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NASA Slams the Moon

J. Kelly Beatty

S&T: CASEY REED

NASA's "crash and splash" gambit dredged up water from a darkened lunar crater — but not nearly as much as scientists expected to find.

If you look up "dry" in a dictionary, you won't find the Moon's picture next to the definition — but it should be. By the mid-1970s, the dusty rocks returned by six teams of Apollo astronauts and three Soviet robotic missions had all but certified that the stark lunar landscape contains no water whatsoever.

Yet comets *do* slam into the Moon now and then, bringing water and a host of other volatile compounds. Where does it all go? In 1979 geochemist James Arnold revived a radical idea first proposed two decades earlier: Some of the water from those collisions should become "cold-trapped" in the frigid floors of craters near the lunar poles, where — by a quirk of orbital geometry — the Sun never shines.

If water actually accumulates in these inky recesses, how can we tell it's there? Photographs of the craters' floors showed only blackness, and other efforts to probe them proved inconclusive or contradictory. For example, during the 1990s the Clementine and Lunar Prospector orbiters found tantalizing indirect evidence that deposits of frozen water might lie below a foot or two of lunar grit near the poles, yet in 2003 radar scans with the giant Arecibo dish found nothing of the sort.

It turns out that the Moon isn't as absolutely bone dry as had once been thought. Alberto Saal (Brown University) and others recently found trace amounts of water in little beads of a rare volcanic glass that erupted onto the lunar surface billions of years ago (*S&T:* July 2008, page 14). Meanwhile, spectrometers on three spacecraft have detected water molecules clinging to surface rocks across much of the lunar landscape (January issue, page 16).

But if humans are ever going to call the Moon home, they'll need more than whiffs of water to survive, so the exploratory focus keeps returning to those enigmatic polar shadows and what kind of icy cache might lie hidden within them.

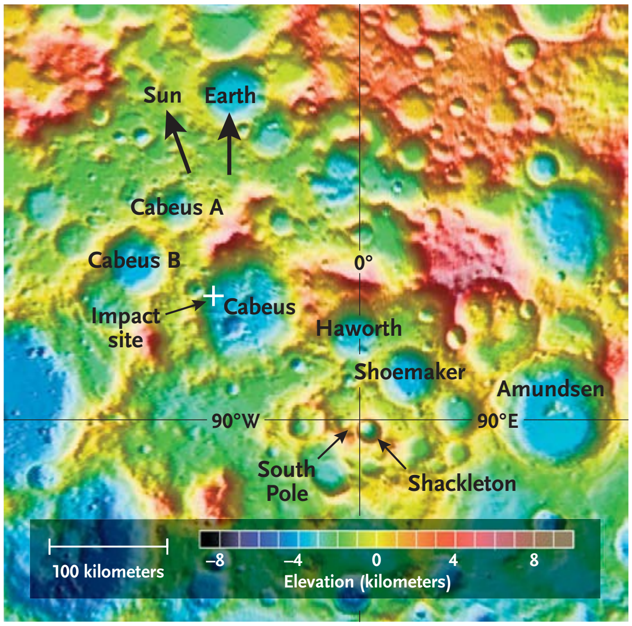
The Bullet

A few years ago scientists and engineers at NASA's Ames Research Center designed a mission to help settle the debate (*S&T:* June 2009, page 20). Their concept was simple: Slam a big enough bullet into a permanently shadowed lunar crater, and the resulting plume of debris should be infused with water vapor that can be detected and measured spectroscopically once it rises into sunlight.

If only it had been that easy!

What became the Lunar Crater Observation and Sensing Satellite (LCROSS) started its mission smoothly enough. Last June 24th the spacecraft hitched a ride atop an Atlas V booster and a Centaur upper stage that combined to propel NASA's Lunar Reconnaissance Orbiter (the primary payload) toward the Moon. LRO soon separated and, five days later, eased itself into lunar orbit. Meanwhile, the Centaur remained attached to LCROSS, which carried the brains and maneuvering thrusters needed to steer the spent rocket to its target. The coupled craft swung past the Moon, coasted onto a looping trajectory, and awaited a climactic return encounter.

