The Lunar Environment: Asset or Liability?

Paul D. Spudis
Johns Hopkins University Applied Physics Laboratory
paul.spudis@jhuapl.edu

Astrophysics Enabled by The Return to the Moon
Space Telescope Science Institute
Baltimore MD
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The Vision for Space Exploration

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

"It is time for America to take the next steps. Today I announce a new plan to explore space and extend a human presence across our solar system. We will begin the effort quickly, using existing programs and personnel. We’ll make steady progress – one mission, one voyage, one landing at a time.

President George W. Bush - January 14, 2004
A Platform to Observe the Universe

No atmosphere; full spectrum from DC to gamma-rays visible from lunar surface

Far side of Moon only known place in universe permanently shielded from Earth’s radio noise

Stable platform permits extremely sensitive instruments to be built and operated

Dark areas near poles a natural resource for cooled IR detectors

Natural topography can be used to construct large dish antennas

Cold, dark sky; two weeks of night time (permanent at poles)
The nature of the Moon

A rocky planetary object, differentiated into crust, mantle, and core

Heavily cratered surface; partly flooded by lava flows over 3 Ga ago

Since then, only impacts by comets and asteroids, grinding up surface into chaotic upper layer of debris (regolith)

Regolith is easily accessed and processed; likely feedstock for resource extraction
### Some general properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Moon</th>
<th>Mars</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>kg</td>
<td>7.34 x 10^{22}</td>
<td>6.42 x 10^{23}</td>
<td>5.98 x 10^{24}</td>
</tr>
<tr>
<td>GM</td>
<td>km^3 s^{-2}</td>
<td>4896.6</td>
<td>42828.3</td>
<td>398930.3</td>
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<tr>
<td>Density</td>
<td>kg m^{-3}</td>
<td>3340</td>
<td>3920</td>
<td>5520</td>
</tr>
<tr>
<td>Equatorial Radius</td>
<td>kg</td>
<td>1737</td>
<td>3393</td>
<td>6378</td>
</tr>
<tr>
<td>Volume</td>
<td>km^3</td>
<td>2.2 x 10^{10}</td>
<td>1.63 x 10^{11}</td>
<td>10.82 x 10^{11}</td>
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<tr>
<td>Surface Area</td>
<td>km^2</td>
<td>37.9 x 10^6</td>
<td>1.44 x 10^8</td>
<td>5.11 x 10^8</td>
</tr>
<tr>
<td>Oblateness</td>
<td></td>
<td>201.6 x 10^{-6}</td>
<td>1960.4 x 10^{-6}</td>
<td>1.0827 x 10^{-3}</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td></td>
<td>0.395</td>
<td>0.345-0.365</td>
<td>0.332</td>
</tr>
<tr>
<td>Equatorial Gravity</td>
<td>m s^{-2}</td>
<td>1.62</td>
<td>3.71</td>
<td>9.83</td>
</tr>
<tr>
<td>Escape Velocity</td>
<td>m s^{-1}</td>
<td>2.37</td>
<td>5.03</td>
<td>11.19</td>
</tr>
<tr>
<td>Surface Magnetic Field</td>
<td>G</td>
<td>&lt;2 x 10^{-3}</td>
<td>&lt;5 x 10^{-4}</td>
<td>0.31</td>
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<tr>
<td>Average Temperature</td>
<td>K</td>
<td>253</td>
<td>210</td>
<td>275</td>
</tr>
<tr>
<td>Atmospheric Pressure</td>
<td>Pa</td>
<td>&lt;10^{-7}</td>
<td>560</td>
<td>10000</td>
</tr>
</tbody>
</table>
The Lunar “Atmosphere”

Lunar surface is an excellent vacuum
Surface pressure ~ $10^{-12}$ torr
“Atmosphere” is primarily of solar wind derivation, a collisionless gas
Ne, Ar, He, H$_2$
Solar wind gases present transiently
Na exosphere visible during eclipse

