Priorities in Lunar Science

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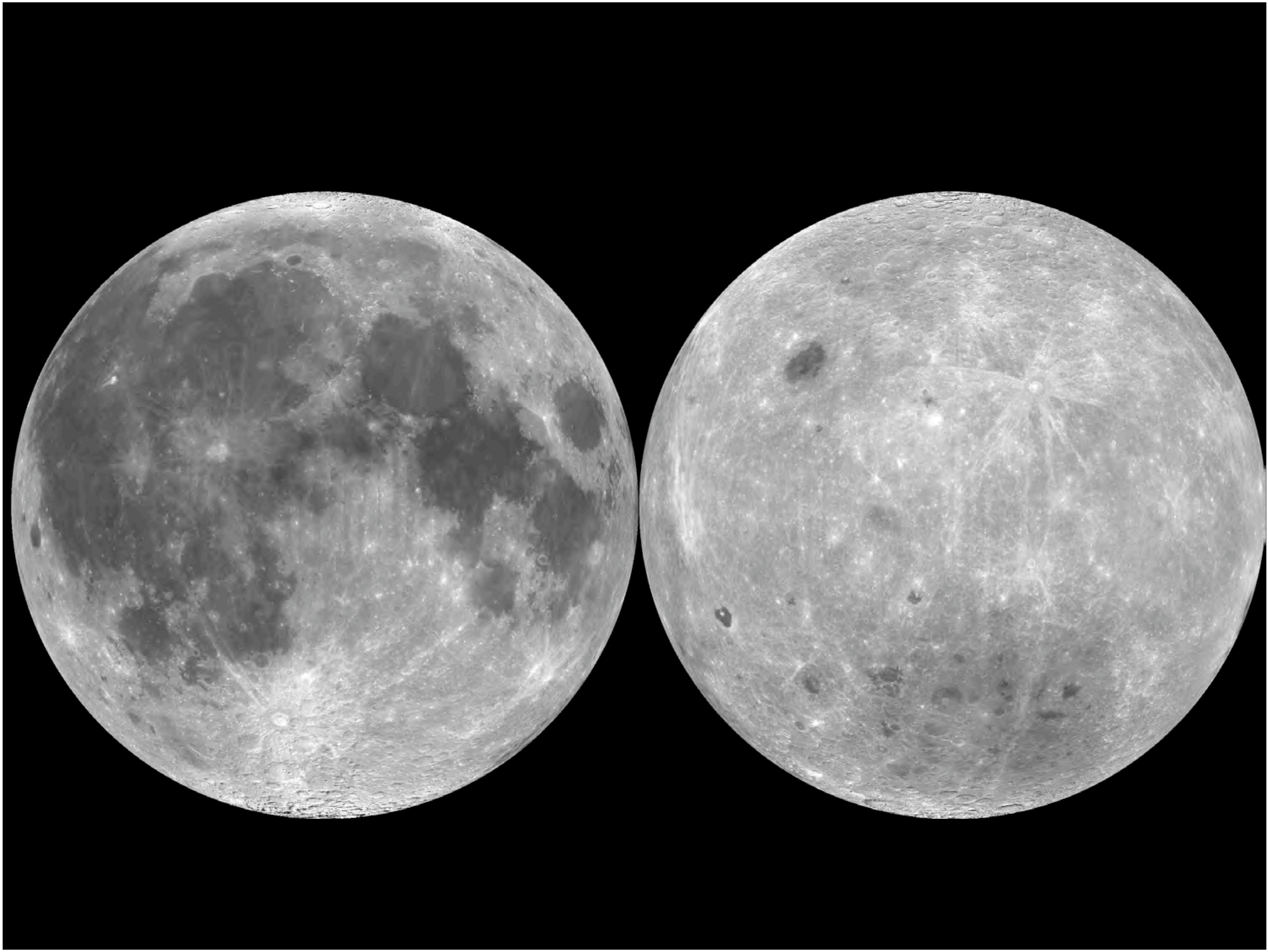
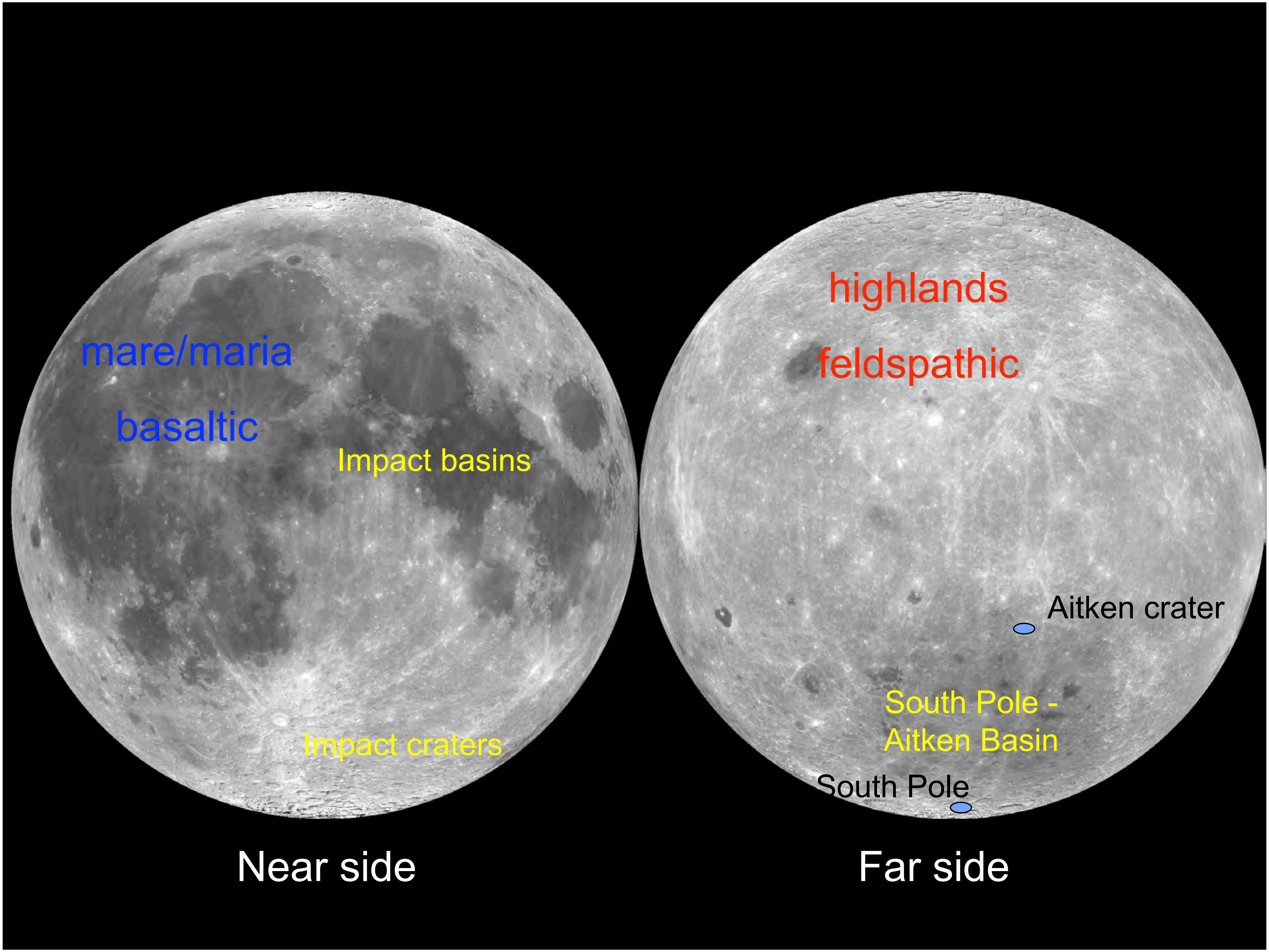
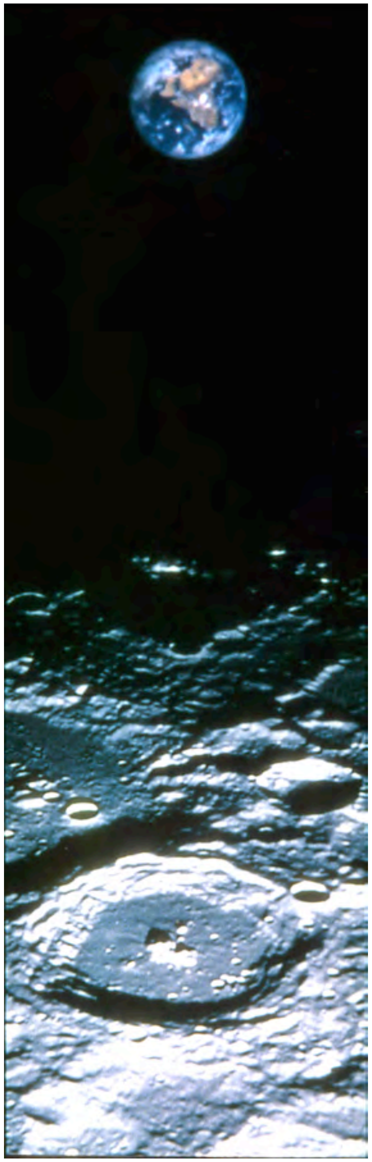



highlands
feldspathic
mare/maria
basaltic
Impact basins
Impact craters
Aitken crater
South Pole -
Aitken Basin
South Pole
Near side
Far side

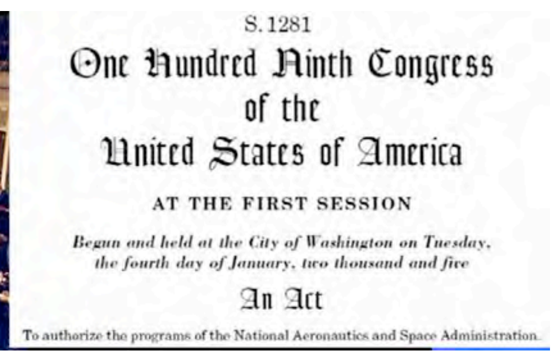
Why the Moon?



