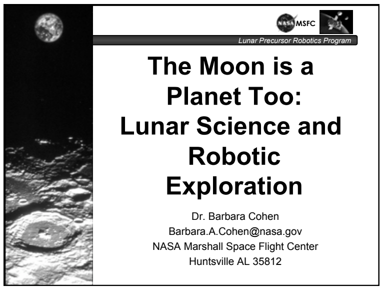
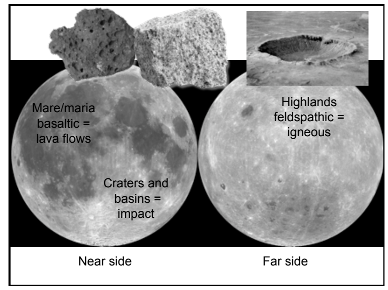
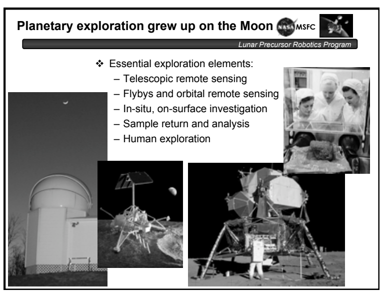
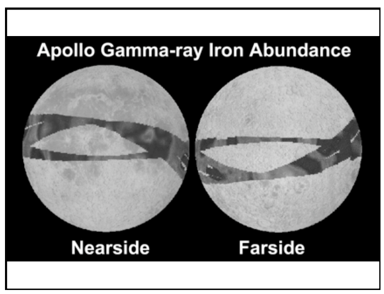
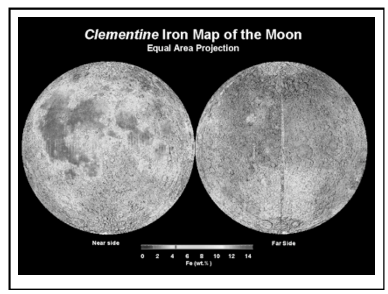
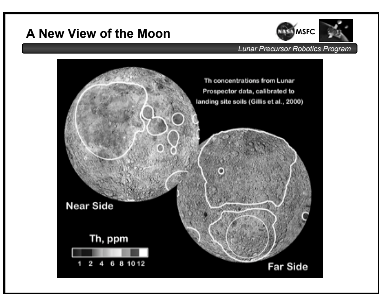


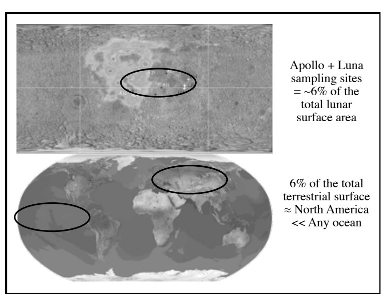




### Going back to the Moon for the first time

*Lunar Precursor Robotics Program*

- ❖ First lunar exploration era 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!

| | Mars | Moon |
|---|---|---|
| Best orbital resolution | 2 cm/px | 100 m/px |
| Topography | 600m | several km |
| Gravity field | 2 km | 10's of km |
| Global mapping orbiters | 5 | 2 |
| Robotic rovers | 2+1 | 2 (Russian) |
| Furthest separation of landing sites | 180 deg, eq + polar | 60 deg, eq only |

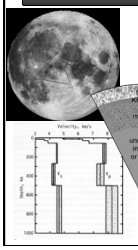
## The Moon is a terrestrial planet

*Lunar Precursor Robotics Program*

- 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

## The Moon is a differentiated planet

*Lunar Precursor Robotics Program*

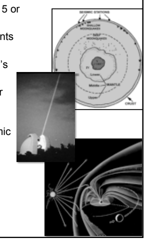



- Crust on near side is 30-40 km thick, far side is thicker (60 km); it is broken up to 10's of km; lateral variations exist
- LMO hypothesis says that a mantle exists; geochemical arguments hypothesize that it is layered and different composition than Earth's; possible seismic discontinuity at ~500 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

*Lunar Precursor Robotics Program*

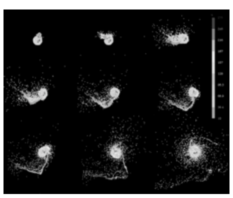
- Thousands of moonquakes (~1 magnitude 5 or greater event per year)
- Heat flow from decaying radioactive elements
- Induced magnetic fields from solar wind interaction and passage through the Earth's magnetotail
- Orbital changes and libration due to interior structure
- Active ballistic atmosphere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



