The Moon's Role in the Exploration of the Solar System

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(with apologies to people from whom I have poached graphics)

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Ames Research Center
Moon’s Role

- **Science**
  - Lunar science – in situ
  - Lunar observatory
  - Laboratory experiments

- **Test bed**
  - Technology validation
  - Operations demonstration

- **Resources**
  - Fuel
  - Life support

- **Public Engagement**
  - Excitement
  - Tangible goals
  - Visibility

- **Commercial Opportunities**

- **National Security**

- **Premise:** Continued program of solar system exploration with humans and a presence in cislunar space ± Mars.
ISECG Mission Scenario

Low-Earth Orbit
- International Space Station

Beyond Low-Earth Orbit
- Test Missions
- Asteroid Redirection
- Explore Near-Earth Asteroid
- Near-Earth Objects
  - Rosetta
  - Hayabusa2 (Sample Return)
  - OSIRIS-REx (Sample Return)

Commercial or Government-Owned Platforms

Lunar Vicinity
- Extended Duration Crew Missions
- Potential Commercial Opportunities
- Staging Post for Crew to Lunar Surface
- Humans to Lunar Surface
- Lunar Exploration Missions
  - LADIEE
  - Luna 25
  - Luna 27 (Sample Return)
  - RESOLVE
  - SELENE-2
  - SELENE-3
  - Apollo
  - Human-Assisted Sample Return

Moon
- Multi-Destination Transportation Capabilities
  - Orion & SLS
  - Russian Piloted System
  - Advanced Electric Propulsion
  - Evolvable Deep Space Habitat
  - Orion & SLS
  - Initial Cargo Delivery
  - Small Cargo Lander
  - Human Surface Mobility
  - Crewed Lunar Lander
  - Orion & SLS (Upgrade)

Mars
- MMX
- ISRO Mars Orbiter Mission
- ExoMars 2016
- InSight
- ExoMars 2018
- Mars 2020
- JAVA Mars Precursor
- Human-Assisted Sample Return
- Mars Sample Return Mission Opportunities
- Human-Scale EDL Test Mission Opportunities

Sustainable Human Missions to the Mars System

Icon indicates first use opportunity. Commercial/institutional launchers not shown.
Lunar Science – Recent Missions

- LRO/LCROSS
- Kaguya
- Chang’e 1 & 2 & 3
- SMART 1
- ARTEMIS
- LADEE
- GRAIL
- Chandrayaan
Lunar Science – Surface Missions

- Chang’e
- Luna
- Apollo
- Surveyor
Lunar Exploration Analysis Group (LEAG)
Understand the environmental impacts of lunar exploration.
Development and implementation of sample return technologies and protocols.
Characterize the environment and processes in lunar polar regions.
Understand the dynamical evolution and space weathering of the regolith.
Understand lunar differentiation.
Understand volcanic processes.
Understand the impact process.
Determine the stratigraphy, structure, and geological history of the Moon.
Understand formation of the Earth-Moon system.
Understand the impact history of the Inner Solar System as recorded on the Moon.
Regolith as a recorder of extra-lunar processes.

Scientific Context for Exploration of the Moon: Final Report
Bombardment history of the inner solar system uniquely revealed on the Moon.
Structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated body.
Key planetary processes are manifested in diversity of lunar crustal rocks.
The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history.
Lunar volcanism provides a window into the thermal and compositional evolution of the Moon.
The Moon is an accessible laboratory for studying the impact process on planetary scales.
The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.
Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state.
Lunar Science - Observatories
Moon - Test Bed

- Surface or Cislunar Space
- Deep space environment
- Deep space radiation environment (at least part time)
- Low gravity (1.622 vs. 3.771 m/sec/sec)
- Fine-grained, granular surface material (magnetic)
- Proximity – communication, safety, risk reduction
Long Duration Flight
Surface Ops
Evils of Regolith and Dust
Evils of Regolith and Dust
Understand Interplay Between Humans and Robots

“When does the human become the tool of choice for solar system exploration?”