- The Moon today presents a record of geologic processes of early planetary evolution:
  - Interior retains a record of the initial stages of planetary evolution
  - Crust has never been altered by plate tectonics (Earth) planetwide volcanism (Venus), or wind and water (Mars & Earth)
  - Surface exposed to billions of years of volatile input
- The Moon holds a unique place in the evolution of rocky worlds - many fundamental concepts of planetary evolution were developed using the Moon
    - The Moon is ancient and preserves an early history
    - The Moon and Earth are related and formed from a common reservoir
    - Moon rocks originated through high-temperature processes with no involvement with water or organics

U.S. Space Policy (VSE)

- Conceived in response to loss of Columbia Space Shuttle, 2003
- Five steps:
  - Return Shuttle to flight
  - Complete ISS assembly and retire Shuttle
  - Build new human spacecraft (CEV) for transport beyond LEO
  - Return to the Moon with people and robots to explore and prepare for voyages beyond
  - Human missions to Mars and other destinations
- Proposed by President Bush, endorsed by 109th Congress, now national policy


S.1281

One Hundred Ninth Congress
of the
United States of America

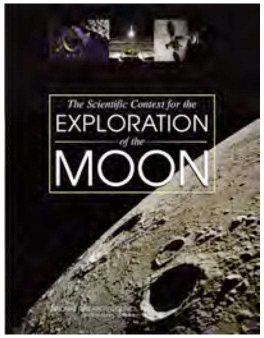
AT THE FIRST SESSION

Begun and held at the City of Washington on Tuesday, the fourth day of January, two thousand and five

An Act

To authorize the programs of the National Aeronautics and Space Administration.

Science roadmap for the Moon



The Scientific Context for
EXPLORATION
of the
MOON
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

From: Mary Cleave, NASA Associate Administrator for Science [SMD]

To: Lennard Fisk, Chair of Space Studies Board of NRC/NAS

Dates: June 2006 - May 2007

Primary Tasks

Identify a prioritized set of scientific goals that can be addressed in the near term (~2006-2018) by robotic lunar missions and in the mid term (~2018-2023) by astronauts on the Moon.

Suggest which of the identified scientific goals are amenable to orbital measurements, in situ study, or terrestrial analysis via the return of lunar samples to the Earth.

Secondary Tasks

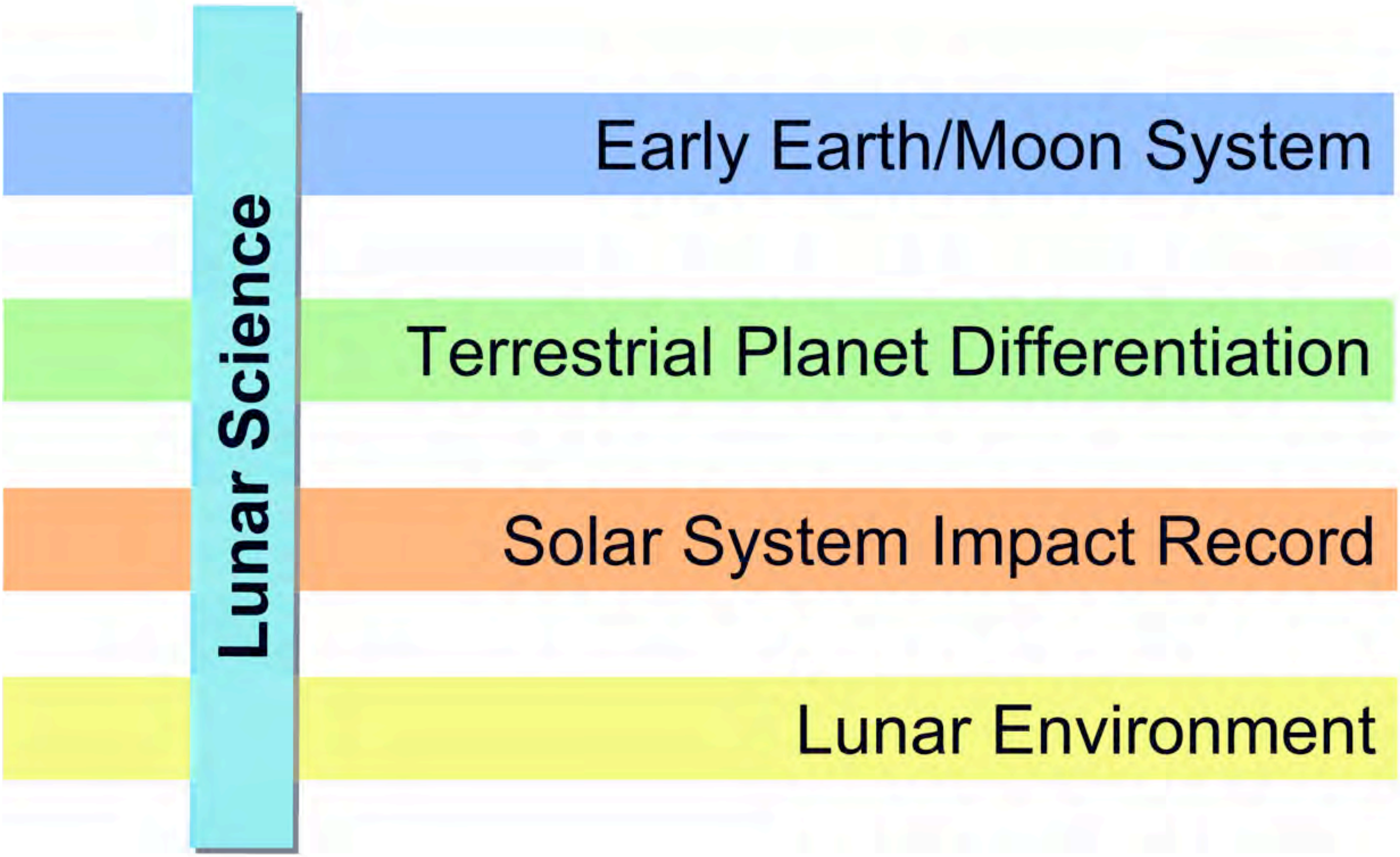
Comment on those areas where there is a synergistic overlap between measurements addressing scientific goals and measurements required to ensure human survival or resource utilization.

Collect and characterize possible scientific goals that might be addressed on or from the Moon in the long term (i.e., after ~2023) and deserve further study.

Science roadmap for the Moon

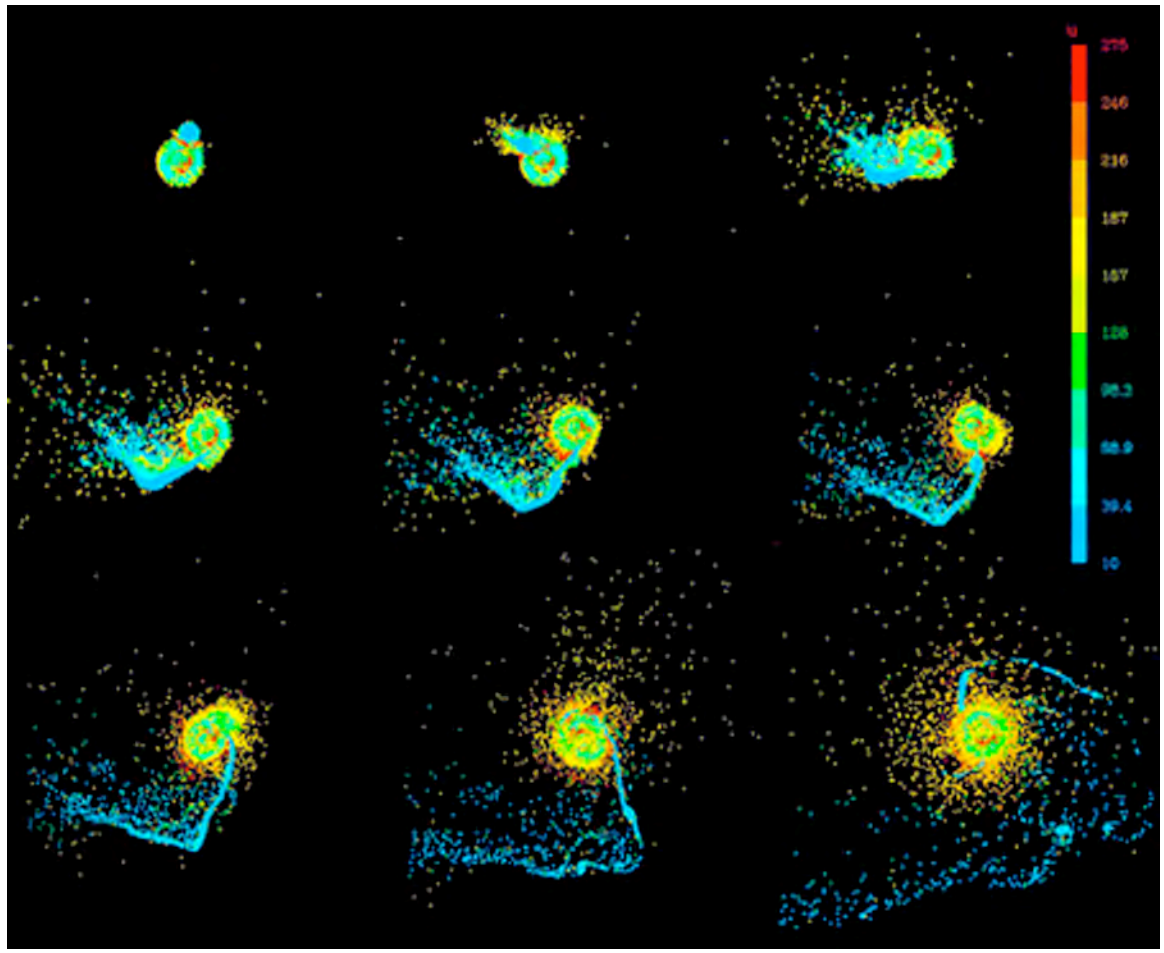
- GEORGE A. PAULIKAS, The Aerospace Corporation (retired), Chair
- CARLÉ M. PIETERS, Brown University, Vice Chair
- WILLIAM B. BANERDT, Jet Propulsion Laboratory
- JAMES L. BURCH, Southwest Research Institute
- ANDREW CHAIKIN, Science Journalist, Arlington, Vermont
- BARBARA A. COHEN, University of New Mexico
- MICHAEL DUKE, Colorado School of Mines
- ANTHONY W. ENGLAND, University of Michigan
- HARALD HIESINGER, Westfälische Wilhelms-Universität, Münster
- NOEL W. HINNERS, University of Colorado
- AYANNA M. HOWARD, Georgia Institute of Technology
- DAVID J. LAWRENCE, Los Alamos National Laboratory
- DANIEL F. LESTER, McDonald Observatory
- PAUL G. LUCEY, University of Hawaii
- S. ALAN STERN, Southwest Research Institute
- STEFANIE TOMPKINS, Science Applications International Corporation
- FRANCISCO P.J. VALERO, Scripps Institution of Oceanography
- JOHN W. VALLEY, University of Wisconsin-Madison
- CHARLES D. WALKER, Independent Consultant, Annandale, Virginia
- NEVILLE J. WOOLF, University of Arizona