Their ride got bumpy in late August, when wild firings of LCROSS's thrusters squandered more than 300 pounds (140 kg) of fuel before engineers regained control. Enough remained, barely, for the spacecraft to line up the Centaur on its eventual lunar target. The pair separated about 9 hours, 40 minutes before impact.

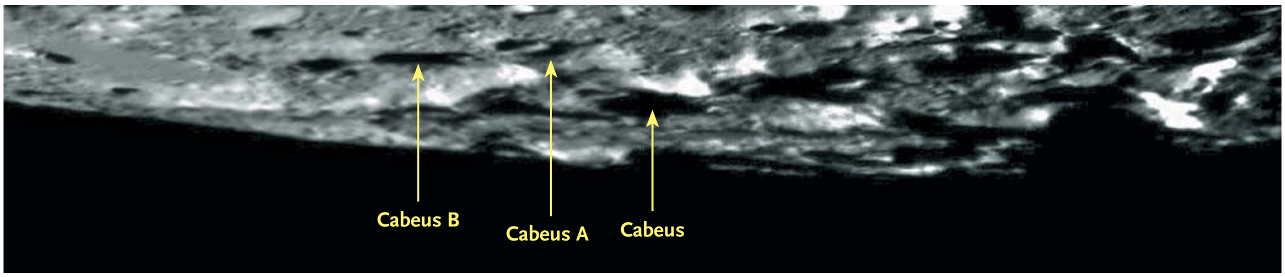


NASA / GODDARD SPACE FLIGHT CENTER

Using a laser altimeter aboard the Lunar Reconnaissance Orbiter, researchers have constructed this map of the terrain near the Moon's south pole. Note how the large ridge on the rim of Cabeus blocks the LCROSS impact site from view on Earth.

The late-June launch favored a southern aim point. Back on Earth, NASA managers argued over which crater would likely yield the most water. The final targeting decision relied heavily on scouting reports from LRO instruments, particularly its Russian-built Lunar Neutron Exploration Detector, which senses where hydrogen (in water, presumably) is concentrated in the lunar landscape.

But LEND was sending back mixed messages. According to principal investigator Igor Mitrofanov (Space Research Institute, Moscow), the strongest hydrogen counts were generally *not* associated with the areas that never see the Sun. One of the few shadowed sites that passed the "LEND test" was Cabeus, an obscure crater at latitude 85° south that's 61 miles (98 km) across, and it eventually got the managers' nod.



NEW MEXICO STATE UNIVERSITY

This view of the Moon's south pole, taken with a 24-inch telescope, closely matches the lighting geometry and libration seen from Earth at the time of LCROSS's impact. The LCROSS team initially targeted a spot within Cabeus A but later switched to Cabeus.

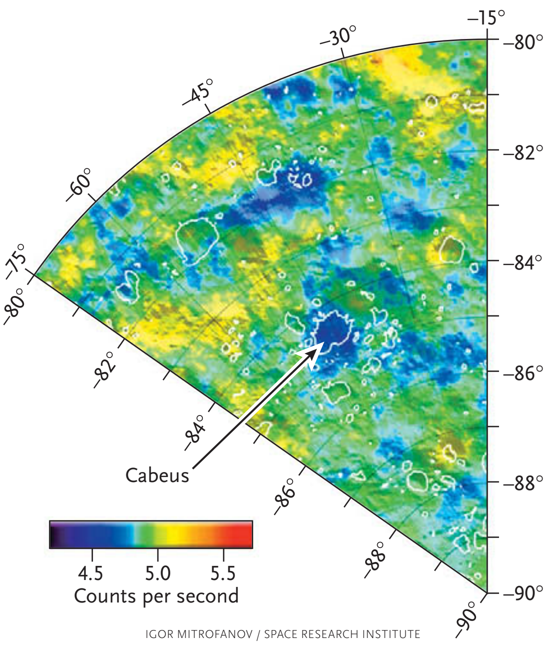
Just as critical was the Centaur impact's timing — October 9th at 11:31 Universal Time. At that moment LRO would be almost directly over the crash site, just 48 miles up, and a waning gibbous Moon would be high in the night sky for giant telescopes in Hawaii, California, Arizona, and New Mexico. Also looking on would be the Hubble Space Telescope, Odin (a Swedish satellite equipped to detect water), and two Earth-imaging satellites swung toward the Moon. Legions of amateurs also trained scopes on the Moon's south pole.

