale cratering may affect the chemical and tectonic evolution of the outer portions of planets; e.g., the triggering of igneous activity or the breakup of crustal plates. As a consequence, understanding the cratering process is important for the interpretation of a large variety of remote-sensing efforts, including photogeology, geochemistry, geophysics, mineralogy, petrography, and chronology.

Neither the physical nor chemical processes that occur during a single impact event are understood quantitatively, although terrestrial and lunar research has provided some insight. The understanding of single cratering events is necessary before the effects of multiple impacts can be assessed. Energy scaling laws must be established to quantitatively relate projectile characteristics such as density, velocity, mass, and angle of incidence to target properties such as compressive strength, density, and gravitational acceleration. Once scaling is accomplished, it will be possible to determine the relative proportions of plasma, vapor, melt, and shocked and unshocked materials as well as the crater geometry produced by each event and the ultimate distribution of target and projectile material.

On planetary bodies with virtually no atmosphere, the surface layer is composed of impact-comminuted debris (regolith). Studies of the lunar regolith indicate a dynamic, evolving system of physical and chemical processes. Evolution of planetary regoliths depends on target composition, porosity, and temperature as well as characteristics of the meteoroid environment such as effective mean impact velocity, mass-frequency of meteoroids, and effective gravitational cross-section of a planet for micrometeoroid capture. Thus, both similarities and differences can be expected among planetary regoliths.

For planets with virtually no atmosphere, electromagnetic radiation, solar wind ions, and highly energetic galactic cosmic rays penetrate to the solid surface except for charged particles that may be partially or wholly deflected by planetary magnetic fields. This bombardment can produce changes in the lattice structure and composition of regolith grains. These effects should be more intense near the Sun. Much of the atomic irradiation and its effects are preserved in grain surfaces that may hold a record of its past variations throughout the solar system. Cosmic ray interaction products have been valuable for studying the Sun, for dating lunar craters, and for determining rates of regolith turnover, and they will undoubtedly prove to be of similar value for other planetary surfaces.

The importance of electromagnetic and atomic interactions with planetary bodies lies in the variety of ways that such interactions provide information on the planet. Reflected or absorbed-and-reemitted electromagnetic radiation forms the basis of optical and other spectral studies of planetary bodies. For example, techniques to determine chemical and mineral compositions of planetary surfaces involve spectral measurements at a variety of characteristic wavelengths from microwave to X-ray. These studies range from ground-based measurements of asteroids to orbital measurements of the lunar surface. However, many of these measurements are quite sensitive to the effects of surface radiation damage and micrometeorite impact. Continued investigations using both returned lunar samples and laboratory simulations are required to study the effects of solid-state damage on spectral studies.

10.0 PLANETARY GEOSCIENCE QUESTIONS CATEGORIZED BY OBJECT

In the preceding sections, a framework of planetary geoscience was developed along evolutionary lines in which processes were emphasized. In this section, the important planetological questions are categorized according to the major planetary objects or category of objects. For each planetary object (or category) in the solar system, characteristics are identified that are either unique or exist to a considerably greater degree in that object than in others. This section poses important planetary geoscience questions for those planets or objects that offer the greatest likelihood of providing answers. However, several important classes of questions cannot be answered by studying a single planet. These questions generally relate to comparative planetology, which is the comparison of characteristics and processes of one planet with those of other planets in order to gain insight into more fundamental theories regarding the solar system. These comparisons are considered at the end of this section.

10.1 Mercury

Why Mercury is unique

1. It has the highest density at standard temperature and pressure of all planets.

2. There is virtually no atmosphere.

3. It contains a combination of an internal dipolar magnetic field and the highest planetary flux of solar particles and electromagnetic radiation.

4. As the planet closest to the Sun, it is associated with that part of the nebula having the highest temperature and pressure.

5. It maintains a highly eccentric orbit whose period is in 3/2 resonance with the rotational period.

Interesting and important questions

1. Is the bulk composition highly refractory as might be expected by formation near the Sun?

2. What is the source of the magnetic field?

3. What is the effect of bulk chemical composition on tectonic activity and evolution? Do crustal asymmetries exist in all terrestrial planets?