Lunar science is fundamental science



Lunar framework: Giant impact

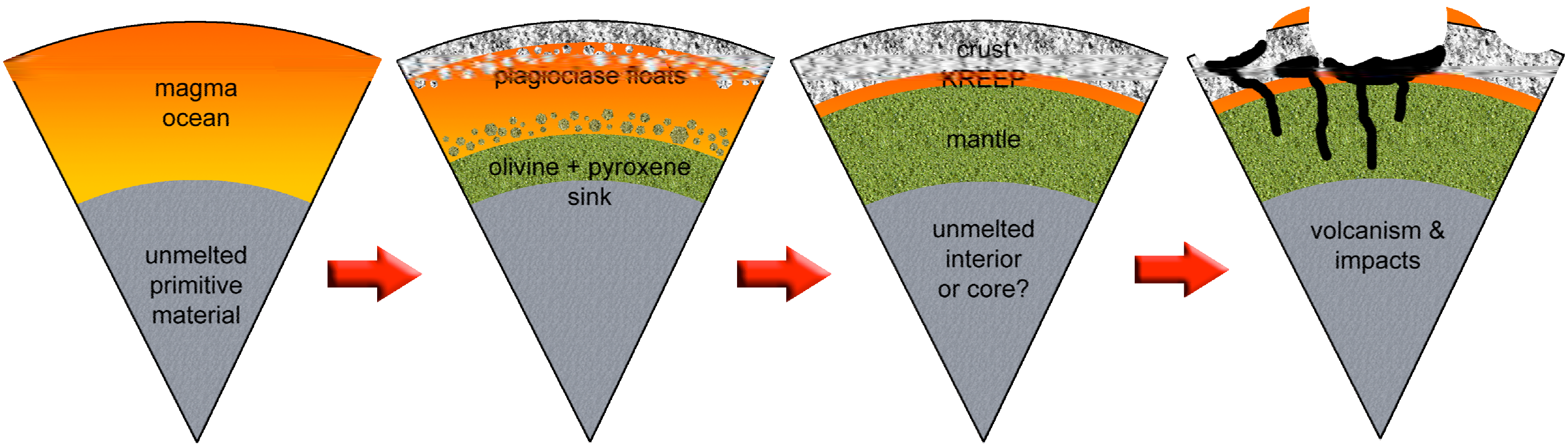
- Mars-sized body slammed into the proto-Earth at 4.56 Ga
- Moon formed out of crust/upper mantle component - lack of metal
- Moon material was hot - lack of volatile elements
- Moon/Earth have shared angular momentum & oxygen isotopes



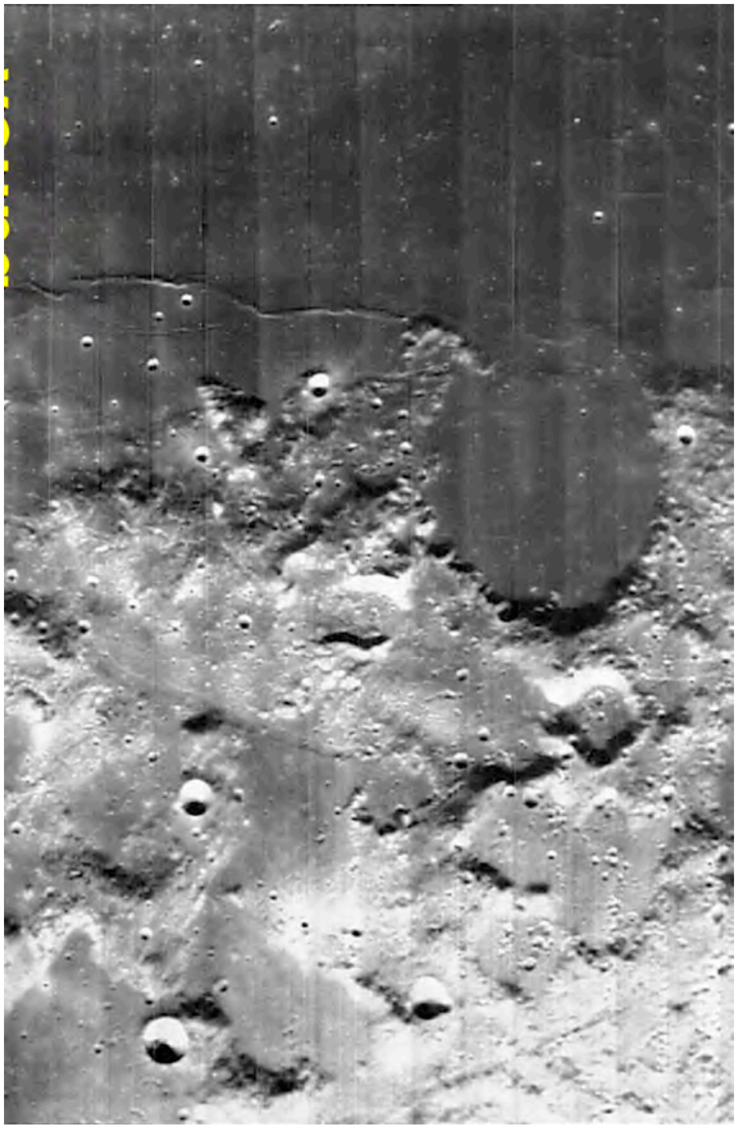
Lunar framework: Magma ocean

Lunar Precursor Robotics Program

- Differentiation via igneous processes
- Basaltic volcanism via mantle density overturn
- Incompatible elements in KREEP layer
- Redistribution by impact processes



Lunar framework: Crater history

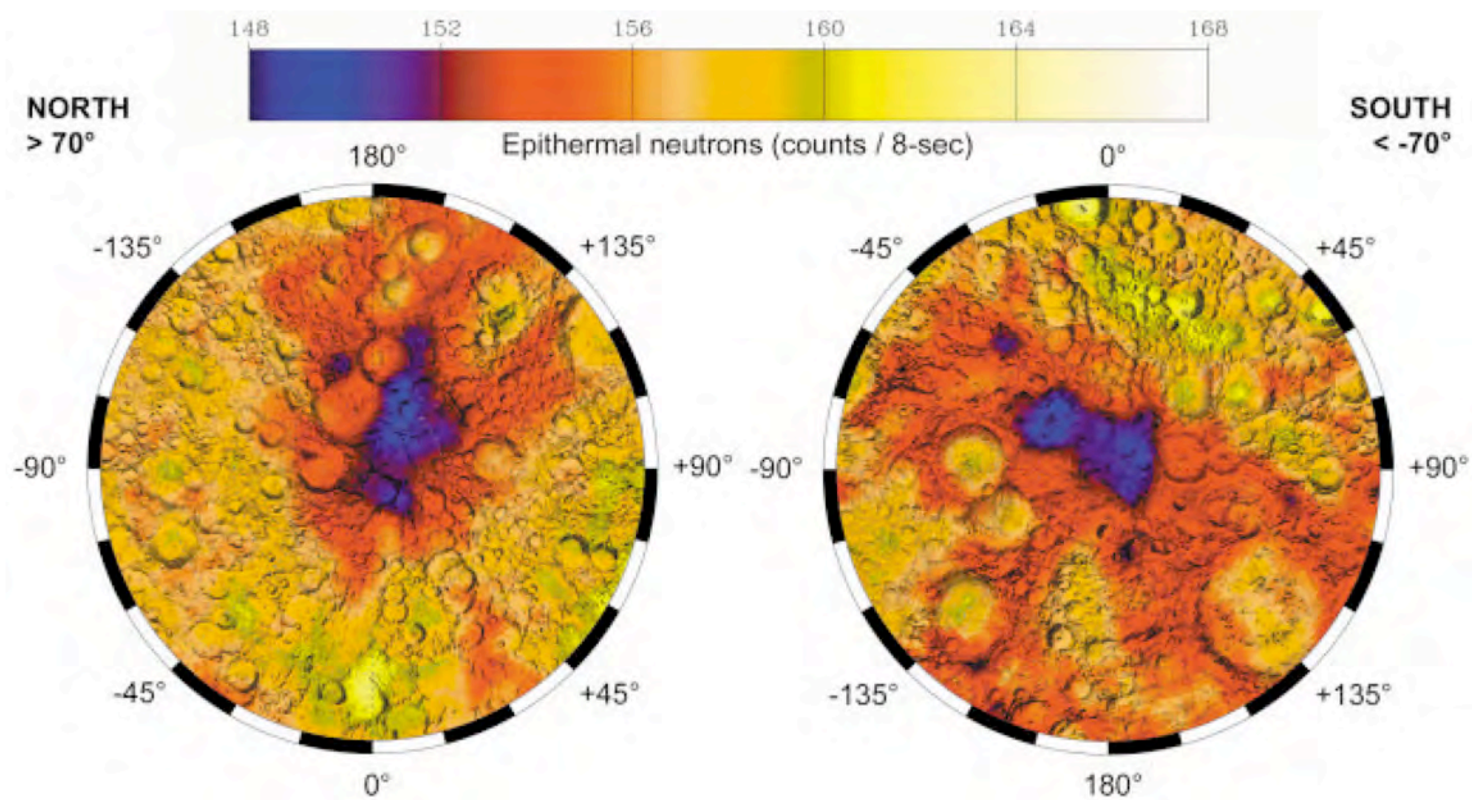


- The Moon is the only place where the link is forged between radiometric ages of rocks and relative ages by crater counting
- Crater record of the Moon reflects the flux of impactors in the inner solar system
- Bombardment history of the Moon is magnified on the Earth

