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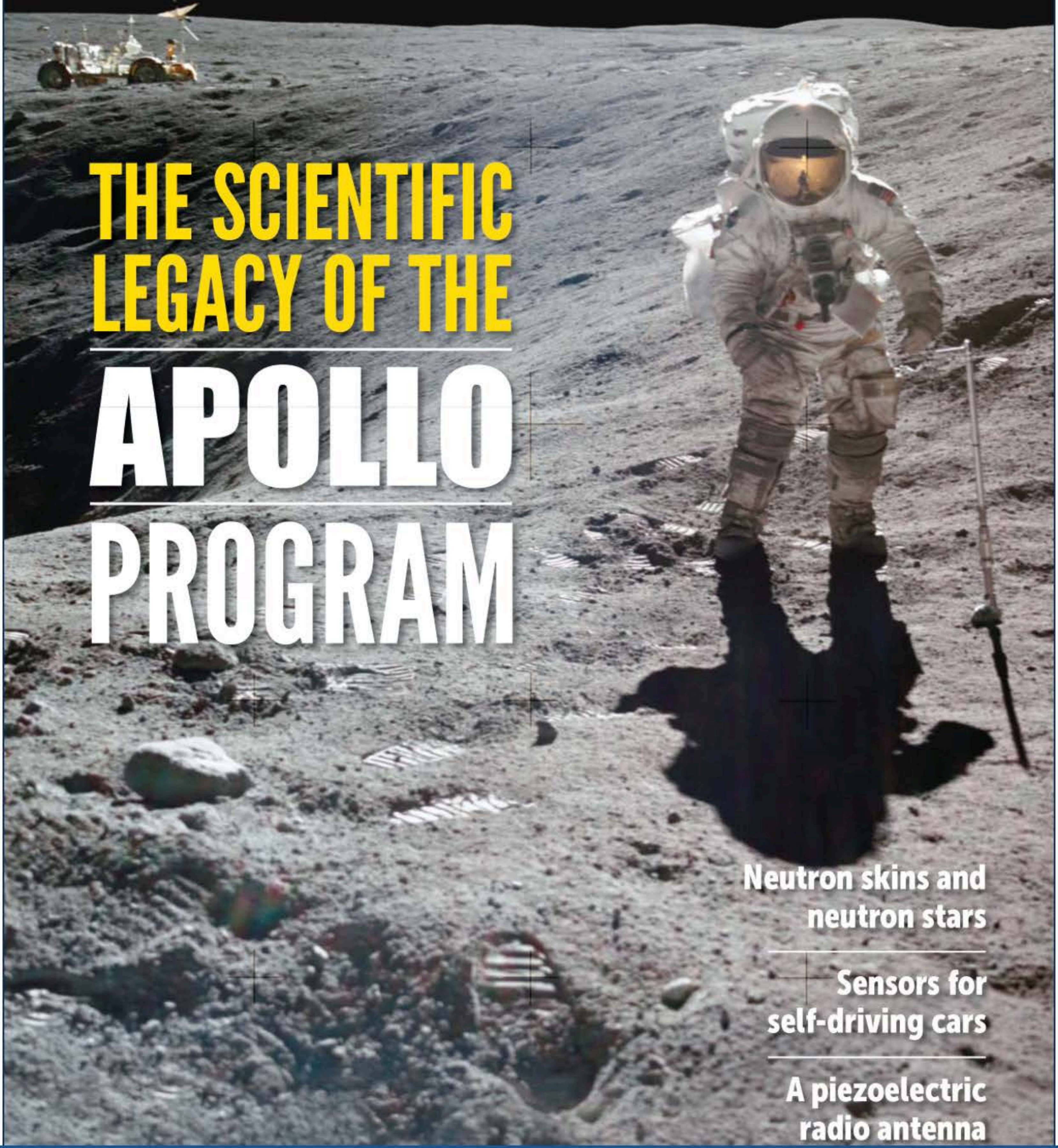


THE SCIENTIFIC LEGACY OF THE APOLLO PROGRAM

Neutron skins and neutron stars

Sensors for self-driving cars

A piezoelectric radio antenna

Destination Moon

Charles Day

On 26 March the National Space Council met at the US Space and Rocket Center in Huntsville, Alabama. There, the council's chair, Vice President Mike Pence, announced the administration's new goal of returning American astronauts to the Moon by 2024. Seven weeks later the Trump administration added an extra $1.6 billion to its FY 2020 NASA budget request to fund the mission, which NASA has named Artemis after the twin sister of the Greek Sun god, Apollo. Far more funding will be needed in the next four annual budgets.

Five years is unlikely to be enough time. On 30 May the US Government Accountability Office (GAO) issued its 11th annual assessment of NASA's biggest projects. Three of them—the Space Launch System, the Orion Multi-Purpose Crew Vehicle, and Exploration Ground Systems—are essential to landing astronauts on the Moon. The GAO auditors found that, together, the systems are $1.8 billion over budget and 38 months late. NASA's average launch delay, at 13 months, was the longest the office had found since 2009, when it first started reviewing the space agency's performance.

Whereas the GAO is skeptical of NASA's ability to meet its own deadlines, Pence repeatedly stressed the need to revisit the Moon soon. "Urgency must be our watchword," he told his Huntsville audience. "Failure to achieve our goal to return an American astronaut to the Moon in the next five years is not an option." NASA, he said, had to become leaner, more accountable, and more agile.

Given what it will take to return astronauts to the Moon by 2024, it's worth examining just how urgent the goal really is. The scientific case is perhaps the easiest one to assess. In 2011 the National Research Council published its most recent decadal survey of planetary science. When the committee members evaluated scientific opportunities, returning astronauts to the Moon was not White House policy. Without the prospect of piggybacking on a manned mission, the Moon was considered a potential destination for robotic missions along with all the other bodies in our solar system.

The decadal survey made recommendations for two classes of missions, flagship and the smaller yet still ambitious New Frontiers. Retrieving samples from the surface of Mars was the highest priority among flagship missions, followed by visits to Jupiter's moon Europa and the planet Uranus.

Lunar science was the goal of one of five recommended candidates for the next New Frontiers mission: Specifically, retrieving samples from the ice-rich, deeply impacted Aitken basin at the Moon's south pole. The scientific payoff would be great. Indeed, the south pole is the intended destination of the 2024 Moon shot. But the next New Frontiers mission, to be announced later this month, will be either to Saturn's moon Titan or to comet 67P/Churyumov–Gerasimenko.

TURN TO PAGE 22 FOR DAVID KRAMER'S REPORT ON USING THE MOON AS A WAY STATION TO MARS

What of other, nonscientific cases to return astronauts to the Moon by 2024? To his credit, Pence did not equivocate. The US must remain first in space, he said, because the rules and values of space will be written by those who get there first and commit to staying. He's likely correct. In 1979 the United Nations Office for Outer Space Affairs promulgated a treaty to establish regulations for the use of the Moon and other celestial bodies and to grant the UN jurisdiction over them. Eighteen countries have acceded to or ratified the treaty; China, Russia, and the US are not among them. Mining oxygen from lunar rocks and using nuclear power to extract water from permanently shadowed craters—two activities that Pence mentioned in his Huntsville address—contravene Article 11 of the Moon Treaty, which forbids the appropriation of lunar resources by states and companies.

Who might reach the Moon before the US? On 28 November 2018, Dmitry Rogozin, head of Russia's national space agency, announced Russia's intention land a human on the Moon by 2030. Two years earlier, Zhang Yulin, the deputy commander of the China's manned space program, announced the country's intention to land a human on the Moon by 2036.

Does it matter if NASA goes all out to return to the Moon by 2024? Yes, I think it does. In its report, the GAO noted that the combination of NASA's existing overruns and the addition of Artemis will strain NASA's budget: "NASA will have to either increase its annual funding request or make tradeoffs between projects." Those tradeoffs could include the scientifically fruitful robotic missions that the decadal survey identified. I favor returning American astronauts to the Moon, just not at any cost. PT

Quo vadis, NASA: The Moon, Mars, or both?

Fifty years after *Apollo 11*, the US spaceflight program is juggling political and technological factors as it moves toward the red planet, its ultimate destination.

NASA

NASA ADMINISTRATOR JIM BRIDENSTINE stands in front of an artist's depiction of a lunar lander as he addresses an industry forum on the agency's lunar exploration plans.

President Trump, NASA's leadership, Congress, and advocates for human space exploration agree that Mars should be the ultimate destination for the US spaceflight program. But will the administration's plan to send astronauts back to the Moon advance a Mars mission, or could the lunar program draw resources away from Mars and thus delay an excursion to the red planet?

In March of this year, Vice President Pence announced the administration's decision to move up by four years, to 2024, its target date for sending astronauts, including the first woman, to the Moon. But congressional appropriators' rejection of the administration's request to add $1.6 billion to NASA's fiscal year 2020 budget to accelerate the Moon landing program casts doubt on the 2024 goal.

Trump's December 2017 executive order, Space Policy Directive 1, acknowledged the goal of getting to Mars even as it ordered a return to the Moon. The 2017 NASA authorization act—which does not provide funding—also confirmed Mars as the ultimate destination for human exploration.