Much Ado About Something

Right on schedule — and, more critically, on target — the Centaur slammed into Cabeus at 1½ miles per second. Four minutes later, after flying through the debris cloud raised by the rocket's crash, the instrument-laden, 1,300-pound (600-kg) shepherd craft augered in not far away.

Thanks to NASA images streamed live over the internet, the world watched for lunar fireworks. But as space spectacles go, the LCROSS impacts were a bust (see page 18). No incandescent flash lit up the monitors in mission control, nor did billowing plumes of dust stream upward into the sunlight and into view of telescopes back on Earth. Astronomers sifted through flat-lined observations from Hubble, Keck, Gemini, Subaru, and other giant eyes, looking in vain for any trace of the event.

It didn't help that telescopic views of the impact sites were blocked by a high ridge along Cabeus's Earth-facing rim. The plume had to rise at least a mile before it popped into sunlight — and by then, apparently, it had become too diffuse to show up. The only positive sightings from Earth involved a pulse of sodium added to the Moon's tenuous exosphere.



IGOR MITROFANOV / SPACE RESEARCH INSTITUTE

Scientists can indirectly sense the presence of water on the Moon by mapping the "slow" neutrons knocked off its surface by cosmic rays. Fewer neutrons imply the presence of more hydrogen atoms (presumably in water). This data from LRO's Lunar Neutron Exploration Detector shows that Cabeus (arrowed) exhibits strong hydrogen abundance.

DOMINIC HART / NASA-AMES

LCROSS scientists Anthony Colaprete and Kimberly Ennico review early results from the Centaur and spacecraft impacts.

Fortunately, nothing blocked the view of the nine cameras and spectrometers aboard the LCROSS shepherd, which trailed the rocket by about 400 miles. Instruments aboard LRO also had front-row seats. "We are blown away by the data returned," exclaimed LCROSS chief scientist Anthony Colaprete (NASA/Ames Research Center) one week after the mission's culmination. Instruments had detected a flash when the Centaur hit, the rising plume of hot debris that followed, and the crater left behind. In that sense the mission was a smashing success.

The rocket's impact gouged out a pit about 70 to 100 feet (20 to 30 m) across, in line with expectations. A splash of debris extends another few hundred feet beyond the crater rim. But the incandescent flash created by the Centaur's impact was only a third as bright as predicted, a dim blip that the team struggled to find amid the underexposed camera frames.

The debris plume's size and height also roughly matched expectations, growing to about 6 miles across in the first 20 seconds after the impact. But it's now clear that the mass of material tossed from the crater was nowhere close to the 350 tons suggested by some modelers.

NASA

A near-infrared camera aboard LCROSS recorded this view of Cabeus minutes before the spacecraft crashed into it.

Based on small-scale hypervelocity experiments conducted at NASA Ames, impact specialists Peter Schultz and Brendan Hermalyn (Brown University) argue that a low yield should have been expected — both because the empty Centaur collapsed into itself as it hit and because the spray of debris went mostly "out" instead of "up." This explains why the plume remained hidden behind the high ridge and out of view of the telescope armada on Earth.