4. Are surface temperatures and particle fluxes high enough to produce significant effects in the regolith and lattice damage in silicate systems? What is the long-term activity of the Sun? How did micrometeorite bombardment evolve in the innermost solar system? What is the effect of gravity on cratering and regolith formation?

5. How effective is the magnetosheath of Mercury for shielding the surface from the impacts of energetic particles?

6. What is the distribution of radioactive heat sources in Mercury?

10.2 Venus

Why Venus is unique

1. It is the only object in the solar system that has radius, mass, and location similar to Earth, and thus enables comparison between similar objects to the extent of differentiation, tectonic activity, and volcanism.

2. It has a massive CO_2 atmosphere that has the highest density of all atmospheres in the inner solar system.

3. The slow retrograde rotation is in resonance with the orbital motions of the Earth.

4. It is the only object in the inner solar system whose surface cannot be observed remotely in visible light.

Interesting and important questions

1. How do differences or similarities in the following characteristics of Earth and Venus contribute to an understanding of the formation history of both planets?

a. Bulk chemical composition

b. Composition and size of core

c. Nature and source of magnetic field

d. Extent of crust and mantle differentiation

e. Tectonic and igneous activity

2. Why are fluids on Venus composed predominately of CO_2, whereas those on Earth are predominately gaseous nitrogen (N_2) and O_2? Does the Earth have an equivalent amount of CO_2 locked up in carbonates as exists in the Venusian atmosphere? Did Venus ever have appreciable amounts of N_2? Did it ever have any H_2O?

3. How do the shape and mass distribution of Venus relate to the apparent control of its spin by Earth?

4. What surface processes occur on Venus? Are erosion, transportation, and deposition by wind important?

5. What fluids occur in surface materials?

10.3 Earth

Why Earth is unique

1. It is the only planetary object that is readily accessible for extensive and direct study by various techniques. Thus, it furnishes a natural laboratory for the study of many planetary processes.

2. At present, it appears to be the most volcanically and tectonically active planet.

3. It is the only solar system object with highly developed life forms and civilizations.

4. It has a unique atmosphere with large proportions of O_2 and significant H_2O vapor.

5. It has a strong magnetic field that shields the surface from much energetic radiation and particles and that periodically reverses its polarity.

6. It is the only planetary object with oceans and running water presently on the surface.

7. It is highly differentiated.

Interesting and important questions

1. What internal processes control plate tectonic motions? How were they initiated?

2. How have the style and chemical nature of volcanism changed with time? What controlled the changes?

3. At what time and by what processes did life evolve? How was the origin and evolution of life related to the intrinsic evolution of Earth? What were the relative effects of climate, radiation, chemistry, and other environmental variables on the evolution of living organisms?

4. What were the chemical reactions that controlled the evolution of the atmosphere? What was the timing of these reactions? What were the relative effects of planetary degassing, evolution of living organisms, and oceanic evaporite deposition at various stages of this evolution?

5. What causes reversals in the Earth's magnetic field? Does the field remain null for significant periods during reversals?

6. When did major structural units such as the core, crust, and mantle of the Earth form?

7. When and by what process did the oceans form?

10.4 Moon

Why the Moon is unique

1. The ratio of mass-of-Earth to mass-of-Moon is much smaller than any other planet-satellite system.

2. The bulk composition of the Moon contrasts with bulk composition of the Earth.

3. It is the only sampled satellite, and the only old and heavily cratered terrain yet sampled. It is the only other planetary-sized object studied adequately for detailed comparison of internal structure, extent of differentiation, volcanic activity, chronology, and thermal history with those of the Earth.

4. The center of mass is offset from center of figure.

5. There is distinct asymmetry of surface features and all presently filled mare basins are on near side.

6. The returned samples were formed in a magnetic field that no longer exists.

Interesting and important questions

1. How and where did the Moon form? Data from the Apollo Program suggest that it formed near Earth, probably in conjunction with the formation of Earth; but capture by Earth and fission from Earth remain as less probable

possibilities. Was the mechanism of formation of the Earth-Moon system related to formation of other planet-satellite systems?