Lunar framework: Volatile record

Lunar Precursor Robotics Program

- Lunar plasma environment, atmosphere, regolith and polar regions in permanent shade constitute a single system in dynamic flux that links the interior of the Moon with the space environment and the volatile history of the solar system



Lunar science themes

1) The bombardment history of the inner Solar System is uniquely revealed on the Moon
2) The structure and composition of the lunar interior provides fundamental information on the evolution of a differentiated body
3) Key planetary processes are manifested in the diversity of lunar crustal rocks
4) The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history
5) Lunar volcanism provides a window into the thermal and compositional evolution of the Moon
6) The Moon is an accessible laboratory for studying the impact process on planetary scales
7) The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies
8) Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study only while the environment remains in a pristine state

1. The bombardment history of the inner Solar System is uniquely revealed on the Moon

- Lunar impact history is uniquely intertwined with that of Earth
  - early intense impacts and possible periodicity affect habitability - atmosphere, environment, and early life
- Correlation between surface crater density and radiometric age is the basis for estimating surface ages on all other solid bodies
  - significant uncertainties remain in absolute ages of specific craters

Fundamental questions:

1a. Test the cataclysm hypothesis by determining the spacing in time of the creation of lunar basins.

1b. Anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin (South Pole-Aitken Basin).

1c. Establish a precise absolute chronology.

1d. Assess the recent impact flux.

1e. Study the role of secondary impact craters on crater counts.

2. The structure and composition of the lunar interior provides fundamental information on the evolution of a differentiated body

- Common formation affected the early thermal state and subsequent geologic evolution of Earth and Moon
- Both underwent primary differentiation involving the formation of a (presumably) iron-rich core, a silicate mantle, and a light crust.
- The initial bulk composition and conditions during differentiation are frozen into in lunar chemistry, structure, and dynamics

Fundamental questions:

2a. Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales.

2b. Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle.

2c. Determine the size, composition, and state (solid/liquid) of the core of the Moon.

2d. Characterize the thermal state of the interior and elucidate the workings of the planetary heat engine.

3. Key planetary processes are manifested in the diversity of lunar crustal rocks

- Magma ocean model – crust+ mantle, modified by thin basalt flows and impacts that scrambled the upper crust
- Remote sensing and sample analyses reveal lateral and vertical variations in composition, age, and mode of emplacement
- Traditional, dichotomous mare-highland classification is inadequate

Fundamental questions:

3a. Determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation.

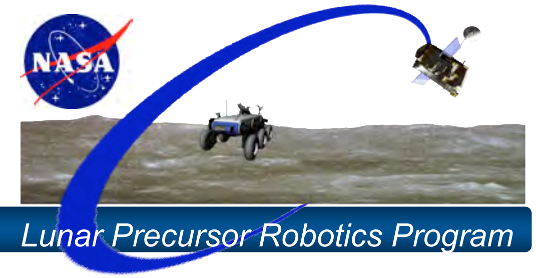
3b. Inventory the variety, age, distribution, and origin of lunar rock types.

3c. Determine the composition of the lower crust and bulk Moon.

3d. Quantify the local and regional complexity of the current lunar crust.

3e. Determine the vertical extent and structure of the megaregolith.

4. The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history



- Small obliquity allows topographic lows (craters) to be permanently shaded at 50K
- Lunar poles record a history of volatile flux through the inner solar system over the lifetime of the traps
- Diversity of potential sources and of transport, trapping, loss, and retention mechanisms

Fundamental questions:

4a. Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.

4b. Determine the source(s) for lunar polar volatiles.

4c. Understand the transport, retention, alteration, and loss processes that operate on volatile materials at permanently shaded lunar regions.

4d. Understand the physical properties of the extremely cold (and possibly volatile rich) polar regolith.

4e. Determine what the cold polar regolith reveals about the ancient solar environment.

5. Lunar volcanism provides a window into the thermal and compositional evolution of the Moon

- More-complex models of the magma ocean require compositional, temporal, and geophysical constraints to be effective.
- Connections between composition, location, and age of volcanic activities are limited.
  - Lunar sample collection yields detailed composition and age data, but lack geologic context
  - Global remote sensing data reveals volcanic rock compositions that do not appear in the sample collection

Fundamental questions:

5a. Determine the origin and variability of lunar basalts.

5b. Determine the age of the youngest and oldest mare basalts.

5c. Determine the compositional range and extent of lunar pyroclastic deposits.

5d. Determine the flux of lunar volcanism and its evolution through space and time.

6. The Moon is an accessible laboratory for studying the impact process on planetary scales

- Impact cratering is a fundamental process that affects all planetary bodies.
- Terrestrial models and experiments scaled for lunar gravity, but many unscaleable processes
- Moon provides several orders of magnitude, from micrometeorite impacts to the largest basin in the solar system, the South Pole-Aitken Basin

Fundamental questions:

6a. Characterize the existence and extent of melt sheet differentiation.

6b. Determine the structure of multi-ring impact basins.

6c. Quantify the effects of planetary characteristics (composition, density, impact velocities) on crater formation and morphology.

6d. Measure the extent of lateral and vertical mixing of local and ejecta material.

7. The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies

- Regoliths on airless bodies
  - representative rocks from both local and distant sources
  - alteration products induced by meteoroid and micrometeoroid impacts,
  - implantation of solar and interstellar charged particles, radiation damage, spallation, exposure to ultraviolet radiation, etc.

Fundamental questions:

7a. Search for and characterize ancient regolith.

7b. Determine physical properties of the regolith at diverse locations of expected human activity.

7c. Understand regolith modification processes (including space weathering), particularly deposition of volatile materials.

7d. Separate and study rare materials in the lunar regolith.

8. Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study only while the environment remains in a pristine state

- Lunar atmosphere nearest and most accessible surface boundary exosphere (Mercury, satellites, Kuiper Belt objects)
- Surface sputtering, meteoritic vaporization processes, exospheric transport processes, gas-surface thermal and chemical equilibration
- Fragile - lunar landing will perturb for weeks to months

Fundamental questions:

- 8a. Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further activity.
- 8b. Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy.
- 8c. Use the time-variable release rate of atmospheric species such as 40Ar and radon to learn more about the inner workings of the lunar interior.
- 8d. Learn how water vapor and other volatiles are released from the lunar surface and migrate to the poles where they are adsorbed in polar cold traps.

Prioritized goals

1a. Test the cataclysm hypothesis by determining the spacing in time of the creation of the lunar basins.

1b. Anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin (South Pole-Aitken Basin).

1c. Establish a precise absolute chronology.

4a. Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.

3a. Determine the lateral extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation.

2a. Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales.

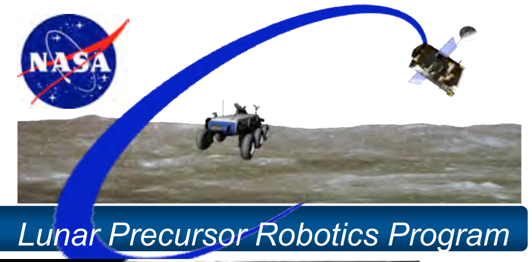
2b. Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle.

8a. Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity.

2c. Determine the size, composition, and state (solid/liquid) of the core of the Moon.

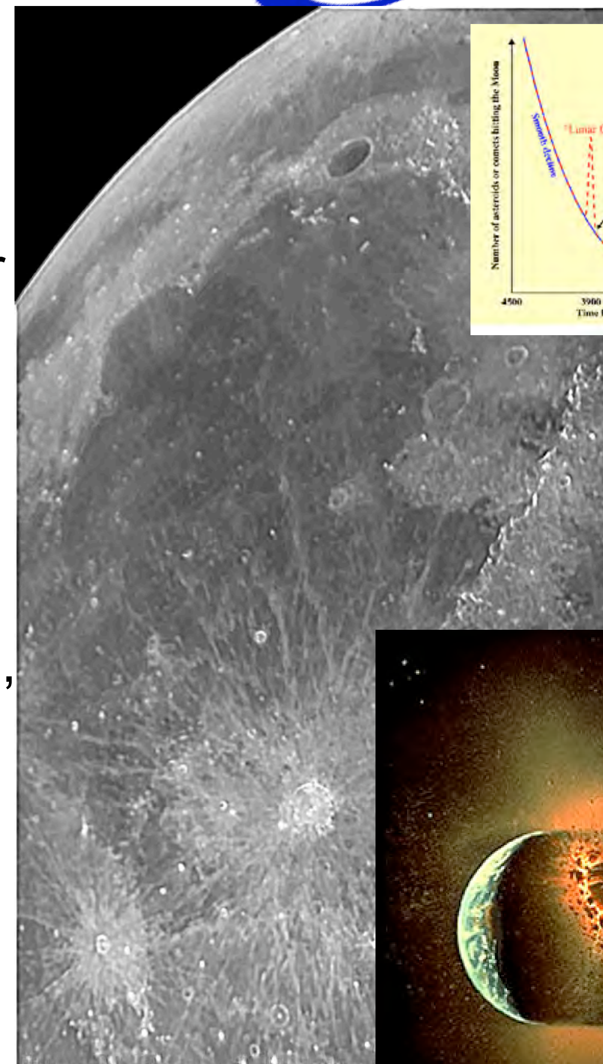
3b. Inventory the variety, age, distribution, and origin of lunar rock types.