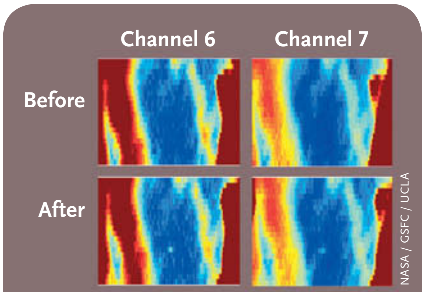
It's also possible that the Centaur pancaked into the crater's floor, instead of hitting nose first. "It was definitely rotating or tumbling," notes observer Marc Buie (Southwest Research Institute), who tracked the rocket's final hours with the 2.4-meter reflector at Magdalena Ridge Observatory in New Mexico.

A Strange Brew

Not until mid-November, after poring over the results for several weeks, was Colaprete finally able to announce that two LCROSS instruments had seen clear evidence of water vapor in the towering plume of hot dust and gas. An infrared spectrometer recorded two distinct water absorption bands at 1.4 and 1.85 microns, and another spectrometer registered ultraviolet emission lines from 306 to 310 nanometers — telltale tracers for hydroxyl (OH) radicals created when water molecules dissociate in sunlight.

So there *is* water, at least within Cabeus, and as Colaprete said during a November 13th press briefing, "We didn't just find a little bit, we found a significant amount." He estimates that the part of the plume in the instruments' field of view contained about 220 pounds (100 kg) of water vapor, about 25 gallons if it were liquid. Clearly, there's no giant slab of ice lying beneath the crater's floor. Instead, the water is mixed with (and perhaps chemically bound to) the rubbly mix of dust and larger particles. Estimating the plume's ice-to-rock ratio will be challenging because researchers must determine how much debris was excavated and how much of that was observed.

LCROSS found other spectral fingerprints besides water — apparently the blossoming debris cloud had other interesting "flavorings" mixed in. Mission scientists are still combing through their spectra, but candidate compounds include carbon dioxide (CO_2), carbon monoxide (CO), and various hydrogen-bearing molecules such as methane (CH_4), methanol (CH_3OH), and ethanol (C_2H_5OH). The team has ruled out contamination from the Centaur itself.

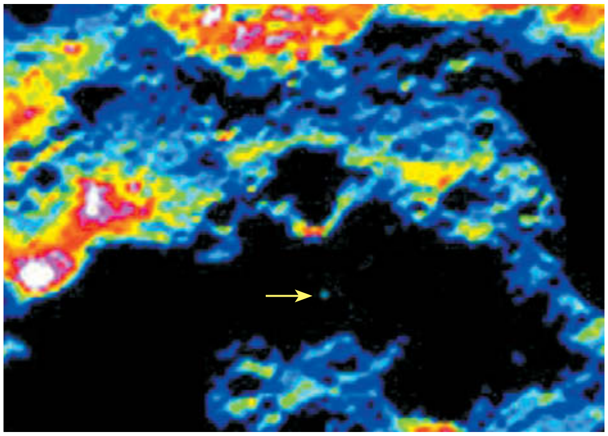


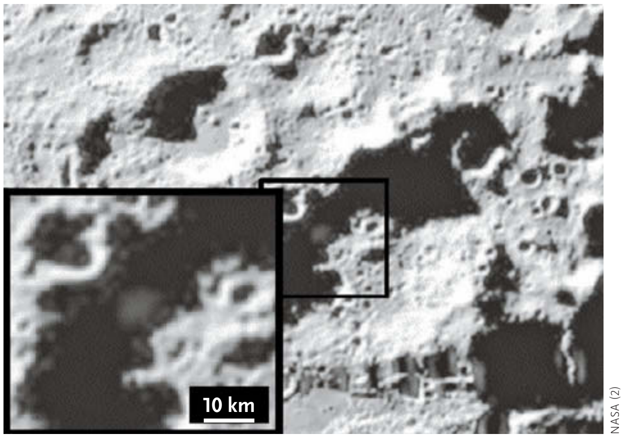
These scans from two of Diviner's thermal channels show the Cabeus region before and after the Centaur impact. The blast site reached a peak of several hundred degrees Celsius.

