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Lunar Reconnaissance Orbiter

Changing the face of the Moon

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Contributing writer

After the Apollo 17 astronauts returned to Earth 40 years, ago ending the final manned lunar landing mission, the science community quickly arrived at a consensus: The Moon was dead.

From 1964 to 1972, NASA distributed to the science community thousands of photographs taken by three Ranger hard landers, five lunar orbiters, five Surveyor soft landers, seven lunar orbiting Apollos, and 12 U.S. astronauts working (not just walking) on the Moon.

An international effort was under way to unravel the secrets contained in the images and in 840 lb of lunar rock and soil carried back by the six Apollo missions that landed successfully.

The USSR had its own research efforts, using thousands of images from its Luna spacecraft and a half-pound of lunar soil returned to Earth by three Soviet robotic sample return missions.

Many secrets were unlocked, but all of the analysis indicated that the Moon was indeed a profoundly dry geologic corpse, having been dead for at least the last billion years of its 4.5-billion-year history.

During nearly 20 years of study following Apollo, nothing changed in this regard. As respected Brown University lunar scientist Peter H. Schultz put it in 1991, "The 'Dead Planet Paradigm' is well established in lunar science."

The 1994 Clementine and 1998 Lunar Prospector missions returned minerology data from lunar orbit but did not address active geologic activity. Prospector, however, found preliminary evidence for water ice.

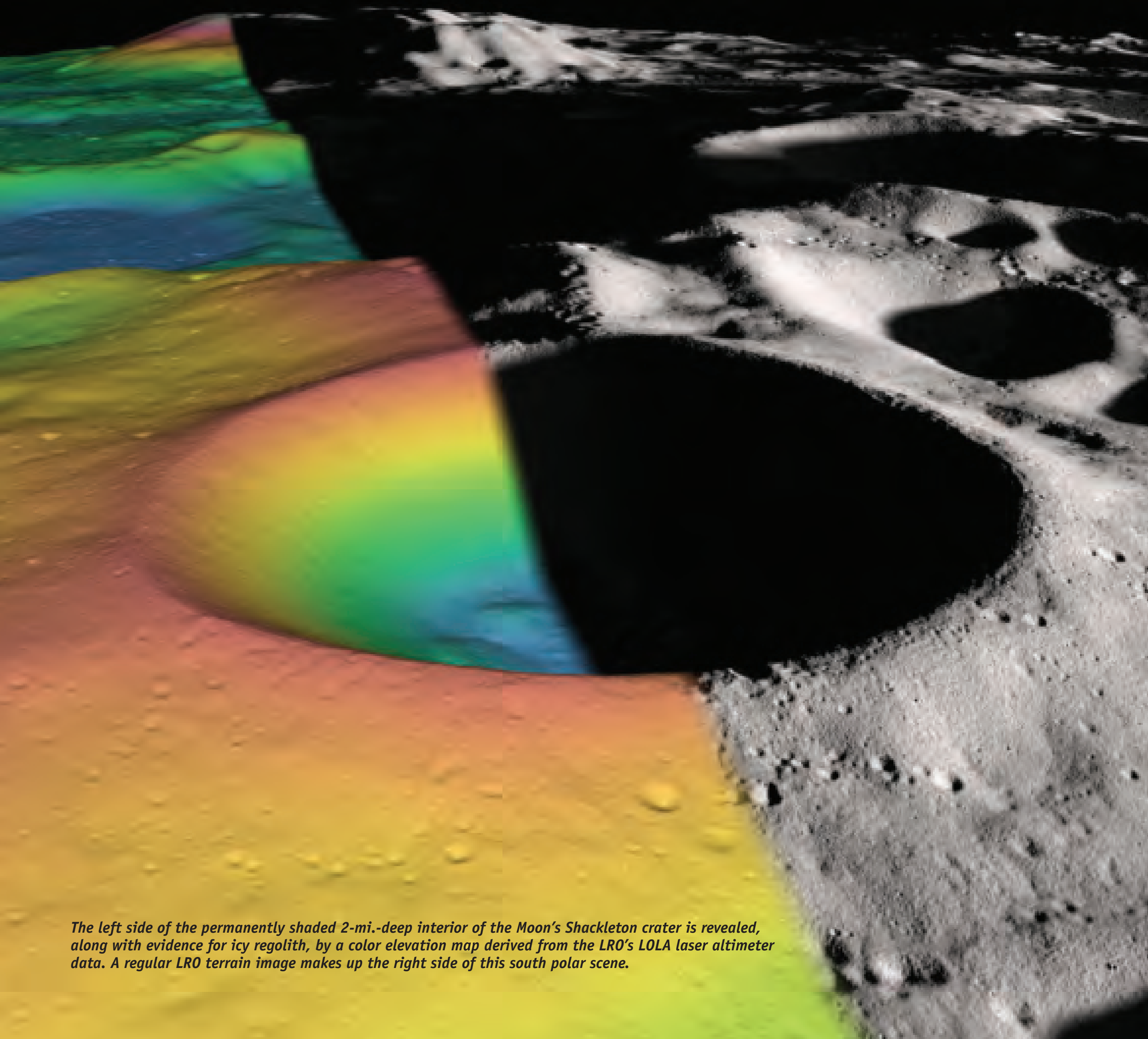
It's alive!