“How should the ratio of humans to robots change over time to meet that goal?”
Understand Interplay Between Humans and Robots - Robots

Pro

Expendable – risky situations
Excellent at boring, repetitious tasks – listening to me
Environmentally robust – operate in extreme environments
Continuous to near-continuous duty cycle – don’t sleep

Con

Limited intellectual capability – they only do what they are asked, usually
Slow - data rate, power constrained
Limited payload
Expensive

I’m sorry Clive, I’m afraid I can’t do that.
Understand Interplay Between Humans and Robots - Humans

Pro

- Intellectually flexible – orange soil at Apollo 17
- Adaptable to different situations
- Communicate ideas not just data
- Mechanically flexible – Hubble, ALSEP
- Ability to handle difficult terrain – rock strewn ejecta
- Ability to distinguish critical data from mass of irrelevant information

Con

- Require life support
- Need to sleep, eat, and …
Lunar Resources

# Apollo 11 soil (mare) Apollo 16 soil (terrae)

<table>
<thead>
<tr>
<th>Element</th>
<th>Apollo 11</th>
<th>Apollo 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>20-100 ppm</td>
<td>4-40 ppm</td>
</tr>
<tr>
<td>He*</td>
<td>19-80 ppm</td>
<td>3-35 ppm</td>
</tr>
<tr>
<td>Ar</td>
<td>1.3-12 ppm</td>
<td>0.7-3 ppm</td>
</tr>
<tr>
<td>Xe</td>
<td>0.5-3.8 ppm</td>
<td>0.2-1 ppm</td>
</tr>
<tr>
<td>C</td>
<td>100-200 ppm</td>
<td>30-280 ppm</td>
</tr>
<tr>
<td>N</td>
<td>20-80 ppm</td>
<td>4-200 ppm</td>
</tr>
<tr>
<td>K</td>
<td>1000-1800 ppm</td>
<td>380-1100 ppm</td>
</tr>
<tr>
<td>P</td>
<td>480-650 ppm</td>
<td>130-1100 ppm</td>
</tr>
<tr>
<td>S</td>
<td>660-1500 ppm</td>
<td>470-640 ppm</td>
</tr>
<tr>
<td>F</td>
<td>75-520 ppm</td>
<td>27-105 ppm</td>
</tr>
<tr>
<td>Cl</td>
<td>3-40 ppm</td>
<td>12-270 ppm</td>
</tr>
</tbody>
</table>

* $^{4}\text{He}/^{3}\text{He} = \sim 2500$

1 m$^3$ of lunar regolith contains enough hydrogen, carbon, nitrogen, potassium, and other trace elements to make lunch for two – two cheese sandwiches on rye, two colas (flavored with real sugar, although there’s enough Cl to sweeten it with Splenda instead), and two large plums.

L. Taylor
Lunar Resources

Oxygen and hydrogen are valuable commodities
  Oxygen - human consumption and oxidizer
  Hydrogen (H_2O) - life support, radiation shielding, propellant, fuel cells

Present on the Moon - small amounts (H_2) or tightly bound to metals (O)
  Significant amounts of time and energy to extract, purify, and store
  Heat regolith to 700° C to drive off solar wind H_2, higher temperatures to crack oxygen
  Movement and handling of large amounts of regolith

Lunar polar ice is a concentrated, easily usable form of hydrogen and oxygen
  Remove water by heating to 100° C
  Might be possible to extract \textit{in situ}
  Electrolyze water into component H_2 and O_2, liquefy and store
  Relatively simple processing compared to solid-gas or liquid-gas reactions
Lunar Resources

Define the resource
Understand how to extract it
Calculated the costs
Make a decision

Drives the outpost site selection process
  Distance to ore
  Power for production
  Transport of resource
Lunar Resources - Demonstration

Demonstrate
  Excavation and transport
  Recovery of volatiles
  Cryogenic storage and transfer

Requires advanced power, mobility, large landed payload capacity
Lunar Resources - Processing, Storage, Use
Visible Milestones
Public Engagement
Public Engagement
Planète Interdite

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EN COULEURS CINEMASCOPÉ

WALTER PIDGEON · ANNE FRANCIS
LESLIE NIELSEN

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FIVE DECADES
TWO YEARS IN THE MAKING!

DESTINATION MOON

color by Technicolor

Produced by GEORGE PAL - Directed by IRVING PICHET - Screenplay by RIP VAN RONKEL, ROBERT HEINLEIN and JAMES O'HANLON

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