## Lunar framework: Giant impact

*Lunar Precursor Robotics Program*

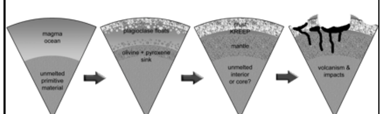
- Mars-sized body slammed into the proto-Earth at 4.56 Ga
- Moon formed out of crust/upper mantle component - lack of metal
- Moon material was hot - lack of volatile elements
- Moon/Earth have shared angular momentum & oxygen isotopes



## Lunar framework: Magma ocean

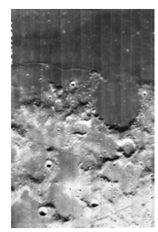
*Lunar Precursor Robotics Program*

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




## Lunar framework: Crater history

*Lunar Precursor Robotics Program*

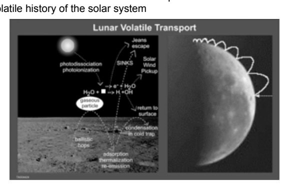


- The Moon is the only place where the link is forged between radiometric ages of rocks and relative ages by crater counting
- Crater record of the Moon reflects the flux of impactors in the inner solar system
- Bombardment history of the Moon is magnified on the Earth

## Lunar framework: Volatile record

*Lunar Precursor Robotics Program*

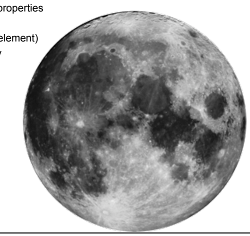
- Lunar plasma environment, atmosphere, regolith and polar regions in permanent shade constitute a single system in dynamic flux that links the interior of the Moon with the space environment and the volatile history of the solar system




## The current lunar surface

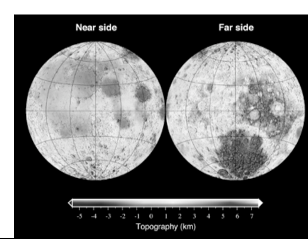
*Lunar Precursor Robotics Program*

- Regolith physical properties
- Rock frequency
- Chemistry (major element)
- Crater morphology
- Dust
- Micrometeoroids
- Radiation
- Magnetic field
- Atmosphere
- Lighting
- Thermal
- Topography



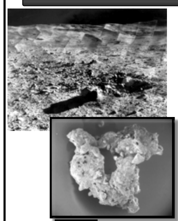
## Topography

*Lunar Precursor Robotics Program*



## Regolith and soil

Lunar Precursor Robotics Program

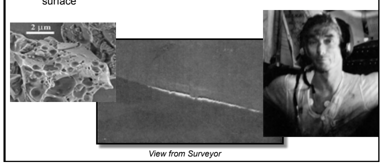



- Lunar "soil" is top 10's of cm; lunar regolith is top kms of surface
- Dominated by breaking rocks via impact, but fine particles are glued back together by melting
- 5% of the surface are "rocks" occurring mostly around fresh craters
- 95% of the regolith is <1 mm (soil)
- Soil particle size distribution very broad - "well graded" in geo -engineering terms
- High specific surface area - 8x surface area of spheres with equivalent particle size distribution

## Lunar dust

Lunar Precursor Robotics Program

- Dust = <50 micrometers; makes up 40-50% 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




View from Surveyor

## Rock composition

Lunar Precursor Robotics Program

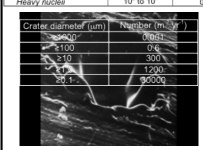
- Dark = basalt (lava flows) (sometimes called mare)
  - Olivine, pyroxene, ilmenite
- Light = feldspathic (original crust) (sometimes called highlands)
  - Feldspar, olivine, pyroxene
- KREEP = Potassium-rare earth elements-phosphorus, also Th, U, etc. Compositional component, not a rock on its own
- BUT to first order, all rocks are silicates with a limited range of bulk composition:

| | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | FeO | MgO | CaO | $Na_2O$ |
|---|---|---|---|---|---|---|---|
| A12 basalt | 44.9 | 3.6 | 8.9 | 20.5 | 10.6 | 9.8 | 0.3 |
| A12 soil | 46.2 | 2.6 | 12.1 | 17.2 | 10.4 | 9.9 | 0.4 |
| A17 basalt | 39.0 | 11.9 | 9.0 | 18.8 | 8.5 | 10.8 | 0.4 |
| A17 soil | 44.5 | 2.8 | 18.9 | 10.3 | 10.0 | 12.3 | 0.4 |
| Anorthosite | 45.6 | 0.1 | 33.4 | 1.0 | 1.2 | 19.1 | 0.4 |

