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QUANTUM'S PROMISE

Inside the revolution

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The moon still beckons

The Obama White House shifted NASA away from returning astronauts to the moon, but a new presidential administration may see matters different y next year. Tom Jones explains the lunar allure and why it makes sense to go back.

Stanley Kubrick's 1968 film, "2001: A Space Odyssey," opens its space sequences with a journey to the moon, where the U.S. operates an expansive base beneath the floor of the crater Clavius in the southern hemisphere. Astronauts skim over the stark lunar terrain in a rocket-driven bus, heading to an excavation where geologists have unearthed an ancient, mysterious sentinel.

The vision of this groundbreaking sci-fi film outpaced reality. After Apollo, the U.S. dropped plans for more extensive human exploration, and today the first party of colonists has yet to arrive on the moon. Although no human voyage is on anyone's current launch schedule, space agencies around the globe are planning a new wave of robotic exploration of our nearest celestial neighbor, driven by its proximity, scientific potential and the promise of useful natural resources. If only some of these missions find what they're looking for, the results may spur humans to follow.

A "supermoon" photographed from Earth in 2014.

The dynamic moon

Scientific exploration of the moon took a pause after Apollo and the Soviet Union's Luna robotic missions four decades ago. Those efforts barely scratched the surface of the moon's scientific potential, but a flurry of robotic missions in the last decade reminds us that the moon tells a complex, 4.5-billion-year story that's still being written.

An exhibit at the National Air and Space Museum, "A New Moon Rises," in Washington, D.C., showcases some of the most recent and revealing photos taken by the Lunar Reconnaissance Orbiter Camera, LROC, which continues to circle the moon. Images on the museum's website show a variety of perspectives and suggest a surprising level of geological activity in the recent past. These are the scenes that will greet human explorers when we finally return.

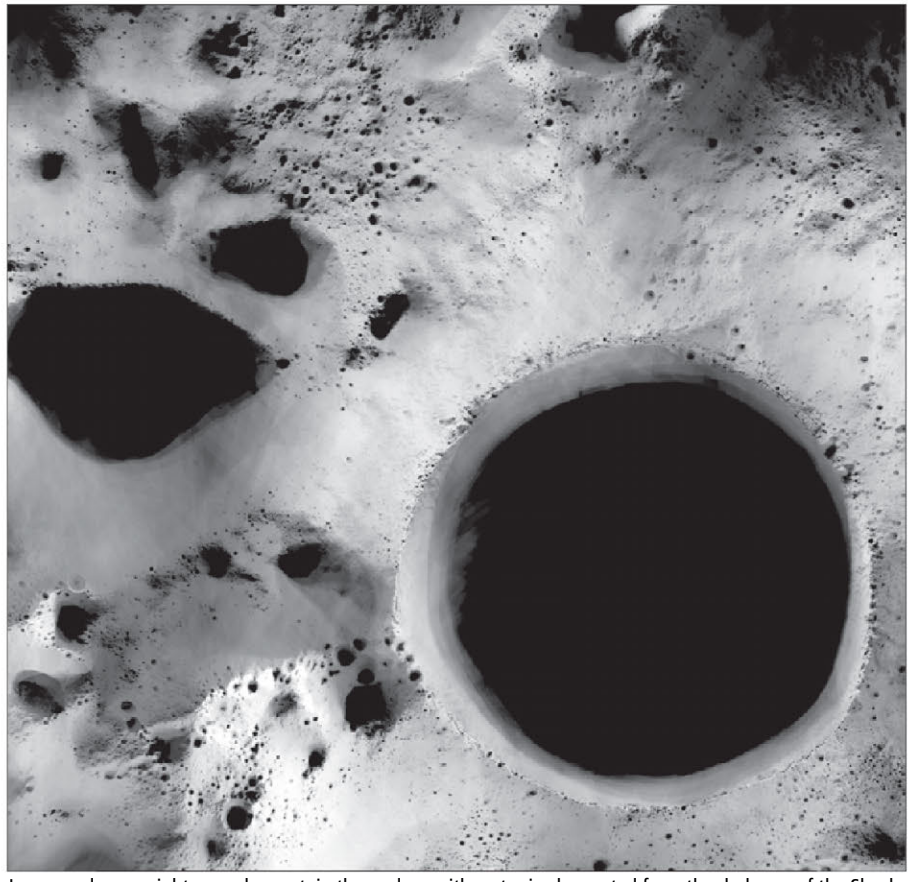
The images demonstrate that the moon is still changing. Slowly cooling over billions of years, the lunar interior has steadily contracted, buckling the overlying crust into scallop-edged faults, called lobate scarps. Some of these scarps are relatively free of impact craters, so they must have formed fairly recently. New examples may still be forming today.