And now, just over a decade into the 21st century, interest in the Moon has been resurrected by NASA's Lunar Reconnaissance Orbiter. LRO images of the Moon show: It's alive!

"Many, many people have felt that the Moon is geologically dead. What we are finding is that this is totally wrong. The Moon appears to be geologically active—now!" says Thomas R. Watters, a senior scientist and planetary geologist at the Smithsonian National Air and Space Museum in Washington, D.C.

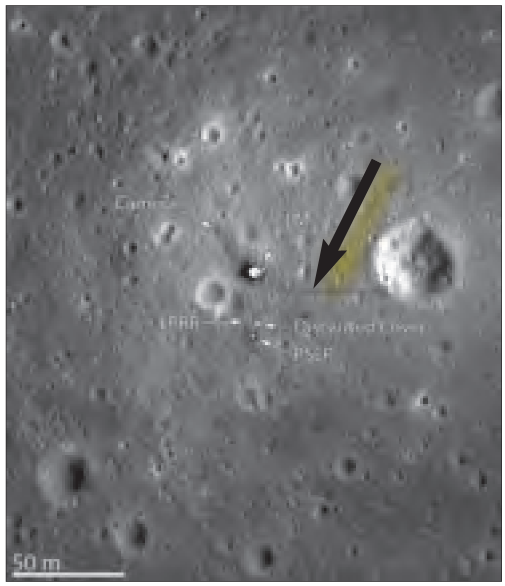
"One of the really, really exciting returns from the LRO mission is that we are now seeing growing evidence of very young geologic activity on the Moon,"

NASA's Lunar Reconnaissance Orbiter is aptly named, uncovering long-held secrets not just about the Moon but also about the lunar programs of former earthly space rivals. The myriad images it has produced have led to one block-buster revelation that is breathing new life into lunar science. Details provided by LRO's advanced suite of instruments are literally putting a new face on 'the man in the Moon.'



The left side of the permanently shaded 2-mi.-deep interior of the Moon's Shackleton crater is revealed, along with evidence for icy regolith, by a color elevation map derived from the LRO's LOLA laser altimeter data. A regular LRO terrain image makes up the right side of this south polar scene.

On landing day 42 years ago Neil Armstrong took this shot after he had walked to the crater rim and looked back west to the lunar module. Credit NASA Goddard/Arizona State.



LRO image of the Apollo 11 landing site from an altitude of only 12 mi., with an 8-in. resolution, shows the tracks of Neil Armstrong (dark arrow) created when he walked 200 ft each way to the 80-ft-diam. Little West crater. Visible are Eagle's descent stage, the lunar ranging retroreflector, and the passive seismometer experiment.

says Watters, who is also a member of the LRO camera team. He points out that the new features that LRO is spotting could have been formed as recently as 50 million years ago or even more recently—a very short time relative to the 4.5 billion-year age of the Moon.