2. Does the compositional difference of the Moon from the Earth require its formation by impact of a large body (Mars-size) into the Earth rather than a process of accumulation of many bits and pieces by collisions near the Earth?

3. Does the early cratering history of the Moon reflect a circumstance of its formation or capture that is essentially unique in the solar system, or is its early cratering history a measure of similar phenomena over a large part of the solar system?

4. How applicable to other planetary bodies is our current understanding of formation processes of lunar basalts, breccias, and regolith?

5. Does the remanant magnetism of early formed lunar rocks require an internally generated, early magnetic field that later was somehow "turned off"?

6. Do the asymmetry, tidal bulge, and offset center of mass require any unique dynamical processes during early lunar history?

10.5 Mars

Why Mars is unique

1. It is the only solar system object with surface processes comparable enough to Earth (surface shows evidence of weathering, condensates, and igneous activity) to allow comparison of similar types of weathering, erosion, transportation, deposition, and lithification.

2. The solid surface of Mars is the most readily accessible for scientific study among the inner planets.

3. Its Tharsis uplift is associated with the largest gravity anomaly known to exist in the planetary system.

4. Its wind appears to be the dominant erosional and depositional mechanism at the present time, although water may have been important in the past.

5. It displays the largest volcanoes known in the solar system.

Interesting and important questions

1. What is the composition of Mars?

2. Does life exist on Mars?

3. Did flowing liquids create the braided channels? Does significant permafrost exist? What are the mechanisms of wind erosion and particle transport? How do winds form large dunes similar to terrestrial ones?

4. Why does Mars have such large, relatively young volcanoes? How old are they? Does volcanic activity still occur? Has tectonic activity caused the variable surface terrain?

5. What has been the meteorite impact history of Mars? How efficiently have the craters been eroded by weathering processes? How old are the oldest craters? What causes the chaotic terrain? Are the satellites of Mars captured asteroids or remnants from the accretion of Mars?

6. Does Mars have a conducting core?

10.6 Asteroids, Comets, Meteoroids, and Meteorites

Why asteroids, comets, meteoroids, and meteorites are unique

1. The main belt of asteroids occurs in the zone of transition between the inner, terrestrial-like planets and the massive outer planets.

2. Some asteroids appear very primitive and are presumed to have not undergone significant alterations within a planetary body since the formation period. Others appear to be differentiated objects. Comparisons are made with spectral properties of meteorites, many of which are thus presumed to be collisional fragments of asteroids.

3. Comets are perhaps the most primitive or undifferentiated components of the solar system. Some may have formed outside the orbit of Pluto. They are not stable in the inner solar system and give off copious quantities of gas and dust for perhaps a few thousand years although inactive nuclei may continue to exist for millions of years, or more.

4. Meteoroids are those solid objects in space that are not clearly identified as comets or considered as asteroids. They include the smallest solid bodies in the solar system and have short collisional lifetimes (typically, 10 000 to 1 000 000 years) in the inner solar system.

5. Meteorites are those meteoroids, asteroids, or perhaps inactive comets that intersect the Earth's orbit and survive atmospheric entry. They represent the oldest measured samples of the solar system.

Interesting and important questions

1. How many distinct objects initially formed in the asteroid belt? What chemical and isotopic variations existed among these objects and how did these variations arise?

2. Why did some asteroids undergo differentiation, whereas others remained primitive? What were the energy sources for differentiation? What were the time scales? Do answers to these questions apply to larger planetary objects?

3. What has been the collisional interaction history of asteroids? Have asteroids supplied most of the large objects that have bombarded the inner planets over the past?

4. Can specific asteroids be correlated with definite classes of meteorites?

5. What is the origin, history, and ultimate fate of comets? What is their composition? What is their true, as opposed to observed, heliocentric orbital distribution? Are some asteroids or meteorites derived from comets?

6. Do comets represent material from which the outer planets accreted?

7. What is the probability that cometary fragments will survive interplanetary collisions, be perturbed into Earth-crossing orbits, and survive atmospheric entry to become meteorites? How can such meteorites be identified, if they exist?

