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SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

JANUARY 2021

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Looking for Ice IN THE DARK

Several tiny spacecraft are launching to tell us more about the water ice that lurks in shadowed craters on the Moon.

Flashlights help us find our way through pitch-black forests or a house that's just lost power. But researchers want to use a flashlight in another way: to find and characterize water ice in one of the darkest, coldest places in the solar system — the Moon.

Astronomers already know that patches of ice exist on the lunar surface at both the north and south poles. Hidden from direct sunlight and thus extremely cold, these regions are where ice delivered by comet impacts and other processes can gradually accumulate and survive on geologic time scales. The distribution of water ice in these *cold traps* varies between the poles, from place to place, and even within a single deposit.

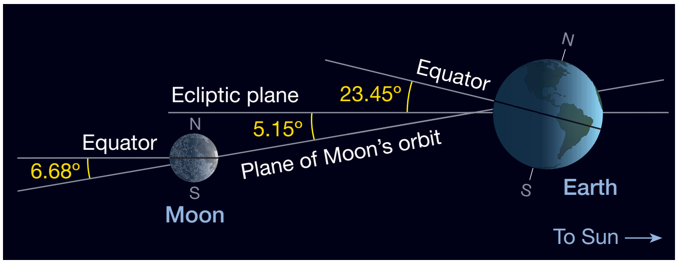
But scientists know little about this ice. To explore these frozen regions, Barbara Cohen (NASA Goddard) leads the Lunar Flashlight mission, a CubeSat about the size of a box of detergent that will fly to the Moon in late 2021. The probe will scan dark craters near the lunar south pole to better understand deposits of water ice there. It's one of several to be carried aboard Artemis 1, the first (and uncrewed) trip of NASA's new astronauts-to-the-Moon program. Other upcoming probes will also investigate lunar ice, helping to pave the way for the first NASA-built Moon rover and, perhaps, the eventual development of a cislunar economy.

Ground Truth

Water on the Moon is not a new idea. In pretelescopic times, people speculated that the lava plains called *maria* (Latin for seas) actually were seas. In the early 20th century, William H. Pickering even penned wildly speculative articles about vegetation and insect migrations in the crater Eratosthenes and wrote of "The Snow Peaks of Theophilus."

In 1952, geochemist Harold Urey noted that because the Moon's spin axis is tilted a mere 1½° from the axis of its orbit around the Sun, *permanently shadowed regions* (PSRs) should exist at the lunar poles, in which frozen water molecules and other volatile compounds might be present. In

▼ **SUNLESS SECRETS** Located almost exactly at the Moon's south pole, the crater Shackleton has a rim 21 km (13 miles) across that's bathed in near-constant sunlight — and a floor that never sees even a glint of it. A new generation of spacecraft will soon probe such permanently shadowed regions for the abundant water ice that scientists think lies hidden from view.



▲ **LOCKED IN PLACE** The near-vertical orientation of the Moon's spin axis to the ecliptic plane creates pockets of permanent sunlight and nighttime on the floors of craters near the lunar poles.

