

Headline Article

April 24, 2018

New Age for Lunar Exploration

--- A change in the National Space Policy adds a lunar emphasis to NASA exploration programs.

Written by G. Jeffrey Taylor and Linda M. V. Martel

Hawai'i Institute of Geophysics and Planetology



Lunar-focused research and plans to return to the lunar surface for science and exploration have reemerged since the Space Policy Directive-1 of December 11, 2017 amended the National Space Policy to include the following, "Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations."

In response to this revision, NASA proposes a Lunar Discovery and Exploration Program in the U.S. fiscal year 2019 Budget Request. It supports NASA's interests in commercial and international partnerships in Low-Earth Orbit (LEO), long-term exploration in Cislunar space beyond LEO, and research and exploration conducted on the Moon to inform future crewed missions, even to destinations beyond the Moon. (Cislunar refers to the volume of space between LEO and the Moon's orbital distance.) The lunar campaign strengthens the integration of human and robotic activities on the lunar surface with NASA's science, technology, and exploration goals.

Reference:

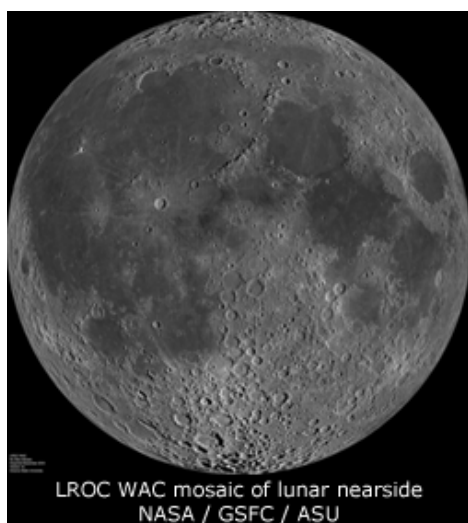
- [Presidential Memorandum](#) (December 11, 2017)

Lunar Exploration

It is not surprising that the Moon is a prominent feature in ancient human mythology. It is the largest and brightest object in the night sky and changes its shape and apparent size during the course of a month. It has puzzling lighter and darker areas. Galileo transformed the mysterious Moon into an object of scientific study, reporting in 1610 that the silvery shape-changing orb had mountains and lowlands. It was another world. Humans did not know much about the mountains and lowlands even after early telescopic observations, but since NASA's [Apollo](#) program and its precursor missions (including observations with modern telescopes), we have learned much about the Moon, and its craters, lava flows, highlands, lowlands, polar regions, mantle, and metallic core. Many questions remain, so a focus on lunar science is timely.



"The general appearance however was like one vast ruin of nature." So concludes a description of the Moon by William Scoresby (1789-1857) accompanying an engraving by John Emslie, published by James Reynolds circa 1851 (shown at left, from the [Science Museum, London](#)). Scoresby had viewed the Moon through Lord Rosse's telescope, the largest of the 19th century [[historical lithograph of the telescope](#)]. The words capture the lack of knowledge and emphasize how far we've come in understanding Earth's Moon in the intervening ~170 years.



This global mosaic of images of the Moon obtained by the Lunar Reconnaissance Orbiter Camera (LROC) shows features in far greater detail than Emslie's engraving. LROC obtains images of the surface at high spatial resolution, to ~50 cm/pixel, enough to identify the Lunar Module descent stages at the Apollo landing sites. In addition to LROC, the Lunar Reconnaissance Orbiter carries a laser altimeter (LOLA) that has produced a shockingly precise global topographic map and an infrared instrument (Diviner) that measures temperature of the surface (especially useful in permanently-shadowed regions near the poles). Other post-Apollo missions carried other useful instruments to measure the chemical composition and mineral abundances of the surface and of the atoms and molecules present in the tenuous lunar atmosphere (officially called an exosphere because the molecules do not collide).

