New

North rim of the Cabeus crater, just after LCROSS crash-landed here.

Moon

It is wetter, weirder, and a lot more valuable than we knew. No wonder Earth's nearest neighbor in space is suddenly attracting a ton of interest.

BY **ANDREW GRANT**

The minute the astronauts of *Apollo 16* safely splashed down in the Pacific Ocean on April 27, 1972, the only thing Larry Taylor could think about was getting his hands on another sample of moon rocks. Taylor, a planetary geochemist at Purdue University and self-described "lunatic," had examined hundreds of rocks that astronauts had brought back since first landing on the moon three years earlier. He soon recognized that this batch was different. The rocks were rusty, which suggested the presence of a substance supremely important to scientists and space explorers alike: water. The buzz throughout the community of lunar-rock scientists was electric, but Taylor had doubts. Any traces of water were most likely contamination from Earth, he decided; through analyzing other samples, he had come to believe that the moon was dry.

Over the years, Taylor's skepticism hardened into conventional wisdom. "I was very vehement against lunar water," he says. "Sometimes the people with the biggest mouth win."

Last October 9, conventional wisdom got ripped to shreds. On that day a small NASA rocket slammed into a 60-mile-wide crater named Cabeus, a permanently shadowed dent very close to the lunar south pole. The extreme heat of the collision caused grains of water ice and other substances that had been frozen for billions of years to vaporize. A larger spacecraft followed a few minutes later to sniff the vapor cloud and send measurements back to Earth before itself crashing into the lunar surface. Preliminary findings from the mission—called LCROSS, for Lunar Crater Observation and Sensing Satellite—show that at the impact site water may account for about 5 percent of the lunar crater's soil by weight, says Anthony Colaprete, principal investigator. That is as dry as the driest deserts on Earth, yet still far wetter than most scientists expected. Says Taylor, "I had to eat my shorts."

The findings have transformed our idea of the moon from a desiccated dead zone into a complex and lively world. Researchers are now involved in several projects that trace the origins of lunar water, perhaps all the way back to the fateful moment billions of years ago when the moon was formed. At the same time, new research indicates that the moon continually produces its own water through a strange mating ritual between hydrogen from the sun and oxygen on the ground. And stunning new spacecraft images show fault lines, volcanic domes, and solidified lava flows on the lunar surface, forcing a reevaluation of long-held beliefs about the moon's early evolution. Four decades after

Apollo, Earth's nearest neighbor in space is still full of surprises.

According to the latest thinking, lunar water is derived from comets that struck the moon billions of years ago, when the solar system was young. The ice they carried would have vaporized from the impact, settling eventually in permanently shadowed craters near the north and south lunar poles, where the extreme cold (below –400 degrees Fahrenheit, according to recent observations) would have preserved it almost indefinitely. This extraordinary storage ability could help explain NASA's detection in early March of 650 million tons' worth of ice at the moon's dark, cold north pole. LCROSS also supported this theory when it crashed into the south pole by uncovering, in addition to water, other elements that are abundant on comets: carbon dioxide, hydrogen sulfide, and methane.