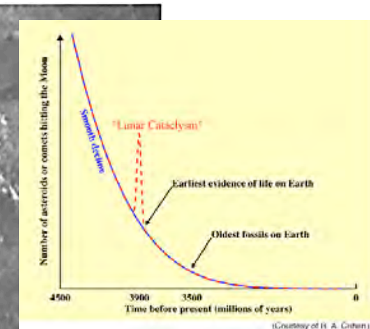
8b. Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy.



1a. Test the cataclysm hypothesis by determining the spacing in time of the creation of the lunar basins.

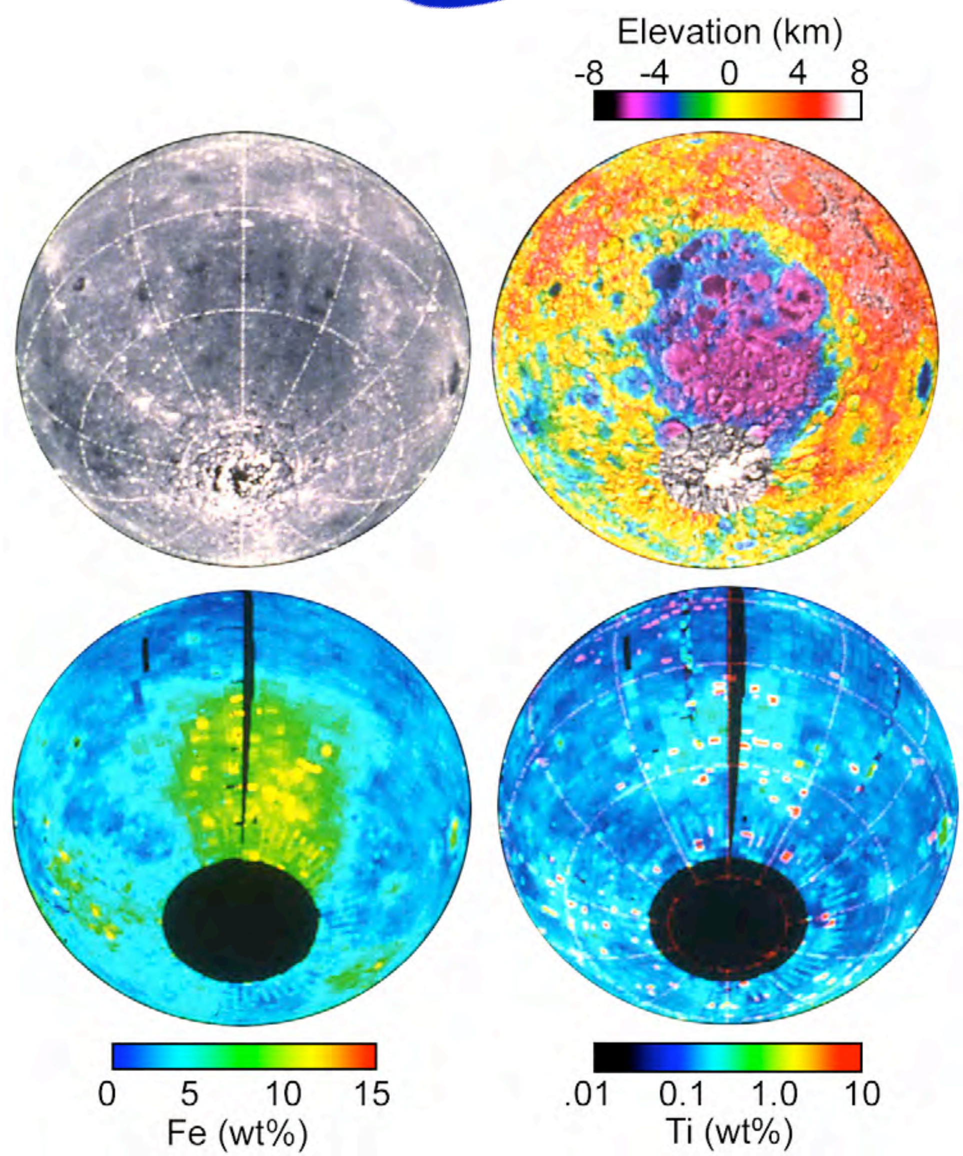
- The history of impacts in the early Earth-Moon system, in particular around 3.9 Ga, the time that life was emerging on Earth, is a critical chapter in terrestrial planet evolution.
- Understanding this period is important for several reasons: as tests of our models of the impact rate, planetary accretion, impact frustration of life, magma ocean formation and evolution, and extension and verification of the chronology.
- Geochronology <0.02 Ga requires sample returns from the oldest impact basins combined with high-resolution imaging from orbit.





1b. Anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin (South Pole-Aitken Basin).

- SPA is stratigraphically the oldest basin on the Moon, but the absolute age is unconstrained.
- Requires multiple-system geochronology with precision that can only be obtained in Earth-based laboratories with returned samples.



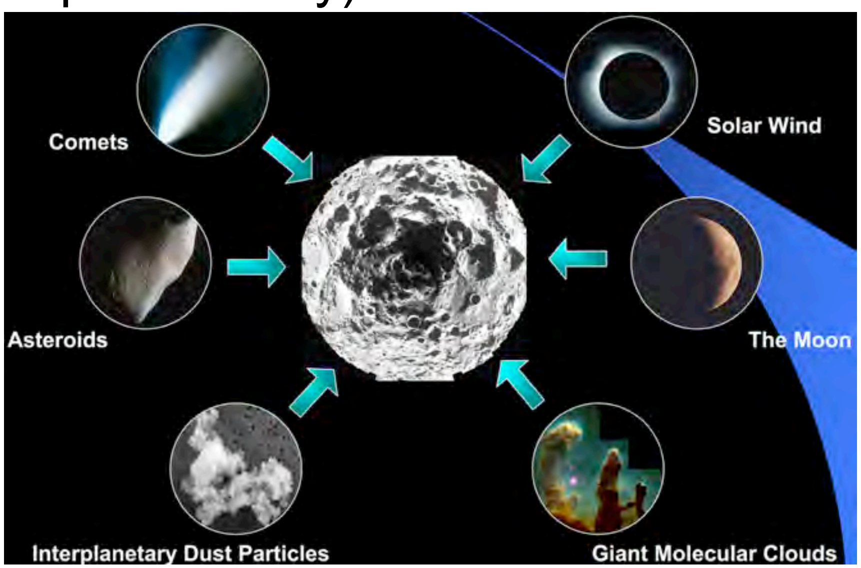
1c. Establish a precise absolute chronology

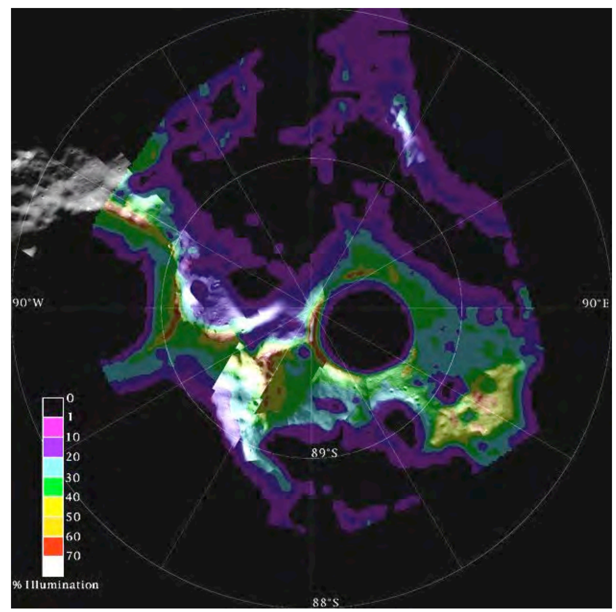
- A well-calibrated lunar chronology can be used to date unsampled lunar regions and applied to date planetary surfaces of other planets in the inner solar system
- An absolute lunar chronology is derived from combining lunar crater counts with radiometric sample ages

- Requires geochronology to 10’s of Myr, sample return from several key benchmark craters, young lava flows, and old impact basins, and imagery at high spatial resolution

4a. Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.