Regardless of exactly when it may happen, is putting humans back on the lunar surface truly a prerequisite for going to Mars? "I wish I could give you a really crisp, black and white answer, but it is a bit nuanced," says Scott Hubbard, who was director of NASA's Ames Research Center and NASA's first Mars program manager.

"This debate has been going on for decades," says Hubbard. "You can make a solid case that you can send people to Mars with only minimal testing at the Moon." As far back as 1991, aerospace engineer Robert Zubrin and colleagues at Martin Marietta (now Lockheed Martin) floated a Mars Direct plan, which eschewed a return to the Moon and the associated components of NASA's proposed lunar and Martian flight architecture.

Hubbard points to another proposal by three scientists at NASA's Jet Propulsion Laboratory (JPL) in 2015. It relied heavily on a set of elements already built or planned by NASA, such as the Space Launch System (SLS) heavy-lift rocket, the four-person Orion capsule, a deep-space habitat, and a 100 kW solar-electric-propelled "tug" for transporting supplies ahead of a human landing. The plan entailed few if any operations on the lunar surface and avoided complicated development programs such as nuclear-thermal propulsion. The JPL proposal envisioned an initial human mission landing on Phobos, the larger of Mars's two moons, in 2033, with a Mars touchdown in 2039.

More recently, SpaceX has proposed flying humans directly to Mars aboard its planned "starship." Paul Wooster, SpaceX's principal Mars engineer, told the Humans to Mars Summit (H2M) in May, "It's not unreasonable" that the company will put people on the planet by the mid 2020s.

Jonathan Lunine, a Cornell University astronomer who cochaired a National Academy of Sciences (NAS) review of NASA's human spaceflight program in 2014, says that "from a strictly engineering point of view," a direct-to-Mars approach is feasible. "But you increase the risk tremendously, from two points of view: One, you're not going to be testing a lot of technologies until you actually get to Mars; and two, politically, because you don't have an intermediate goal in a program that is going to stretch significantly in time beyond what Apollo was."

Returning to the Moon would build momentum in a human spaceflight program that hasn't ventured beyond low-Earth orbit since the Apollo program ended in 1972. "If we wait until Mars, the whole government spaceflight program will collapse of its own weight," says John Logsdon, emeritus professor of space policy at George Washington University. "There's a pretty convincing case for making the Moon a first goal, but not the last goal."

Ken Bowersox, deputy associate administrator for NASA's human exploration and operations mission directorate, told H2M attendees that "everything we do [on the Moon] is intended to inform our journey to Mars." A timetable for when humans could make such a trip could come as soon as 2025, he said.

An alternate route

"Mars is the ultimate destination for human exploration of the inner solar system; but it is not the best first destination," concluded the 2009 report of an advisory committee commissioned by the Obama administration. The findings of the panel, chaired by retired Lockheed Martin CEO Norman Augustine, led to the administration's decision to excise the Moon as a destination for NASA's exploration program (see PHYSICS TODAY, December 2009, page 25). The committee advised that alternate destinations—a lunar orbit, an asteroid, or a Lagrange point—were equally as useful as the surface of the Moon.

Obama chose an approach, outlined in the report, of sending a crewed spacecraft into a stable orbit near the Moon, from which a manned mission would embark to a small asteroid. The rock would be physically redirected into an orbit near the Moon. In addition to being less expensive than landing on the Moon, a lunar orbiting spacecraft, the Augustine committee noted, could be a launching point for a Mars mission that would avoid the energy and fuel required to escape the Moon's gravity. But the asteroid-redirect plan garnered little support from scientists.

Obama science adviser John Holdren says the administration concluded that "there was little point in putting astronauts on the Moon again, more than 50 years after we did it the first time, unless we were going to do significantly more when we got there—meaning in our view setting up a crewed base." At the time, NASA estimated the cost of putting a crewed base on the Moon at $60 billion to $80 billion, he says. "We saw no prospect of such a sum materializing on any time scale of planning interest."

Although the Augustine panel said no viable human spaceflight program could be carried out for less than a $3 billion addition to NASA's budget, Holdren says Obama decided that the asteroid-redirect route could at least be started for an extra $1 billion per year, the amount of additional funding Obama was willing to request from Congress.

Holdren estimates NASA will have to find an additional $5 billion each year to meet its 2024 Moon-landing target.

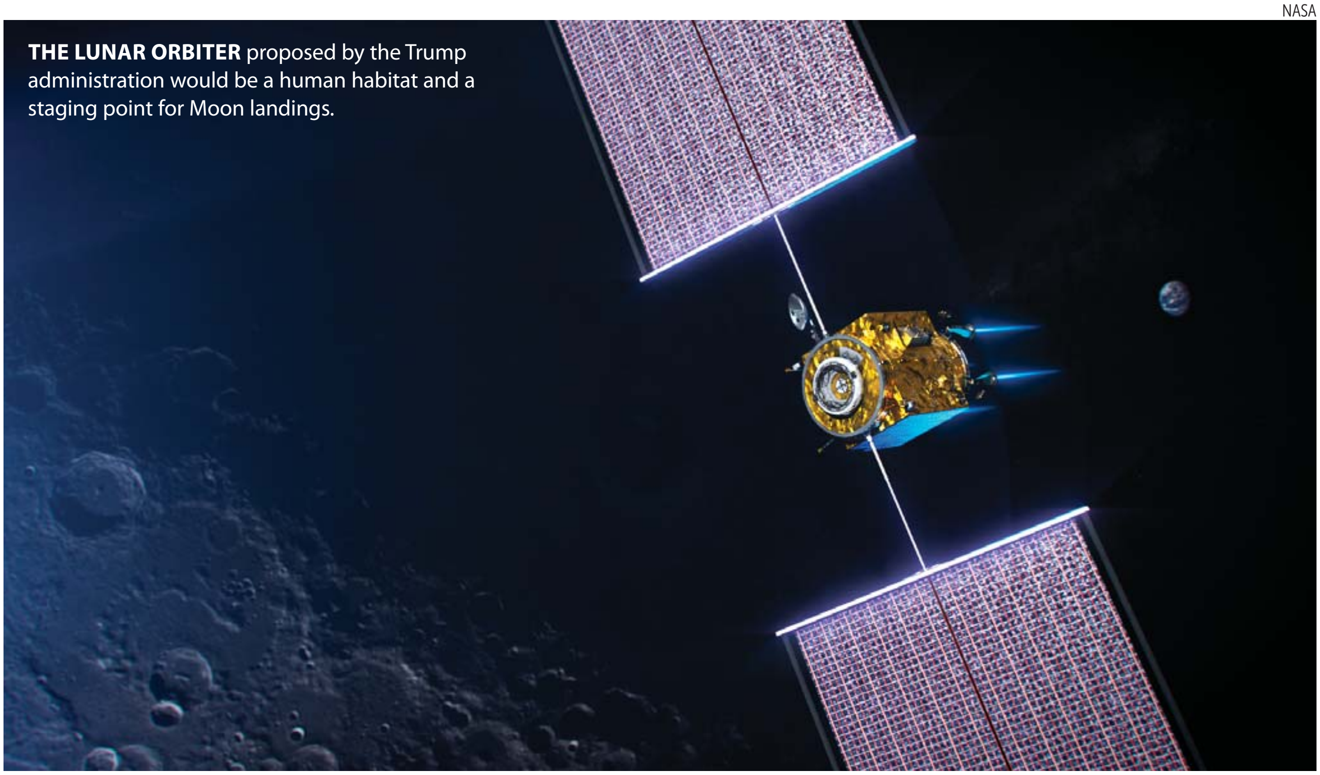
A proving ground

To NASA administrator Jim Bridenstine, who assumed NASA's helm in April 2018, the Moon is "the proving ground" and "the path to get to Mars in the safest, fastest way possible. When we accelerate humans to the Moon we are by definition accelerating humans to Mars," he told the H2M conference. In following Trump's directive, NASA plans to establish a permanently staffed outpost on the lunar surface in 2028.

William Gerstenmaier, NASA associate administrator for human exploration and operations, told the House Science, Space, and Technology Committee in May that the Moon "provides an opportunity to demonstrate new technologies that we will use on crewed Mars missions: power and propulsion systems, human habitats, in-space manufacturing, life support systems, and *in situ* resource utilization."

Clive Neal, a University of Notre Dame engineering professor and lunar exploration advocate, says going directly to Mars risks a repeat of the Apollo experience. Despite its success, Apollo was canceled due to its expense, and NASA

NASA



THE LUNAR ORBITER proposed by the Trump administration would be a human habitat and a staging point for Moon landings.

lacked any follow-on program. "You'll wind up doing a one-and-done," Neal says. "There won't be longevity or sustainability in a program." Unlike distant Mars, he adds, the Moon offers opportunities for commercial participation.

