Lunar Precursor Robotics Program
MSFC

The Moon is a Planet Too:
Lunar Science and Robotic Exploration

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Planetary exploration grew up on the Moon

- Essential exploration elements:
  - Telescopic remote sensing
  - Flybys and orbital remote sensing
  - In-situ, on-surface investigation
  - Sample return and analysis
  - Human exploration

1968
1994

A New View of the Moon

Apollo + Luna sampling sites = ~6% of the total lunar surface area

6% of the total terrestrial surface ≈ North America << Any ocean

Going back to the Moon for the first time

- First lunar exploration provided the blueprint for our entire planetary exploration program
- Lunar science through Apollo 17 told us about commonality of planets and uniqueness of the Moon
- We've explored the solar system with this knowledge but we haven't explored the Moon for its own merits
- We know more about the surface of Mars than we do about the Moon!

Best orbital resolution

- Mars: 2 cm/px
- Moon: 100 m/px

Surface detail

- Mars: 0.3 m
- Moon: 10 m

Global mapping orbiters

- Mars: 5
- Moon: 2

Radar survey

- Mars: 2 (Russian)
- Moon: 2 (Soviet)

Forced intermission of landing sites

- Mars: 20 days per season
- Moon: 30 days per cycle

Chromitite Iron Map of the Moon

Nearside Farside

Highlands basaltic = impact
Mare/maria basaltic = lava flows
Craters and basins = impact

Apollo Gamma-ray Iron Abundance

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The Moon is a terrestrial planet
- 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 (Venus & Mars)
- The Moon has a three-layered structure and forms from a accretional event
  - Moon rocks originated through high-temperature processes with no involvement with water or organics

The Moon is a differentiated planet
- Crust on near side is 30-40 km thick, far side is thicker (60 km); it is broken up to 10's of km, lateral variations exist
  - LMO hypothesis says that a mantle exists; geochemical arguments hypothesize that it is layered and different composition than Earth's mantle
  - Possible seismic discontinuity at ~500 km on the lunar nearside
- Magmatism was most active > 3 Ga; heat flow in the mantle was higher in the past
  - Probably a small (250-350 km) core

The Moon is an active planet
- Thousands of moonquakes (~1 magnitude 5 or greater event per year)
  - Heat flow from radioactive decay of elements
  - Induced magnetic fields from solar wind interaction and passage through the Earth's magnetotail
  - Orbital changes and libration due to interior structure
  - Active ballistic atmosphere made up of outgassed elements, solar wind, and cosmic radiation
  - Micrometeorite witness plate
  - Surface charging and discharging

Lunar framework: Giant impact
- More likely to have formed into the proto-Earth at 4.56 Ga
- Herformed out of a collision between component - lack of metal
- Moon material was hot - lack of volatile elements
- Moon/Earth have shared angular momentum & oxygen isotopes

Lunar framework: Magma ocean
- 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 this link is forged between radiometric ages of rocks and relative ages by crater counting
- Crucial record of the Moon reflects the flux of impactors in the inner solar system
- Expressed on the surface of the Moon is a reflection of the solar system

Lunar framework: Volatile record
- 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

The current lunar surface
- Regolith physical properties
  - Rock frequency
  - Chemistry (major element)
  - Crater morpholgy
  - Dust
  - Micrometeoroids
  - Radiation
  - Magnetic field
  - Atmosphere
  - Lightning
  - Thermal
  - Topography

Topography
Regolith and soil
- Lunar "soil" is top 10% of cm lunar regolith is top 10% of surface
- Dominated by breaking rocks via impact, but the particles are glued back together by melting
- 5% of the surface are "rocks" occurring mostly around fresh craters
- 65% of the regolith is < 1 mm (soil)
- Soil particle size distribution very broad - "well graded" in geo-engineering terms
- High specific surface area - 8x surface area of spheres with equivalent particle size distribution

Lunar dust
- Dust = <50 micrometers; makes up 45-60% of the lunar regolith
- Dust readily kicked up by walking and the LRV and adheres to everything, hard to rub off; highly abrasive, BUT settles out readily
- Dust is probably photostatically charged and probably levitates with terminator crossings BUT there is not a thick coat of dust on every surface
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Rock composition
- Dark = basalt (lava flows) (sometimes called mare)
- Light = feldspathic (original crust) (sometimes called highlands)
- KREEP = Potassium-rare earth elements-phosphorus, also Th, U, etc. Compositional component, not a rock on its own
- But to first order, all rocks are isolates of bulk composition:

