

Decadal Survey 2013-2022

Chapter 5 “Moon” Summary

[CHECK ALL INFORMATION FROM THE ORIGINAL DOCUMENT.

Download it at: http://www.lpi.usra.edu/decadal/2013_2022/]

Take Home Message (page 5-24):

Priority [Lunar] mission goals include:

- Sample return from the South Pole-Aitken Basin region;
- A lunar geophysical network, as identified in this chapter.

Other important science to be addressed by future missions include:

- The nature of polar volatiles (e.g., Lunar Polar Volatiles concept described in Appendices D and G);
- The significance of recent lunar activity at potential surface vent sites;
- The reconstruction of both the thermal-tectonic-magmatic evolution of the Moon;
- The impact history of the inner solar system through the exploration of better characterized and newly revealed lunar terrains.

Such missions may include orbiters, landers and sample return.

The goals for research concerning the inner planets for the next decade are threefold:

- Understand the origin and diversity of terrestrial planets. *How are Earth and its sister terrestrial planets unique in the solar system and how common are Earth-like planets around other stars? Addressing this goal will require constraining the range of terrestrial planet characteristics, from their compositions to their internal structure to their atmospheres, to refine ideas of planet origin and evolution.*
- Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life. What conditions enabled life to evolve and thrive on the early Earth? *The Moon and Mercury preserve early solar system history that is a prelude to life.* Venus is a planet that was probably much like Earth but is now not habitable. *Together, the inner planets frame the question of why Earth is habitable, and what is required of a habitable planet.*
- Understand the processes that control climate on Earth-like planets. What determines the climate balance and climate change on Earth-like planets? Earth’s climate system is extraordinarily complex, with many inter-related feedback loops. To refine concepts of climate and its change, it is important to study other climate systems, like Venus, Mars and Titan, which permit us to isolate some climate processes and quantify their importance.

UNDERSTAND THE ORIGIN AND DIVERSITY OF TERRESTRIAL PLANETS.

Constrain the bulk composition of the terrestrial planets to understand their formation

from the solar nebula and controls on their subsequent evolution.

Basic information on surface composition, internal structure, and volatile inventories provides important constraints on the bulk major-element composition of the terrestrial planets. While little progress has been made in the last decade to help determine Venus's bulk composition, major strides have been made in understanding the bulk compositions of Mercury and the Moon.

Substantial research efforts in the last decade using Lunar Prospector and Clementine data, plus new basaltic lunar meteorites, have provided refined estimates of the compositions of the lunar crust and mantle. New observations from Apollo samples have been interpreted as indicating that the bulk volatile content of the Moon is more water-rich than had been thought; if true, this has profound implications for the origin of the Earth-Moon system.

Important Questions:

- What are the proportions and compositions of the major components (e.g., crust, mantle, core, atmosphere/exosphere) of the inner planets?
- What are the volatile budgets in the interiors, surfaces and atmospheres of the inner planets?
- How did nebular and accretionary processes affect the bulk compositions of the inner planets?

Future Directions for Investigations and Measurements

- Improved understanding of the various types of rock and regolith making up the crusts and mantles of the inner planets.
- Sample return of crust and mantle materials from the Moon.
- Key geophysical objectives include characterization of the Moon's lower mantle and core.

Characterize planetary interiors to understand how they differentiate and dynamically evolve from their initial state.

Knowledge of the internal structure of the terrestrial planets is key to understanding their histories after accretion. Differentiation is a fundamental planetary process that has occurred in numerous solar system bodies. Important aspects of differentiation include heat loss mechanisms, core formation processes, magnetic-field generation, distribution of heat-producing radioactive elements, styles and extent of volcanism, and the role of giant impacts. Analysis of lunar samples implies the Moon formed hot, with a magma ocean more than 400 km deep. The heat of accretion that led to magma oceans on Earth and the Moon may have been common to all large rocky planets, or may have been stochastically distributed based on the occurrences of giant impact processes.

Important Questions:

- How do the structure and composition of each planetary body vary with respect to location, depth, and time?
- What are the major heat-loss mechanisms and associated dynamics of their cores and mantles?
- How does differentiation occur (initiation and mechanisms) and over what timescales?

Future Directions for Investigations and Measurements

Key lunar investigations include:

- Determining the locations and mechanisms of seismicity and characterization of the lunar

- lower mantle and core.
- New analysis of the ages, isotopic composition, and petrology (including mineralogy) of existing lunar samples, of new samples from known locations, and of remotely sensed rock and regolith types, and continued development of new techniques to glean more information from samples will form the basis of knowledge for the detailed magmatic evolution of the Moon.
- Experimental petrology, fluid, and mineral physics and numerical modeling of planetary interiors are crucial to understand processes that cannot be directly observed and provide frameworks for future observations

Characterize planetary surfaces to understand how they are modified by geologic processes.