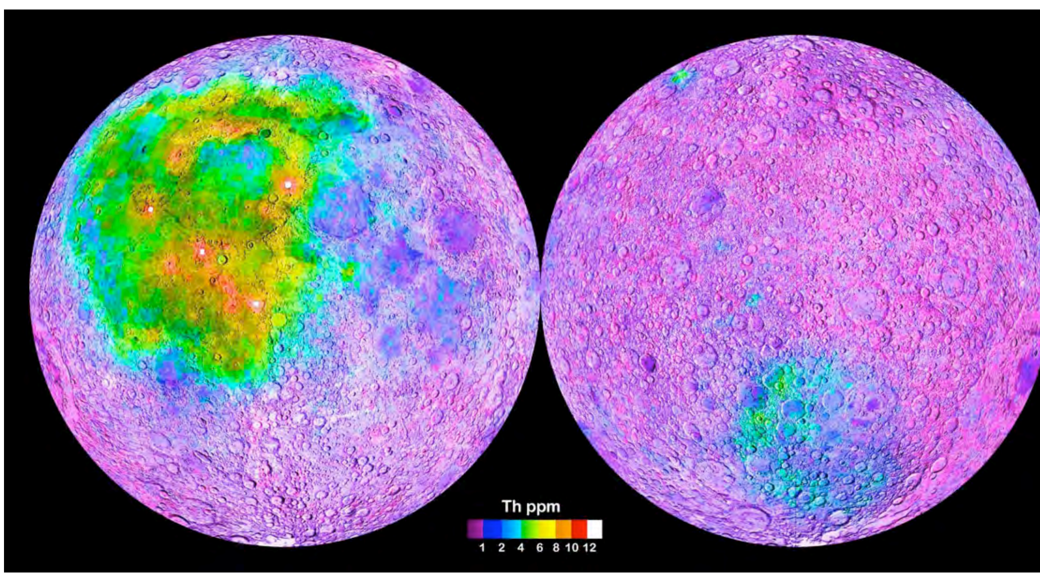
- The extremely low temperature surfaces in permanent shade at the lunar poles have been accumulating volatile-bearing materials for at least 2 billion years.
- Information on the history of volatile flux in the recent solar system and is a natural laboratory for studying how volatiles develop in the space environment.
- Landed missions to the poles and in situ investigations (mass spectrometry).

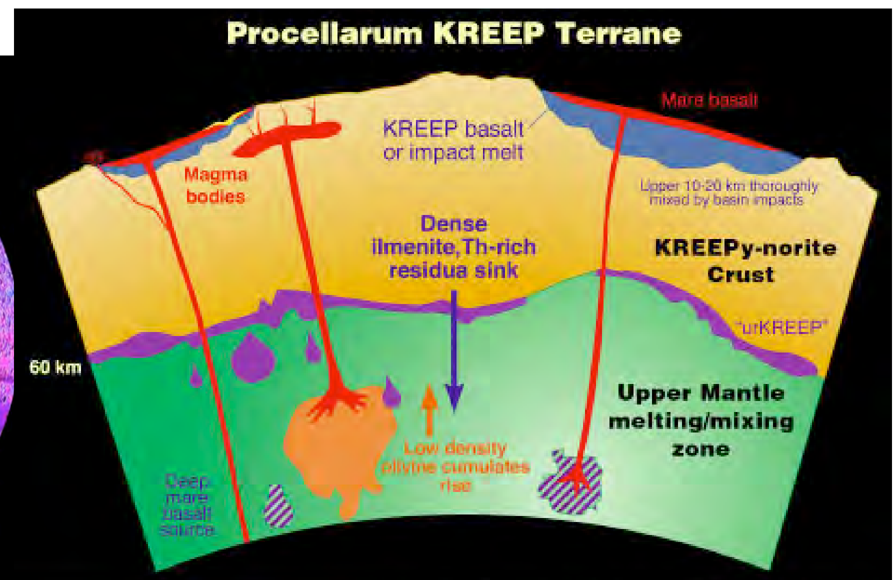




3a. Determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation.

- Many details of the differentiation process can be told through the geochemistry and distribution of key lunar rock types
- Regional orbital remote sensing to identify areas that contain these rocks and how they fit into the global picture.
- Geophysical data, particularly seismic profiling of the lunar crust, help identify the depth and extent of important layers in the lunar crust.
- Targeted sample return allows study of these products in the same detail as for the Apollo samples.

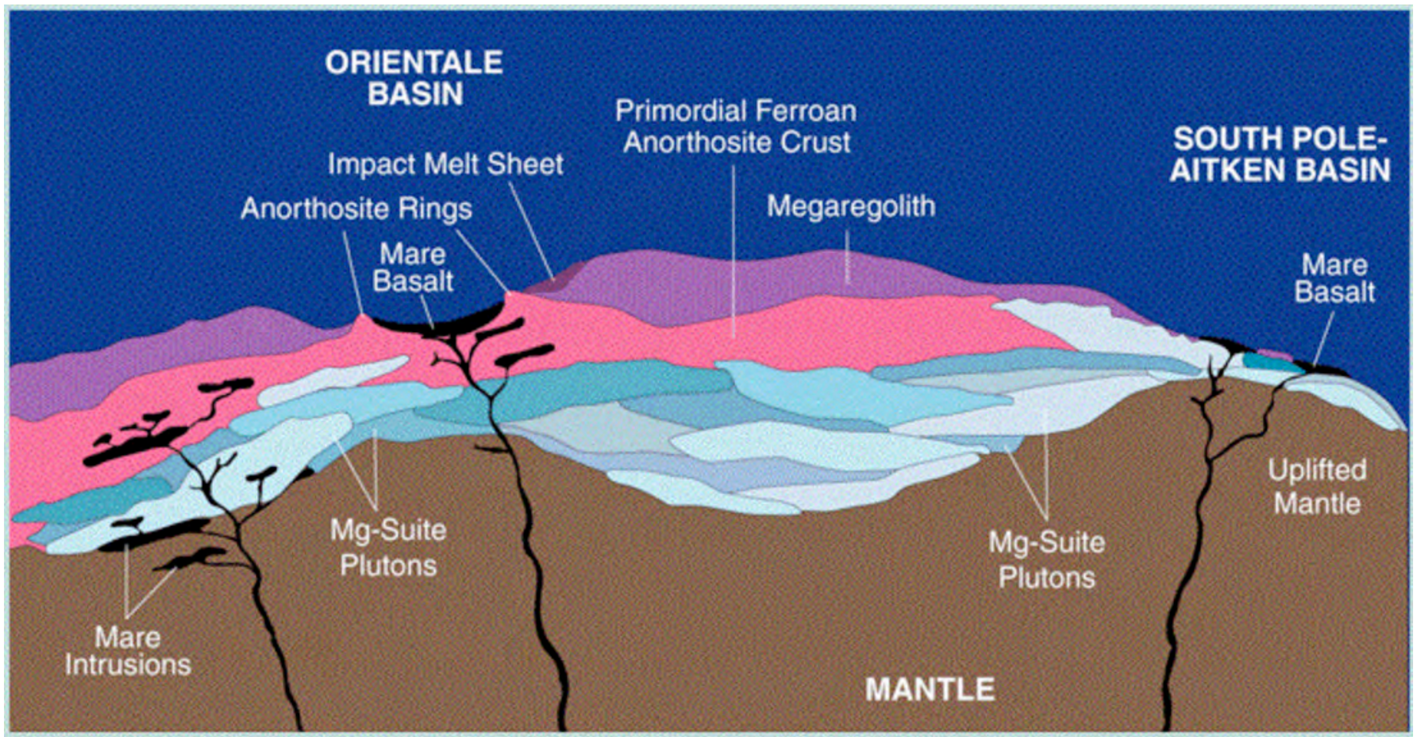




(Graphic by Brooks G. Bays, Jr. based on diagram by Brad Jolliff.)

2a. Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales.

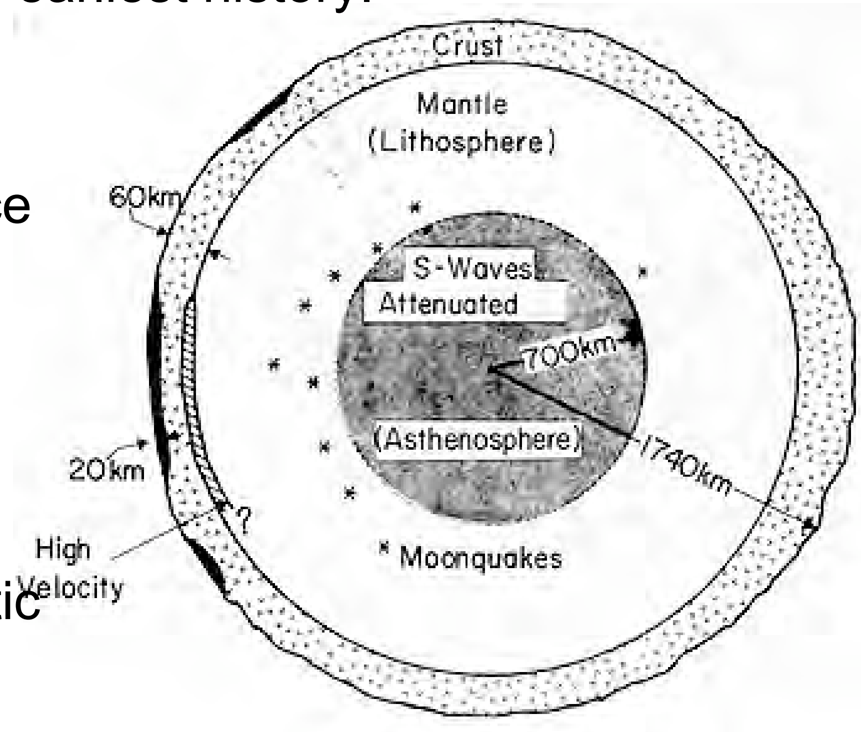
- The lunar crust volume fixes the extent of differentiation of the original lunar material
- Differences between the upper and lower crust, along with global-scale variations in thickness, provide essential clues to the processes that formed the outermost portions of the Moon.
- A seismic network of at least regional extent is essential for providing this information.



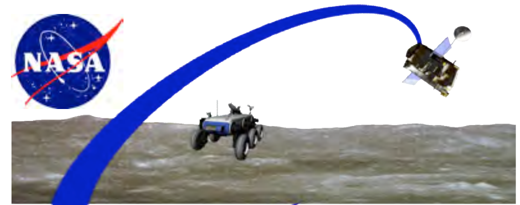
(Graphic by Nancy Hulbirt for PSRD based on a concept by Paul Spudis, APL.)

2b. Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle.