"The full understanding of the LCROSS data may take some time; the data are that rich," says Colaprete, who adds that with methanol in the water, he would not drink it until it was purified.

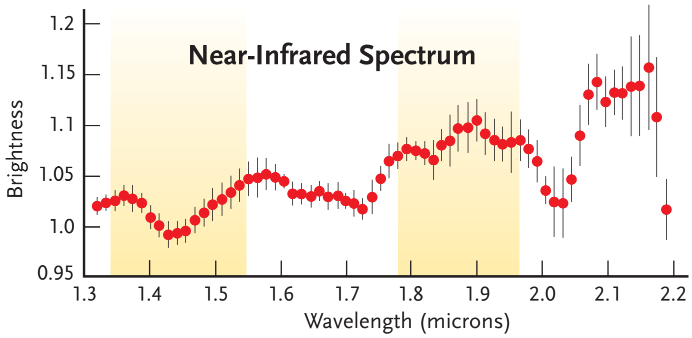
Geochemists had a hunch that the crash might dredge up a strange brew. They'd been tipped off back in mid-September by Diviner, an LRO instrument designed to map surface temperatures. Its sensors found that the polar regions are far colder than expected, as low as 35 K (–397°F) in some spots. As improbable as it is remarkable, the shadowed floors within Cabeus and its neighbors are the most frigid places known in the *entire solar system!* According to Diviner principal investigator David Paige (UCLA), "The temperatures in these super-cold regions are definitely low enough to cold-trap water ice, as well as other more volatile compounds, for extended periods."

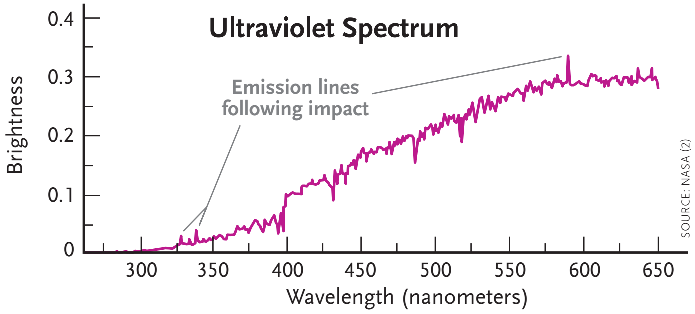
So what else might be lurking in the lunar shadows? One tantalizing candidate comes from LRO's Lyman-Alpha Mapping Project instrument. LAMP probed the ultraviolet spectrum of the impact plume after it had





Left: **From an altitude of about 400 miles, LCROSS's mid-infrared camera caught a faint thermal signature when the Centaur rocket slammed into Cabeus.** ***Right:*** **A visible-light camera on LCROSS's shepherding craft captured the post-impact plume of debris.**