8. How are different classes of asteroids from different parts of the asteroid belt selected through these same collisions, perturbations, and atmospheric entry to become meteorites?

9. Can the observed meteorite populations be extrapolated back through these processes and correlated reasonably with expected distributions?

10. What detailed chronology of condensation and formation processes in the early solar system are preserved in asteroids, comets, meteoroids, and meteorites?

11. What is the source of magnetization of meteorites?

10.7 Satellites of the Outer Planets

Why satellites of outer planets are unique

1. They are the only accessible solid material besides comets available in the outer solar system.

2. Jupiter, Uranus, and Saturn have extensive satellite systems that do not exist around any other planets.

3. Some satellites represent the high-volatile, low-temperature, and pressure extreme of condensation processes in the solar nebula.

Interesting and important questions

1. What differences in bulk chemical composition exist in the satellites of the outer planets as a function of radial distance from their central planets? Which satellites formed around Jupiter and which are captured? What is the nature of the rings of Saturn?

2. What volatile chemical compounds and elements condensed on these satellites? What is the nature of their surfaces?

3. Have the larger satellites experienced tectonic or igneous activity? Have the satellites differentiated? What has been their cratering history?

4. What is the origin of the atmosphere of Titan?

5. Do any of the satellites display internal magnetic fields?

10.8 Comparative Planetology

Interesting and important questions

1. What planetary objects are presently volcanically or tectonically active? What is the depth and origin of present quake activity?

2. To what extent is bulk compositional variation (shown in planetary objects from Mercury to the outermost planets) caused by compositional and temperature differences in the solar nebula, and to what extent is it caused by chemical fractionations during solid body accretion?

3. Why do some planets have massive cores and some planets appear to have thick crusts, whereas some apparently do not? Why and how do bulk composition and availability of energy sources, the important factors that trigger and control planetary differentiation, vary from object to object? What are the energy sources for this differentiation?

4. Several planetary objects including the Earth, Moon, Mars, and Vesta show evidence of tectonic and/or igneous activity through part of their history. What important factors control these activities and what are the energy sources?

5. Many planetary objects reveal extensive, early bombardment of their surface, which for the Moon ended ~3.9 eons ago. What differences and similarities existed in the early bombardment history of planetary objects? What were the sources and compositions of the bombarding objects? To what extent did this bombardment control crustal structure and early igneous activity?

6. Some planets apparently have hemispherical asymmetries in their crust that date from early in their histories. What is the cause of this asymmetry?

11.0 DIRECTIONS IN PLANETARY GEOSCIENCE

The extensive research in planetary geoscience is commonly categorized by the association of each project with one or more of the objects and phenomena of the solar system. These objects and phenomena, however, are not discrete and unrelated entities. Rather, they result from a continuum of possibilities that arise from the operation of a few universal processes. The existence of these processes makes comparative planetology a powerful tool for understanding the evolution of the solar system. Plate tectonics on the Earth and the genesis of the rigid crust on the Moon are manifestations of the same process of planetary differentiation as determined by the parameters of planetary mass, concentration of radioactive elements, and accretion history. The same basic accretion process created both Mercury and Jupiter, but the chemistry and density of the early nebula varied with distance from the nascent Sun. Clearly the physical properties of each body take on greater significance when viewed in the context of the total system.

As has been shown in the previous sections, the study of important planetary processes involves many disciplines, techniques, and data. The complex and interrelated nature of the processes and the diversity of solar system objects almost assures that fundamental questions about origin and evolution are not addressable from a simple set of measurements or observations. Characterization and understanding of the solar system require a full and balanced partnership between actual planetary observations and complementary studies of planetary processes by laboratory and modeling techniques.

Placing planetary science in the context of important solar system processes provides a firm scientific basis for developing an exploration strategy. This exploration strategy must include both observations and complementary studies. This approach is in contrast to, but not inconsistent with, past exploration strategy that alternated missions to the inner and the outer solar system in response to the dramatic difference between the gaseous, low-density outer planets and the rocky, higher-density terrestrial planets. Placed in the context of contributing to the contemporary knowledge of solar system processes, specific missions can be better evaluated. For example, the current level of understanding of planetary evolution is hampered by uncertainties in formational environments, time scales, and accretional mechanisms. Thus, "arrested" objects become very important. Comets and some asteroids may represent primitive stages in the accretion process, as they are now understood, and, therefore, may be windows to the early solar system. The rings of Saturn may have similar significance to the mechanisms of accretion.