New data from Clementine, Lunar Prospector, LRO, and various international missions (Smart-1, Kaguya, Chang'e-1, Chandrayaan-1) illustrate a diversity of surface features on the Moon, including fault scarps, lava tubes, impact melt pools, polygonal contraction features, and possible outgassing scars. The timing and extent of lunar magmatism has been extended via crater counting and new meteorite samples. Understanding of impact processes has been enhanced by models of crater formation and ejecta distribution, and knowledge of the lunar impact flux has been improved using dynamical modeling and new ages for lunar samples. Although the nature of lunar polar volatile deposits was probed by the LCROSS impactor mission and by instruments aboard LRO and Chandrayaan-1, the form, extent, and origin of such deposits are not fully understood.

Important Questions:

- What are the major surface features and modification processes on each of the inner planets?
- What were the sources and timing of the early and recent impact flux of the inner solar system?
- What are the distribution and timescale of volcanism on the inner planets?
- What are the compositions, distributions, and sources of planetary polar deposits?

Future Directions for Investigations and Measurements

- Major advances in our understanding of the geologic history of the inner planets will be achieved in the coming decade through orbital remote sensing of Venus, the Moon and Mercury, as well as in situ data from Venus and the Moon.
- Key among these are global characterization of planetary morphology, stratigraphy, composition, and topography, modeling the time variability and sources of impacts on the inner planets;
- Continued analysis of sample geochronology to help provide constraints on the models.
- Also crucial is developing an inventory and isotopic composition of lunar polar volatile deposits to understand their emplacement and origin, modeling conditions and processes occurring in permanently shadowed areas of the Moon and Mercury.

UNDERSTAND HOW THE EVOLUTION OF TERRESTRIAL PLANETS ENABLES AND LIMITS THE ORIGIN AND EVOLUTION OF LIFE.

The Moon and Mercury are unlikely to harbor life, but they provide critical records of processes and information about the early solar system when life emerged on Earth. Fundamental objectives that will help understand how the evolution of terrestrial planets enables

and limits the origin and evolution of life are as follows:

Understand the composition and distribution of volatile chemical compounds.

Understanding the distribution of volatiles in the inner solar system has advanced significantly in the past decade, due in large part to ongoing NASA spacecraft missions and research programs. Remote sensing of the Moon has shown that broad areas near the poles contain significant hydrogen; recent radar data suggest some of this hydrogen is present as water ice. The LCROSS impact experiment detected abundant volatiles at one shadowed polar region. Results from the Moon Mineralogy Mapper (M³) spectrometer on India's Chandrayaan-1 spacecraft have detected widespread water (or hydroxyl) in regolith at higher latitudes. In addition, sample analyses show that some beads of lunar volcanic glass and minerals from mare basalts contain concentrations of hydrogen high enough to suggest that their parent magma contained as much water as Earth's mantle. These results are new and their interpretation is still in flux, but they may overturn the conventional wisdom that the Moon is "dry."

Important Questions:

- How are volatile elements and compounds distributed, transported, and sequestered in near surface environments on the surfaces of the Moon and Mercury? What fractions of volatiles were outgassed from those planets' interiors, and what fractions represent late meteoritic and cometary infall?
- What are the chemical and isotopic compositions of hydrogen-rich (possibly water ice) near the Moon's surface?
- What are the inventories and distributions of volatile elements and compounds (species abundances and isotopic compositions) in the mantles and crusts of the inner planets?

Future Directions for Investigations and Measurements

Key to constraining the character of volatile chemical compounds on **Venus**, the Moon and **Mercury** are determining:

- (1) The state, extent, and chemical and isotopic compositions of surface volatiles particularly in the polar regions on the Moon and Mercury;
- (2) The inventories and isotopic compositions of volatiles in the mantles and crust of all the terrestrial planets; and
- (3) The fluxes of volatiles to the terrestrial planets (e.g., by impact) over time.

Also key is the continued evaluation of the effects of meteoroid impact fluxes and intensities on the development and evolution of life on the inner planets through analysis of the impact record on the Moon and **Mercury**.

Understand the effects of internal planetary processes on life and habitability.

It is crucial to understand how planetary environments can enable or inhibit the development and sustainment of prebiotic chemistry and life. Also important are the initiation and termination of planetary magnetic fields, which can enable shielding of a planet's surface from external radiation.