## Radiation, atmosphere, and micrometeorites

Lunar Precursor Robotics Program

| | Energy (MeV/nucleon) | Flux ($cm^{-2}$ $s^{-2}$) | Penetration depth (cm of Al) | Max dose |
|---|---|---|---|---|
| Solar wind | $10^{-3}$ | $10^{8}$ | $10^{-6}$ | 0 |
| Solar energetic particles | | | | |
| *Protons* | 1 to $10^{3}$ | $<10^{5}$ | 1 to $10^{2}$ | <10 Gy |
| *Helium nucleii* | 1 to $10^{3}$ | ~1% | 1 to $10^{2}$ | ~1% |
| Galactic cosmic radiation | | | | |
| *Protons* | $10^{2}$ to $10^{4}$ | 2 | 1 to $10^{3}$ | 0.02 Sv/yr |
| *Heavy nucleii* | $10^{2}$ to $10^{4}$ | 0.2 | $10^{-1}$ to $10^{2}$ | 0.23 Sv/yr |



| Crater diameter (μm) | Number ($m^{-2}$ $yr^{-1}$) |
|---|---|
| ≥1000 | 0.001 |
| ≥100 | 0.6 |
| ≥10 | 300 |
| ≥1.0 | 1200 |
| ≥0.1 | 30000 |

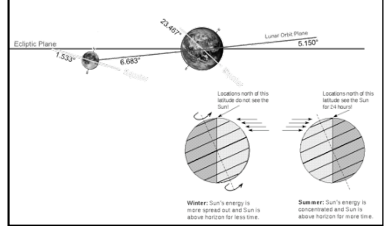
- Ne, He,H from the solar wind
- Ar outgassing from lunar interior (decay of K)
- Na, K, ballistic particles liberated from silicates
- $H_2O$, $CO_2$, $CH_4$, $NH_3$ from exogeneous sources (comets & asteroids)

## Impact craters

Lunar Precursor Robotics Program

## The "dark side" and eternal light

Lunar Precursor Robotics Program




## Latitude-dependent environment

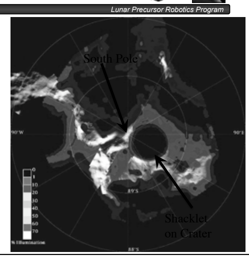
Lunar Precursor Robotics Program

| | Equatorial | Polar |
|---|---|---|
| Temperature | -150°C to +100°C | -50°C ± 10°C<br>50K in shadowed craters |
| Sunlight | ~354 hours<br>± 90° Incidence Angle | ~ 530 to 708 hours<br>± 1.7° Incidence Angle |
| Darkness | ~354 hours | 0 to 148 hours<br>(discontinuous) |
| H Content (avg.) | 10-90 ppm | >150 ppm * |
| Resource Potential | Solar wind gases<br>Bound oxygen | Solar wind gases<br>Bound oxygen<br>Shadowed volatiles |
| Direct-to-Earth Communications | Continuous on near side<br>None on far side | Discontinuous<br>but predictable<br>(~1/2 time in Earth view) |

## Polar sunlight and shadow

Lunar Precursor Robotics Program

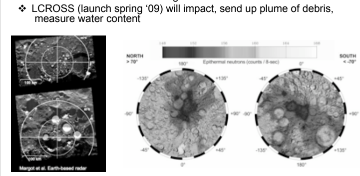
- Because of solar inclination angle, topography is important at the poles
- Some polar high points are in near -permanent sunlight
- Some polar crater floors are in permanent shadow - cold traps!