A continuing assessment of both the level of understanding of important solar system processes and gaps where critical information is needed will provide a proper basis for balancing detailed study and exploration missions.

11.1 Planetary Observations

Observational data include those acquired by Earth-based (ground or Earth orbital) remote sensing, by planetary spacecraft, and from returned samples including meteorites. Planetary spacecraft can be categorized into three basic types (flybys, orbiters, and landers) that acquire fundamentally different types of data. A popular, current concept regards the study of any object as the linear sequence Earth-based observation, flyby, orbiter, lander (or probe), and finally a sample return. Yet, any exploration strategy should treat this sequence as secondary. Each type of observational mode produces data that are unique and complementary to those from other modes. Earth-based or Earth-orbital astronomy is relatively economical and provides an appropriate avenue for proving new techniques. However, the overall capability of spacecraft is simply not available from Earth. Flybys provide reconnaissance data crucial to the design of more complex missions. Their potential for observing several bodies on one mission make them particularly attractive. Orbital missions are critical to planetology because they may provide global surveys of mass distributions, surface chemistry, surface heat flux, magnetic fields, and morphology - all of which are useful in the selection of future landing sites. Such data provide much of man's information on the chemical composition, internal structure, and evolutionary history of an object. Large quantities of diverse data must be reduced and synthesized in order to extract this information. Landers or probes can provide a wide range of in situ chemical and physical data such as seismic measurements that can be made only from the surface. Sample return provides a small amount of material for detailed and broad-ranging studies that would be economically unfeasible with remote analytical techniques. Returned samples from the Moon have demonstrated the importance of numerous analytical studies that cannot be automated for spacecraft missions within the scope of current technology. In particular, radioactive dating studies and petrographic analyses are crucial for understanding the processes, time scales, and sequences of planetary development. Before sample-return missions from planetary objects that may harbor living organisms, a substantial effort should be directed toward the concerns about possible back-contamination of Earth by such organisms.

11.2 Complementary Studies

Complementary studies consist of the data and knowledge derived from laboratory, theoretical, modeling, and instrument-development studies. Laboratory studies include physical property studies, experimental petrology, partitioning of elements, and simulations of such processes as condensation and hypervelocity impacts. Theoretical studies provide the foundation for interpreting data. Modeling is the major technique for integrating data sets and extracting important implications from the data considered as a whole. Instrument-development studies are necessary for the exploration and development of new techniques to provide information that is scientifically important for understanding certain processes and to ensure that the best available instruments are used. Penetrators, probes, and Earth-orbiting remote-sensing techniques are examples.

Complementary studies provide two necessary inputs for using the observational data. First, they provide the basis for interpreting the data in terms of physical and chemical parameters. For example, theoretical studies of electronic transitions in silicates and laboratory measurements in lunar samples provide the basis for interpreting infrared reflectance spectra in terms of surface mineralogy. Secondly, they provide the basis for extracting information about the processes from the observations. For example, knowledge of both the thermal conductivity of planetary materials and heat transfer mechanisms (conduction, liquid convection, solid-state convection) are required to convert surface heat flow data into information about the thermal state of the interior of a planet.

12.0 CONCLUDING STATEMENT

Again it should be emphasized that a successful program of planetary geoscience clearly must be balanced to include observations of a variety of solar system objects, complementary laboratory, theoretical, and modeling studies, and instrument development. The inclusion of all aspects is essential because the investigation of only a few objects with a limited scientific base does not provide sufficient information to solve many of the most basic questions. In addition, planetary geoscience requires that a concerted effort be made to bring together data and knowledge from many diverse fields of science and technolgoy if the complex and fascinating questions of the origin and evolution of the solar system are to be answered.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, March 2, 1977
383-85-00-00-72

NASA-JSC