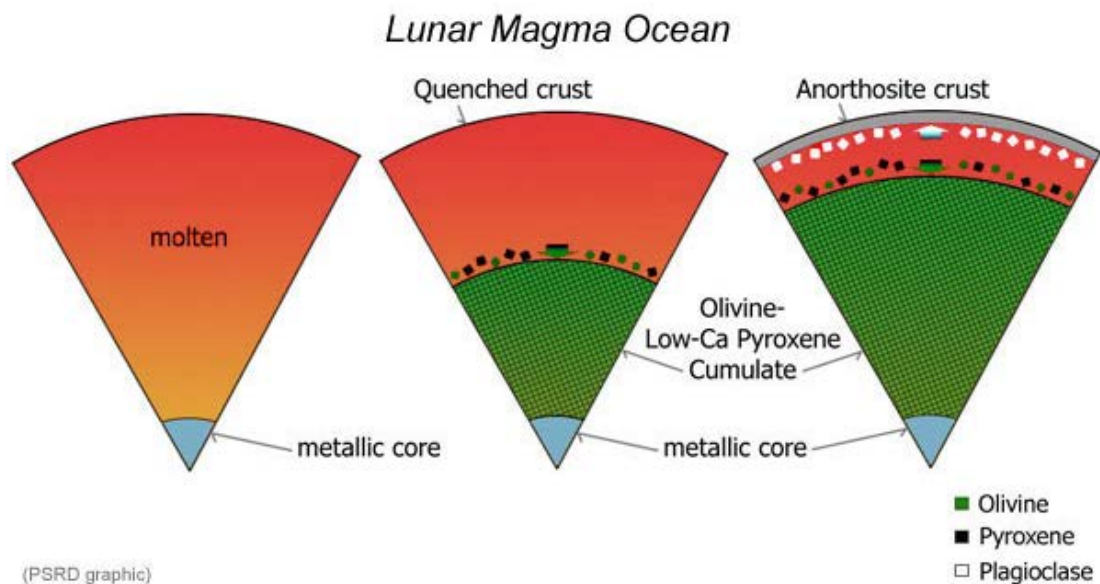


NASA/Eugene Cernan

The centerpiece of past lunar exploration was the U.S. Apollo program, a dramatic and inspiring adventure that sent the first scouting parties to explore the stark lunar surface. This photograph shows Astronaut-geologist Harrison H. (Jack) Schmitt standing next to a large boulder at the Apollo 17 landing site in Taurus-Littrow valley. The dune buggy he and Astronaut Eugene Cernan used is parked on the right. The samples returned by Schmitt and Cernan have been studied in considerable detail (though more needs to be done!), as have the samples returned by the other five Apollo missions that landed on the Moon's nearside. Even after almost 50 years of enthusiastic studies of the Apollo samples, there is more to learn. In fact, in 2017 Jack Schmitt teamed up with other lunar specialists to integrate his field observations and photographs with sample data and the wealth of recent remote sensing data. See [PSRD Cosmospark: Apollo 17 at Taurus-Littrow: New Perspectives from the Geologist in situ](#).

Discoveries

Analysis of the first lunar samples showed unambiguously that the dark areas on the Moon (the **maria**) are composed of lava flows, somewhat different in composition than basalts on the Earth, but still recognizable as basalts. Previous hypotheses were that the maria were either completely unmelted primary lunar rock or were places where dust collected in a low-density fluffy powder that the lunar landers would sink through. Those ideas were proven wrong; it's good to have data. The **highlands** were a surprise. They are composed mostly of plagioclase feldspar. From little pieces of feldspar-rich rocks in the soil returned by the first lunar mission (Apollo 11), John Wood and colleagues at the Smithsonian Astrophysical Observatory boldly proposed that the highlands contain a lot of plagioclase because the Moon melted when it formed and when plagioclase formed, the crystals floated and accumulated to create the primary lunar crust. Thus was born the **magma ocean concept**.



Three panels, from left to right, illustrate the lunar magma ocean concept. [LEFT] The cartoon depicts a molten Moon when it formed (probably completely molten, but we really do not know for sure). [CENTER] As the magma ocean cooled, dense minerals sank, forming the lunar mantle that later melted again to form the magmas that erupted as basalt to flood the maria. [RIGHT] Eventually, plagioclase feldspar crystallized and floated, forming the primitive, anorthosite crust. This concept has been questioned, but is still viable, and has been applied to other rocky bodies, even asteroids. The magma ocean concept changed our view of planet formation away from one that portrayed the rocky planets as forming cold and then heating up via the decay of the radioactive elements thorium, uranium, and potassium.