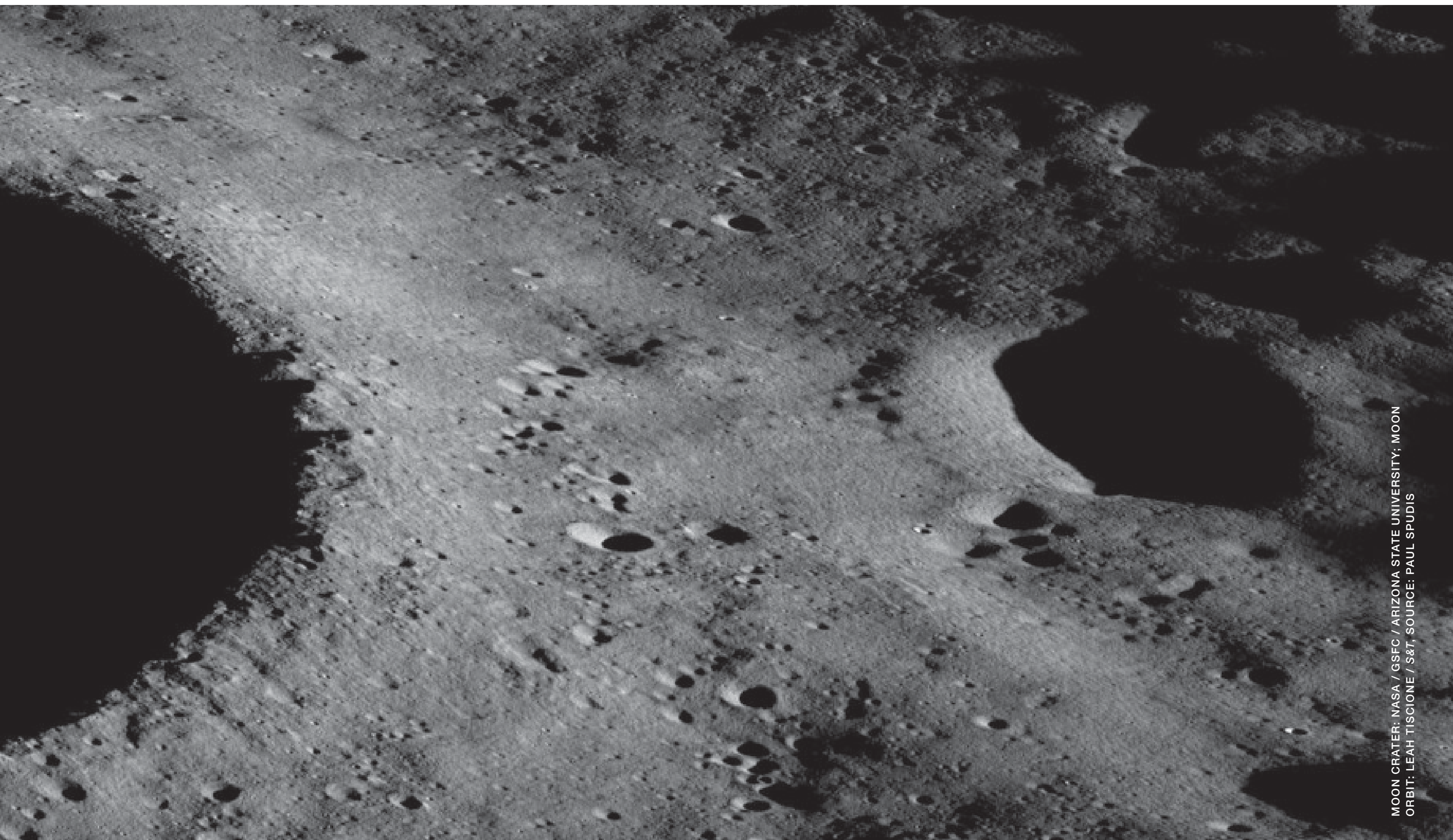
1961, Caltech scientists Kenneth Watson, Bruce Murray, and Harrison Brown extended that idea, suggesting that "water is actually far more stable on the lunar surface [than other volatiles] because of its extremely low vapor pressure at low temperatures and that it may well be present in appreciable quantities in shaded areas in the form of ice."

Space missions eventually proved they were right. In 1994, the Clementine orbiter confirmed that PSRs do exist on the Moon, pinging some with radio waves. The signals came back strong enough to indicate that among the polar rocks were likely deposits of water ice, which reflects radio energy more strongly than rock does. Four years later, an orbiter called Lunar Prospector found more evidence, indirectly detecting hydrogen atoms (presumably in water molecules) on and just below the surface. In a strange denouement, however, when the team deliberately crashed the craft into a PSR, they detected no water in the ejecta.

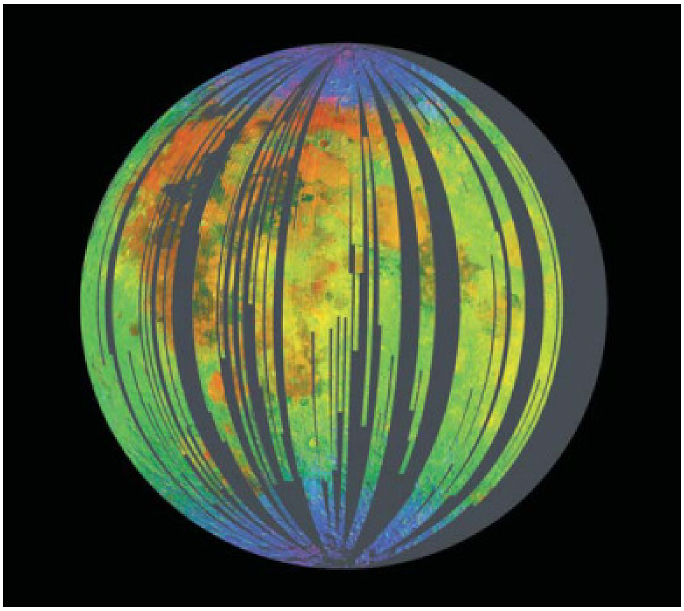
More than a decade would pass before the next leaps in lunar-ice research. During flybys of the Moon in 1999 and 2008, respectively, NASA's Cassini and Deep Impact spacecraft found tantalizing evidence for water on the lunar surface as they sped by.