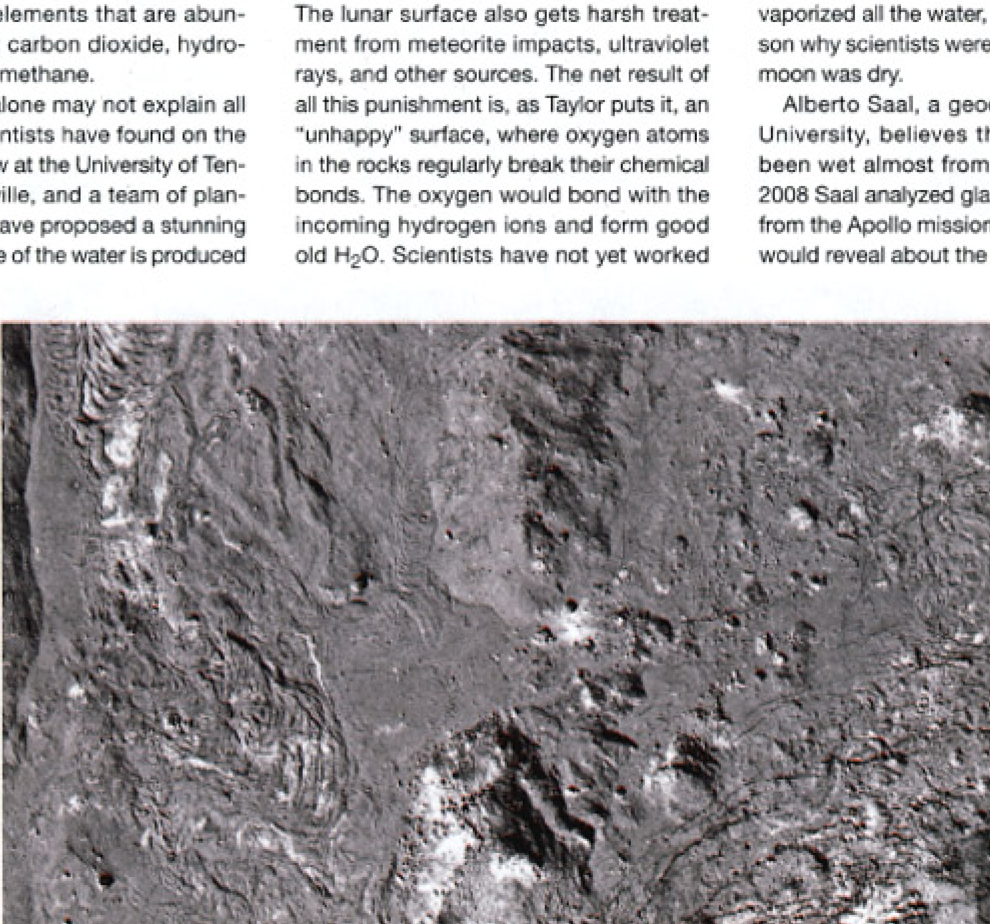
Still, comets alone may not explain all of the water scientists have found on the moon. Taylor, now at the University of Tennessee at Knoxville, and a team of planetary scientists have proposed a stunning hypothesis: Some of the water is produced by processes taking place on the surface right now. The key evidence comes from the Indian lunar probe Chandrayaan-1 and data from the 1998 Lunar Prospector mission. Together they reveal what Taylor calls lunar "dew": a smidgen of water distributed all over the moon's surface. The probes detected a daily fluctuation in the strength of the water signal, suggesting that the moon somehow produces small amounts of water at dawn before sizzling temperatures burn it off during the two-week-long lunar day.

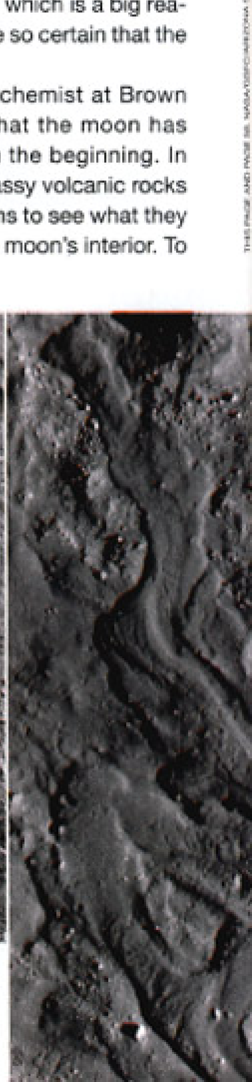
If the moon produces its own water, so might other **seemingly dry, airless bodies** like Mercury or the asteroids. Water may exist where we least expected it.