Each Apollo LM landing temporarily doubled mass of lunar atmosphere
Expected complete dissipation within a few weeks

Behavior of released water on lunar surface needs to be characterized
Water is released naturally (impact) and artificially by human activities
Need to understand how released vapor spreads and dissipates
Moon has no natural magnetosphere

- Minor anomalies of magnetized crust distributed around the Moon; not strong enough to significantly deflect energetic particles

Lunar surface is a “hard” radiation environment

- Radiation similar to cislunar space
- Moon swings through Earth geomagnetic tail once per month

Flux of very high energy cosmic rays (trans-Gev) largely unknown ($\sim 10^4/m^2/s$)

Secondary environment from surface interaction with GCR needs to be characterized

- Relevant to using regolith for habitat protection
Seismic Environment

Lunar seismicity is 3-5 orders of magnitude lower than Earth. Moon is anhydrous, leading to very high-Q (low seismic attenuation). Artificial seismic signals dampened out within ~10 km. Ground motions typically less than 1 nanometer. Shallow-level moonquakes occur frequently; epicenters are unknown. Theoretical seismic hazard to habitat, but chances of outpost being on or near an epicenter remote. Need to globally characterize lunar seismicity.
Micrometeorite Environment

Nothing to impede impact of all-sized debris; r.m.s. impact velocity ~ 20 km s\(^{-1}\)

Estimated flux:

<table>
<thead>
<tr>
<th>Crater Diameter ((\mu m))</th>
<th># craters / m(^2) / yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>3 (\times) 10(^5)</td>
</tr>
<tr>
<td>&gt; 1</td>
<td>1.2 (\times) 10(^4)</td>
</tr>
<tr>
<td>&gt;10</td>
<td>3 (\times) 10(^3)</td>
</tr>
<tr>
<td>&gt;100</td>
<td>6 (\times) 10(^{-1})</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>1 (\times) 10(^{-3})</td>
</tr>
</tbody>
</table>

Microcraters from 1-10 \(\mu m\) will be common on exposed lunar surfaces

Craters ~100 \(\mu m\) dia. ~ 1 / m\(^2\) / yr

Effects of secondary impact ejecta not well quantified
Thermal Conditions

Surface temperature dependant on solar incidence
- Noontime surfaces ~ 100° C
- Coldest night temperatures ~ -150° C

Temperature variations minimal below surface ≥ 30 cm (-23°± 5° C)

Polar areas are always either dark or at grazing solar incidence
- Lit polar areas have sunlight ~ 1° incidence
  - Average temperatures ~ -50° ± 10° C

Dark areas are very cold
- Uncertainty in lunar heat flow values suggest cold traps between 50 and 70 K
Permanently shadowed areas have very low model temperatures (~ 50-70 K) and act as cold traps (e.g., Vasavada et al. 1999)
Uncertainty largely a reflection of unknown value for heat flow of Moon (2.2 - 3.1 µW cm⁻²)
Temperatures may vary substantially in the shallow subsurface
At these temperatures, atoms and molecules of volatile species cannot escape
The Far Side: Radio Astronomy Paradise?

Far side of Moon is permanently shielded from Earth view
Sun, Jupiter in view as Moon slowly rotates (708 hours)
Diffractive effects make limbs (82° to 98° long.) and poles less attractive for radio astronomy
Depending on wavelength, radio-silent zones can be found within a few tens of kilometers of the limbs (~75 km @ 1 MHz)
Most of far side is rough terrain, but some smooth areas are found (far side maria, highland plains)
The Poles: A Unique Lunar Environment

Near vertical orientation of lunar spin axis results in zones of light and darkness

Dark areas are very cold (50-70 K); permit relatively simple passive cooling of IR detectors

Sunlight areas provide continuous power, benign thermal environment

Complete, continuous views of given celestial hemisphere

Many bowl-shaped craters, natural landforms that can adapted for astronomical use