By November 2008, India's Chandrayaan 1 satellite had arrived in lunar orbit, observing the terrain below with a suite of 10 experiments. Two of those, including the NASA-funded Moon Mineralogy Mapper (M^3), detected the spectrum of water-bearing compounds on the surface, and an instrumented probe released by the orbiter persistently detected whiffs of water vapor before it slammed into the Moon.

Then, on October 9, 2009, a NASA team deliberately crashed a Centaur rocket body into Cabeus, a large crater situated close to the Moon's south pole. The Lunar Crater Observation and Sensing Satellite (LCROSS) trailed the empty rocket stage in order to observe the ensuing plume of debris, which rose some 16 kilometers (10 miles). LCROSS kept recording data until it too slammed into the crater's



MOON CRATER: NASA / GSFC / ARIZONA STATE UNIVERSITY; MOON ORBIT: LEAH TISCIONE / S&T, SOURCE: PAUL SPUDIS



◀ **ICY FROSTING** This composite map, made at three infrared wavelengths by a NASA spectrometer aboard India's Chandrayaan 1 spacecraft, uses blue to denote small amounts of water and hydroxyl (OH) on the surface of the Moon. Their abundance clearly increases nearer the north and south poles.

floor. During the Centaur's impact, NASA's Lunar Reconnaissance Orbiter recorded a momentary flash and kept an eye on the temporary cloud of material. Its findings electrified the planetary-science community: Water ice and other volatiles were clearly detected.

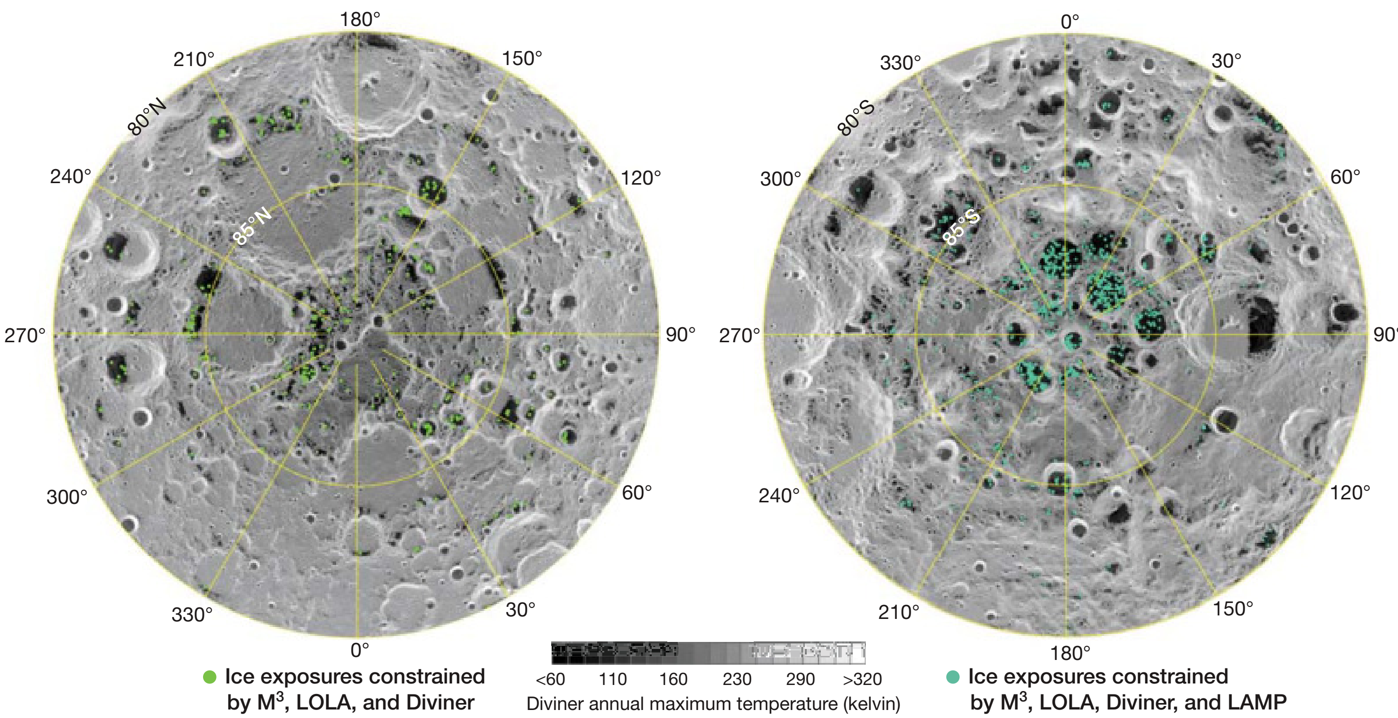
Nearly 10 years later, Shuai Li (University of Hawai'i) and colleagues combed more carefully through M^3's data and found spectroscopic evidence of light reflecting off water ice in many PSR locations surrounding the lunar poles. While less than 4% of the total sunless surface exhibits the spectral features of water ice, here and there up to 30% ice (by mass) might be mixed with the dusty regolith.