That was just the beginning for this 2-ton marvel. Developed by NASA Goddard, the $504-million LRO was launched in June 2009 from Cape Canaveral on board a United Launch Alliance Atlas V rocket. LRO's other major achievements include:

•Extremely high resolution imagery that sheds new light on human lunar exploration and the U.S./Soviet race to the Moon, including unmanned Soviet Moon lander mysteries. LRO has focused in on all six of the Apollo landing sites, discovering among other things Neil Armstrong's specific footprints on the Moon and the still-'flying' American flags of Apollo 12, 16, and 17—the final flag, planted by Gene Cernan and Jack Schmitt on December 12, 1972.

•Transmitted data indicating the Moon has at least 6.6 billion tons of water ice. Future explorers could use the ice for drinking water, radiation shielding, or oxygen for breathing, and use the hydrogen for rocket propellant by combining it with oxygen.

•Location and mapping of very specific places where major deposits of the important mineral lunar ilmenite can be found. This titanium-iron oxide mineral is highly enriched with magnesium and would be critical in the development of a Moon base, scientists believe. Oxygen can be easily extracted from lunar ilmenite, which would also be used to fashion building materials for permanent structures. The mineral's earthly version is mined in 13 countries.

•The discovery of titanium fields on the Moon, with concentrations of the mineral 10 times higher in lunar ore than in titanium ore on Earth. In studying LRO images, scientists noticed that some areas of lunar seas are reddish and some are blue. The color variations point to concentrations of titanium and iron.

•The finding that the Moon's north polar region is home to one of the coldest places in the entire solar system, at nearly -415 F.

•Images and terrain elevation data that are being forged into new maps of unprecedented detail, for human and robotic mission landing sites and for pinpointing the Moon's diverse geologic features and resources. The spacecraft is returning so much high-resolution data that the LRO team believes it could map much of the lunar surface at a resolution of 19.7 in./pixel.

Preserving the mission

The LRO mission was approved as a precursor to the Constellation manned lunar program, conceived in response to the Vision for Space Exploration. President George W. Bush had announced the vision in 2004 as a way to transition NASA back to flights beyond Earth after completion of the ISS and the phase-out of the space shuttle.

LRO's mission at that time was to create new high-resolution lunar maps, pinpoint water and mineral resources that could support manned outposts, and scope out the best new sites for renewed manned lunar landings and habitation, starting in 2020 under Constellation.

But on Feb. 1, 2010, President Barack Obama announced his intent to cancel the foundering Constellation program. It was just seven-and-a-half months after the $504-million LRO had been launched on a mission specifically to support Constellation.

NASA decided to continue LRO's mission in its originally planned Exploration Phase lunar polar orbit for a year at 31 mi. altitude, to support future landings whenever they might resume. LRO took images with resolutions as good as 19.7 in./pixel from this orbit.

A wider audience

Ironically, the first major user of such publicly available advanced maps and landing site products may well be China. It has launched its own Chang'e lunar orbiter, which is far less capable than LRO.

For launch later this decade, China and India are both developing robotic lunar rovers that likely will make use of LRO data. China will decide in the next five years whether to pursue a manned lunar program that would also use key LRO-discovered lunar resources and terrain data for the landing of Chinese astronauts on the Moon around 2030.

In addition, LRO data will be used for planning by nearly two dozen U.S. and international ventures competing for the $30-million Google Lunar X Prize to send privately developed rovers to the Moon.

Under a new Science Phase plan begun in 2010, the LRO orbit was dropped down to about 12-mi. altitude to achieve image resolutions of 8 in. above key targets such as Apollo landing sites, and to search for important missing or crashed Soviet lunar spacecraft.