Another fascinating concept arose from analyses of lunar samples and studies of how planets might have been assembled from a hierarchy of smaller objects. Before the Apollo program and for a decade after it, three ideas for lunar origin were debated: *Co-accretion*, in which the Earth and Moon formed as a binary system. *Fission*, in which the young Earth was spinning so fast that it flung out a big blob that became the Moon. And *capture*, wherein a fully-formed Moon makes a close approach to the young (probably still forming) Earth and the gravitational interaction between them ends up with the Moon orbiting the Earth. For sound reasons based on chemical compositions of the Earth and Moon, and on the physics of gravity and orbital motions, most planetary scientists thought that all three ideas were flawed beyond repair.

So, why not another idea? That new idea burst forth at the Origin of the Moon Conference, held in Kailua-Kona, Hawai'i, in 1984 [[conference notes](#)]. Because of our improved understanding of the composition of the Moon and Earth, our improved understanding of the impact process, and the availability of computer power, the **Giant Impact hypothesis** blossomed in Hawai'i, embracing participants like a fragrant flower lei of 'awapuhi, 'ilima, and pikake. Not everyone at the conference bought into the idea, but it has remained an important tenant of lunar science while imaginative ideas for giant impacts are being explored.



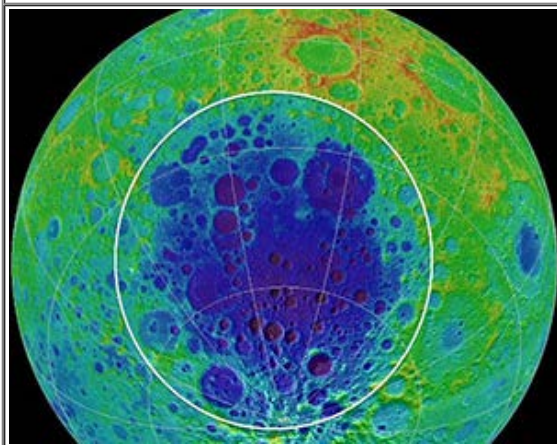
Painting by William K. Hartmann.

Artistic view of the giant impact origin of the Moon painted by William K. Hartmann, one of the creators of the giant impact hypothesis. In the traditional version, a Mars-sized impactor collides with the growing Earth, sending enough material into orbit around the Earth to form the Moon. Details are still being worked out! [[artwork source](#)]

Great Progress, But We Do Not Know Everything

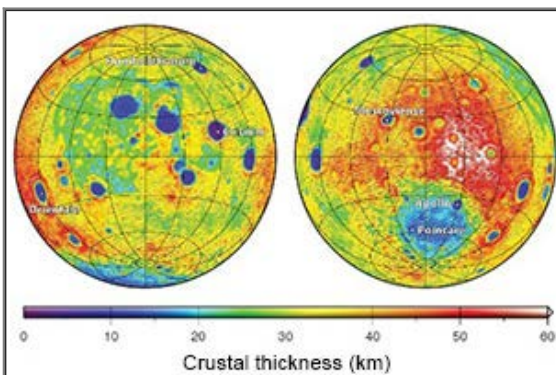
Lunar scientists have made tremendous strides in understanding lunar formation, its differentiation into crust, mantle, and core, its bombardment history and the impact process, magma production through time, evolution of its dusty and fragmental regolith, and some characteristics of the permanently-dark regions at the lunar poles. But they do not know everything and discoveries have led to new, sophisticated questions. The Scientific Context for the Exploration of the Moon, a report by the National Research Council in 2007, outlined eight concepts and associated science goals [[report link](#)]. The extent to which we have made progress in each of the concepts was examined in August, 2017, by a Specific Action Team of the Lunar Exploration Analysis Group (LEAG). Their report was released in February, 2018 [[report link](#)]. It concluded that significant progress has been made in each concept area, but that the job is far from complete in any of them. It also added three additional concept areas. On the following pages are a brief summary of the concepts.