Taylor has some ideas about how the moon manufactures its water. Since the moon has virtually no atmosphere, high-energy hydrogen ions ejected from the sun continually bombard the surface and break chemical bonds in the rocks. The lunar surface also gets harsh treatment from meteorite impacts, ultraviolet rays, and other sources. The net result of all this punishment is, as Taylor puts it, an "unhappy" surface, where oxygen atoms in the rocks regularly break their chemical bonds. The oxygen would bond with the incoming hydrogen ions and form good old H_2O. Scientists have not yet worked out all the details of this mechanism—Colaprete says it "needs to be teased out a little more"—but if it proves correct, the consequences could stretch far beyond the lunar surface. If such a process occurs on the moon, Taylor says, it might also take place on other seemingly dry, airless bodies, such as Mercury or the asteroids. Water may exist where we least expected it.

While Taylor focuses on the present, some of his colleagues are using the discovery of water to learn more about the moon's distant past. Currently the leading theory of how the moon formed is the giant impact hypothesis, which proposes that an object the size of Mars slammed into the infant Earth 4.5 billion years ago and knocked off large, molten chunks. These chunks floated around for a while and glommed onto one another, forming the moon. According to computer models, such a collision would have created searingly high temperatures that would have vaporized all the water, which is a big reason why scientists were so certain that the moon was dry.

Alberto Saal, a geochemist at Brown University, believes that the moon has been wet almost from the beginning. In 2008 Saal analyzed glassy volcanic rocks from the Apollo missions to see what they would reveal about the moon's interior. To





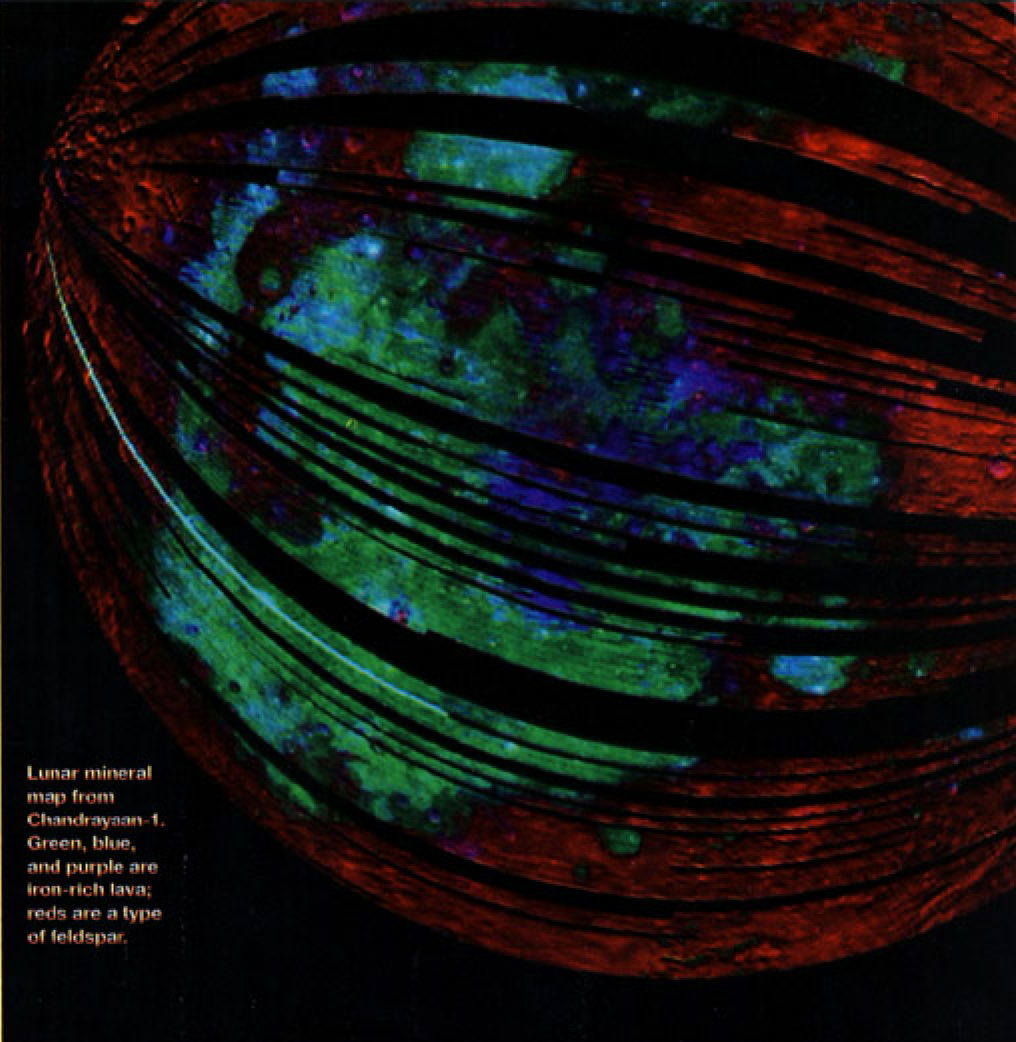
THE YOUNG HOT MOON
Detailed images show the moon's Giordano Bruno (left) and Mandel'shtam F craters, captured by the Lunar Reconnaissance Orbiter's camera. The smooth, fluid-like features are the result of catastrophic meteorite impacts that melted rock and created lavalike flows. Scientists want to explore the precise mechanics of these impacts.