The lunar seas, or maria, created by giant asteroid impacts, quickly filled with vast ponds of fluid basalt lava, with a thin rock crust overlying the still-scalding reservoir of liquid rock. As this basalt cooled and contracted, surface faults called "wrinkle ridges" formed. Along these ridges, the LROC has images of boulders shaken loose by moonquakes triggered by the recent buckling of these lava plains.

The moon's surface was long thought to be static, changing only when pummeled by asteroids and comets. But lava flows lacking the usual carpet of impact craters point

to volcanic activity within the last 10 million to 100 million years in the moon's history. The LROC team has discovered more than 60 such examples. Some recent flows have erupted onto crater floors; these "puddled" lavas suggest that radioactive heat within the moon may still be producing subsurface pockets of liquid rock. The existence of these radioactive element concentrations may revise geochemists' estimates of the moon's internal composition. Some of the most intriguing volcanic features are "skylights," pits formed when the crust on top of underground channels of flowing lava collapsed after the eruption ended, emptying the cave beneath. Peering into these cavities reveals collapsed rubble and layers of basalt lava flows; these lava caves could serve as natural radiation shelters for future astronaut habitats.

The most surprising lunar discovery in the last 20 years is that it is not a bone-dry, ancient relic, but a geologically changing world with accessible water in its polar regions. Scientists have also detected trace amounts of hydroxyl, molecules consisting of an oxygen and hydrogen atom, possibly formed by solar wind action. But polar water ice deposits will be of most value to explorers.



NASA/Goddard Space Flight Center/Arizona State University

Lunar explorers might someday sustain themselves with water ice harvested from the darkness of the Shackleton crater and other impact sites on the moon. This image was created from thousands of photos taken by NASA's Lunar Reconnaissance Orbiter Camera. Black represents areas that never receive sunlight.

Moon moisture

When the Pentagon's Clementine probe bounced S-band radio signals off the lunar surface in 1994, the data suggested the presence of water ice on the shady side of craters near its south pole. Lunar probes since then have repeatedly suggested the same. Because the sun's rays slant obliquely across the poles, some deep crater floors are entirely hidden from the sun. Lunar Prospector in 1998 found evidence for about 1 to 3 cubic kilometers of water ice, but this neutron-spectrometer data couldn't rule out hydroxyl as the hydrogen source.

After India's Chandrayaan-1 orbiter reflected radar signals off the surface in 2009, scientists concluded that the north polar region indeed harbors some 600 billion kilograms of water ice (over half a cubic kilometer of water), likely in the form of small, pebble-sized chunks mixed with the lunar soil, called regolith.

NASA's Lunar Crater Observation and Sensing Satellite, LCROSS, was intentionally crashed into the south polar region of the moon in 2009, creating a debris plume that LRO examined for traces of water. The data showed that regolith in the crater Cabeus contains about 6 percent water ice by mass.

When NASA's Lunar Reconnaissance Orbiter examined the sunshadowed Shackleton crater near the south pole with its laser altimeter, it found evidence that at least 20 percent of the crater floor is covered in ice. LRO's Mini-RF radar frequency experiment also indicated that polar ice is probably mixed as small particles in the lunar regolith.