Important Questions:

- What are the timescales of volcanism and tectonism on the inner planets?
- How are planetary magnetic fields initiated and maintained?

Future Directions for Investigations and Measurements

Progress can be made in understanding how internal processes affect planetary habitability

through focused measurements and research that “follow the volatiles” from the interiors, to the surfaces, to escape from the atmospheres of the inner planets. Future investigations should include:

- Determining the transport rates and fluxes of volatile compounds between the interiors and atmospheres of the inner planets;
- Constraining the styles, timescales and rates of volcanism and tectonism on Venus, the Moon and Mercury through orbital and in situ investigations;
- Measuring and modeling the characteristics and timescales of planetary magnetic fields and their influence on planetary volatile losses and radiation environments.

Understand the effects of processes external to a planet on life and habitability.

External processes can be crucial enablers or inhibitors of the origin and evolution of life. Understanding of these external processes overlaps partially with the objective of understanding the composition and distribution of volatile chemical compounds. In other words, volatiles can be brought to a planet or leave via external processes (e.g., comet impacts delivering volatiles, or solar wind removing them). The origin and evolution of life can be influenced by other external processes such as stellar evolution, atmospheric losses to space, effects of impacts, orbital interactions of planetary bodies, cosmic ray fluxes, supernovae, and interstellar dust clouds.

Important Questions:

- What are the mechanisms by which volatile species are lost from terrestrial planets, with and without substantial atmospheres (i.e., Venus versus the Moon), and with and without significant magnetic fields (i.e., Mercury versus the Moon)? Do other loss mechanisms or physics become important in periods of high solar activity?
- What are the proportions of impactors of different chemical compositions (including volatile contents) as functions of time and place in the solar system?
- What causes changes in the flux and intensities of meteoroid impacts onto terrestrial planets, and how do these changes affect the origin and evolution of life? What are the environmental effects of large impacts onto terrestrial planets?

Future Directions for Investigations and Measurements

- Fundamental models of volatile delivery and loss relevant for understanding how processes external to a planet can enable or thwart life and prebiotic chemistry can be constrained by investigation of loss rates of volatiles from planets to interplanetary space, in terms of solar intensity, gravity, magnetic field environment, and atmospheric composition.
- Also key are to characterize volatile reservoirs that feed volatiles onto terrestrial planets after the main phases of planetary accretion (e.g., a late chondritic veneer, heavy bombardment) and to evaluate impact intensity and meteoritic and cometary fluxes to the terrestrial planets through time, including calibration of the lunar impact record.

UNDERSTAND THE PROCESSES THAT CONTROL CLIMATE ON EARTH-LIKE PLANETS.

Minor for the Moon

Determine how solar energy drives atmospheric circulation, cloud formation and chemical cycles that define the current climate on terrestrial planets.

Characterize the record of and mechanisms for climate evolution on Venus, with the goal

of understanding climate change on terrestrial planets, including anthropogenic forcings on Earth.

Recent results for the other inner planets have placed better constraints on rates and mechanisms of volatile loss. For the Moon, a pyroclastic origin has also been postulated for some deposits, with similar implications for volatile content and release. And, there is a tantalizing hint that a few areas of the Moon have recently released gases.

Important Questions:

- What is the relative role of water on the terrestrial planets in determining climate, surface geology, chemistry, tectonics, interior dynamics, structure, and habitability?
- What is the history of volcanism and its relationship to interior composition, structure and evolution (e.g., outgassing history and composition, volcanic aerosols and climate forcing)?
- How has the impact history of the inner solar system influenced the climates of the terrestrial planets?
- What are the critical processes involved in atmospheric escape of volatiles from the inner planets?

Future Directions for Investigations and Measurements

Other important aspects are to improve understanding of the role of life in terrestrial planet climate evolution and the likely divergent paths of inhabited and lifeless planets, and to better characterize the impact bombardment history of the inner solar system as it has affected the habitability of Earth, Mars, and Venus through time.

Constrain ancient climates on Venus, and search for clues into early terrestrial planet environments so as to understand the initial conditions and long-term fate of Earth's climate.

Important Questions:

- Do volatiles on Mercury and the Moon constrain ancient atmospheric origins, sources and loss processes?
- How did early extreme ultraviolet flux and solar wind influence atmospheric escape in the early solar system?

INTERCONNECTIONS: Links to other Planetary Bodies

Impacts are ubiquitous across the solar system, and provide an important chronometer for the dating of surface regions on objects throughout the solar system. Unraveling solar system impact history has relied heavily on the lunar impact record. Both the Moon and Ganymede retain an impact signature that suggests a late heavy bombardment due to migration of the gas giants. The impactors themselves, derived mostly from asteroids and comets, provide important clues to evolution of the early solar system and the building blocks of the planets and their satellites.