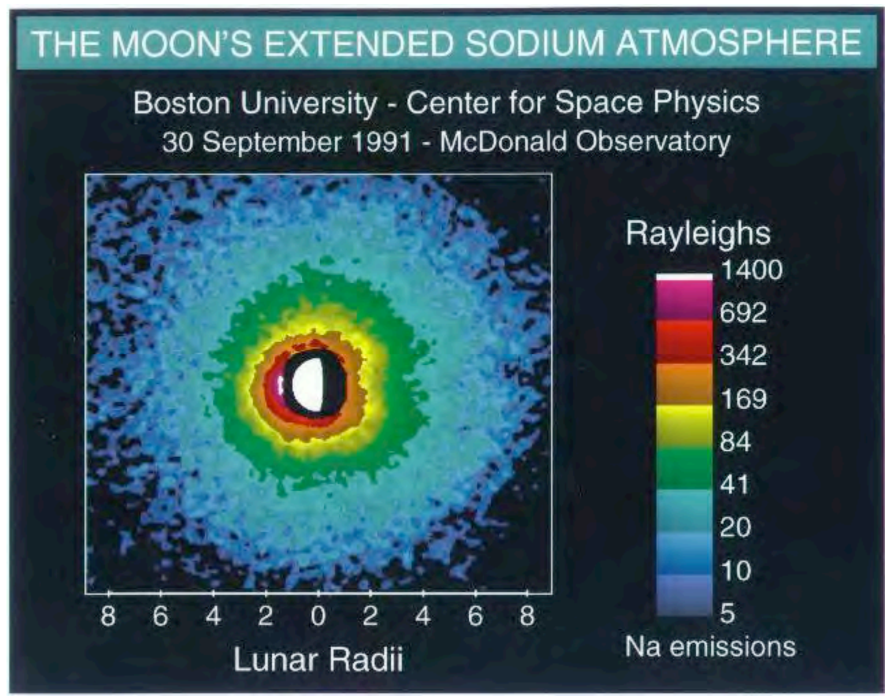
- The structure of the mantle has been affected by the initial differentiation of the Moon and subsequent evolution, such as mantle overturn and sub-solidus convection.
- All of these processes left their marks in compositional and mineralogical stratification, and detailed knowledge of this structure may allow us to decipher the Moon's earliest history.
- The seismic discontinuity tentatively identified by the Apollo seismic experiment has particular significance in differentiation models, as it may represent the base of the original magma ocean.
- The only effective methods for probing the lunar mantle are global-scale seismology and electromagnetic sounding.



8a. Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity.



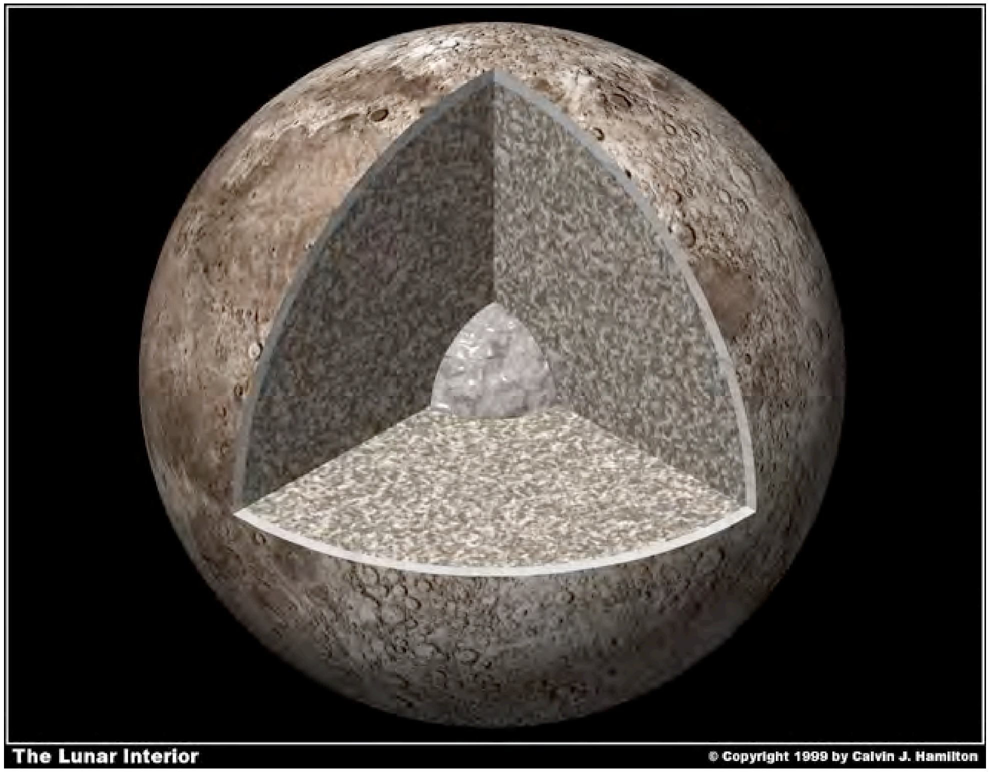
- 90 percent of the atmospheric constituents are unidentified.
- Need dayside and nightside measurements.
- Crucial that these measurements be made before the atmosphere is perturbed by future human landings.
- Both orbital and surface deployments of mass spectrometers are needed to make the required measurements.



2c. Determine the size, composition, and state (solid/liquid) of the core of the Moon.

Lunar Precursor Robotics Program

- At this point the very existence of a metallic lunar core, while likely, has not been fully established.
- Core size and composition play a fundamental role in determining the initial bulk composition of the Moon and the subsequent differentiation of the mantle, as well as the Moon's thermal and magnetic history.
- Measurements from a globally distributed network of seismometers, augmented by electromagnetic sounding and precision laser tracking of variations in lunar rotation, will be necessary to characterize the lunar core.



3b. Inventory the variety, age, distribution, and origin of lunar rock types.

- Moon produced a rich diversity of rocks by numerous geologic processes - erupted basalts, emplaced plutons, impact-melt sheets
- Understanding when and how the diversity of lunar rocks formed and how they are at present distributed allows the prediction of where else on the Moon they may be located, even if they are not expressed at the surface.
- Laboratory analysis of returned samples from diverse locations on the Moon enables complete, high-precision geochemical, mineralogical, and isotopic characterization of diverse lunar rocks.
- Higher-resolution geochemical and mineralogical remote sensing databases are crucial in providing geologic context for unusual lithologies.

8b. Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their effects on lunar exploration and lunar-based astronomy.

- Because of illumination by sunlight and the impact of the solar wind, the dust is electrostatically charged and is levitated and transported by electric fields produced by the solar wind.
- The transport of the dust and its deposition on surfaces will place important limitations on human activities and on astronomical observations that may be planned for the Moon.
- “To observe dust levitation and transport our standard dust impact detectors will not work as they require impact speeds on the order of km/s. A combination of piezoelectric sensors and dust charge measurements will have to be developed. Also, both passive and active optical experiments could be used to detect levitated dust clouds. Scattered solar illumination, or an in situ laser could be used to measure the time dependent spatial and size distribution of dust above the lunar surface.”

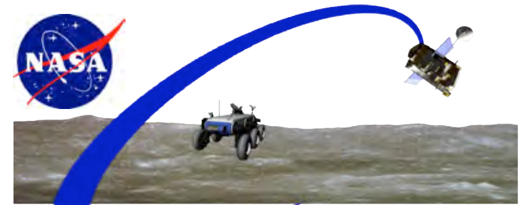
What's not on the list

- Investigations being addressed in the near term: Radiation environment, topography, temperature, high-res photography
- Human health and safety
- Astronomy and earth observing
- In situ resource utilization
- Finding terrestrial rocks
- Testing giant impact hypothesis
- Specific instrumentation

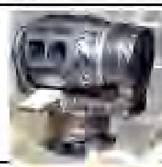
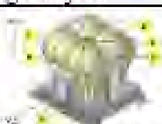
Current missions

	SMART-1 [ESA]	SELENE [JAXA]	Chang'e [CNSA]	Chandrayaan1 [ISRO]	LRO/LCROSS [NASA]
Launch	2003	2007	2007	2008	2008
Orbit	400 x 4000 km polar	100 km polar circular	200 km polar circular	100 km polar circular	50 km polar circular
Objectives	Technology demonstration; investigate poles; Sept 2006 impact ending	Study lunar origin and evolution; develop technology for future lunar exploration	Surface structure, topography, composition; particle environment	Simultaneous composition and terrain mapping; demonstrate impact probe	Improve geodetic net; evaluate polar areas; study radiation environment
Instruments	AMIE, CIXS, SIR, plasma experiments	TC, MI, SP, relay satellites, X-ray, g-ray; laser altimeter; radar sounder, magnetometer, plasma imager	4-band microwave, IIM, X-ray, gamma-ray, WA stereo, energetic ions, laser altimeter	TMC, HySI, LLRI, HEX, Impact probe + C1XS, SARA, SIR2, miniSAR, M3, RADOM	LOLA, LROC, LAMP, LEND, CRaTER, Diviner, Impactor