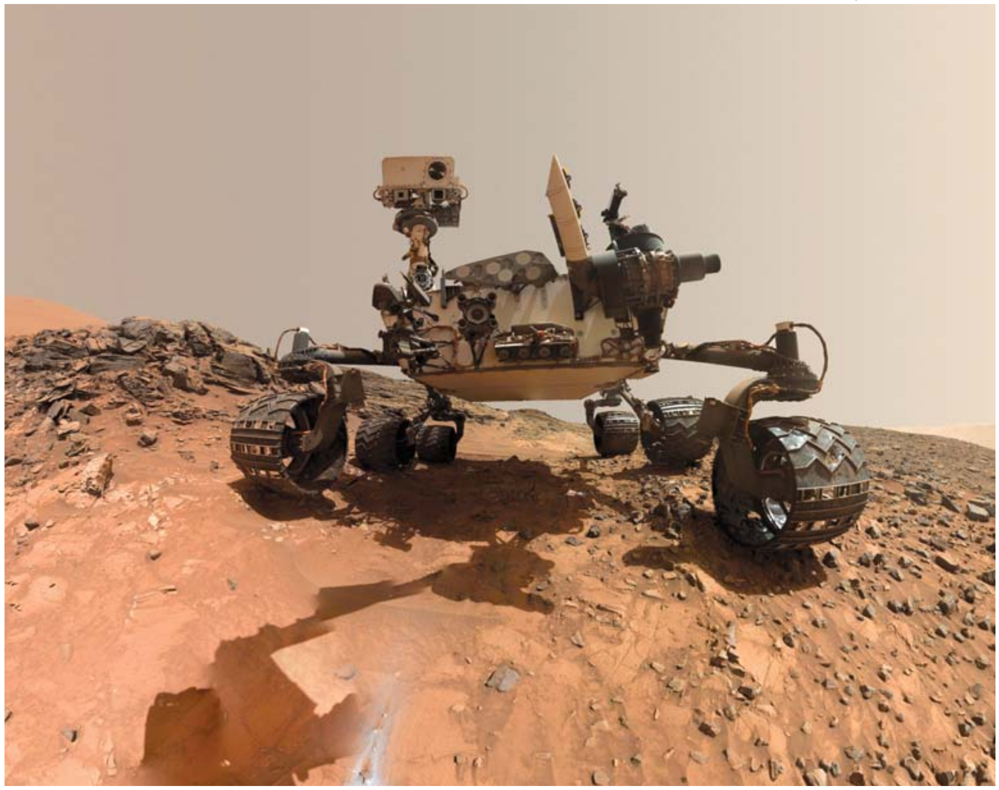
NASA in late May awarded 10-year contracts totaling $250 million to three companies to begin transporting nearly two dozen payloads of instruments and other equipment to the lunar surface in late 2020. The agency's FY 2020 budget request included $1 billion for development of lunar landers by the private sector. Billionaire Jeff Bezos recently unveiled a mockup of a lunar lander being developed by his company, Blue Origin, although he provided no design details.

The poles of the Moon could hold, in permanently shaded craters, millions of tons of water ice that could be used to produce liquid oxygen and hydrogen to fuel a Mars-bound spacecraft, Neal and other experts say. Developing that resource could obviate the need to transport fuel from Earth. Additionally, surrounding a spacecraft with a meter-thick coating of water could protect astronauts from radiation on the way to a Mars orbit, says Neal.

NASA plans to use the Moon program, which it calls Artemis, to demonstrate several major components of the proposed Mars mission architecture. They include the lunar-orbiting command and control platform, to be assembled in space, from which reusable landers would embark from and return to the Moon and where astronauts would be stationed for months at a time. The gateway, as the platform is known, could also be useful for assessing the psychosocial and physical effects of long-duration space travel beyond near-Earth orbit. NASA officials envision initial crew visits of up to 30 days to the gateway and longer visits as additional modules are delivered. NASA in May awarded a $375 million contract to Maxar Technologies of Colorado to build the first section of the gateway, the power and propulsion element. It's due for launch in 2022. At least one other section will be needed to accommodate the planned 2024 landing.

Last year, the Sixth Community Workshop for Achievability and Sustainability of Human Exploration of Mars, a group of 70 experts on lunar and Martian exploration and science operations, compiled a list of technologies required for Mars that would benefit from experience gained from lunar operations. Among the transportation and propulsion needs were cryogenic propellant management, landers, and vehicle servicing and refueling. Operations on the Martian surface that could be advanced with knowledge from the Moon included human health and biomedicine, power systems, manned exploration rovers, and space suits. Others were *in situ* resource utilization—essentially living off the land—communications, and habitats and labs. The 2014 NAS report listed entry, descent, landing, advanced in-space propulsion and power, and radiation safety among key requirements for a Martian mission.

NASA



THIS SELF-PORTRAIT OF THE MARS *CURIOSITY* ROVER at a location known as Mount Sharp shows the dusty and rocky terrain that future astronauts may encounter. For scale, the rover's wheels are 50 centimeters in diameter and about 40 centimeters wide.

The proposed 2024 Moon landing will use the SLS and the Orion crew vehicle. Both were designed with lunar travel in mind. The first crewed flight of the SLS–Orion system is planned to orbit the Moon in 2022. The Government Accountability Office (GAO) reports that as of September 2018, the cost of the SLS, which NASA had scheduled for its initial launch last November, had grown by $1 billion, or 10% over its 2014 baseline estimate, and will not meet its rescheduled June 2020 launch target. NASA officials remain hopeful of an SLS launch late next year. Orion, which was supposed to fly uncrewed atop the SLS last fall, was at least $379 million, or 6%, over budget as of mid 2018, according to the GAO. Prime contractor Lockheed Martin expects further cost growth.

Maintaining focus

The NAS report stressed that systems developed for the Moon or other intermediate destinations should keep the Mars mission in mind. Lunine and others worry that relevance to Mars may be "traded away" in a sprint to get to the Moon by 2024. "The danger is that we will end up repeating an Apollo style landing on the Moon as an accomplishment in itself, and once again that will be the end," Lunine says, mirroring Neal's concern. Once humans return, "people will say that's great, what's next? And the what's next is you would have to start from scratch, and there's no impetus to start from scratch."

Casey Dreier, chief advocate and senior space policy adviser at the Planetary Society, agrees. "You have to have very disciplined, focused, and deliberative decisions made on what to do if Mars is your long-term goal. If you say we have to land in 2024, do you really have the time or ability to focus on how that will work in a Mars environment? Probably not."

Going to the Moon "would still represent a remarkable increase in capability from what we have right now for human spaceflight," Dreier says. "I'll happily see humans walking on the Moon if that means getting out of low-Earth orbit."

Another problem with NASA's current course, says Hubbard, is the high cost of maintaining humans in space, as evidenced by the more than $3 billion NASA spends on the International Space Station (ISS) each year. The maintenance burden on NASA's budget will grow much greater if a permanent habitation is set up on the Moon, and that will leave far less money for a Mars development program, he notes.

Key differences between Moon and Mars environments won't allow for direct transfer of some elements, such as landers and manned rovers. Martian surface gravity is 38% of Earth's, compared with the Moon's 17% terrestrial fraction. Mars's atmosphere provides some protection from radiation, whereas the Moon's does not. Although dust is a hazard for humans and equipment on both bodies, dust storms occur only on Mars.

The NAS cautioned against wasting NASA resources and time on "dead-end" development programs that won't be of use on Mars. Notably, the academy listed the single-use descent stage of the lander design for the 2024 lunar surface mission.

Propulsion systems are likely to differ from one destination to the other. Whereas the SLS–Orion system is conventionally fueled, NASA is eyeing both solar-electric and nuclear propulsion for Mars travel. The NAS study recommended nuclear propulsion for Mars travel, saying the power levels of the best solar-electric systems are far too low to use in human transit. Specifically, it called for developing both nuclear-thermal, in which a fluid such as liquid hydrogen is heated to high temperature to create thrust, and nuclear-electric, in which electricity generated by a nuclear reactor is used to drive a propellant at high speed. Neither has been deployed in space.

The two technologies are separate from radioisotope thermal generators, a nuclear technology that has powered more than two dozen spacecraft since the 1960s. Those devices generate thermal energy from the radioactive decay of plutonium-238, but aren't powerful enough for propulsion. (See PHYSICS TODAY, December 2017, page 26.)

Time-frame estimates for a crewed Mars landing range from 2033 to the 2040s and beyond. The launch window to the quickest path to Mars opens only every other year. The Science and Technology Policy Institute (STPI), which supports the White House Office of Science and Technology Policy, concluded that 2037 would be the earliest feasible date and 2039 the more likely date for a launch to the red planet. It said that 2033, the date proposed in the 2017 NASA authorization act, "is infeasible under any budget scenario and technology development and testing schedules."

The NAS report committee estimated that the earliest crewed surface mission to Mars will occur between 2040 and 2050, assuming that the ISS is extended to 2028 and that the human spaceflight budget is increased at twice the rate of inflation.

The STPI put the total cost of a NASA spaceflight program leading to a Mars landing in 2037 at $217 billion, including $121 billion devoted to Mars-related hardware development. Of the total, $34 billion has been spent to date for the SLS and Orion programs. Lunine was less definitive when he told a House hearing in May that it would require hundreds of billions of dollars.