Instrument suite

Though its original justification for approval had been cancelled, during both its Exploration and Science mission phases LRO began making breakthrough discoveries. Lunar and planetary scientists in general, as well as future mission planners, will use information from the entire LRO instrument suite, which includes:

•CRaTER (cosmic ray telescope for the effects of radiation). This Boston University/MIT instrument is characterizing the lunar radiation environment, allowing scientists to determine potential impacts for future astronauts and the materials used to protect them.

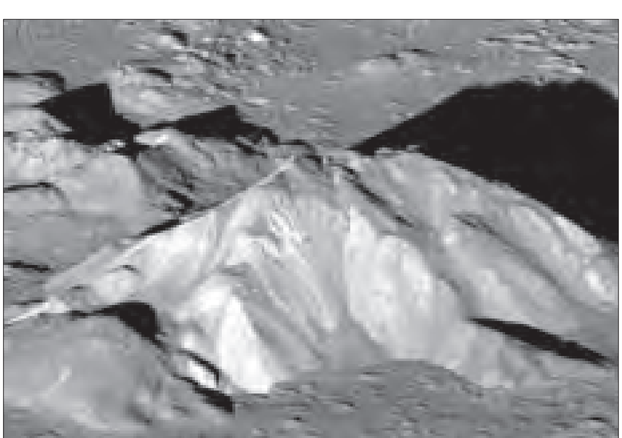
•LAMP (Lyman-Alpha mapping project). The LAMP instrument has found surface water ice in south polar regions. It is also providing images of permanently shadowed regions illuminated only by starlight and the glow of interplanetary hydrogen emissions, the Lyman-Alpha line. The instrument was developed and built at the Southwest Research Institute in San Antonio, Texas.

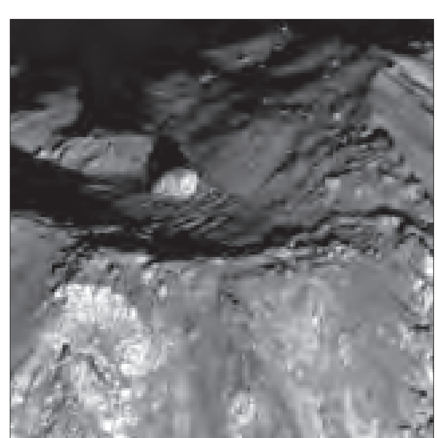
•DLRE (diviner lunar radiometer experiment). The DLRE has identified areas cold enough to preserve ice for billions of years, as well as rough terrain, rock abundances, and other landing hazards. Diviner was developed and built by UCLA and JPL.

•LEND (lunar exploration neutron detector). This instrument is creating high-resolution maps of hydrogen distribution and gathering information on the neutron component of the lunar radiation environment. These data have also been used to identify water ice near the Moon's surface. LEND was developed and built by the Russian Institute for Space Research in Moscow.

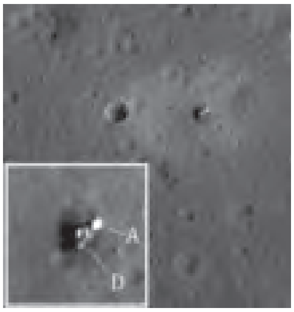
•LOLA (lunar orbiter laser altimeter). LOLA has been measuring the slope of potential landing sites and lunar surface roughness. It also has been generating a high-resolution 3D map of the Moon.

•Mini-RF. This Goddard instrument is a small synthetic aperture radar that helps to find ice deposits.