Lunar Science Concepts



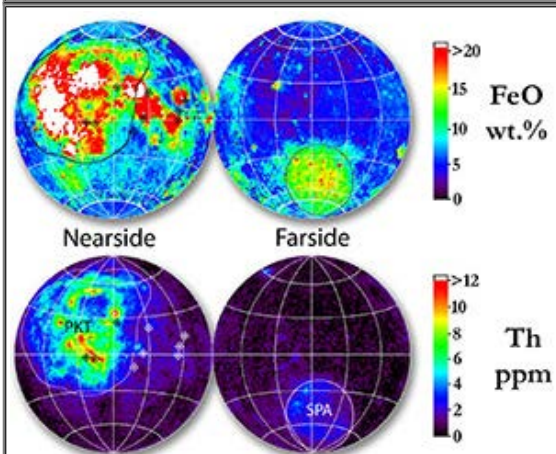
1. The bombardment history of the inner Solar System is uniquely revealed on the Moon

The enormous South Pole–Aitken (SPA) basin is over 2200 km across, outlined in white on the LOLA topographic map. It is stratigraphically the oldest basin on the Moon, making determining its age important for understanding bombardment history of the inner Solar System. [[image source](#)] [[PSRD articles related to SPA basin](#)]



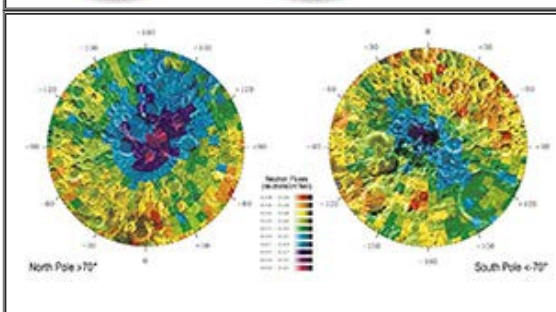
2. The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body

The thickness of the lunar crust was determined by NASA's GRAIL gravity mission. More information is needed about the mantle underlying it. [[image source](#)] [[PSRD article related to differentiation of the Moon](#)]



3. Key planetary processes are manifested in the diversity of lunar crustal rocks

The lunar surface is composed of distinct geochemical terranes. Data are from the Lunar Prospector gamma-ray spectrometer. [[image source](#)] [[PSRD articles related to lunar geochemical terranes](#)]



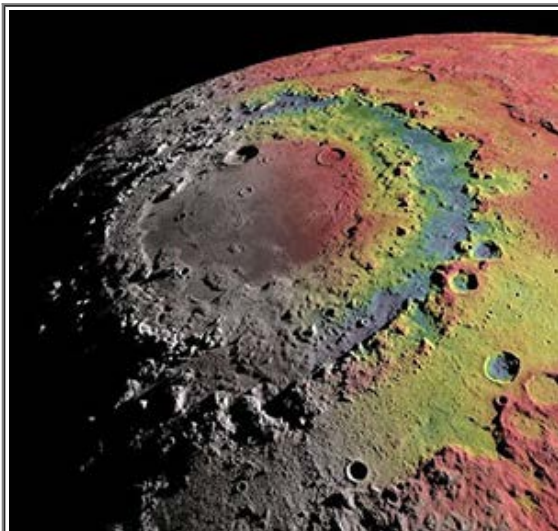
4. The lunar poles are special environments that may bear witness to the volatile flux over the latter part of Solar System history

Neutron fluxes at the lunar poles are shown by colors superimposed on lunar topographic map. Blue and purple colors indicate higher hydrogen contents (probably in water ice). [[image source](#)] [[PSRD articles related to the lunar poles](#)]



5. Lunar volcanism provides a window into the thermal and compositional evolution of the Moon

Thin section of a lunar mare basalt as viewed in polarized light in a microscope. The ages and compositions of lava flows hold the record of lunar magmatism through time, hence of the Moon's thermal history. Photomicrograph by G.J. Taylor. [[PSRD articles related to lunar magmatism](#)]