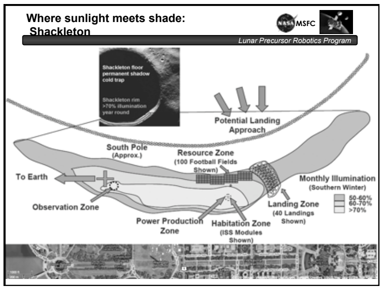


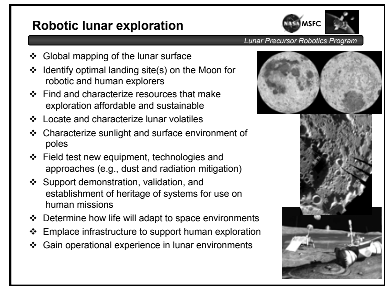

## Ice?

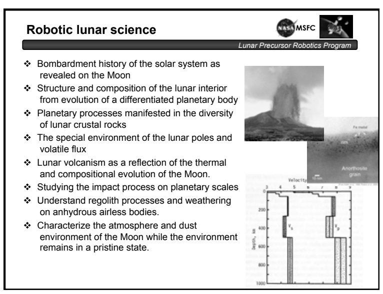
Lunar Precursor Robotics Program

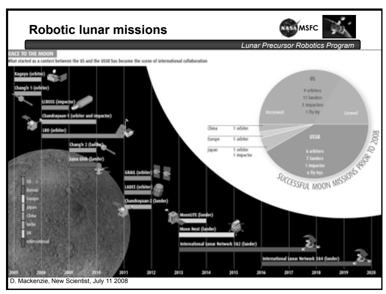
- Lunar Prospector (1998) discovered decreased neutron density at lunar poles – consistent with ~150 ppm enhanced hydrogen
- Not yet known whether it is entirely coincident with permanently shadowed craters or in what form
- If water ice, probably 0.5 wt%, adsorbed onto regolith particles, radar observations rule out large sheets or blocks of ice
- LCROSS (launch spring '09) will impact, send up plume of debris, measure water content

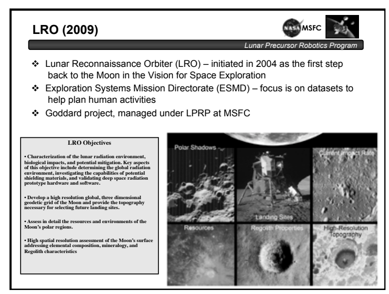


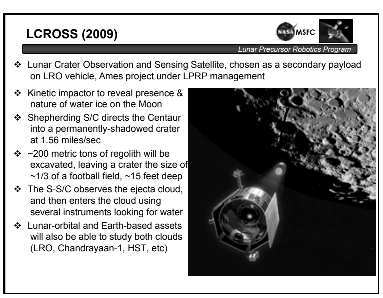

Where sunlight meets shade:
Shackleton
Lunar Precursor Robotics Program
Shackleton floor permanent shadow cold trap
Shackleton rim >70% illumination year round
Potential Landing Approach
South Pole (Approx.)
Resource Zone (100 Football Fields Shown)
To Earth
Monthly Illumination (Southern Winter)
50-60%
60-70%
>70%
Observation Zone
Landing Zone (40 Landings Shown)
Power Production Zone
Habitation Zone (ISS Modules Shown)

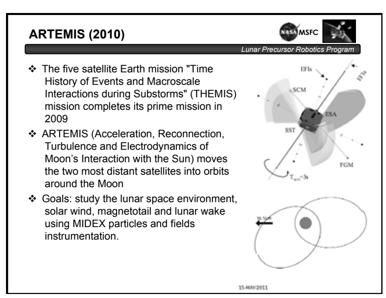

Robotic lunar exploration
Lunar Precursor Robotics Program
❖ Global mapping of the lunar surface
❖ Identify optimal landing site(s) on the Moon for robotic and human explorers
❖ Find and characterize resources that make exploration affordable and sustainable
❖ Locate and characterize lunar volatiles
❖ Characterize sunlight and surface environment of poles
❖ 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

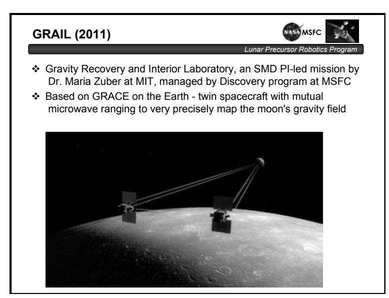

Robotic lunar science
Lunar Precursor Robotics Program
❖ Bombardment history of the solar system as revealed on the Moon
❖ Structure and composition of the lunar interior from evolution of a differentiated planetary body
❖ Planetary processes manifested in the diversity of lunar crustal rocks
❖ The special environment of the lunar poles and volatile flux
❖ Lunar volcanism as a reflection of the thermal and compositional evolution of the Moon.
❖ Studying the impact process on planetary scales
❖ Understand regolith processes and weathering on anhydrous airless bodies.
❖ Characterize the atmosphere and dust environment of the Moon while the environment remains in a pristine state.