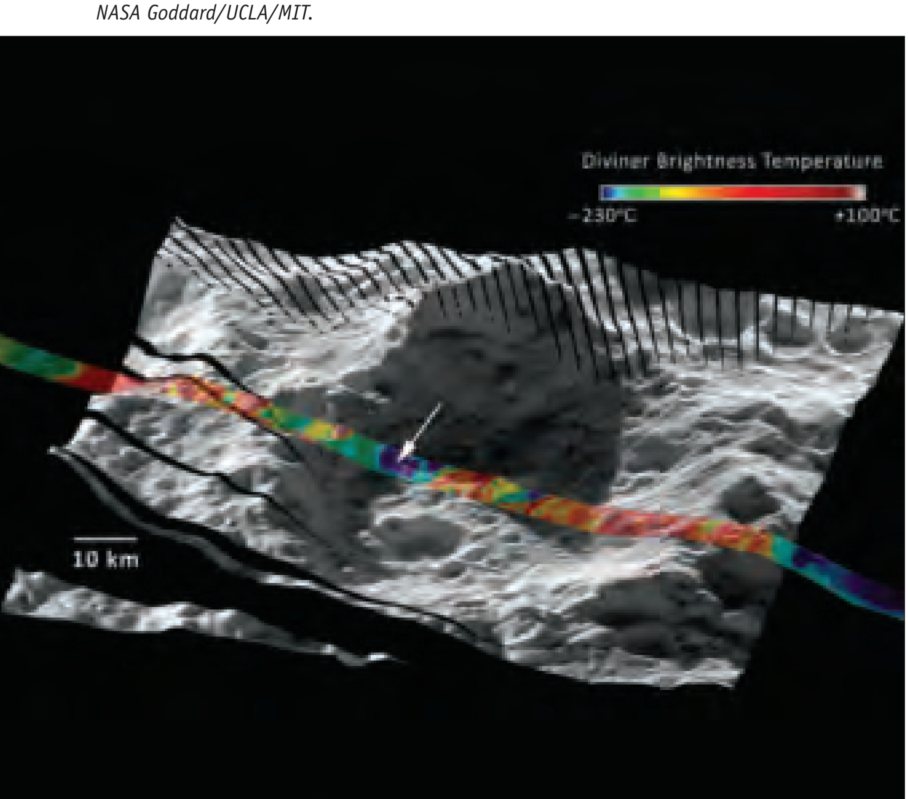




The LRO camera system captured the spectacular 6,500-ft central peak of the giant rayed crater Tycho (left). The peak was formed by the rebound of the lunar surface moments after an asteroid gouged out the crater 108 million years ago. Closer examinations (right) found the dot visible atop the central peak turned out to be a 400-ft-diam. lunar boulder—that would squash the Rose Bowl—sitting in rippled and hardened lava melt formed at the moment of impact then rained down on the peak moments after its thrust upward. Credit: NASA Goddard/Arizona State.



LRO geologists used lobate scarps, like this one on the Moon's far side, to help confirm that the Moon is still geologically active. In this particularly dramatic example, a thrust fault pushed crustal materials (arrows) up the side of Gregory crater, indicating that the Moon's crust was contracting in recent geologic time. Other features showed that the Moon's crust is expanding. Image courtesy: NASA Goddard/ Arizona State.



The LCROSS/Centaur impact location (arrow) is seen on an LRO digital terrain model created by the spacecraft's LOLA laser altimeter. Atop that has been overlaid a multicolor Diviner radiometer temperature swath acquired about 90 sec after impact, which launched a 12-mi.-high plume containing evidence of water ice. Credit: NASA Goddard/UCLA/MIT.

•LROC (lunar reconnaissance orbiter camera). There are actually two narrow-angle cameras on the LROC system taking high-resolution black-and-white images of the surface and capturing images of the poles with resolutions down to about 3.3 ft. A third, wide-angle camera is taking color and ultraviolet images over the surface at 330-ft resolution. The LROC system was developed at Arizona State University in connection with Malin Space Science Systems, San Diego. Narrow-angle camera image resolutions of 8 in. are being taken from as low as 12-mi. altitude.

By mid-2011, at a point where LRO operations transitioned from the Exploration Phase to the Science Phase, the LROC team at Arizona State University issued a new lunar global map with a resolution of 328 ft per pixel. To enhance the topography of the Moon, this map was made from images collected when the angle of the Sun was low on the horizon.