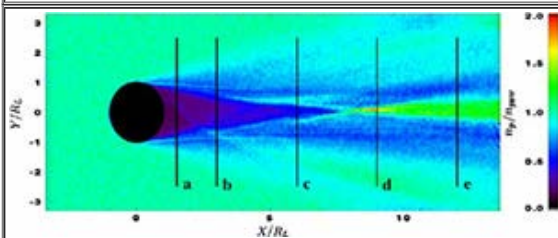
6. The Moon is an accessible laboratory for studying the impact process on planetary scales

The Moon's 580-mile-wide Orientale basin has three distinct ring structures. The image shows the basin's gravitational signature obtained by the GRAIL mission (red indicates excess mass, blue indicates mass deficits), which the GRAIL science team used to reconstruct the formation of the basin and its rings. [[image source](#)] [[PSRD articles related to lunar basins](#)]



7. The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies

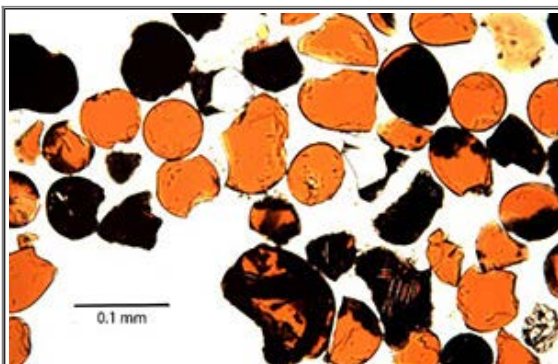
The dusty, fragmental lunar regolith contains a record of the Sun's history and represents a natural experiment for the effect of the space environment (vacuum, solar wind and solar flares, light, and micrometeorite bombardment on the physical and optical properties of the surface. [[image source](#)] [[PSRD articles related to regolith](#) and [PSRD articles related to space weathering](#)]



8. Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state

Simulation of the interaction of the solar wind with the Moon. The Artemis mission analyzed the ionic density of the exosphere and its interaction with the surface, solar wind, and Earth's magnetotail. [[image source](#)]

New Goals in Lunar Exploration written in 2018 LEAG Report



The lunar volatile cycle

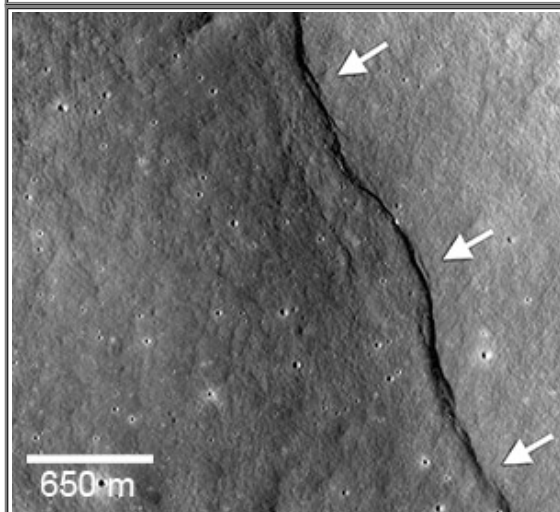
Once thought dry, we now know that it contains H₂O and OH in its interior. In addition, hydrogen is added to the surface by the solar wind and H₂O is added by impacting comets and hydrous asteroids. How these reservoirs interact and affect water concentrations in polar regions needs to be understood. Photomicrograph by G.J. Taylor. [[PSRD articles related to lunar volatiles](#)]



The origin of the Moon

Details of lunar origin are far from clear. Testing sophisticated, imaginative models for lunar origin requires more data on the composition of the Moon. [[artwork source](#)] [[PSRD articles related to origin of the Moon](#)]

Lunar and Planetary Institute



Lunar tectonism and seismicity

Arrows point to a young fault on the Moon. The abundance, types, and magnitudes of moonquakes reveal much about the lunar interior and the stresses acting on it. Regions with active scarps may be hazardous places to establish a lunar base. [[image source](#)] [[PSRD articles related to the lunar interior structure](#)]