"Nobody believed there would be useful information in data collected from PSRs," Li explains. After all, how can you get reflectance spectra from a place without light? But Li decided to look after Apollo 15 astronaut Dave Scott told him that the Moon's rough topography can scatter light into shadows. Studying data with such weak signals was arduous, but the researchers found what they were looking for.

Meanwhile, other scientists using new laboratory techniques found trapped water inside Apollo samples from the Moon (*S&T:* Aug. 2018, p. 26). The Apollo-era paradigm of a bone-dry Moon was dead.

The Moon's Water Cycle

Water molecules have accumulated in shadowed regions over eons through direct deposit by other bodies, such as comets,



▲ **TREASURE MAPS** Colored dots show where water ice exists in the floors of permanently shadowed craters within 10° of the Moon's north *(left)* and south poles. These dots represent positive detections using a combination of instruments on the Lunar Reconnaissance Orbiter and Chandrayaan 1 spacecraft. Curiously, the coldest crater floors don't always have ice deposits — one notable example is the large crater Amundsen, on the 90° longitude line at the south pole. A closer look at the south pole is on the facing page.

and from volcanic gas that still leaks from the lunar interior. Water ice bonds tightly to bits of lunar dust and rock a few centimeters below the surface. Micrometeorite impacts release the water into the Moon's barely-there exosphere; sunlight's warmth and the solar wind can also send the molecules hopping about the lunar surface or launch them into the exosphere. Some molecules migrate randomly to PSRs, where the water apparently remains stable. The craters are very cold, about −240°C (−400°F).

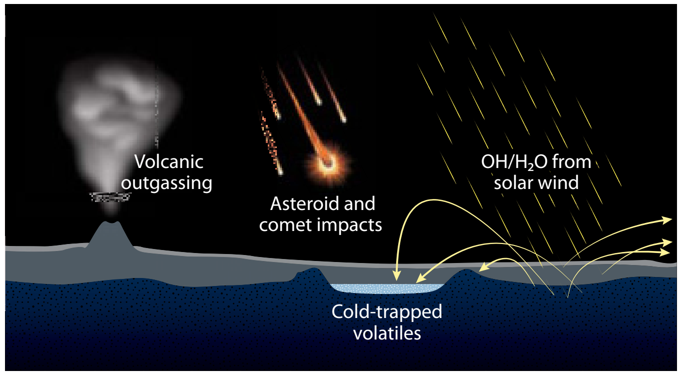
Ariel Deutsch (then at Brown University) and colleagues extended the analysis of Li's team by estimating the ages of craters near the lunar south pole. Most of the permanently shadowed real estate lies within 20 large craters at least 3.1 billion years old that contain patchy deposits of surface-exposed ice. But, puzzlingly, some ancient craters that should have ice deposits do not, possibly having baked during a reorientation of the Moon's spin axis and a resultant wandering of the lunar poles long ago.

Another mystery is why only about a quarter of 100 younger craters, all less than 15 km wide, show detectable exposures of water ice on their hidden floors. This ice is perhaps less ancient, having been delivered relatively recently by micrometeorites (instead of larger impactors in the distant past) and by the solar wind stirring up water molecules elsewhere on the surface. Or perhaps the water originated in some of the large ancient craters nearby. Some researchers suggest that the ice in both older and younger craters should be roughly the same age, because much older ice would have been destroyed over time by impacts and other causes. No one knows for sure.