Although Bridenstine and other officials have repeatedly insisted that the cost will be shared with international partners, there have been few if any specifics. If the US wants to reduce the cost, says Lunine, "it will need the kind of international contributions that we have never seen before in human-piloted programs." For example, the US has borne 85% of the cost of the ISS and even pays for seats on Soyuz flights to the station. Moreover, he and others note, relations with China have deteriorated to the point that cooperation may not be possible. The other big challenge, Lunine adds, is how to cooperate with other nations without giving away US technologies.

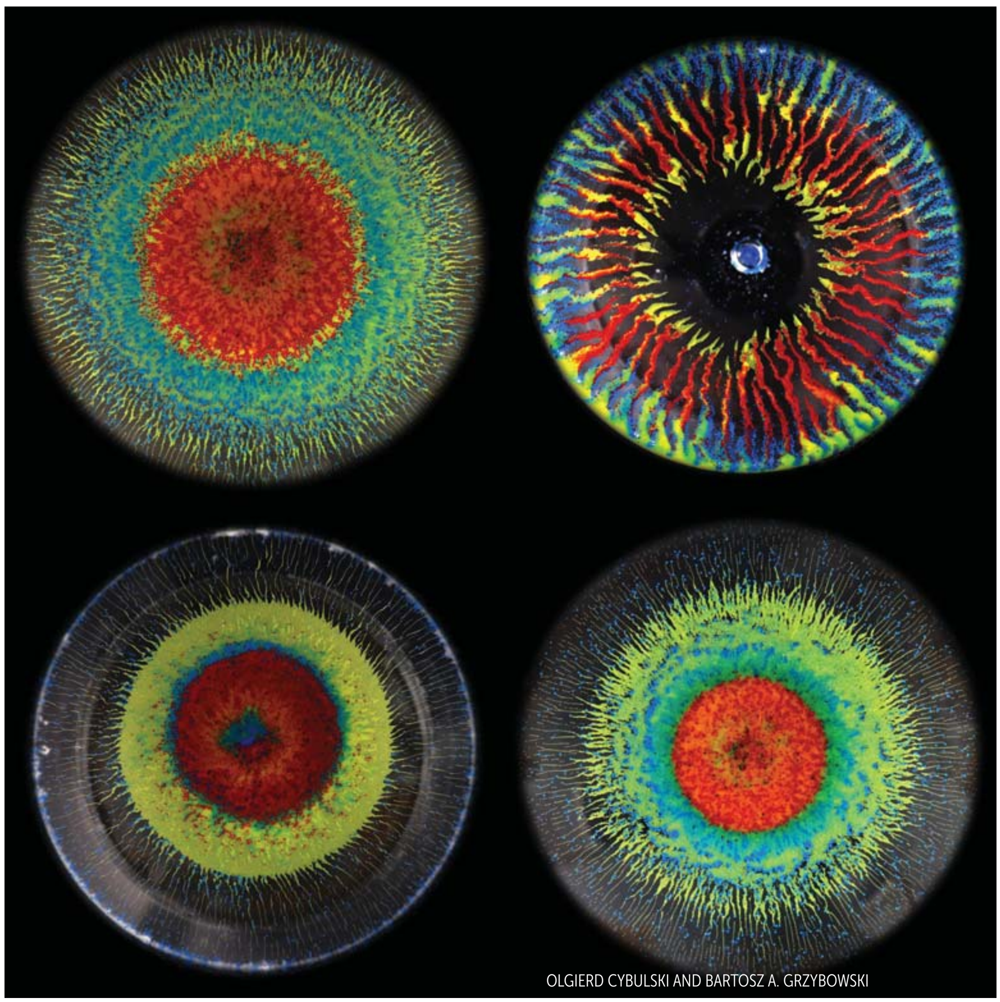
David Kramer

Domestic quarrels cloud future of South Korea's Institute for Basic Science

The country's network of curiosity-driven research centers is a scientific and cultural experiment.

Since its founding in 2011, the Institute for Basic Science (IBS) in South Korea has largely lived up to its ambitious goals. It has attracted top scientists, produced world-class science, and made inroads in internationalizing the country's research community. For continued success, however, the IBS must win over both the country's other scientists and its current politicians and convince them that the big federal investment in a relatively small number of investigators is worthwhile.

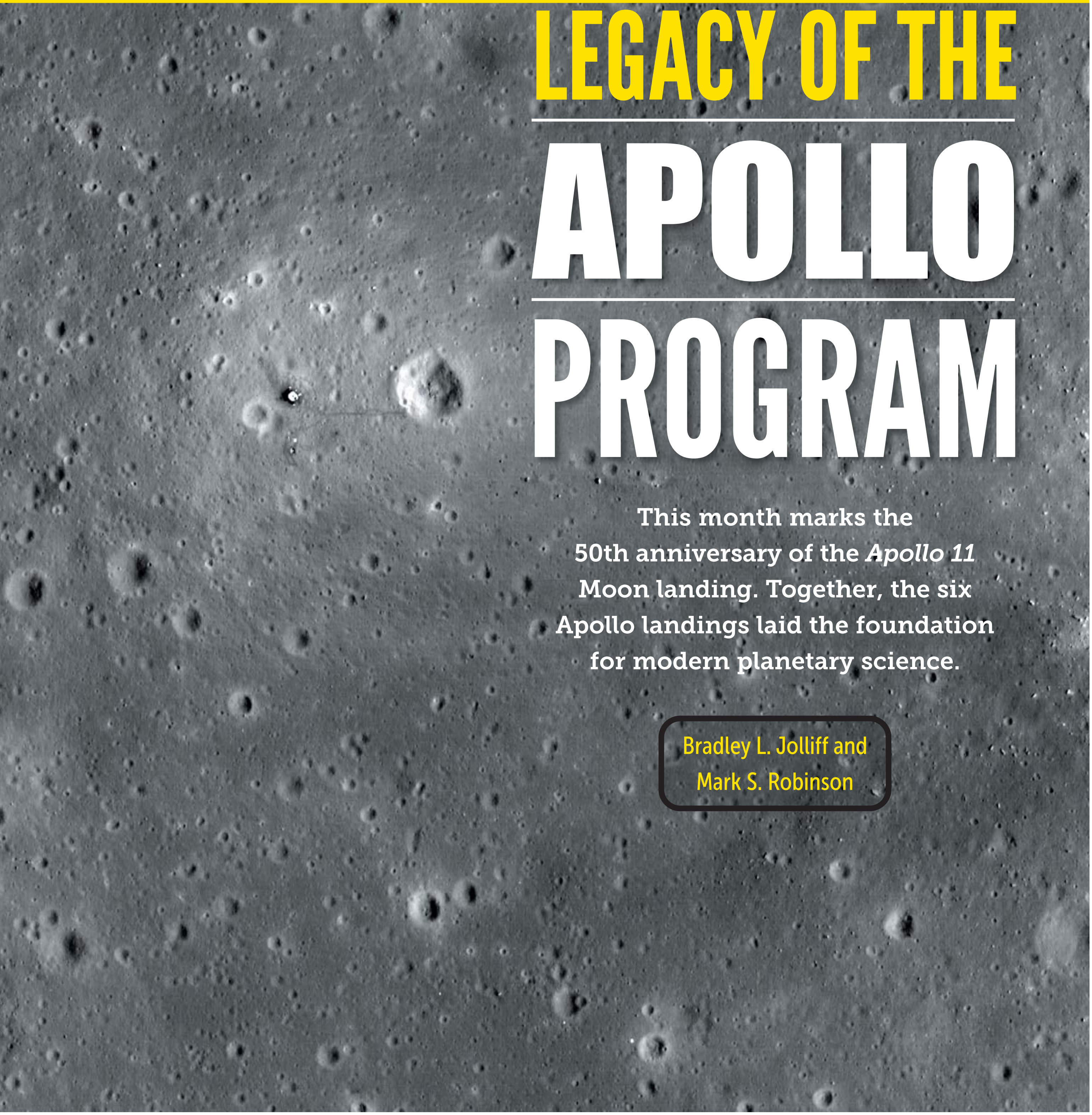
When the IBS was created, South Korea had an impressive track record in applied science and manufacturing; the auto and electronics industries are examples. In launching the new initiative, the country's then president Myung-bak Lee noted that countries at the forefront of