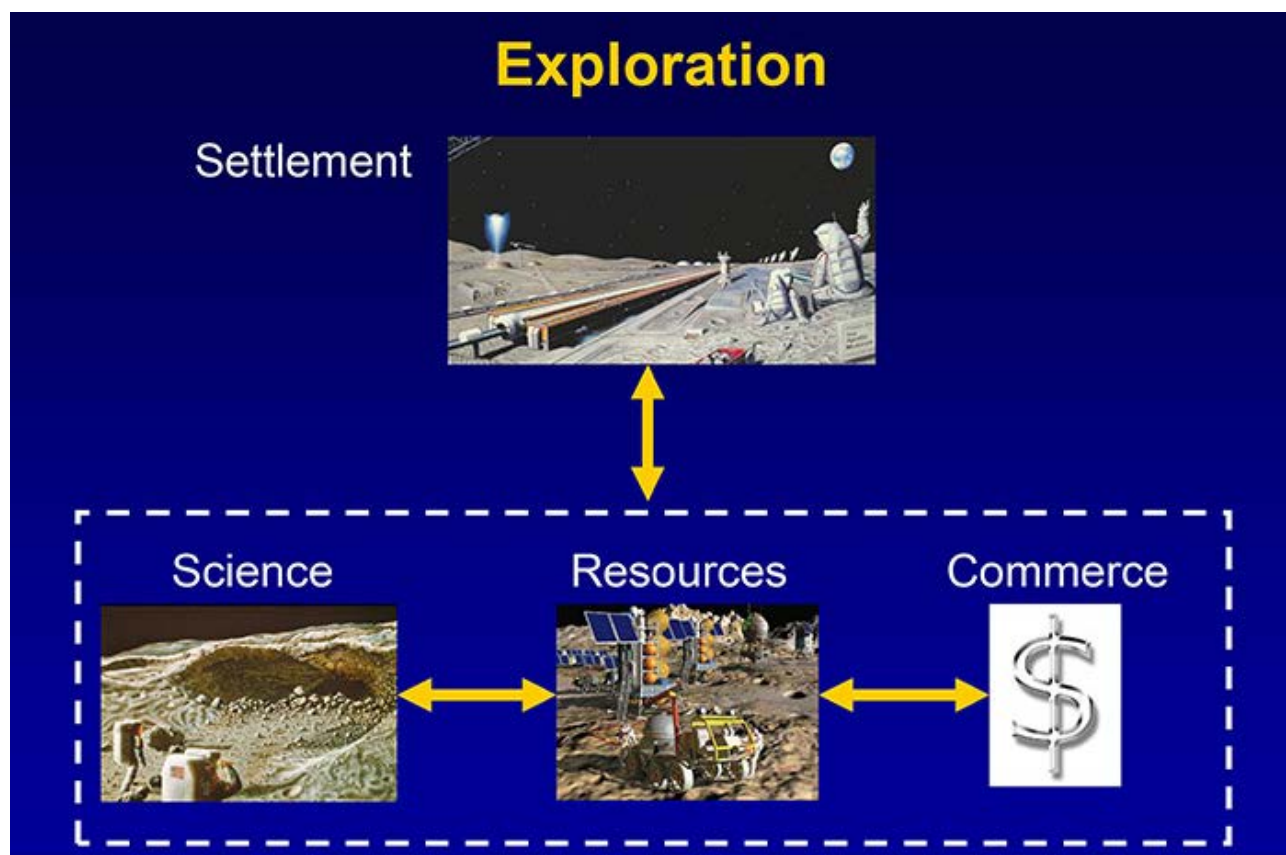
To continue to make progress, NASA's Lunar Discovery and Exploration Program provides additional opportunities for research in lunar science. This includes an enhanced lunar sample analysis campaign and the possibility of opening one of the core tubes returned from the Moon that has remained sealed for almost fifty years. The agency also envisions a series of small, then larger robotic missions to lunar orbit and to its surface. To make these missions most effective, NASA began a lunar-centric instrument development program called Development and Advancement of Lunar Instrumentation (DALI). The program's goal is to have a new generation of instruments ready for flight by about 2021.

Lunar Resources and Expanding Earth's Economic Sphere

A central aspect of President George W. Bush's Vision for Space Exploration, announced in 2004, was the idea of a robust space exploration program to advance the scientific, security, and economic interests of the United States. This involves permanent settlement of space, beginning with the Moon, so humans can learn to live and work in space. The President's science advisor, John Marburger, expressed the economic argument [in a [2006 speech](#)] saying that a central goal of the Vision for Space Exploration was to "incorporate the Solar System in our economic sphere."