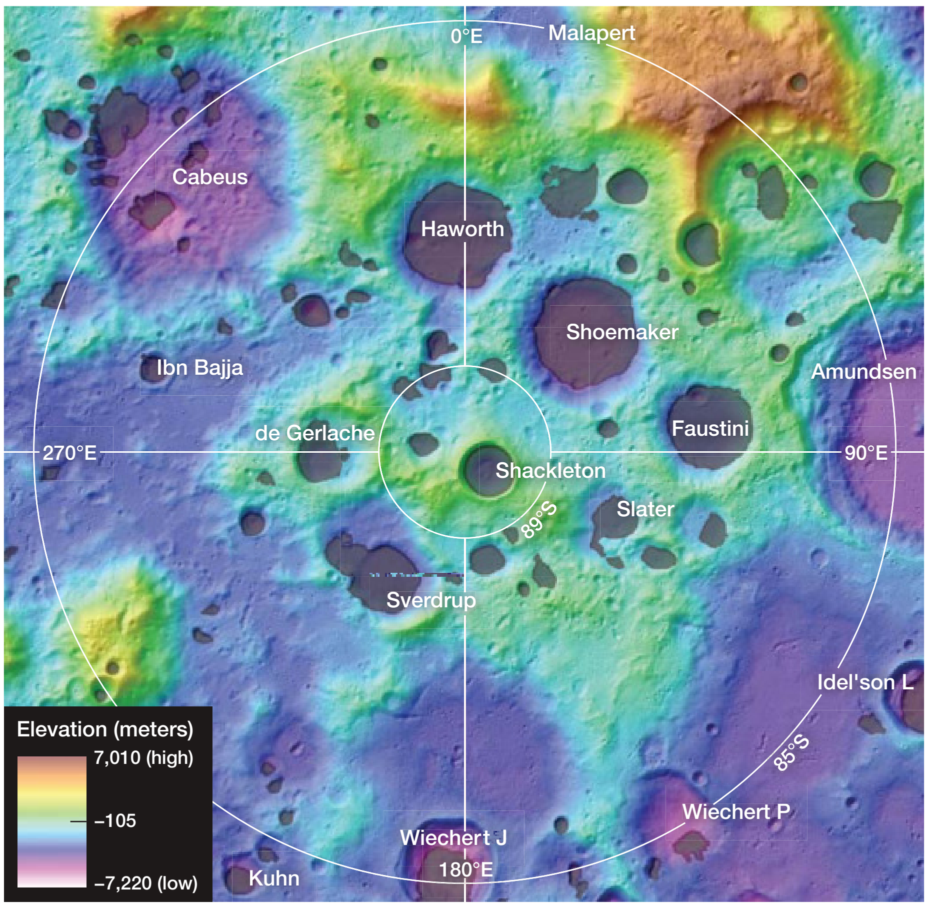
There's a lot we don't know. Says Deutsch: "What are the origins of the ice? What processes are responsible for the delivery, modification, and destruction of ice, and what are the relative strengths of these processes? What is the physical form of the ice (thickness, abundance, texture, etc.)? How does ice vary with depth [and] on lateral length scales?"

There may even be more icy craters than scientists have suspected. Lior Rubanenko (Stanford) and colleagues evaluated the depth and slope of thousands of lunar craters and found that the ones near the south pole are up to 50 meters shallower than equivalent sites closer to the equator. The likely culprit? Water ice filling the bottoms. Strangely, the shallowing trend does not hold with north-polar-region craters.

All told, Rubanenko and colleagues suggest that there might be up to 100 billion metric tons of lunar water ice — roughly the volume of Lake Tahoe, and much higher than others have estimated.



▲ **CRYO-CACHING** Water can reach the Moon's surface via the impact of water-rich asteroids or comets, the escape of gas from its deep interior, or the interaction of energetic solar-wind particles with lunar rocks. Over time, much of this water vapor migrates to permanently shadowed areas near the lunar poles, where it freezes on contact with the frigid surface and forms deposits.



▶ **WHERE THE DARK IS** A shaded-relief topographic map of the terrain within 5° of the Moon's south pole reveals how many craters have deep floors that are hidden from direct sunlight (gray shading). Note that some floors (such as in Cabeus at upper left) are only partly in permanent shadow.

LUNAR COLD-TRAP PROCESSES: GREGG DINDERMAN / S&T, SOURCE: KEVIN CANNON; SOUTH POLE MAP: JULIE STOPAR & HEATHER MEYER / LUNAR & PLANETARY INSTITUTE

The Next Wave of Exploration

Researchers might not have to guess much longer, as a trio of pint-size spacecraft are being readied to hitchhike to the Moon as secondary payloads on NASA's Artemis 1 mission. One of them is Lunar Flashlight, which the Jet Propulsion Laboratory touts as "the first CubeSat to reach the Moon, the first planetary CubeSat mission to use green propulsion, and the first mission to use lasers to look for water ice."

Barbara Cohen explains that scientists largely agree that lots of water ice lies just *under* the surfaces of PSRs. But Lunar Flashlight is looking for something slightly different: surface water ice. "There are multiple lines of observation that are consistent with water ice frost at the surface," she says. "But each observation could also be explained by other properties. Lunar Flashlight will be the final verification that it is or isn't water ice frost — if it is abundant enough for us to observe."

Using four near-infrared lasers, Lunar Flashlight will record the reflectivities and crude spectra of both ice-free rock and ice itself. Three craters have caught Cohen's eye: Haworth, Shoemaker, and Faustini. Though they are similar in size and lie next to one another at the south pole, the amount and distribution of water ice in each is different. This is puzzling.

Related investigations await two other CubeSats set to fly on Artemis 1. Morehead State University's Lunar IceCube will use an infrared spectrometer to look for water in all its forms across a swath of the Moon, trying to understand, among other things, how water and other volatiles move. Arizona State University, meanwhile, will fly LunaH-Map very low over the Moon, to do more precise neutron spectroscopy.