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<th>Element</th>
<th>A12 Basalt</th>
<th>A12 Soil</th>
<th>A17 Basalt</th>
<th>A17 Soil</th>
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</tbody>
</table>

Impact craters
- Because of solar inclination angle, topography is important in the poles
- Some polar high points are in near-permanent sunlight some polar crater floors are in permanent shadow - cold trap

Polar sunlight and shadow
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Radiation, atmosphere, and micrometeorites
- Ne, He, H from solar wind
- Ar outgassing from lunar interior (decay of K)
- Na, K, sulfur particles
- H2O, CO2, CH4, NH3 from exogeneous source (comets & asteroids)

Ice?
- LCROSS (launch spring 2009) will impact, send up plume of debris, measure water content
Where sunlight meets shade:

- Robotic lunar science
  - Global mapping of the lunar surface
  - Identification and characterization of the Moon for robotic and human exploration
  - Final and comprehensive resources that make robotic and human exploration possible
  - Locate and characterize lunar volatiles
  - Characterize sunlight and surface environment of polar craters
  - Field core equipment, technologies and approaches (e.g., dust and outgassing mitigation)
  - Support demonstration, validation, and establishment of heritage of systems for use on future missions
  - Develop and test new approaches to space environments
  - Singulate infrastructure to support human exploration
  - Gain operational experience in lunar environments

- Robotic lunar missions
  - Global mapping of the lunar surface
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- LRO (2009)
  - Lunar Reconnaissance Orbiter (LRO) — initiated in 2009 as the first step back to the Moon in the Vision for Human Exploration
  - Exploration Systems Mission Operations (ESMO) – science in an orbit to help plan human activities
  - Ground project manager at LPRP at MSFC

- LCROSS (2009)
  - Lunar Crater Observation and Sensing Satellite, chosen as a secondary payload on LRO vehicle. Assigned under LPRP management
  - Kinetic impact to reveal presence & nature of water ice on the Moon
  - Shepherding ISC during the Centaur stage 2 and semi-enclosed crater entry
  - 2050 metric tons of regolith will be excavated, entering in order the size of ~1/2 of a football field, ~15 feet deep
  - The SI-S/C obtains the samples in a semi-enclosed crater using instruments on Earth
  - Lunar earth and Earth-based assets will also be able to study lunar ice

- GRAIL (2011)
  - Gravity Recovery and Interior Laboratory, an SMAP precursor mission
  - Dr. Maria Zuber at MIT, managed by Discovery program at MSFC
  - Based on GRACE on the Earth - missions with mutual microwave ranging to very precisely map the Earth’s gravity field

- ARTEMIS (2010)
  - The five-satellite Earth mission "Time History of Events and Macroscale Interactions during Substorms" (THEMIS) mission completed its prime mission in 2008
  - ARTEMIS (Accelerated, Reconnaissance, Turbulence and Electrodynamics of Space Environment) moves to the two most distant satellites into orbits around the Moon
  - Study the solar plasma environment, solar wind, magnetosphere and lunar wake using MODIS instruments and radio instrumentation.
LADDEE (2011)

- Lunar Atmosphere, Dust and Environment Explorer, Ames/GSFC
- Instrument: Neutral Mass Spectrometer, UV/VIS spectrometer, Dust counter

- LADEE goals:
  - Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity
  - Determine if the Apollo-era observations of diffuse emission at 10s of km above the surface were due to glow or dust
  - Document the dust impactor environment (size-frequency) to help guide design engineering for the outpost and also future robotic missions.

L.N. (2014)

- International Lunar Network - a geographical network to accomplish high priority science, but difficult for any single agency to accomplish on its own
- US and international lander missions, 2-4 US landers planned, project at MSFC/APL, managed by Lunar Science Program at MSFC
- Science Goals:
  - Determine the thickness of the lunar crust (upper and lower)
  - Characterize the chemical/physical stratification in the mantle
  - Determine the size, composition, and state (solid/liquid) of the core of the moon.
  - Characterize the thermal state of the interior

Summary

- The moon is an active, differentiated, terrestrial planet.
- Understanding the Moon is a window to all rocky planets.
- Lunar robotic missions provide early science return to obtain important science and engineering objectives, rebuild a lunar science community, and keep our eyes on the Moon.
- Science enables exploration and science is enabled by exploration - both are necessary activities for a sustained human presence in the solar system