The Moon: Our Next Destination in Space

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NASA Johnson Space Center
September 17, 2007
The Vision for Space Exploration

National response to loss of Columbia Space Shuttle, Feb. 1, 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
VSE is now national policy

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
What’s It All About?

A journey, not a race
Incremental steps, cumulative
No turning back
Build-up space-faring infrastructure
Robotic precursors lead the way
Expanding sphere of human “reach”
Human-robotic partnership and synergy
Can humans thrive off-planet?
Why the Moon?

It’s close (3 days) and accessible (as near as GEO)
Alien yet familiar; Earth is visible to crew and TV audiences
Moon can be reached with existing or derived launch systems
Transport system to Moon can also access GEO, cislunar, Earth-Sun Lagrangians, and some NEOs
Retire risk to future planetary missions by re-acquiring experience and testing with lunar missions
Development of lunar resources would be major advance in space logistics capability
Advance science, improve engineering state-of-the-art, inspire country
The Moon is important for....

**Science**
A natural laboratory of planetary processes and history; a platform to observe the universe

**Inspiration**
A place to learn to live and work in space

**Resources**
A source of materials and energy
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>
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<tbody>
<tr>
<td>Mass</td>
<td>kg</td>
<td>$7.34 \times 10^{22}$</td>
<td>$6.42 \times 10^{23}$</td>
<td>$5.98 \times 10^{24}$</td>
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<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>
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<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>$2.2 \times 10^{10}$</td>
<td>$1.63 \times 10^{11}$</td>
<td>$10.82 \times 10^{11}$</td>
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<tr>
<td>Surface Area</td>
<td>km$^2$</td>
<td>$37.9 \times 10^{6}$</td>
<td>1.44 x 108</td>
<td>$5.11 \times 10^{8}$</td>
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<tr>
<td>Oblateness</td>
<td></td>
<td>$201.6 \times 10^{-6}$</td>
<td>$1960.4 \times 10^{-6}$</td>
<td>$1.0827 \times 10^{-3}$</td>
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<tr>
<td>Moment of Inertia</td>
<td>m s$^{-2}$</td>
<td>0.395</td>
<td>0.345-0.365</td>
<td>0.332</td>
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<tr>
<td>Equatorial Gravity</td>
<td>m s$^{-2}$</td>
<td>1.62</td>
<td>3.71</td>
<td>9.83</td>
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<tr>
<td>Escape Velocity</td>
<td>Km s$^{-1}$</td>
<td>2.37</td>
<td>5.03</td>
<td>11.19</td>
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<td>Surface Magnetic Field</td>
<td>G</td>
<td>$\leq 2 \times 10^{-3}$</td>
<td>$\leq 5 \times 10^{-4}$</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>
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<tr>
<td>Atmospheric Pressure</td>
<td>Pa</td>
<td>$&lt;10^{-7}$</td>
<td>560</td>
<td>100,000</td>
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</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 transiently present
Na exosphere visible during eclipse

Each Apollo LM landing temporarily doubled mass of lunar atmosphere
Complete dissipation thought to be complete 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
Radiation Environment

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 (~$10^4$/m²/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 (µm)</th>
<th># craters / m² / yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>3 x 10⁵</td>
</tr>
<tr>
<td>&gt; 1</td>
<td>1.2 x 10⁴</td>
</tr>
<tr>
<td>&gt; 10</td>
<td>3 x 10³</td>
</tr>
<tr>
<td>&gt; 100</td>
<td>6 x 10⁻¹</td>
</tr>
<tr>
<td>&gt; 1000</td>
<td>1 x 10⁻³</td>
</tr>
</tbody>
</table>

Microcraters from 1-10 µm will be common on exposed lunar surfaces

Craters ~100 µm dia. ~ 1 / m² / 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 beyond 30 cm below surface (-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
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
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 \( \mu \text{W cm}^{-2} \))

Temperatures may vary substantially in the shallow subsurface

At these temperatures, atoms and molecules of volatile species cannot escape
Does ice exist on the Moon?