"The three missions represent the first ad hoc constellation of SmallSats fielded to study the Moon," says Benjamin Malphrus, who leads the Morehead State team. Each craft uses a propulsion system and trajectory specific to its mission, which is why Lunar Flashlight will be the first of the CubeSat trio to reach the Moon.

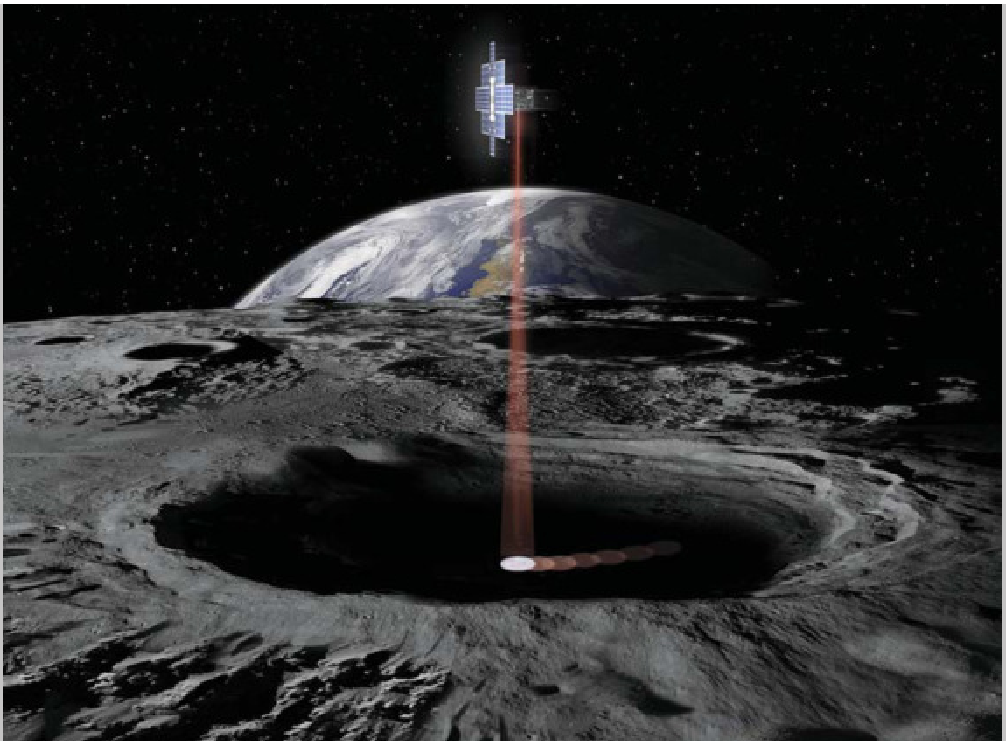
Working with a CubeSat requires "a whole collection of tweezers," jokes LunaH-Map's lead mechanical engineer, Joe DuBois (Arizona State University). "It's like working on a cell phone or something." The CubeSat is about a quarter the size of the "small" satellite DuBois cut his teeth on in the 1990s, and its computer is not even twice the size of a Rubik's cube. This means the assembly area is small, too — just a few tables and computers behind glass so visitors can see the work proceed. Only about three or four people are physically working on LunaH-Map, DuBois says.

Although these satellites are small, they can be intimidating, admits Craig Hardgrove (Arizona State University). "There is no playbook to look towards for guidance." But the potential of these missions to pioneer new approaches to solar system exploration is exciting. "I think maybe we, along with all the other planetary CubeSat developers, are writing [the playbook] now."

Shining Some Light on the Problem

Then there's the mission named for a creature that doesn't like the cold but, on the Moon, will seek it out.

NASA's Volatiles Investigating Polar Exploration Rover (VIPER) is slated to launch in late 2023 and be delivered to the lunar south pole by the Griffin lunar lander. Engineered



NASA / JPL

▶ **CUBESATS** *Left:* NASA's Lunar Flashlight will use lasers at four near-infrared wavelengths to illuminate permanently shadowed regions near the lunar south pole and record the reflected pulses for evidence of water ice lying atop the surface. *Center:* IceCube's infrared spectrometer will measure the distribution of water and other volatiles across the entire lunar globe (not just shadowed areas) as a function of time of day, latitude, and the age and composition of the Moon's rock-and-dust regolith. *Right:* The LunaH-Map spacecraft will record neutrons coming from the lunar surface that have interacted with hydrogen atoms (presumably in water molecules).

for a 100-day mission, the fully robotic rover will be NASA's longest-running mobile lunar mission yet and will hunt for ice on or below the surface in selected southerly PSRs.