"Because the Moon is so close, and because we have a dedicated ground station, we are able to bring back as much data from LRO as from all the other planetary missions combined," says LRO project scientist Richard Vondrak of NASA Goddard. LRO's DLRE is providing new data sets regarding the Moon's surface. These include maps of visual and infrared brightness, temperature, rock abundance, nighttime soil temperature, and surface mineralogy. The data are in the form of more than 1,700 digital maps at a range of resolutions that can be overlaid easily on other lunar data sets.

LAMP, which collects information to help identify surface water ice deposits, especially in permanently shadowed regions of the Moon, also has new data. Among its new products are maps of far-ultraviolet brightness, albedo, and water ice data, as well as instrument exposure, illumination, and other conditions. As a complement to the high-resolution digital elevation maps, representing 3.4 billion measurements that the LOLA team has already released, the team is also delivering new maps of slope, roughness, and illumination conditions.

"All these global maps and other data are available at a very high resolution," says Goddard's John Keller, the LRO deputy project scientist. "With this valuable collection, researchers worldwide are getting the best view of the Moon they have ever had." The complete data set contains the raw information as well as high-level products such as mosaic images and maps. It also includes more than 300,000 calibrated data records released by the LRO camera team.

The data that prove the Moon is still geologically alive involve images showing that the lunar surface is both expanding and contracting.

How LRO made its key discovery

In August 2010, the LRO camera team identified physical signs of contraction on the lunar surface, in the form of lobe-shaped cliffs known as lobate scarps. The scarps are evidence the Moon shrank globally in the geologically recent past and might still be shrinking today. The team saw these scarps widely distributed across the Moon and concluded it was shrinking as the interior slowly cooled. The features were seen during Apollo, but their implications were not recognized.

Then in late 2011, additional LRO images revealed something totally different. This time the images showed the Moon's crust was also being stretched, a completely opposite process that formed tiny valleys in a few small areas on the lunar surface. Research analyzing high-resolution images obtained by the LRO cameras show small, narrow trenches typically much longer than they are wide. This indicates the lunar crust is being pulled apart at these locations. These linear valleys, known as graben, form when the Moon's crust stretches, breaks, and drops down along two bounding faults.

The graben were an unexpected discovery. They provided contradictory evidence that, in addition to regions contracting as shown by the newly discovered lobate scarps, other regions of the lunar crust are also being pulled apart, as indicated by the graben. "This pulling apart tells us the Moon is still active," Vondrak points out. "LRO gives us a detailed look at that process."

Striking water

The search for water resources, a major part of LRO's mission, got under way with a bang, literally.

Carried as a piggyback payload on the same launch with LRO was the $79-million LCROSS (lunar crater observation and sensing satellite) developed by NASA Ames in Mountain View, California.

Major new data about the presence of large quantities of water ice on the Moon were obtained by the targeted impact of the Atlas V's spent 2.5-ton Centaur upper stage, which struck a permanently dark south polar crater. That 6,200-mph impact was equivalent to detonating 2 tons of TNT on the lunar surface.

The resulting 5-mi.-high plume was followed just minutes later by the highly instrumented 1,370-lb LCROSS spacecraft, which flew through the plume, transmitting data before it too hit the lunar surface nearby. LRO also collected data from both plumes as it flew overhead.

LCROSS found an estimated 350 lb of water ice or water vapor within the debris cloud, and nine water-related chemical compounds, according to NASA Ames scientist Tony Colaprete and other LCROSS researchers. This was a major success for the program, even though no U.S. mission to use such resources is currently planned.

Exploring a crater

In another example of LRO finding water ice, the spacecraft has returned data that indicate ice may make up as much as 22% of the surface material in famous Shackleton crater at the lunar south pole.

Named after Antarctic explorer Ernest Shackleton, the crater is 2 mi. deep and over 12 mi. wide. Its floor has been in shadow for billions of years, making it extremely cold—and likely to have trapped multibillion-year-old ice delivered to the Moon eons ago via impacting comets and asteroids.