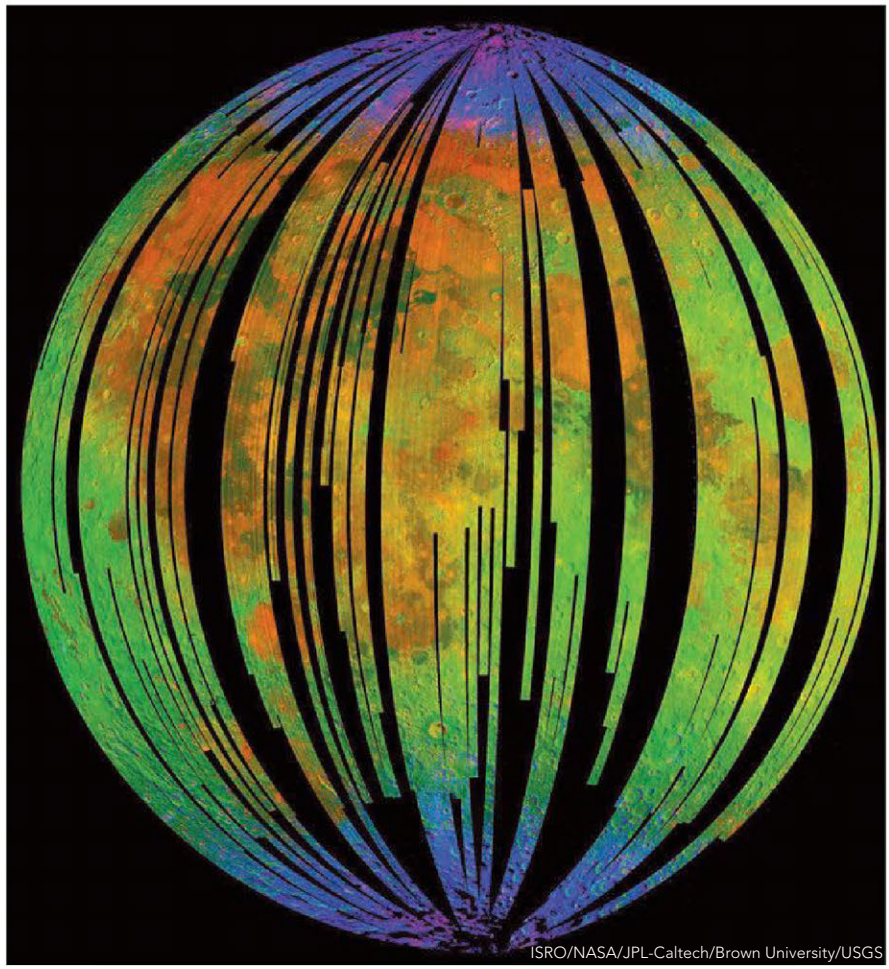
Although we know lunar water ice is there, we don't yet know its spatial extent, overall concentration and whether it exists in the regolith as small chunks, crystals or massive slabs. The only way to determine all that would be to send robots to the surface near the polar regions.

A robotic return

Chemical rockets can get a craft to the moon in just three days or so, and traffic around the moon is starting to increase. In the last decade,

China, Europe, Japan and the U.S. each have sent spacecraft to scrutinize it from orbit. In 2013, China also landed the Chang'e 3 probe, which deployed a short-lived rover, the first surface visit to the moon since 1976.

The surface is also the target of the next generation of lunar probes. India is readying a 2018 lander mission, and China is preparing its Chang'e 5 sample return mission for a launch sometime next year. The European and Russian space agencies are proposing a Luna-Resurs craft that would be launched in about 2025 to place a drilling and analysis package at a polar crater. The craft would drill 1 to 2 meters into the icy regolith to determine the water content.



Water was mapped on the moon in 2009 by NASA's Moon Mineralogy Mapper, an instrument on the Indian Space Research Organization's Chandrayaan-1 spacecraft. The blue indicates the presence of water ice in the polar-region regolith, as lunar soil is known.