OLGIERD CYBULSKI AND BARTOSZ A. GRZYBOWSKI

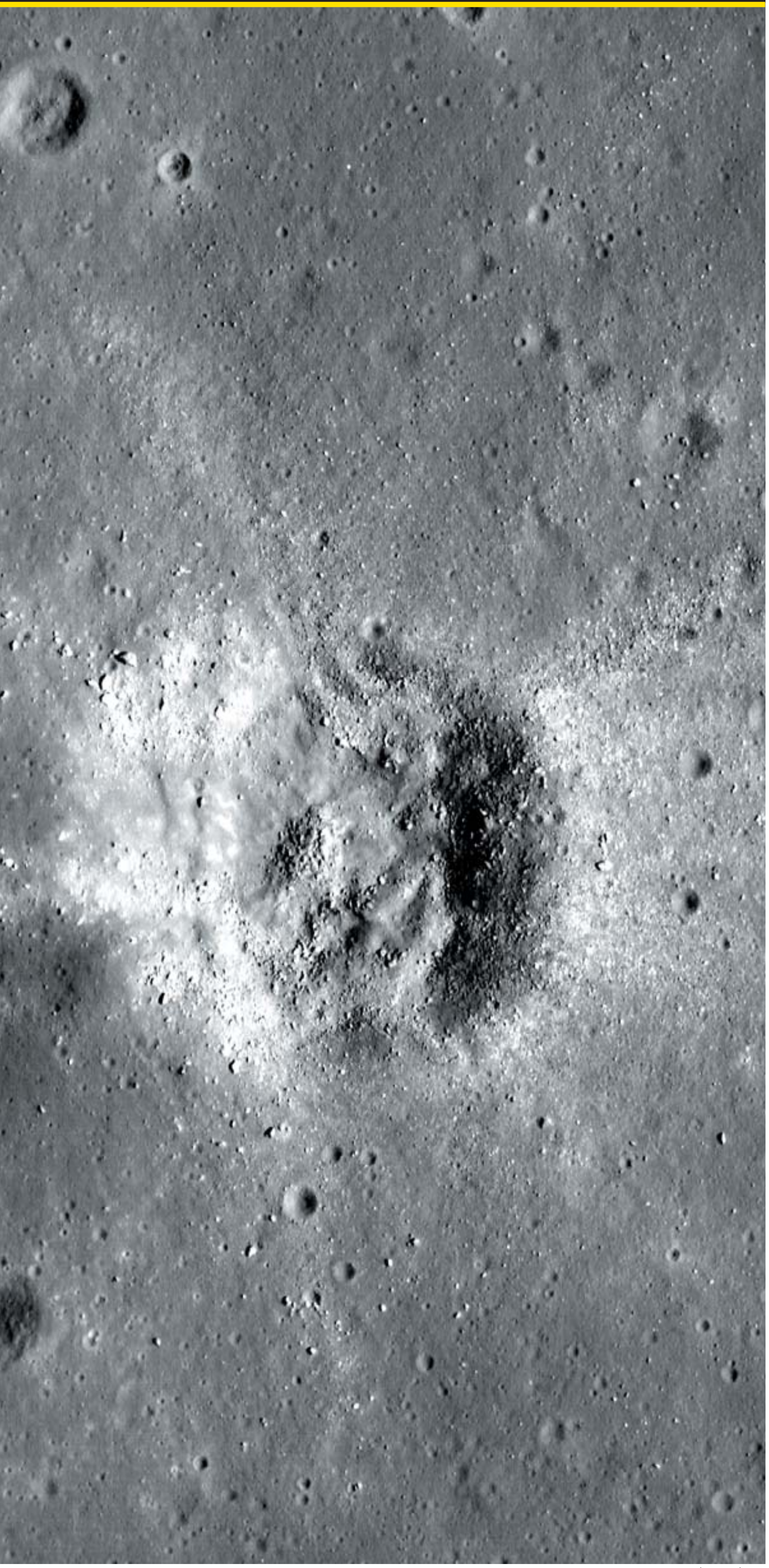
MICROPARTICLES SUSPENDED IN A ROTATING DENSE FLUID self-organize into dynamic patterns. Researchers at the Institute for Basic Science Center for Soft and Living Matter in South Korea study these nonequilibrium systems to gain insight into symmetry breaking and pattern formation in rotational frames of reference. The four images are snapshots with different rotational histories; they show the same mixture of three kinds of polyethylene microparticles that differ in density, size, and color.

THE SCIENTIFIC LEGACY OF THE APOLLO PROGRAM



This month marks the 50th anniversary of the *Apollo 11* Moon landing. Together, the six Apollo landings laid the foundation for modern planetary science.

Bradley L. Jolliff and Mark S. Robinson


NASA/GSFC/ASU

Brad Jolliff is the Scott Rudolph Professor of Earth and Planetary Sciences at Washington University in St Louis, in Missouri. **Mark Robinson** is a professor in the School of Earth and Space Exploration at Arizona State University in Tempe and the principal investigator of the NASA Lunar Reconnaissance Orbiter Camera.

On 20 July 1969, *Apollo 11* astronauts Neil Armstrong and Edwin "Buzz" Aldrin landed on the Moon while Michael Collins orbited in the command module *Columbia*. "Tranquility Base here. The *Eagle* has landed" became one of the most iconic statements of the Apollo experience and set the stage for five additional Apollo landings.

Each of the Apollo missions explored carefully selected landing sites and conducted a variety of experiments to probe the lunar interior and measure the solar wind. Well-trained astronauts made geologic observations and collected samples of rock and regolith, the impact-generated layer of debris that composes the lunar surface. Over a half century of study, the samples have revealed abundant information not only about the Moon's origin and history but also about the workings of our solar system.

Apollo 11

Results from the *Apollo 11* mission established key paradigms of lunar and planetary science. After a harrowing descent to the surface, Armstrong set the *Eagle* down on the cratered basaltic plains of *Mare Tranquillitatis*. Extravehicular activity was brief—just two and a half hours during that first mission—and included setting up surface experiments and exploring a small cluster of craters near the lunar module and Little West Crater some 60 meters away, as shown in figure 1. Aldrin's iconic *Apollo 11* bootprint photo revealed much about the lunar soil, including its fine-grained nature, its cohesiveness, and its ability to pack tightly together.

The Early Apollo Scientific Experiment Package contained, among other instruments, a passive seismometer and a laser-ranging retroreflector. Although designed to work for only three weeks, the seismometer provided a first key look at lunar seismic data. The seismometers brought to the Moon during the *Apollo 12*, *14*, *15*, and *16* missions were used as a larger network to probe the interior structure and measure thousands of moonquakes that would eventually be detected.

The retroreflector on *Apollo 11* was the first of five eventually delivered to the Moon. Active laser ranging still precisely measures the Moon's distance as it slowly recedes from Earth. Some 22 kg of samples were collected during that mission. (Collectively, the missions returned a total of 382 kg of material, and the last, *Apollo 17*, carried 111 kg.) The regolith, used as filler in the rock box, was separated from the rocks back on Earth and analyzed for its contents. The fine-grained particles, labeled 10084 and known as "Armstrong's packing soil," may be the most studied geologic sample in history.

The rocks turned out to be largely basalt—volcanic rock formed by partial melting in a planet's (or moon's) interior. They contained higher concentrations of titanium than any basalts on Earth but were otherwise made of familiar minerals, primarily the Mg-Fe-Ca silicate mineral pyroxene, the Ca-Al silicate mineral plagioclase, and the Fe-Ti oxide ilmenite.

Radiometric dating found the basalts to be more than 3.5 billion years old, and isotopic relationships between rock and regolith materials suggested that the Moon itself is ancient, having formed earlier than 4.4 billion years ago.[1] Although the volcanic rocks contain vesicles, indicative of gas release upon eruption, they lack evidence of any other alteration and are nearly devoid of water, carbon dioxide, and other volatiles. (See the Quick Study by Lindy Elkins-Tanton, PHYSICS TODAY, March 2011, page 74.) Lunar rocks are also completely barren of any signs of life.

The regolith samples proved invaluable in the rich variety of materials contained within them (see, for example, figure 2). Meteor and asteroid impacts, pervasive in lunar history, ejected bits of rock tens to hundreds of kilometers in all directions. Volcanic glasses, impact glasses, and breccias—rock fragments that became mixed during those impacts—were all part of the regolith. So were agglutinates, a new type of welded soil particle produced by micrometeorite impacts in the regolith. Mixed in with that local material were small fragments of plagioclase-rich rock (anorthosite) from the distant highlands.

In 1970 geologist John Wood and others inferred that anorthosite crystals floated toward the surface of a magma ocean, where they accumulated to form a plagioclase-rich crust.[2] Denser minerals such as pyroxene and olivine, by contrast, sank to form the lunar mantle. The Moon thus formed hot and underwent differentiation early in its history. (See PHYSICS TODAY, February 2008, page 16, and the article by Dave Stevenson, November 2014, page 32.) That early history was unraveled from only a handful of small rock fragments found in the regolith.

Building on success

Apollo 12 followed quickly in November 1969. The lunar module *Intrepid* executed a pinpoint landing within walking distance of the pre-Apollo *Surveyor 3* spacecraft. The landing site afforded the possibility of sampling not only local rocks and regolith but also materials ejected from Copernicus Crater, 350 km away. Part of *Apollo 12*'s payload included a seismometer, magnetometer, solar-wind spectrometer, and ion and dust detectors—all powered by a radioisotope thermoelectric generator. In addition to taking hardware from *Surveyor 3* for the trip back to Earth, the astronauts explored several craters and collected material excavated from different depths to establish a stratigraphy of the subsurface.