his surprise, he discovered not only that the rocks contained water but that the concentrations were greatest in the center. The implication is that the water was within the original lava that formed those rocks and so must still be present in the moon's interior. If the water had come from contamination after the lava hardened, the water concentration would have been greater on the outside. "It's really changing the way we look at things," says Jeff Taylor, an expert in lunar geology at the University of Hawaii. "We don't even know how water got to Earth, so understanding the origins of lunar water is very interesting."

Saal's research suggests that water might have withstood the heat of the impact that formed the moon. As the moon cooled, magma from its interior spewed onto the surface, eventually hardening to form the landscape we see today. Some of this magma might have contained water-bearing compounds that remained on the surface. "I don't think we can discard the possibility that surface water could have come from volcanic eruptions," Saal says. The next step, he adds, is to compare the hydrogen and oxygen in samples of lunar ice with those same elements in the volcanic glass samples from Apollo.

More insight into the moon may come next year from NASA's Gravity Recovery and Interior Laboratory (GRAIL), twin spacecraft that will orbit the moon and map its gravitational field in search of clues about its interior structure. GRAIL and many of the other current robotic missions were planned in the expectation that humans would soon be returning to the moon. NASA's change of direction makes that unlikely in the next couple of decades, but the revolution in lunar science has been a happy by-product. And when humans do finally return, they will know much more about the risks and resources there—particularly where to find water that could be used to make fuel for rockets and oxygen to breathe. Larry Taylor even hopes future astronauts will learn to harness the moon's method of producing water to manufacture their own. "We need to learn to live off the land," he says.

For the record, Taylor has no problem laughing at his past work—as he did recently when his colleagues presented him with a cake depicting a man's bare backside. "There is water, and I'm very happy about that," he says. "I don't mind eating my shorts." ◘



Lunar mineral map from Chandrayaan-1. Green, blue, and purple are iron-rich lava; reds are a type of feldspar.

There's Hydrogen In Those Hills

BY JENNIFER BARONE

Like many children of the 1960s, Bill Stone grew up wanting to be an astronaut. He chased the dream farther than most. He studied hard and got his doctorate in engineering. In 1980 he applied to NASA's astronaut training program and got rejected. Then he applied again, and again. After nine tries, NASA finally invited him down to Houston for an interview, only to eliminate him in the semifinals. Even then, Stone did not give up.

A new hope came last summer. Data from several probes and telescopes confirmed unequivocally that the moon harbors vast reserves of hydrogen, in the form of water. Hydrogen is the stuff of rocket fuel. The groundbreaking news was no surprise to Stone: His imagination had already gotten fired up at the first hints of water from the Clementine mission in 1994. He pictured lunar factories mining the regolith for hydrogen. He saw the moon as a gigantic gas station in the sky, with rockets stopping by on their way through the solar system and beyond and perhaps earthly tourists someday visiting lunar hotels.