The solar-powered VIPER will be big: golf-cart size and weighing 430 kilograms (950 pounds). On board will be three spectrometers and a 1-meter-long drill to sample regolith and ice. With headlights and a camera, VIPER will provide dramatic, close-up views of *luna incognita* — the never-before-seen interior of areas that have not witnessed sunlight in eons. The lighting conditions and extreme temperature variations between sunlit and dark areas, swinging between −243°C and 27°C (−405°F and 80°F), present significant engineering challenges.

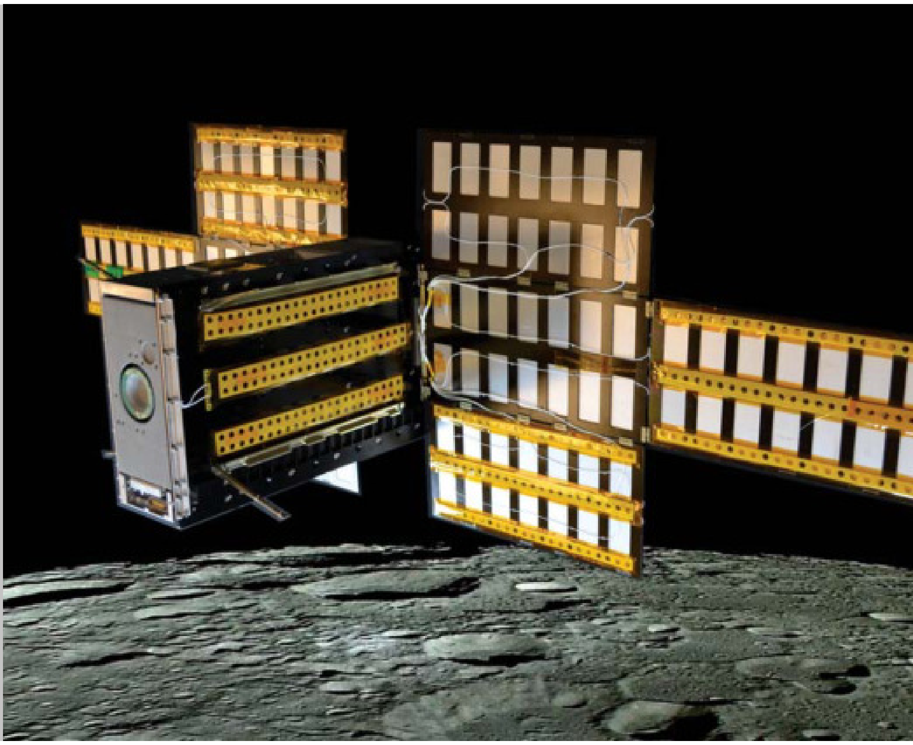
So, too, the ground itself. It's unclear just how loose or compacted the terrain will be, so VIPER, as mission planners write, "can drive sideways or diagonally, spin in a circle and move in any direction without changing the way it's facing." If it gets stuck, the rover will even be able to move each wheel independently to free itself.

The rover will be told where to go, then get there on its own. With the need to recharge batteries and avoid extended dark, cold spells, VIPER will drive to higher terrain when it needs sunlight.

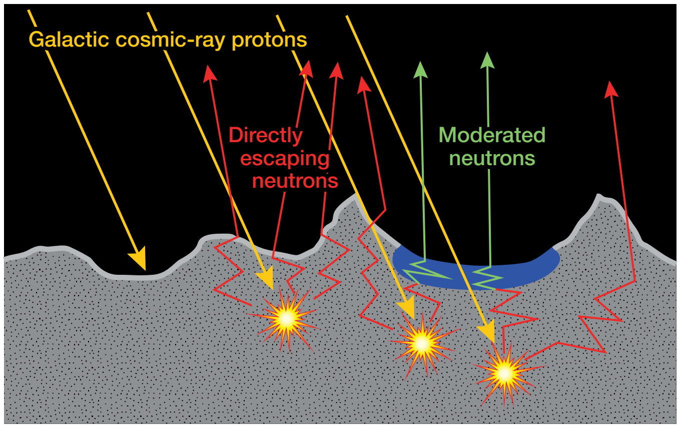
The trio of spectrometers are "absolutely killer instruments," says Richard Elphic (NASA Ames Research Center), team leader for VIPER's Neutron Spectrometer System. The NSS acts like a bloodhound, he explains. Like a bloodhound, the instrument will keep its nose close to the ground, in this case a meter or two above the regolith. Because the hydrogen in water has a strong effect on neutron flux, the rover will sniff out changes in hydrogen abundance and help clarify how ice's distribution changes with topography, temperature, lighting, and other factors.

VIPER project manager Daniel Andrews (also NASA Ames) says that prior missions "answered the big dumb binary question" about whether there was water ice or not on the Moon. But "we didn't make great quantifiable measurements. We need a better understanding of the volatiles at the polar regions." If scientists can get such measurements at the south pole, then they will be able to extrapolate at least somewhat to the north pole.