Besides several types of basalts, the astronauts sampled rocks that were likely part of a spoke-like ray of material ejected from Copernicus Crater. Among the materials were ropy glasses and nonbasaltic rocks, which offered evidence that the crater had formed 800 million years ago.[3] The inferred age of Copernicus Crater and subsequent dating of other impact craters and volcanic surfaces became the foundation for lunar chronology. The ground-truth data allow us to relate the size and frequency of impact craters per unit area to the age of the surface under study (see figure 3). And that relationship forms the basis for the relative chronologies of impact and volcanic events on the solar system's other rocky planets—Mercury, Venus, and Mars.[4]

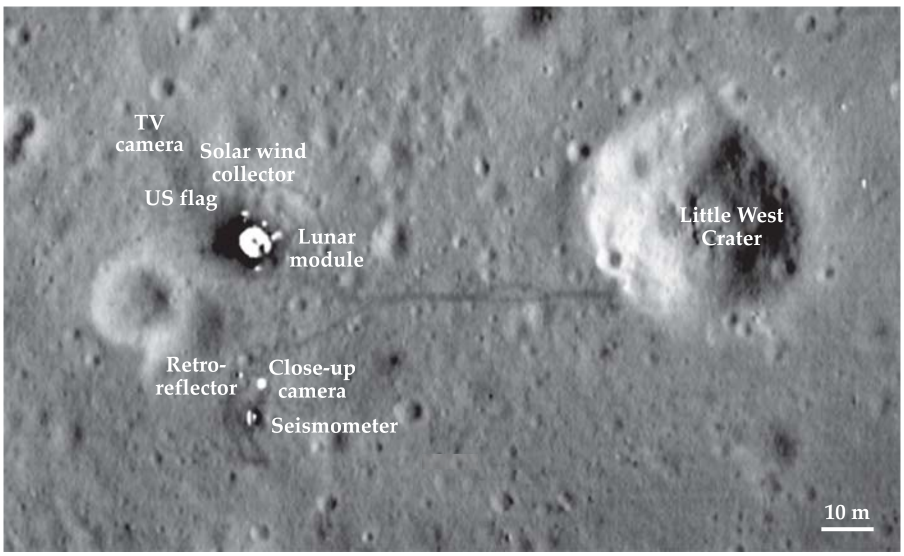


FIGURE 1. THE *APOLLO 11* LANDING SITE shows locations where a US flag, television camera, and surface experiments were placed by astronauts Neil Armstrong and Edwin "Buzz" Aldrin. As they placed instruments and walked around the landing site, the disturbed soil left a visible path. (Image courtesy of NASA/GSFC/ASU.)

The *Apollo 12* samples proved remarkably diverse. The material known as KREEP—rich in potassium, rare-earth elements, and phosphorus—was found in impact-melt rocks and rare granites. Several types of basalt, distinct from those found at the *Apollo 11* landing site, came from the underlying sequence of lava flows.

The *Apollo 14* lunar module *Antares* was the first to land on terrain that differed from flat volcanic plains. Analysis of orbital photos of the location, known as the Fra Mauro formation, indicates that the rocks there came from the enormous Imbrium basin-forming impact event, which occurred more than 600 km to the north. Fra Mauro breccias were determined to have

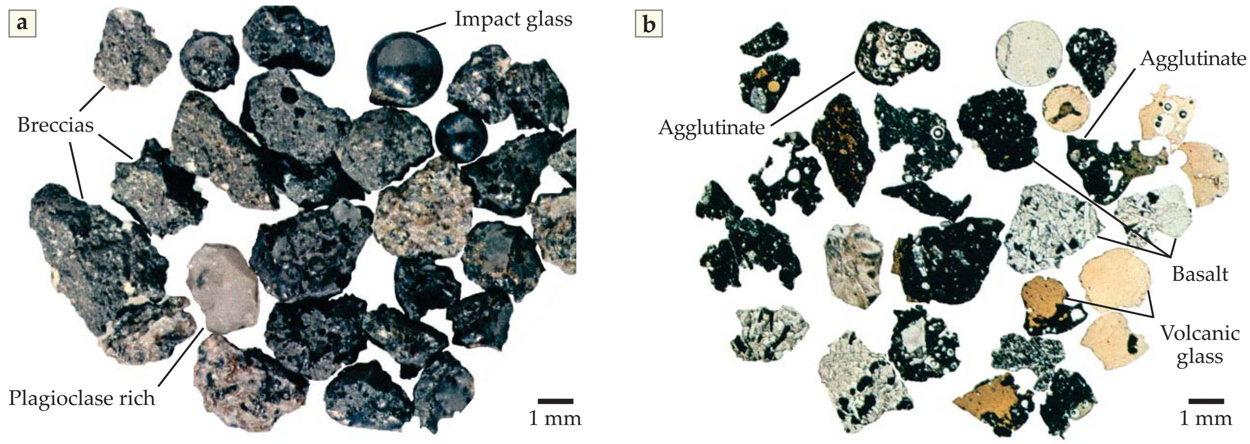


FIGURE 2. SOIL PARTICLES FOUND IN THE MOON'S SURFACE DEBRIS, or regolith, during the *Apollo 11* mission. **(a)** Shown here are rock fragments (impact breccias); volcanic and impact glasses; fused particles (agglutinates); a light-colored, plagioclase-rich fragment; and pieces of volcanic basalt. **(b)** The same rock particles are sliced optically thin for study by transmitted-light microscopy. (Images are from John Wood, Smithsonian Astrophysical Observatory.)

formed about 3.9 billion years ago. Because Imbrium is known from relative stratigraphy to be one of the youngest of the impact basins, almost all the other basins must have formed before that time. Excavated from deep in the lunar crust, the Imbrium rocks are rich in KREEP.[5] Exposure ages of samples ejected from the nearby Cone Crater revealed the crater to be 50 million years old, providing another key datum in lunar chronology.[6]

Apollo 15 and *16*

Launched in the summer of 1971, *Apollo 15* was the first of the so-called J missions, which included the first lunar rover and longer extravehicular activity—nearly 19 hours on the lunar surface—during which astronauts collected some 77 kg of samples and explored more complex geology. The lunar module *Falcon* landed on another flat mare deposit close to the spectacular Apennine mountains. Some peaks rise up to 4000 m above the landing site and are part of the rim of the Imbrium basin. A key mission goal was for the astronauts to traverse the base of Mons Hadley Delta, one of the Apennine peaks, to search for ancient crustal material brought up from the depths when the basin was formed.

One of the most remarkable finds was a clod of green pyroclastic glass beads, which represented material from deep in the mantle brought up rapidly, without crystallizing, to the surface during the eruption of a massive fire fountain. Perhaps the most famous of the samples whose collection was enabled by the rover was "Seatbelt Rock," a highly vesicular basalt shown in figure 4 and discovered by mission commander David Scott. Knowing that the astronauts were short on time and that mission control would not approve a stop to collect the rock, Scott used the excuse of stopping to fasten his seatbelt—hence the name—during which he quickly picked it up.[7]

Trained to look for coarsely crystalline rocks that might represent deep crustal material, Scott and others recognized the importance of yet another sample, "Genesis Rock," by its light color and coarse, reflective crystal facets. The rock proved to be anorthosite, considered a plagioclase flotation cumulate of the magma ocean and thus a pristine sample of lunar crust. Isotopic analyses confirmed that the rock is indeed ancient—more than 4 billion years old. But analyses also revealed a complex thermal and shock history that obscures when it actually formed. Collection and documentation of the rocks in their geologic contexts, along with precise locations and descriptions by the astronauts, enabled the construction of exquisitely detailed maps and cross sections of the landing sites.[8]

Another advance with the J missions was addition of the Scientific Instrument Module (SIM) on the *Endeavor*. It enabled systematic orbital remote sensing using panoramic and mapping cameras; x-ray and gamma-ray spectrometers, which determined elemental compositions; and a laser altimeter for topography. SIM bay observations by the *Apollo 15, 16*, and *17* missions provided an approximately equatorial swath of data for the lunar surface that researchers used to extrapolate from "Apollo-zone" areas to the entire Moon. The J-mission orbital observations had to last the scientific community until the 1990s, when the *Clementine* and *Lunar Prospector* spacecraft acquired global remote sensing.

Apollo 16 was the only mission that explored lunar highlands far from the maria. The lunar module *Orion* gently landed near mountainous terrain known as the Descartes highlands. The main scientific goal was to investigate the origin of the Cayley plains, a region adjacent to those highlands and thought, prior to the mission, to have formed from silica-rich rocks and ash deposits. The Cayley plains actually overlap the mountainous Descartes formation and are thus younger. From orbital photography, geologists interpreted the Descartes formation as ejecta from the ancient Nectaris basin, whose rim is less than 300 km away.

Apollo 16 astronauts took advantage of the sampling opportunities afforded by two impact craters, North Ray and South Ray, by landing between them. Using the rover, they sampled ejecta from both to determine their ages—yet more data points for the lunar chronology. The relatively smooth Cayley plains were shown to have formed as an impact-related deposit, most likely by material ejected from Imbrium. Among the rocks ejected from North Ray and South Ray Craters were impact-melt, fragmental, and regolith breccias. The latter, composed of lithified regolith, were significant because they provide a time-stamped snapshot of the output of the Sun via trapped solar-wind gases at the time the regolith breccias formed.

The largest Apollo sample ever returned was a 12 kg breccia nicknamed "Big Muley," after Bill Muehlberger, who led the *Apollo 16* and *17* field geology teams. The side of the rock that faced up on the lunar surface is dotted with an abundance of pits from its exposure to micrometeorites. An important legacy of the Apollo missions is the superb training that was incorporated into the program. That training allowed the astronauts to work directly with scientists at mission control to optimize the fieldwork. The approach culminated with the inclusion on *Apollo 17* of a geologist astronaut, Harrison Schmitt.