Even as the Obama administration is turning its back on human exploration of the moon, a small but persistent group of entrepreneurs are pursuing their own plans to embrace it. Virgin Galactic unveiled *SpaceShipTwo*, a commercial spacecraft intended for passenger flights, this past December. Meanwhile, Bigelow Aerospace is developing inflatable modular craft designed to support humans in space. Boeing is developing an orbital refueling station. Stone wants to add the missing piece that could support a booming lunar economy: an outpost to mine hydrogen from icy deposits in the moon's polar craters.

For years Stone has sublimated his passion for space by working on some of the basic technologies of space exploration, such as autonomous robots. By day he was a senior scientist at the National Institute for Standards and Technology. In his spare time he led international expeditions mapping dry and underwater cave systems around the world; eventually he founded a company that builds robots that can probe underground and underwater territory beyond human reach. In the 1990s, when the Clementine and Lunar Prospector missions found tentative evidence of hydrogen on the moon, Stone pricked up his ears. In 2007 he formed the Shackleton Energy Company—named for both the Antarctic explorer and the crater at the lunar south pole that Stone hopes to mine—and began developing a business plan.

Stone believes a nonearthly source of fuel is the keystone of the commercial space industry. Propellant accounts for the vast majority of the weight—and hence the cost—of existing space-bound rockets. It is a vicious cycle: having to load up on all that hydrogen at ground level makes the rockets heavy, increasing the amount of fuel they need to escape the gravitational clutches of Earth. "Whatever it is that you want to do in space, you have to pay by the kilogram," Stone says.

A source of rocket fuel beyond Earth's gravity would slash the cost of space travel dramatically; propellant can account for 95 percent of the mass of current launches. Having fuel stations in low Earth orbit, Stone believes, will bring down the cost of space travel enough to make it widely accessible and truly profitable. Stone's proposed venture would create rocket fuel by melting water ice from the moon's soil, purifying it (exactly how, he says, is a trade secret), and splitting it into hydrogen and oxygen, perhaps using a solar-powered electrolysis system. "In surveys," Stone says, "tens of thousands of people have told researchers that their primary interest in space is going there themselves." As Virgin Galactic, Bigelow Aerospace, and other ventures come up to speed, the availability of fuel will be a key enabler.

Stone has volunteered to be among the first people to fly to the moon without enough in the tank for a return trip. He and a handful of others would carry just enough fuel and supplies to get there, establish a base, and set up mining and manufacturing operations. This scheme would be

Economy-Class Spaceflight

WHEN PRESIDENT OBAMA announced that NASA would get no money next year for its Ares I booster and Orion space capsule, he did more for private spaceflight than an army of venture capitalists. With the space shuttle facing retirement by early 2011, Obama opened the way for private firms to take over transportation services for NASA's astronauts.

The big questions are whether NASA can loosen its reins on the private firms while maintaining adequate control, and whether the companies can meet the challenge of carrying humans safely into space. Private firms have been launching satellites and building components for NASA for decades, but human spaceflight is far more difficult. Then again, despite NASA's lavish expenditures to minimize risk, the agency wound up with safety disasters anyway. The hope is that private firms will do better—or at least no worse—for a lot less money.

Like NASA in the early days of its rocket program, private firms have had their problems. SpaceX's early prototypes failed three times before its Falcon 1 rocket succeeded in orbiting Earth in September 2008. In 2007 three employees of Scaled Composites were killed in an explosion while testing a nitrous oxide delivery system.

In January NASA's Aerospace Safety Advisory Panel declared in a report that no private launch firm is currently certified for carrying humans into space, nor is there even a mechanism by which certification can be earned. NASA is far behind where it needs to be to adapt its internal standards to commercial orbiters, the report said. Elon Musk, head of SpaceX, says his company is already building to NASA's standards and insists its Falcon 9 rocket and Dragon module will be safe. (SpaceX anticipates a launch by May of this year.) NASA's report, he says, seems "politically motivated."