Current missions: LRO/LCROSS

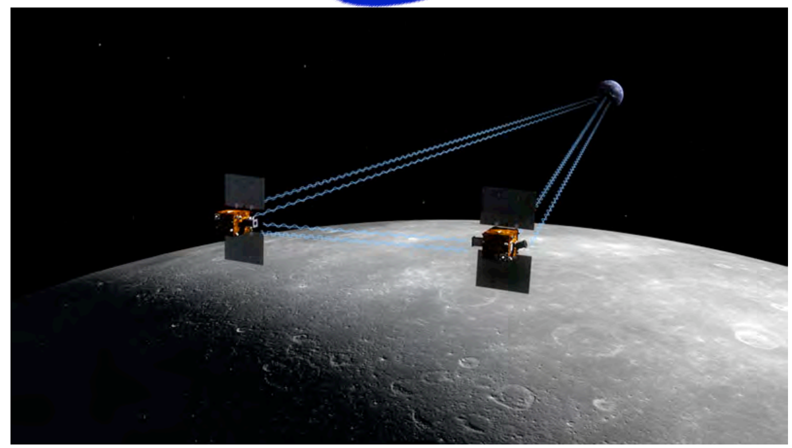


Lunar Precursor Robotics Program

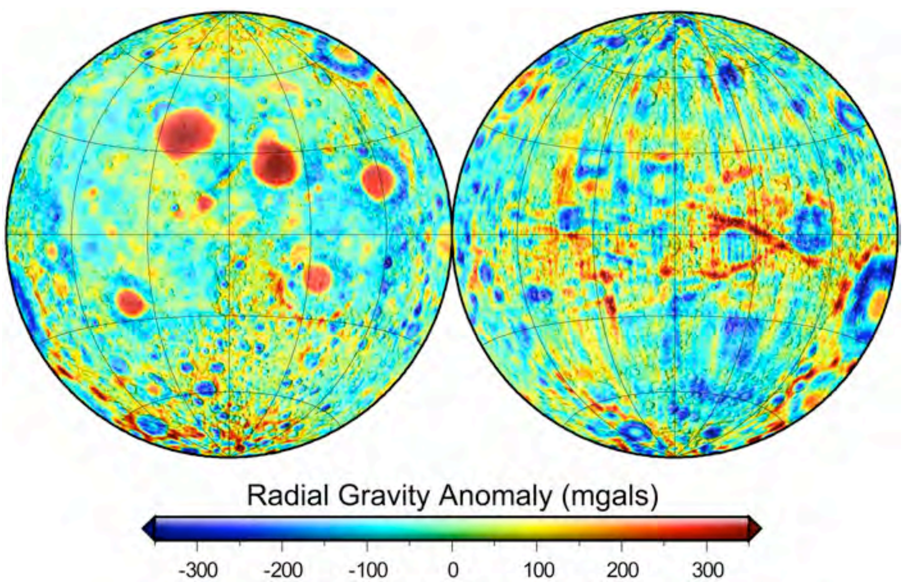
INSTRUMENT	Measurement	Exploration Benefit	Science Benefit
CRaTER  (BU+MIT) Cosmic Ray Telescope for the Effects of Radiation	*Tissue equivalent response to radiation*	*Safe, lighter weight space vehicles that protect humans*	*Radiation conditions that influence life beyond Earth*
Diviner  (UCLA)	*300m scale maps of Temperature, surface ice, rocks*	*Determines conditions for systems operability and water-ice location*	*Improved understanding of volatiles in the solar system - source, history, migration and deposition*
LAMP  (SWRI) Lyman-Alpha Mapping Project	*Maps of frosts in permanently shadowed areas, etc.*	*Locate potential water-ice (as frosts) on the surface*	
LEND  (Russia) Lunar Exploration Neutron Detector	*Hydrogen content in and neutron radiation maps from upper 1m of Moon at 5km scales, Rad > 10 MeV*	*Locate potential water-ice in lunar soil and enhanced crew safety*	
LOLA  (GSFC) Lunar Orbiter Laser Altimeter	*~50m scale polar topography at < 1m vertical, roughness*	*Safe landing site selection, and enhanced surface navigation (3D)*	*Geological evolution of the solar system by geodetic topography*
LROC  (NWU+MSSS) Lunar Recon Orbiter Camera	*1000's of 50cm/pixel images ($125 km^2$), and entire Moon at 100m in UV, Visible*	*Safe landing sites through hazard identification; some resource identification*	*Resource evaluation, impact flux and crustal evolution*

Planned missions: GRAIL

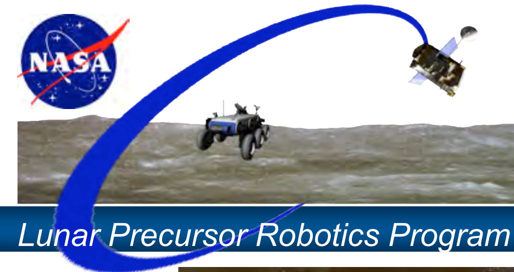
- Lunar gravity field is more irregular than Earth, particularly distorted by "mascons" - mass concentrations beneath some large impact craters
- Carries considerable information about currently unknown interior, particularly crustal thickness



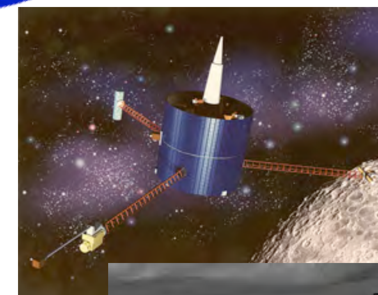
- Global maps of the lunar gravitational field are necessary for science, exploration, and mission engineering
- GRAIL - SMD Discovery mission launches 2011

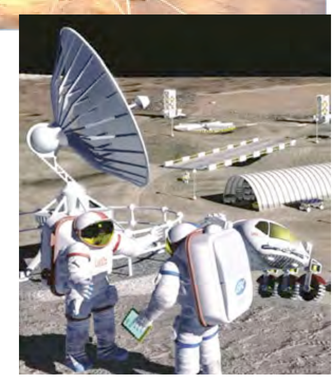


Candidate Lunar Research Strategy for the Near Term



Lunar Precursor Robotics Program





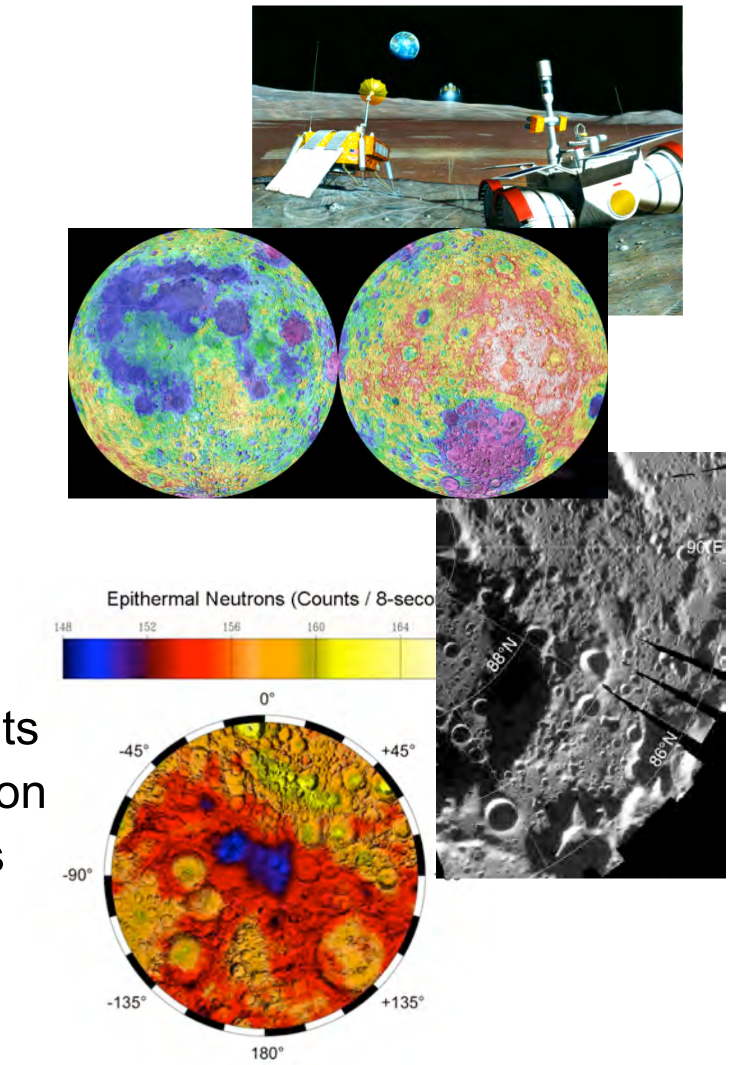
The five highest integrated science implementation priorities could be addressed in this strategy:

1. Utilize information from Apollo and post-Apollo missions or upcoming lunar science missions - low-cost / high-return
2. Conduct a robotic landed mission to explore the lunar polar environment. Determine the nature and source of volatiles within shadowed craters near one of the lunar poles, assess lunar polar atmospheric properties, and emplace a geophysical package that could include seismometer and heat flow experiments.
3. Emplace a geophysical network (4) to include, at a minimum, seismic and heat flow experiments, environmental sensors, and new laser ranging retroreflectors.
4. Conduct two or more robotic sample-return missions: South Pole-Aitken (SPA) Basin and youngest volcanic terrain.
5. Conduct detailed exploration of the lunar crust as exposed in or near a South Polar human lunar outpost.

Robotic lunar exploration objectives

Lunar Precursor Robotics Program

- Accomplish high-priority science goals
- Identify optimal landing site(s) on the Moon for robotic and human explorers
- Find and characterize resources that make exploration affordable and sustainable
- Characterize surface environment at potential landing sites
- Field test new equipment, technologies and approaches (e.g., dust and radiation mitigation)
- Support demonstration, validation, and establishment of heritage of systems for use on human missions
- Determine how life will adapt to space environments
- Emplace infrastructure to support human exploration
- Gain operational experience in lunar environments
- Provide opportunities for industry, educational and international partners



Summary

- *Lunar science* provides a window into the early history of the Earth-Moon system, can shed light on the evolution of other terrestrial planets such as Mars and Venus, and can reveal the record of impacts within the inner solar system.
- Because of its proximity to Earth, the Moon is *accessible* to a degree that other planetary bodies are not.
- Current U.S. Space Policy (VSE) is focused on shuttle/station/Ares/CEV - benefits from *regular cadence of lunar robotic missions* in the interim to keep focus on the Moon as destination
- Next U.S. mission: **lunar lander**, stay tuned for some good news (Feb. 4th)!