Peaks and valleys

Apollo 17 landed in the beautiful Taurus–Littrow Valley, completing the Apollo program in December 1972. The lunar module *Challenger* placed the astronauts in a geologically complex area on the edge of the Serenitatis basin. The valley itself is defined by peaks, shown in figure 5, that tower 2500 meters above the basalt-flooded floor. Mission objectives included ascertaining the age of the basin, determining the age and composition of the basalts, and collecting pieces of ancient crust excavated during the basin's formation.

Mission planners had identified a large, regional pyroclastic ash deposit in orbital images and wanted to find and sample some of that material. A cluster of secondary impact craters, aligned along a ray from the 2400-km-distant Tycho Crater, was seen in the valley along with a light mantle deposit, formed by avalanche, at the base of South Massif. Scientists hypothesized that the craters and the mantle deposit formed as ejecta from Tycho Crater struck the area. Astronauts sampled the light mantle deposit for researchers to determine Tycho's age, as had been done for Copernicus Crater during the *Apollo 12* mission.

Additionally, Schmitt discovered a deposit of orange glass beads as an exposed layer in the rim of Shorty Crater. That material was pyroclastic as well. The color was related to their high Ti content, quite different from the very low Ti of the *Apollo 15* green glasses. Like the green glass, however, the orange-glass soil became one of the most important of the Apollo samples, oft sought for study because it represents one of the most pristine samples of the lunar interior, unmodified by crystallization processes.

Basalts of the Taurus–Littrow Valley formed 3.7–3.8 billion years ago. Impact-melt breccias were sampled from boulders at the base of North and South Massifs, their ages just a few tens of millions of years older than the breccias from Imbrium. Because of the considerably more advanced degradation of Serenitatis basin, it was apparent that many impact basins had formed in that time interval, amounting to a cataclysmic bombardment as also suggested by lead-isotopic analyses.[9] Samples collected on the light mantle deposit and elsewhere in the valley had exposure ages of around 110 million years, and that age was assigned to the Tycho impact event.[10] Ancient crustal rocks greater than 4.0 billion years old were also found among the *Apollo 17* samples. They continue to provide the grist for tests of hypotheses about the origin of the Moon's ancient crust.

Unlike its predecessors, *Apollo 17* carried an active seismic experiment designed to determine the subsurface structure by picking up signals generated by explosive charges. Other experiments probed surface electrical properties, determined the effects of exposure of biological materials to cosmic rays, and used a traverse gravimeter to help map out subsurface structure. The orbiting command service module *America* carried a microwave sounder, an IR radiometer, a far-UV spectrometer, mapping and panoramic cameras, and a laser altimeter. The orbital data sets provided by those instruments would be the last

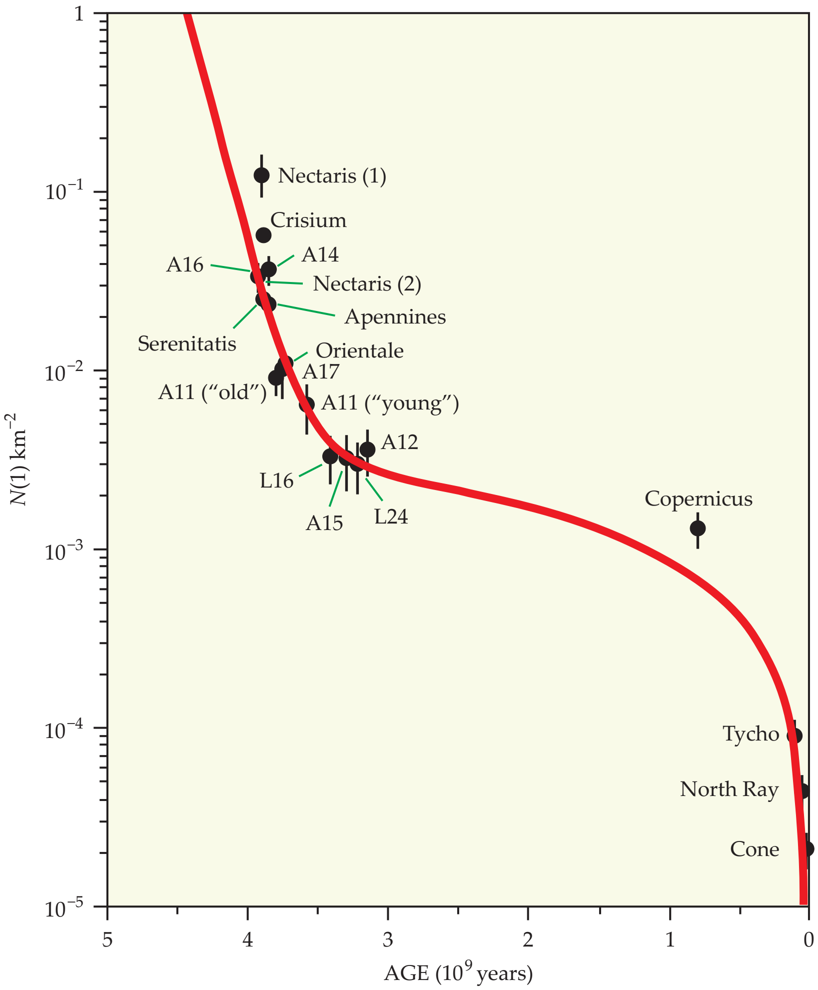


FIGURE 3. LUNAR CHRONOLOGY is based on the ages of lunar samples that represent surfaces on which impact crater size–frequency distributions have been determined. *N*(1) refers to the number of craters that are 1 km in diameter or larger, and the plot relates that number to the crater accumulation time. Numbered labels "A" and "L" refer to Apollo and Luna missions, respectively. Measurements of crater size and frequency distributions come from orbital photographs. (The method and plot are adapted from ref. 4; the age data are taken from ref. 5.)