Tectonic and volcanic styles vary significantly across the solar system. Comparison of active volcanic styles on Venus, Earth, Io, and several of the icy satellites in the outer solar system, and tectonic and volcanic styles on all solid planetary bodies provides information on the mechanisms by which planetary bodies dissipate primordial, tidal and radiogenic heat. In particular, the conditions that lead to planets like Earth with plate tectonics, single-plate bodies like Mercury and the Moon, and the spectrum of bodies with intermediate behavior can be characterized.

Further characterization of current or paleo-dynamos in the cores of the terrestrial planets and satellites of the outer solar system may significantly increase our knowledge of magnetic field generation and evolution in planetary cores.

Planetary exospheres, those tenuous atmospheres that exist on many planetary bodies, including the Moon, Mercury, asteroids, and some of the satellites of the giant planets, are poorly understood at present. Insight into how they form, evolve, and interact with the space environment would greatly benefit from comparisons of such structures on a diversity of bodies.

There may be significant advantages in taking a multi-planet approach to instrument and mission definition and operation. Major cost and risk reductions for future missions can result from a synergistic approach to developing technologies for scientific exploration of planetary bodies. For example, technologies, including sample collection, cryogenic containment and transport, and tele-operation may have application for sample return missions across the solar system.

INTERCONNECTIONS: Links to Astrobiology

Studies of the origin and evolution of volatiles on the terrestrial planets, the effects of early planetary magnetic fields, and variation in the solar wind over time are critical to our understanding of where environments might have existed for the development of life.

An understanding of the impact flux in the early solar system as a function of time, including verification of the reality or otherwise of the late heavy bombardment, provides critical information on potential limits to the early development of life on Earth and other bodies. Age measurements on returned samples from a broader range of impact basins on the Moon would enable greater quantification of the impact history of the inner solar system.

INTERCONNECTIONS: Links to Human Exploration

The Moon is a logical step in the process of continued human exploration of the solar system, and it is conceivable that human precursor missions and human missions might return to the lunar surface in the coming decades. While human precursor missions are not necessarily science driven, science will definitely be a beneficiary of any precursor activity. Lunar scientists can provide critical scientific input to the design and implementation of any human precursor activity to ensure that the science return is maximized within the scope of the mission. Should human missions occur, the presence of geologically trained astronauts on the lunar surface could enable significant scientific in situ activities and make informed down-selections onsite to ensure the return of material with the highest scientific value.

TECHNOLOGY DEVELOPMENT

The lack of an atmosphere at Mercury and the Moon, for example, coupled with their relatively large masses, means that landed missions incur either a substantial propulsion burden for soft landing or large landing shocks at impact. The development of a robust airless body lander system incorporating high-impulse chemical propulsion, impact attenuation, and low-mass subsystems will enable extensive surface exploration in the coming decades.

Venus and Mercury, and to a lesser extent the Moon, also represent extreme thermal environments that will stress spacecraft capabilities. High-temperature survivability technologies such as new materials, batteries, electronics, and possibly cooled chambers will enable long-term in situ missions.

The development of robust scientific instruments and sampling systems, including age-dating

systems, spectrometers, seismometers, and sub-surface drilling and related technologies is also critical in addressing the scientific objectives for the coming decades. New capabilities for in situ age dating are of particular importance, as they can help to provide constraints on models of surface and interior evolution of all the terrestrial planets.

New Frontiers missions—New Frontiers missions remain critical to a healthy program of mission activity throughout the inner solar system, providing opportunities for critical science in more challenging environments and for more comprehensive studies than can be supported under Discovery. A regular cadence of such missions is highly desirable. The committee point to three missions as being particularly important. They are, in priority order:

1. Venus In Situ Explorer,
2. South Pole-Aitken Basin Sample Return, and
3. Lunar Geophysical Network.

Discovery missions—Small missions remain an integral part of the exploration strategy for the inner solar system, with major opportunities for significant science return. A regular cadence of such missions is needed. Such missions may include orbital, landed or mobile platforms that provide significant science return in addressing one or more of the fundamental science questions laid out earlier in this chapter.

The Discovery Program's Value to Exploring the Inner Planets

The proximity of the Moon makes it an ideal target for future orbital or landed Discovery missions, building on the rich scientific findings of recent lunar missions, and the planned GRAIL and LADDE missions. The variety of tectonic, volcanic and impact structures, as well as chemical and mineralogical diversity offer significant opportunity for future missions.