NASA and the private contractors will inevitably remain linked. But will the link be too tight? Entrepreneurs like Musk fear that if NASA imposes its old safety bureaucracy on them, the new system may not be much better than the old one. NASA's challenge is to provide rigorous oversight without choking off private innovation. That might mean tolerating more risk, but danger, Musk says, is part of the dream. "I don't see any way around it. This is a super-difficult thing."

ANDREW MOSEMAN


Falcon 1, SpaceX's flagship rocket, at takeoff in July 2009.

A bird's-eye view of the rim of Milichius A, a 5.6-mile-wide crater, taken by the Lunar Reconnaissance Orbiter's camera last fall.

considerably cheaper than anything NASA would undertake, simply because the agency would never take the calculated risk that the crew would be stranded. Hydrogen propellant could then be cheaply shuttled to stations in Earth orbit on inflatable craft that save on fuel by relying on aerobraking—briefly dipping into Earth's upper atmosphere—to slow down when entering orbit. Stone estimates that the whole process will cost as little as one-twentieth as much as bringing hydrogen up from home.

The project's success would depend not only on how much water is present on the moon but also on how easily we can get at it. So far many of those details are unknown, but Stone is not waiting. This year he will go door-to-door to the world's billionaires "to find the ones interested in seeing history made with their names on it." Up-front costs are projected to run around $20 billion. "With money in hand," he says, "we'll be there in seven years."

Not all would-be lunar entrepreneurs share Stone's seriousness of purpose. David Kent Jones, an engineer with the company Moon Publicity, wants to turn the moon into a huge advertising billboard. Robots would drive around carving messages with their tire treads, which the moon's unfiltered sunlight would bring into sharp relief. "It's like painting the surface of the moon with shadows," Jones says. Moon Publicity began offering licenses last year but had no buyers; Jones is now seeking investors.

One entrepreneur doesn't even have to leave Earth to participate in the lunar land grab. Salesman Dennis Hope, who goes by the title Head Cheese of the Lunar Embassy, claimed ownership of the moon in 1980 and says he has since sold parcels of lunar land to 5 million people online. Prices start at $19.99 per acre. Sales last year came to $4 million, Hope claims.

This whimsical business raises a serious question: Can the moon be owned by companies or individuals? Laws are vague on the subject, but some legal experts suggest treating the moon as just another frontier: The first to go to develop a financial stake in a patch of lunar land would be able to claim property rights. If this view prevails, the moon could be the next Wild West. ■

Next to the Moon

Chang'e A series of three Chinese robotic orbiters.
WHY: To test soft-landing techniques and scout landing sites for future manned missions.
WHEN: The first launched in 2007; a second is planned for later this year.

Gravity Recovery and Interior Laboratory Twin NASA moon orbiters.
WHY: To map the moon's gravity field, which could yield new insights into the structure of its interior.
WHEN: September 8, 2011

The Lunar Atmosphere and Dust Environment Explorer A NASA orbiter.
WHY: To measure the density and composition of lunar dust and see how it varies from month to month.
WHEN: May 1, 2012

Luna-Glob 1 A Russian orbiter.
WHY: To study the moon's interior and look for mineral resources, with the ultimate goal of establishing a fully robotic lunar base.
WHEN: 2012

Chandrayaan-2 India's second moon mission (conducted jointly with Russia), consisting of an orbiter and a rover.
WHY: To analyze the lunar surface and demonstrate new technologies, such as a laser-imaging system, for possible future manned missions.
WHEN: 2013

Google Lunar X-Prize A largely privately funded, $30 million international competition to land a robot safely on the moon, travel 500 meters over the lunar surface, and then send images and data back to Earth.
WHY: To encourage individuals and companies to develop the technology for exploring space.
WHEN: Final deadline to complete the mission is December 31, 2014.

MoonRise A NASA robotic sample return mission to the Aitken crater.
WHY: To find rocks that were originally buried in the mantle, which could shed light on the moon's origins.
WHEN: Currently unscheduled, but NASA officials want to launch no later than 2018.

—BO ZHANG