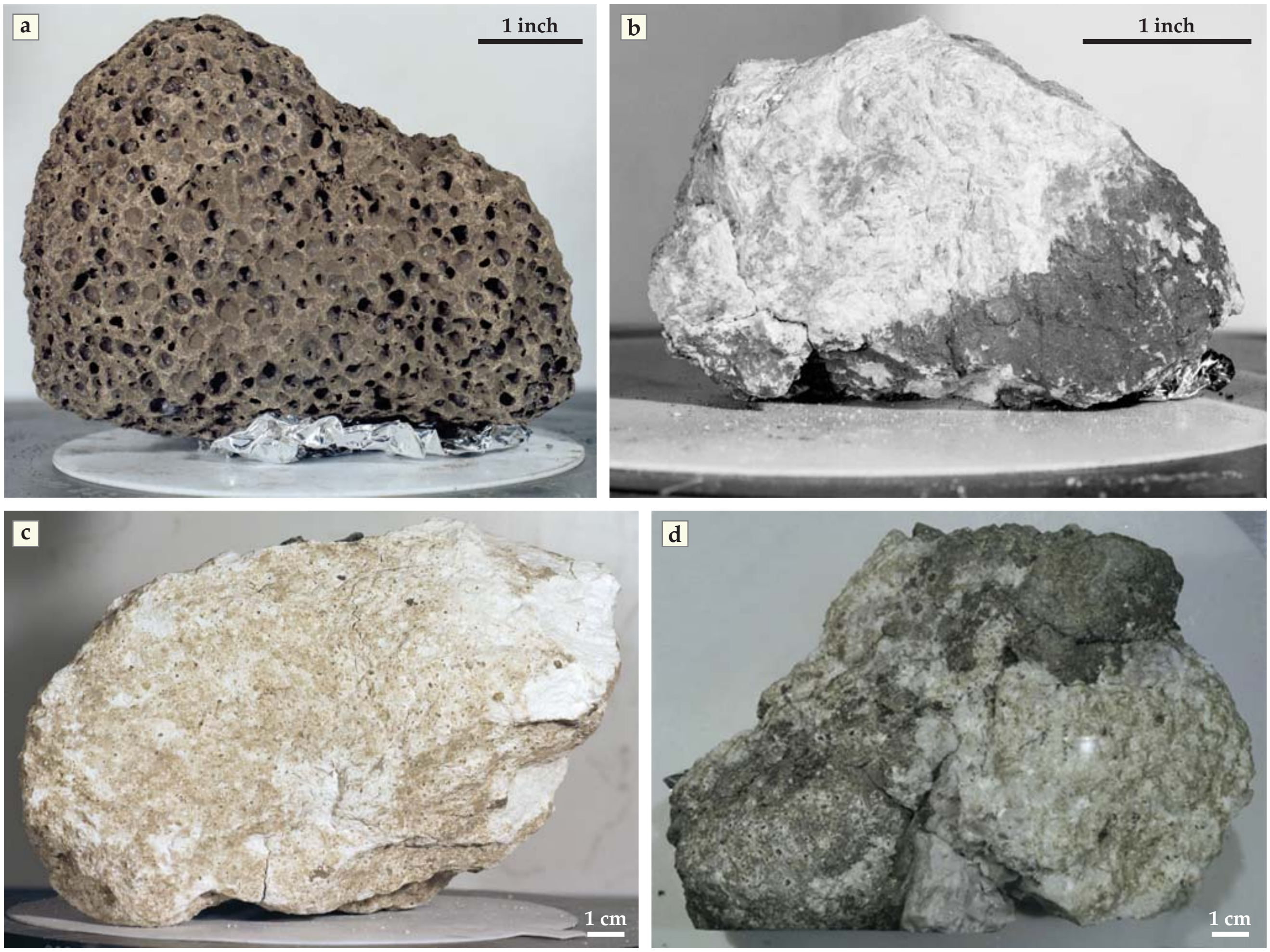


FIGURE 4. ROCKS COLLECTED during *Apollo 15* and *Apollo 16*. **(a)** "Seatbelt Rock" 15016 is a vesicular (porous) basalt. (Adapted from NASA photo S71-46632.) **(b)** "Genesis Rock" 15415 is made of ferroan anorthosite, a major rock type of the lunar crust. (Adapted from NASA photo S71-44990.) **(c)** A 1.8 kg sample of anorthosite, 60025. (Adapted from NASA photo S72-42586.) **(d)** This top surface of an 11.7 kg breccia, 61016, known as "Big Muley," contains numerous tiny impact craters, or zap pits. (Adapted from NASA photo S98-01215.)

direct measurements scientists would have from lunar orbit for more than two decades.

Surface geophysics

The seismic array deployed by *Apollo 12*, *14*, *15*, and *16* continued to transmit data to Earth until September 1977, when the array and other instruments were turned off. More than 12 000 seismic events were detected altogether. Some 7000 of them came from deep moonquakes, which were correlated with tidal forces exerted by Earth's gravity. Others were attributable to meteoroid impacts, the deliberate crashes of booster rockets, and shallow thermal moonquakes caused by the heating and expansion of the crust.

Seismic data provided information about the thickness of the lunar crust, changes in the seismic velocity as waves crossed the crust–mantle boundary, deeper seismic discontinuities in the mantle, and a deep zone of seismic attenuation. Early work estimated the average crustal thickness at 60 km, but modern analyses place it between 30 and 40 km.[11,12]

Ranging to the lunar retroreflectors from Earth continues today. The Moon's irregular rotational motions indicate a partially fluid core. The 2011 Gravity Recovery and Interior Laboratory (GRAIL) mission confirmed a partially molten deep-mantle zone and constrained the size of the fluid outer and solid inner core.[13] (See PHYSICS TODAY, January 2014, page 14.) Coupled with the available Apollo seismic data, the new gravity measurements significantly improve our understanding of the Moon's internal structure.

Samples and curation

The Apollo samples are broadly similar to Earth materials in mineralogy and chemical composition. But their chemistry is distinctly lunar. Moon rocks formed under extremely low oxygen fugacity such that most of the iron they contain is divalent (Fe^{+2}) and most samples contain at least a small amount of iron metal (Fe^0). The Fe-Ti oxides are mostly ilmenite ($FeTiO_3$), but also contain ulvöspinel (Fe_2TiO_4), armalcolite ($(Fe,Mg)Ti_2O_5$) (first found in lunar rocks and named after *Arm*strong, *Al*drin, and *Col*lins), and tranquillityite ($Fe_8(Zr,Y)_2Ti_3Si_3O_{24}$), a new mineral named for the Sea of Tranquillity, where it was found.

The basalts provide insights into the lunar mantle and early differentiation processes. Variations in basalt types reflect a heterogeneous mantle, which lacks a homogenizing process such as Earthlike convection. Owing to ground-truth samples from Apollo, we can infer basalt types from other areas using remote sensing. Volcanic glasses occur in regolith samples from all Apollo sites, with a wide variety of compositions, spanning TiO_2 concentrations from less than 1 weight percent to more

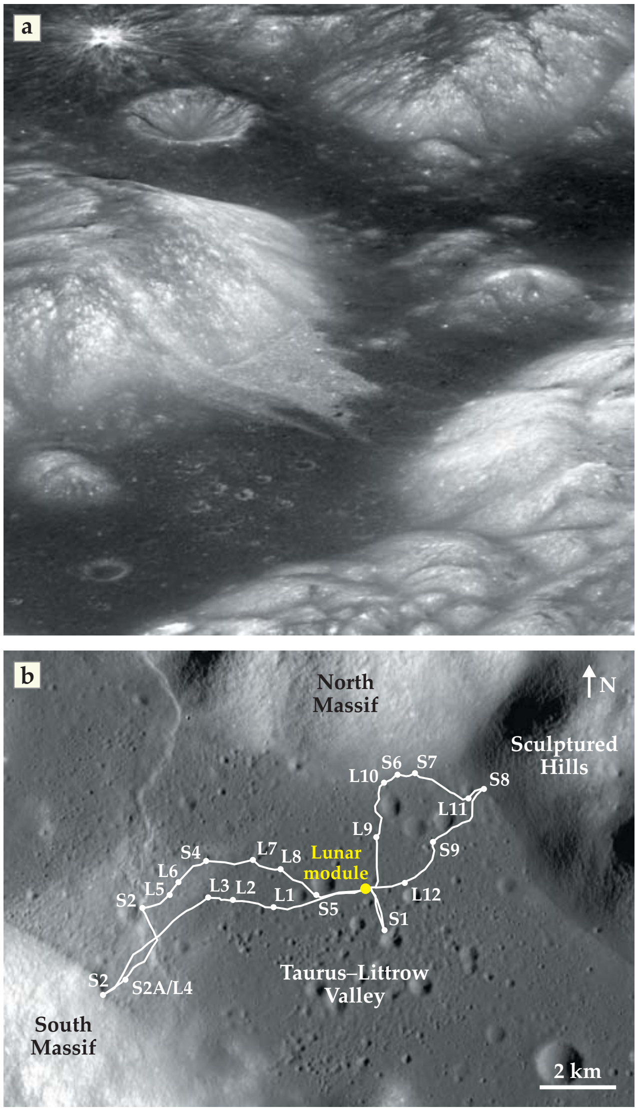


FIGURE 5. TAURUS–LITTROW VALLEY, the landing site for *Apollo 17*. **(a)** In this oblique, 18-km-wide scene looking generally to the west, *Mare Serenitatis* is at the upper right. North is to the right. (Image courtesy of NASA/GSFC/ASU.) **(b)** This view of the valley (the lower left part of panel a) shows the astronaut traverses. Numbered labels "S" and "L" refer to sampling stations and lunar-roving-vehicle stops, respectively. (Image courtesy of NASA/GSFC/ASU.)

than 16 weight percent. Those compositions reflect the heterogeneity of the mantle and late-stage magma-ocean processes that led to areas within the mantle of widely different Ti contents.

During the Apollo program, scientists had the foresight to recognize the value of the samples and established the Curatorial Facility at Johnson Space Center. They set protocols for curation, handling, and allocation in a way that would preserve portions of all samples for future generations, with special care given to the rarest and most important of them.

The protocols ensured that nearly 40 years after they were collected, samples would be available for analysis of indigenous OH and H_2O in volcanic glasses, phosphate minerals, and melt inclusions using new and highly sensitive analytical methods. Those studies revealed that the Moon did not form as depleted of volatiles as was once thought.[14–16] (See also PHYSICS TODAY, January 2016, page 17.) Rather, the Moon heavily degassed the volatiles during the magma-ocean and later volcanic stages. The precise measurement of remanent magnetism in lunar samples revealed that the Moon had an early core dynamo until sometime between 3 billion and 4 billion years ago (reference 17; see also the article by David Dunlop, PHYSICS TODAY, June 2012, page 31).

Gateway to the solar system

The Apollo era exploration and decades of study of lunar samples laid a foundation of knowledge about Earth's nearest neighbor and provided a cornerstone for planetary science. Apollo showed the Moon to be ancient, some 4.5 billion years old and made of materials similar to those on Earth, but consistent with the Moon's smaller size, lower pressure, lack of atmosphere, and lack of any obvious aqueous alteration. Its minerals and rocks bore evidence of an early magma ocean and differentiation into a mantle and crust. Heating and remelting of the interior produced voluminous basaltic volcanism 3-4 billion years ago. From study of Apollo samples and data came the concept of the Moon's formation via a giant impact on early Earth, which still stands as the leading hypothesis for the origin of the Moon. Apollo surface samples gave us our first look at alteration by exposure to galactic cosmic rays, energetic solar particles, and meteorites, ranging from microscopic to asteroidal.

Perhaps the most far-reaching scientific legacy of Apollo is the ongoing exploration of our solar system. The Apollo samples provided the first evidence of the so-called late, heavy bombardment of asteroids, thought to have spiked around 3.9-4.0 billion years ago. Models of the early solar system's orbital dynamics suggest that shifts in the orbits of Jupiter and Saturn may have destabilized early asteroid and cometary belts and led to that cataclysm some 500 million years after the solar system formed.[18]

The Apollo samples and explorations showed that the key to testing those dynamical models is on the Moon, awaiting the next round of surface exploration and sample collection.

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