Robotic lunar missions
Lunar Precursor Robotics Program
SUCCESSFUL MOON MISSIONS PRIOR TO 2008
D. Mackenzie, New Scientist, July 11 2008


LRO (2009)
Lunar Precursor Robotics Program
❖ Lunar Reconnaissance Orbiter (LRO) – initiated in 2004 as the first step back to the Moon in the Vision for Space Exploration
❖ Exploration Systems Mission Directorate (ESMD) – focus is on datasets to help plan human activities
❖ Goddard project, managed under LPRP at MSFC
LRO Objectives
• Characterization of the lunar radiation environment, biological impacts, and potential mitigation. Key aspects of this objective include determining the global radiation environment, investigating the capabilities of potential shielding materials, and validating deep space radiation prototype hardware and software.
• Develop a high resolution global, three dimensional geodetic grid of the Moon and provide the topography necessary for selecting future landing sites.
• Assess in detail the resources and environments of the Moon's polar regions.
• High spatial resolution assessment of the Moon's surface addressing elemental composition, mineralogy, and Regolith characteristics
Polar Shadows
Landing Sites
Resources
Regolith Properties
High-Resolution Topography


LCROSS (2009)
Lunar Precursor Robotics Program
❖ Lunar Crater Observation and Sensing Satellite, chosen as a secondary payload on LRO vehicle, Ames project under LPRP management
❖ Kinetic impactor to reveal presence & nature of water ice on the Moon
❖ Shepherding S/C directs the Centaur into a permanently-shadowed crater at 1.56 miles/sec
❖ ~200 metric tons of regolith will be excavated, leaving a crater the size of ~1/3 of a football field, ~15 feet deep
❖ The S-S/C observes the ejecta cloud, and then enters the cloud using several instruments looking for water
❖ Lunar-orbital and Earth-based assets will also be able to study both clouds (LRO, Chandrayaan-1, HST, etc)

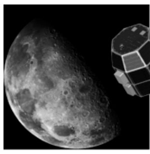

ARTEMIS (2010)
Lunar Precursor Robotics Program
❖ The five satellite Earth mission "Time History of Events and Macroscale Interactions during Substorms" (THEMIS) mission completes its prime mission in 2009
❖ ARTEMIS (Acceleration, Reconnection, Turbulence and Electrodynamics of Moon's Interaction with the Sun) moves the two most distant satellites into orbits around the Moon
❖ Goals: study the lunar space environment, solar wind, magnetotail and lunar wake using MIDEX particles and fields instrumentation.
SCM
ESA
SST
FGM


GRAIL (2011)
Lunar Precursor Robotics Program
❖ Gravity Recovery and Interior Laboratory, an SMD PI-led mission by Dr. Maria Zuber at MIT, managed by Discovery program at MSFC
❖ Based on GRACE on the Earth - twin spacecraft with mutual microwave ranging to very precisely map the moon's gravity field

## LADEE (2011)

Lunar Precursor Robotics Program

- Lunar Atmosphere, Dust and Environment Explorer, Ames/GSFC project, managed by Lunar Science Program at MSFC
- Instruments: 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 astronaut sightings of diffuse emission at 10s of km above the surface were Na glow or dust
  - Document the dust impactor environment (size-frequency) to help guide design engineering for the outpost and also future robotic missions.

## ILN (2014)

Lunar Precursor Robotics Program

- International Lunar Network– a geophysical network to accomplish high priority science, but difficult for any single agency to accomplish on its own
- US and international landed missions, 2-4 US Landers planned, project at MSFC /APL, managed by Lunar Science Program at MSFC
- Science Goals: understand the interior structure and composition of the moon
  - 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

Lunar Precursor Robotics Program

- 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!