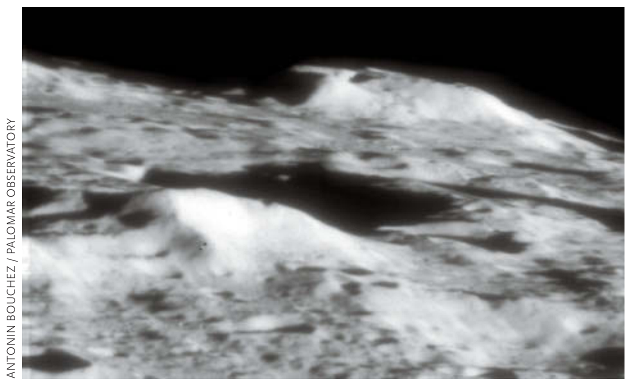




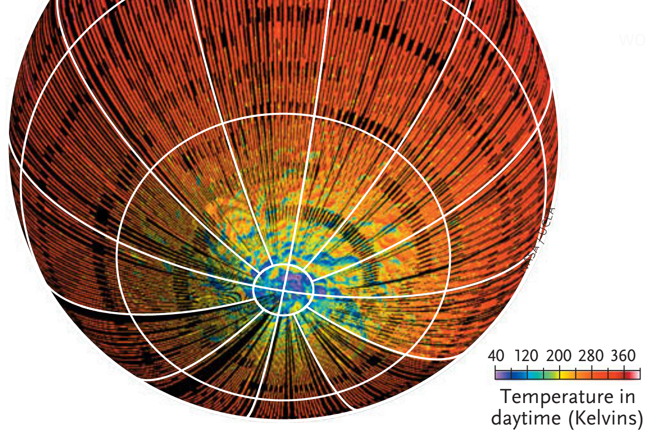
Top: **A near-infrared spectrometer aboard LCROSS recorded several notches (yellow regions) in the ejecta plume's spectrum, which correspond to absorption by water vapor.** ***Above:*** **An ultraviolet/visible spectrometer recorded several emission lines resulting from solar ultraviolet light breaking water molecules apart into hydroxyl (OH) molecules and free hydrogen (H).**

risen high enough to be projected against black space above the lunar limb.

"We definitely saw something," notes LAMP scientist Randy Gladstone (Southwest Research Institute). But that "something" wasn't water. Nor was it oxygen or hydrogen atoms, both of which have strong ultraviolet emissions. There's some hint of hydrogen molecules (H_2) — and though water might be the source, it could also have come from exotic ices such as ammonia (NH_3) or methane, or



Despite rock-steady views, Palomar Observatory's 200-inch reflector saw no hint of a debris plume emerging from behind the large foreground ridge that marks Cabeus's rim. The field of view in this infrared image is 40 arcseconds wide, corresponding to 44 miles (71 km).



Diviner, an instrument aboard the Lunar Reconnaissance Orbiter, revealed that, even during daytime, shadowed areas near the Moon's north pole have the lowest temperatures ever measured in the solar system: 35 K (–397°F).

solar-wind gas trapped in the lunar soil.

LAMP's strongest and most intriguing detection came at the wavelength of 184 to 185 nanometers. Gladstone says the only known elements able to create that particular spectral line are iron, perhaps magnesium . . . and mercury. "Both mercury and iron still look like the best bets for explaining the plume emission we see with LAMP," explains Gladstone, though the match remains tentative and more data-crunching is in progress.

Liquid mercury on the Moon?

In an obscure, decade-old article titled "Don't Drink the Water," George W. Reed, Jr. (then at Argonne National Laboratory) describes how mercury was found in drill tubes of lunar regolith returned by the crews of Apollos 12, 15, 16, and 17; other work suggests it might be present in the Moon's wispy-thin exosphere as well.

No matter what its source, Reed concluded, some of this mercury must end up as deposits in the ultracold interiors of permanently shadowed lunar craters. Moreover, the Centaur slam only needed to heat the target area to about 400 K (260°F) to release any mercury trapped in the dark dirt. Thermal imaging from Diviner argues that the impact site probably got that hot and then some, though analysis of its data continues. Paige notes that it still glowed at least 300 K 90 seconds after the impact.

Now that LCROSS has come and gone, it's still unclear how much water exists on the Moon, how it is distributed, or where it came from. As Paul Spudis (Lunar and Planetary Institute) points out, this mission "presupposed that we understood the Moon well enough to identify in advance the most likely site for ice." Yet, he continues, we still don't know where all the ice deposits are located or what other compounds might be present.

All of that said, last October's splashy LCROSS spectacle represents a first step in obtaining answers to those important questions. ✦

Senior contributing editor ***J. Kelly Beatty*** *always has a drink handy when he observes the Moon. He thanks LCROSS and LRO scientists for sharing their preliminary results as this story was going to press.*