This concept raises the question of how companies can make a profit by exploring space. The answer is straightforward. If the goal of space exploration is the permanent settlement of the Moon, Mars, and beyond, it is imperative to use local resources for habitats, life support, agriculture, food processing, energy generation, industrial equipment, transportation, and communications as we cannot bring it all from Earth. (This list is from

the highly informative book by Peter Eckart, *The Lunar Base Handbook*.) Once we begin to use local products we will be able to begin exporting those that are useful in Cislunar space, such as hydrogen and oxygen for propellant, and then export products made on the Moon using its unique environment such as a hard vacuum and lower gravity. An important aspect of expanding Earth's economic sphere to Cislunar space is that it enables settlement of the Moon. A strong interplay among scientific studies like those described above, resource prospecting and utilization, and commerce all enable permanent settlement of other bodies. The relationship between basic science and resource utilization is reinforced by the fact that much of the work on lunar resources has been done by scientists who study lunar materials.



PSRD graphic by Jeff Taylor. NASA artwork by Pat Rawlings (top and lower left) and unknown (lower middle).

/>

Lunar settlement enables and requires scientific research, resource utilization, and profitable commercial ventures. The centerpiece of permanence is to expand Earth's economic sphere into Cislunar space, then the entire Solar System.

To encourage resource utilization, NASA has created a track in its Broad Agency Announcement titled "Next Space Technologies for Exploration Partnerships-2," which includes a category for proposals to develop methods of in-situ resource utilization. This is an important step towards expanding Earth's economic sphere.

We may be at the beginning of a new age of lunar exploration and settlement of the Moon. Perhaps even a new age of the migration of humans to a body besides Earth and expansion of commerce to Cislunar space. A bustling exploration and economic environment in space is the only way we will be able to know how to (and be able to afford to) send people to Mars and beyond.

Additional Resources

Links open in a new window.

- Eckart, Peter (1999) *The Lunar Base Handbook*, McGraw-Hill Higher Education, 850 p.
- Gillis, J. J., Jolliff, B. L., and Korotev, R. L. (2004) Lunar Surface Geochemistry: Global Concentrations of Th, K, and FeO as Derived from Lunar Prospector and Clementine Data, *Geochimica et Cosmochimica Acta*, v. 68, p. 3791-3805, doi: 10.1016/j.gca.2004.03.024. [[abstract](#)]
- Jolliff, B. L., Gillis, J. J., Haskin, L. A., Korotev, R. L., and Wieczorek, M. A. (2000) Major Lunar Crustal Terranes: Surface Expressions and Crust-mantle Origins, *Journal of Geophysical Research*, v. 105, p. 4197-4216, doi: 10.1029/1999JE001103. [[abstract](#)]
- NASA [NextSTEP](#), Next Space Technologies for Exploration Partnerships. A public-private partnership model seeking commercial development of deep space exploration capabilities to support human spaceflight missions.
- Sibeck, D. G. and 19 others (2011) ARTEMIS Science Objectives, *Space Science Reviews*, v. 165, p. 59-91, doi: 10.1007/s11214-011-9777-9. [[abstract](#)]
- Wieczorek, M. A., Neumann, G. A., Nimmo, F., Kiefer, W. S., Taylor, G. J., Melosh, H.J., Phillips, R. J., Solomon, S. C., Andrews-Hanna, J. C., Asmar, S. W., Konopliv, A. S., Lemoine, F. G., Smith, D. G., Watkins, M. M., Williams, J. G., and Zuber, M. T. (2013) The Crust of the Moon as Seen by GRAIL, *Science*, v. 339(6), p. 671-675, doi: 10.1126/science.1231530. [[abstract](#)]



[[About PSRD](#) | [Archive](#) | [CosmoSparks](#) | [Search](#) | [Subscribe](#)]

[[Glossary](#) | [General Resources](#) | [Comments](#) | [Top of page](#)] [+](#) [Share](#)

2018

<http://www.psrд.hawaii.edu>

psrd@higp.hawaii.edu