Periodic, non-continuous view of Earth
Topography

Global figure is roughly spherical \((r = 1738\ km)\), but with major departures
- South Pole-Aitken basin on far side is major feature

Moon is very “bumpy”; extremes of elevation +8 km to −9 km (same dynamic range as Earth)

Physiography divided into rough, complex bright highlands (terra) and relatively flat, smooth dark lowlands (maria)

Landforms dominated by craters, ranging in size from micrometers to thousands of km across

Smooth flat areas are rare, but occur in maria (modulated by sub-km class cratering)

Small size of Moon makes planetary curvature very abrupt (horizon is \(\sim 2.6\ km\) away for a 2 m tall observer on flat terrain)
Surface morphology and physiography

Craters dominate all other landforms
  Range in size from micro- to mega-meters
  Shape and form change with increasing size (bowl shaped to central peaks to multiple rings)
Maria are flat-lying to rolling plains, with crenulated ridges
  Low relief, all mostly caused by post-mare craters
Few minor landforms
  Domes and cones
  Faults and graben
  Other miscellaneous features
Lunar terrains

**Maria**
- Flat to gently rolling plains
- Numerous craters $D < 20$ km; larger craters rare
- Blockier (on average) than highlands (bedrock is closer to surface)
- Mean (r.m.s.) slopes $4°-5°$

**Highlands**
- Rugged, cratered terrain
- Smoother intercrater areas
- Numerous craters $D > 20$ km
- Large blocks present, but rare; “sandblasted” Moon
- Mean (r.m.s.) slopes $7°-10°$
Terrain Slopes

Mare – Flamsteed ring mare
- Young mare; blocky crater rims
- Smooth flat surfaces (relief ~few meters)
- Mean slopes < 5°; local slopes (in fresh crater walls) up to 25°

Highlands – Kant Plateau
- Ancient highlands; few blocks, but steep slopes
- Rolling to undulating plains (relief on order of meters to tens of meters)
- Mean slopes ~ 10°; local slopes (inside craters) up to 30°
Regolith

The layer or mantle of loose incoherent rock material, of whatever origin, that nearly everywhere underlies the surface of the land and rests on bedrock. A general term used in reference to unconsolidated rock, alluvium or soil material on top of the bedrock. Regolith may be formed in place or transported in from adjacent lands.
Regolith Thickness and Development

Regolith thickness varies by age
Older rock units have thicker regoliths (exposure to impact flux)

Composition mimics that of the bedrock
Exotic material added from beneath bedrock and laterally from adjacent areas

Mare regolith thickness ~3-8 m
Highland regolith thickness >10-15 m
Erosion rates very low (~ 1 mm/10^6 yr)
Turnover higher in shallower levels
Lunar Regolith – The “Soil”

Median particle size of 40-130 µm
Average grain size 70 µm
10-20% of the soil is finer than 20 µm
Dust (<50 µm) makes up 40-50% by volume
95% of lunar regolith is < 1 mm
Soil particle size distribution very broad
“Well graded” in geo-engineering terms
“Very poorly sorted” in geologic terms
High specific surface area 0.5 m² gm⁻¹
8x surface area of spheres with equivalent particle size distribution
### Lunar Regolith