**Clementine**
- Found evidence on one orbit (234) for high same-sense backscatter (high CPR; CBOE?) over dark areas near poles
- Other orbits (e.g., 235; over sunlit areas) show no enhancement

**Lunar Prospector**
- Neutron spectrometer detects “excess” hydrogen, but not phase state
- Enhanced H$_2$ over poles; consistent with ~ 2 % polar ice or solar wind
- No fast neutron signal; upper 10 cm of surface desiccated

**Earth-based radar**
- Patchy, high CPR found in both sunlight and polar darkness
- Surface roughness or two different scattering mechanisms?
Synthesis: Best Guess for Polar Volatiles

Ice exists in dark areas, but its origin and the processes associated with it are unclear
- Could be of cometary, meteoritic, or solar wind origin
- Rates of deposition, and implications for its physical nature, are unknown

Ice deposits cover a minority of the terrain and their concentrations could vary widely leading to a very heterogeneous deposit
- Suggested by distribution of high CPR spots
- Ice concentration unknown, but if heterogeneous, deposits could cover 10-50% of dark area
- Volume scattering at S-band suggests ice bodies of decimeter to decameter scale

Uppermost surface is desiccated; ice occurs at depths between 10 cm and 2-3 m
- From neutron and radar data

Ice is probably not “pure” but contains regolith contaminants of varying concentration
- From current knowledge of regolith formation, evolution, and overturn

Although water ice is expected to dominate, other minor species of cometary origin could be present in useful quantities (e.g., CH$_4$, NH$_3$)
- From astronomical observations of comets
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)
Topography

Global figure is roughly spherical \((r = 1738\ \text{km})\), 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 ~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 $4^\circ$-$5^\circ$

Highlands
Rugged, cratered terrain
Smoother intercrater areas
Numerous craters $D > 20$ km
Large blocks present, but rare; “sandblasted” Moon
Mean (r.m.s.) slopes $7^\circ$-$10^\circ$
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°
Geological Law of Superposition
Younger units overlie or embay older units

Crater density
Older units are more heavily cratered than younger units

Mapped entire Moon using this simple methodology
Lunar time-scale

Based on relations seen around near side crater Copernicus

Five time systems:
- Copernicus - ~1.0 Ga to present
- Eratosthenian – 3.3 to 1.0 Ga
- Imbrian – 3.84 to 3.3 Ga
- Nectarian - ~3.93 to 3.84 Ga
- pre-Nectarian – prior to 3.93 Ga

Absolute ages interpretations based on sample analysis
Geology

Rock types

Maria
- Dark, relatively smooth and uncratered plains
- Fill and embay very large, circular depressions (basins)
- Fluid (basaltic) lavas

Highlands
- Rugged, heavily cratered light-toned
- Saturated with craters of all diameters
- Create structural and topographic framework of Moon
- Ancient crust made up of ground-up, crushed plutonic rocks
Maria

Cover about 16% of the surface
Subdivided on basis of titanium content
Both lava (mare basalts) and pyroclastics (ash; green and orange glass)
Numerous volcanic pits, channels, and features (but vast bulk of craters are of impact origin)
Highlands

Original crust of Moon shattered and broken by impact bombardment

Crust is relatively Al-rich; ancient rocks mixed with impact breccias and melts

Evidence for global and local melting events

Over 40 basins and thousands of large craters
Global compositions

Lunar highlands crust low in Fe, incompatibles; inferred to be Al-rich (magma ocean = anorthosite)
Maria are Fe- and Ti-rich
Anomalous Fe-rich zones in highlands attributable to ancient mare deposits
Rare-Earth elements (incompatibles) concentrated in Procellarum region
Floor of South Pole-Aitken basin is relatively Fe- and REE-rich compared to rest of far side
Lunar History

Origin by giant impact ~4.5 Ga
Global melting (magma ocean) and crustal formation, complete by 4.3 Ga
Heavy impact bombardment (basins) until 3.8 Ga
Lava flooding 3.8 - ~2.0 Ga
Occasional large impacts till present
Continuous regolith formation 4.3 Ga - present
Regolith

Unconsolidated debris overlying bedrock
Derived mostly from rocks below, but includes material transported laterally from distant sites
Virtually all lunar samples we have come from the regolith
Bedrock observed (and possibly sampled) at Hadley Rille, Apollo 15
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 $\mu$m
Average grain size 70 $\mu$m
10-20% of the soil is finer than 20 $\mu$m
Dust (<50 $\mu$m) 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 m$^2$ gm$^{-1}$
8x surface area of spheres with equivalent particle size distribution
Agglutinates

Courtesy Larry Taylor, UTK
Dust, dust, dust!
Mitigation of dust problem

Limit exposure
  Isolate suits outside airlock
  Teleoperation for tasks requiring significant dust interaction

Pave the Moon!
  Microwave regolith in situ to weld into glass
  Use to make roads, landing pads, other infrastructure

Magnetic cleaning
  Much of lunar dust is magnetic (presence of disseminated nanophase Fe)
  Magnetic brushes, clean rooms
Levitated Dust?