▲ **ROVER INVESTIGATION** NASA's Volatiles Investigating Polar Exploration Rover, or VIPER, is a mobile robot that will roam around the Moon's south pole looking for water ice using neutron spectroscopy.



ICECUBE: MOREHEAD STATE UNIVERSITY; LUNAH-MAP: LUNAH-MAP / ARIZONA STATE UNIVERSITY; LUNAR ROVER: NASA AMES / DANIEL RUTTER



◀ **WHAT NEUTRON SPECTROSCOPY DETECTS** Cosmic rays constantly strike the Moon and liberate neutrons, which either get absorbed or scattered by interactions with rocks before escaping to space. But the neutrons lose a bit of energy if they glance off hydrogen atoms before leaving — hydrogen that's very likely bound up in molecules of water. So by recording these less-energetic "moderated" neutrons, scientists can map the extent and abundance of water-ice deposits in the top meter or so of the lunar surface.

The rover will land in an "unbelievably cold" and "very strange, never-seen-before region" that may have very little resemblance to the Moon we think we know, says Andrews. Already mission planners are sifting through thousands of candidate landing sites and traverse patterns, factoring in science needs, access to sunnier terrain, temperatures, sight lines with Earth for communication, and obstacle avoidance.

We'll learn more about such mission needs from a smaller rover called MoonRanger, under joint development by Carnegie Mellon University and CMU-spinoff company Astrobotic. Set to arrive in 2022, it will test navigation, communications, and mapping tools before VIPER lands.

This large-scale lunar exploration effort — joined as well by China (*S&T:* June 2020, p. 34) and other countries — would not be happening if not for the combined allure of scientific discovery and natural resources.

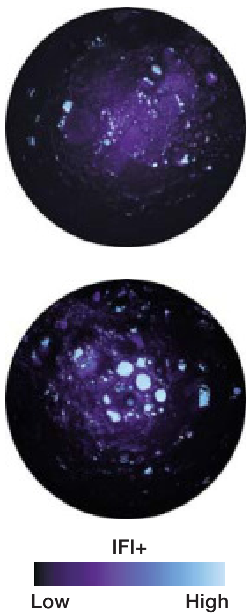
The cache of water and other volatiles stored at the lunar poles will provide valuable information about the creation and evolution of the terrestrial planets, including Earth, says Deutsch. "If we don't have the opportunity to study these records in detail, we lose access to the most accessible and potentially most complete record of the processes that have delivered and modified volatiles in the inner solar system."

Understanding the timing and processes for the deposition of surface and subsurface lunar water ice can also help us understand impact rates over time, Cohen points out.

But although science is in many ways driving the lunar revival, it might be economic activity and even settlements that translate to further progress. Researchers are also studying which deposits would be best for *in situ resource utilization*, processed for crew consumption or rocket fuel.

"On Earth, we've learned a tremendous [amount] about geologic processes and materials in the course of exploring for resources," says Kevin Cannon (Colorado School of Mines). "I think scientists should welcome economic prospecting and development of these ices, because it will result in them getting more data, samples, and new findings than they ever could have hoped for with scientific exploration alone." Given that there might be trillions of metric tons of ice present, it won't be gone any time soon, he adds.

Somewhere, W. H. Pickering may be smiling. There are no blizzards in Theophilus, but there are places on the Moon locked in a kind of interplanetary winter. It's a season that heralds breakthroughs for our understanding of the Moon.



▶ **WHERE'S THE ICE?** These maps show the *ice-favorability index* (IFI), a predictive assessment of which regions near the lunar poles contain the most favorable ice deposits for future mining operations. They apply desired characteristics such as older crater ages, ice stability closer to the surface, and higher areal fraction of cold traps — but not ease of access. North pole on top.

■ **CHRISTOPHER COKINOS** is coeditor of the anthology *Beyond Earth's Edge: The Poetry of Spaceflight*. He teaches at the University of Arizona and is writing a book about the Moon.

WHERE IS THE ICE?

NASA scientists use four categories for where to look for ice on the Moon.

Surface region
Soils on the surface where ice is expected to be stable, such as in permanently shadowed craters

Shallow region
Soils where ice is expected to be stable within 50 cm (20 in) of the surface

Deep region
Soils where ice is expected to be stable at depths of 50–100 cm (20-40 in)

Dry region
Soils where no ice is expected within the top 100 cm (40 in)

NEUTRONS ESCAPING MOON: GREGG DINDERMAN / *S&T*, SOURCE: LUNAH-MAP / ARIZONA STATE UNIVERSITY; MOON MAPS: KEVIN CANNON & DANIEL BRITT / UNIVERSITY OF CENTRAL FLORIDA