The next U.S. craft to bid for the moon will be the NASA Resource Prospector, which is currently in the formulation phase. It will land in a shadowed crater and extend a drill that will retrieve a soil sample from a depth of about a meter to look for water ice. An onboard laboratory will then heat the sample and analyze any water and volatile compounds released. Funded by NASA's Human Exploration and Operations Mission Directorate, the $250 million mission could fly in the early 2020s.

The moon's value to the U.S.

Since the cancellation of NASA's Constellation lunar-return program in 2010, the agency has rarely mentioned "astronauts" and "moon" in the same sentence. Although current NASA policy is to let other nations lead a human return to the moon, critics hope that congressional direction and a new administration will put American explorers back on track for the lunar surface.

One such advocate is planetary scientist Paul Spudis, who argues in his latest book, "The Value of the Moon," that its proximity to Earth, its abundant solar energy and emerging natural resources make the moon simply too important for the U.S. and NASA to overlook for long.

"The big, new revolutionary discovery of the last 20 years is that the moon is not just interesting from a scientific point of view, but that it has utilitarian value," Spudis says. "We can use what it has to offer to create new opportunities in spaceflight."

Spudis was principal investigator for the radar instrument on Chandrayaan-1 and deputy leader of the Clementine science team. In addition to being reachable by today's rockets, the moon's proximity means that Earth-bound engineers can control robots on the moon's surface in near-real time, directing them to explore, build infrastructure, and erect outposts in advance of a human expedition.

The moon is also blessed with abundant energy, essential for any long-term human presence. Elevated crater rims near the poles are bathed in near-constant sunlight, as seen in precise maps drawn from Lunar Reconnaissance Orbiter data. Photovoltaic systems, erected telerobotically on this illuminated high ground, could supply reliable energy for excavation and processing of water ice. This sunny situation means that initial human outposts near the lunar poles need not require massive battery systems or a nuclear reactor that would be expensive to design, test and qualify.

Most importantly, the moon's resources are known to be plentiful enough for practical use in future exploration.

"We've learned there's a water cycle on the moon, with significant deposits of water, in different forms and locations. We don't know how old, how massive, or how concentrated this water is, but there are tantalizing hints that the stuff is present

in massive quantities—at least hundreds of millions of tons, to well over a billion," Spudis says. "We need to get down on the surface and make in situ measurements. We need ground truth, in multiple places, preferably, to resolve the ambiguities."

Spudis thinks the Resource Prospector mission is an essential first step toward those answers.

The moon can't wait

Spudis argues in his book that it is important to America's future economic and national security. The U.S. can't afford to neglect such useful resources in nearby space, ones eyed by China and Russia as well. Rocket propellants produced from that water could enable affordable exploration missions, not only on the moon, but out to nearby asteroids and Mars.

"The next step for human spaceflight is a permanent lunar return, because the Moon has so much to offer us in building capability."

China has discussed oblique plans for a piloted lunar landing sometime in the late 2020s. When could U.S. astronauts return to the moon? That answer lies cloaked in the bone-cracking cold of its permanently shadowed polar craters. The more accessible the ice, the greater the rewards of an accelerated return. But Spudis believes that a U.S. return, this time with international partners, could proceed quickly and affordably, contributing invaluable experience and resources toward our efforts to reach Mars.

"That's the advantage of the moon. Because it's so close, you can do these human-controlled robots on a fairly inexpensive basis. You can't do that on Mars or the asteroids because of the distances, but you can do it on the moon."

To me, a lunar return seems an affordable, practical way to gain experience and access to resources, even as we plan for journeys to nearby asteroids and the Mars system, using much of the same hardware. The Obama administration's decision to forgo the moon was based on politics, not a candid evaluation of the moon's potential. The moon is simply too close and too valuable today to ignore. If the robots find "the right stuff" there, astronauts should follow in their footsteps well before 2030.

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