15 min after sunset  \( T = 0.2 \text{ s} \)

90 min after sunset  \( T = 1.2 \text{ s} \)

160 min after sunset  \( T = 40 \text{ s} \)

View of horizon glow from Surveyor 7
Evidence against lateral transport of dust

**Surveyor 3 spacecraft**
- Exposed on Moon for 31 months
- Analysis of parts returned by Apollo 12 showed no significant "natural" dust accumulation

**LRRR experiment**
- Exposed on Moon for 38 years
- No degradation of optical performance noted

**Sharp geological contacts**
- Some mare-highland contacts are still razor-sharp, after over 3 billion years of "transport"
Resources
Materials and Energy for Space and Earth

Water ice in shadowed regions of both poles

Extract oxygen, metals from lunar materials for construction, propellant

Retrieve solar-wind gases (e.g., hydrogen and other volatiles) implanted on lunar dust grains

Collect solar energy with photoelectric arrays built from lunar materials and beam energy to Earth or cis-lunar space
Resources of the Moon

Materials
- Bulk regolith (soil) has many uses as a building material
- Rocks and soils have common compositions; basaltic (Fe-rich; maria) and feldspathic (Al-rich; highlands)
- Solar wind gases implanted onto dust grains; typical H$_2$ concentration $\sim$ 50-100 ppm
- Apollo 15, 16, and 17 drill cores suggest these concentrations hold to depths of 2 m or more

Energy
- Solar illumination lasts 14 days at lunar equator; extended Sun visibility near poles
- Solar $^3$He also implanted on dust grains at $<$20 ppb concentrations; may ultimately be used as fusion energy source
Unkowns

Global gravity (principally far side)
Global geodesy (need to know where things are)
Dust interactions with plasma, electric fields
Dust toxicity, especially of nanophase and long-term effects
Polar volatiles: presence, abundance, state, make-up
Polar environment; lighting, temperatures
Robotic precursor missions offer:

**Strategic knowledge**
- Location and state of resources
- Environmental properties
- Site-specific knowledge

**Early capability**
- Teleoperated rovers for exploration, reconnaissance, instrument emplacement
- Habitat site preparation, construction, prospecting, resource processing

**Programmatic milestones**
- Early accomplishments keep program momentum
- A “claim-stake” on scarce lunar properties
The Value of Lunar Resources

Materials on the Moon can be processed to make hydrogen and oxygen for use on the Moon and for export to Earth-Moon (cislunar) space.

Propellant produced on the Moon can make travel within and through cislunar space routine.

This eventuality will completely change the spaceflight paradigm.

Routine access to cislunar space has important economic and strategic implications.
Conclusions

The lunar environment, materials, history, and conditions are broadly understood from Apollo and its precursors.

The Moon is an airless, waterless, high radiation, low gravity body. Rough on macro scales in most places, but smooth areas occur at human infrastructure scales.

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

Some key properties are unknown, specifically the polar environment and deposits and the nature and extent of electrostatically levitated dust.

As an ancient world, the Moon allows us to decipher the history of the early Earth and this part of the Solar System.

Learning to use the material and energy resources of the Moon will revolutionize the paradigm of spaceflight.
The Moon – Gateway to the Universe

“If God wanted man to become a space-faring species, He would have given man a Moon.” – Krafft Ehricke

Learn about the Moon, the Earth-Moon system, the solar system, and the universe by scientifically exploring the Moon

Acquire the skills and build the systems on the Moon that we need to become a multi-planet species

Develop and use the material and energy resources of the Moon to create new space-faring capability
For More Information:

Spudis Lunar Resources
Using the Moon to learn how to live and work productively in space

What's this web site all about?

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http://www.spudislunarresources.com