<table>
<thead>
<tr>
<th>Grain Size (mm)</th>
<th>% Weight</th>
<th>Totals</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 - 4</td>
<td>1.67</td>
<td>1.7</td>
<td>100.0</td>
</tr>
<tr>
<td>4 - 2</td>
<td>2.39</td>
<td>4.1</td>
<td>98.3</td>
</tr>
<tr>
<td>2 - 1</td>
<td>3.20</td>
<td>7.3</td>
<td>96.0</td>
</tr>
<tr>
<td>1 - 0.5</td>
<td>4.01</td>
<td>11.3</td>
<td>92.8</td>
</tr>
<tr>
<td>0.5 - 0.25</td>
<td>7.72</td>
<td>19.0</td>
<td>88.7</td>
</tr>
<tr>
<td>0.25 - 0.15</td>
<td>8.23</td>
<td>27.2</td>
<td>81.0</td>
</tr>
<tr>
<td>0.15 - 0.09</td>
<td>11.51</td>
<td>38.7</td>
<td>72.8</td>
</tr>
<tr>
<td>0.09 - 0.075</td>
<td>4.01</td>
<td>42.7</td>
<td>61.3</td>
</tr>
<tr>
<td>0.075 - 0.045</td>
<td>12.40</td>
<td>55.1</td>
<td>57.3</td>
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<tr>
<td>0.045 - 0.020</td>
<td>18.02</td>
<td>73.2</td>
<td>44.9</td>
</tr>
<tr>
<td>&lt;0.02</td>
<td>26.85</td>
<td>100.0</td>
<td>26.9</td>
</tr>
</tbody>
</table>

![Cumulative Probability Scale](image)
Regolith Lithology

Comparative Modal Petrology (1000 - 90 μm)

- Highland Lithics
- Fused Soil = Agglutinate + DMB
- Mafic = Pyroxene + Olivine
- Mare Lithics
- Glass
- Plagioclase

Modal Abundance (Vol%)

Highland Lithics
Fused Soil
Mare Lithics
Glass
Plagioclase
Mafic

Sample Numbers:
- 10824
- 12001
- 12003
- 10822
- 15271
- 64501
- 67461
- 79201
- 78501
- 78221
- 21909
- 22001

Glass
Agglutinates

Courtesy Larry Taylor, UTK
Dust
Levitated Dust?

15 min after sunset
T = 0.2 s

90 min after sunset
T = 1.2 s

160 min after sunset
T = 40 s

View of horizon glow from Surveyor 7

Gene Cernan Apollo 17

Vondrak
Surveyor 3 Spacecraft

Spent 31 months on Moon prior to arrival of Apollo 12 astronauts
Some dust coating on parts noted, but patterns indicated the coatings occurred during Surveyor landing and subsequent Apollo 12 Lunar Module landing
No evidence of “levitated dust” settling on spacecraft
Care will have to be taken to assure landing spacecraft do not spread dust over deployed equipment and instruments on surface

“The observed dust, therefore, originated from both the Surveyor and LM landings, with each contributing a significant amount to various surfaces. "Lunar transport" seems to be relatively insignificant, if evident at all.” — W. F. Carroll and P.M. Blair (1972)

ANALYSIS OF SURVEYOR 3 MATERIAL AND PHOTOGRAPHS NASA SP-284, p. 28
Laser Ranging Retroreflectors

Flown on Apollo 11, 14, and 15
Array of glass cube corner reflectors, deployed ~30 cm above lunar surface
Astronauts deployed carefully, minimizing dust disturbance
Laser returns received immediately and arrays continue in operation today
No evidence of any degradation in laser signal return over lifetime of arrays
(Apollo 11 LRRR on surface for 37 years now)
Lateral Dust Transport?

Levitated dust could move laterally, coating optics and equipment – does it?

Lateral transport on the Moon appears to be very inefficient.

Compositional gradients at Apollo sites are abrupt and well-preserved.

Sharp contacts preserved in remote-sensing data, showing that extensive lateral transport does not occur on the Moon.

Mare Crisium – albedo and Fe concentration

Robinson and Jolliff, 2002
Conclusions

Lunar environment, materials, and conditions are fairly well understood from Apollo and its precursors. Airless, waterless, high radiation, low gravity body. Rough on macro scales in most places, but smooth areas occur at human infrastructure scales.

Properties of some key areas are unknown, specifically the environment and deposits of the poles and the nature and extent of electrostatically levitated dust.

The Moon is a *benign* (not a hostile) environment.

Facility of the lunar surface as a platform for astronomical observation continues to be evaluated.

Filling in missing pieces of strategic knowledge is a principal goal of Lunar Precursor Robotic Program.