A team of NASA and university scientists using laser light from LRO's laser altimeter examined the crater floor. They found it to be brighter than those of other nearby craters, which is consistent with the presence of ice. "The crater's interior is extremely rugged," says Maria Zuber, the team's lead investigator from MIT.

While the crater's floor was relatively bright, Zuber and her colleagues observed that its walls were even brighter. The finding was at first puzzling—scientists had thought that if ice were anywhere in the crater, it would be on the floor, where no direct sunlight penetrates. The upper walls are occasionally illuminated, which could evaporate any ice that accumulates.

A theory offered by the team to explain this puzzle is that 'moonquakes'—seismic shaking brought on by meteorite impacts or gravitational tides from Earth—may have caused Shackleton's walls to slough off older, darker soil, revealing newer, brighter soil underneath. An ultra-high-resolution map created by Zuber's team provides strong evidence for ice on both the crater's floor and walls.

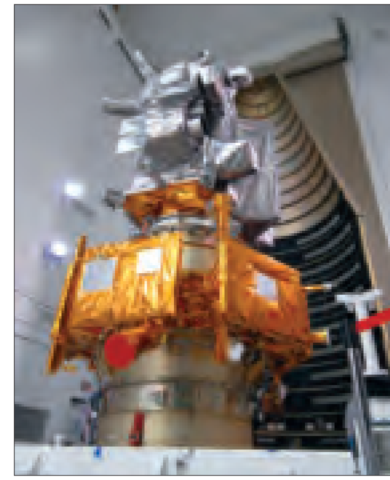
Zuber also leads the GRAIL (gravity recovery and interior laboratory) lunar mission, which has two other spacecraft in lunar orbit mapping gravity variations. The two craft have worked perfectly in tight formation flight, and the $496-millon GRAIL project is being completed well within budget with margin to spare, Zuber says.

Historic shots

While all of LRO's images of the lunar surface are striking, its pictures of the Apollo landing sites with the lunar module descent stages, astronaut footprints, and rover tracks are historic and poignant.

Vondrak notes that detailed examination of the Apollo descent stages shows no dust accumulations, indicating scant dust transport on the airless Moon. "This should allow the human hardware of Apollo left on the Moon to remain intact for 10 million-100 million years," he says.

The new LRO data that prove the U.S. flags at the Apollo 12, 16, and 17 landing sites still fly were assembled by the "Moon Zoo" citizen science project. The flags themselves are not visible. Moon Zoo participants linked then animated numerous LRO high-resolution images of each landing site with different Sun angles. This shows



The Lunar Reconnaissance Orbiter, wrapped in silver insulation, sits atop the gold insulation wrapped LCROSS impact spacecraft before both were attached to Atlas V Centaur upper stage at Cape Canaveral. Credit: NASA KSC.

December marks the 40th anniversary of Apollo 17's last Apollo landing on the Moon. In this LRO image of the Taurus-Littrow site note the tracks of astronauts Gene Cernan and Jack Schmitt to the left of the lunar module and the four-wheeled lunar rover tracks to the right. Credit: NASA Goddard/Arizona State.

that shadows of each flag move as daytime Sun angles change. The fate of the Apollo 14 and 15 flags remains unknown and Apollo 11's flag was blown over by that crew's liftoff from the Moon.

The 8-in., highest resolution imaging of the Apollo sites came as LRO was periodically maneuvered down to only 12-mi. altitude to see lunar geology in extreme new detail. Two things are especially evident at the Apollo 11 site where astronauts Neil Armstrong and Buzz Aldrin touched down on July 20, 1969. One is that Armstrong's footprints are distinctly visible where he trotted behind the Eagle lunar module to look into Little West crater and then photographed the module from that vantage point. The other, taking in LRO's overhead view as a whole, is what a tiny, temporary, and delicate human foothold on another world Tranquility Base is.

Solving other mysteries

The LRO spacecraft is also bringing back to life some historic Soviet missions, including a 38-year-old mystery about a major Soviet Moon mission failure.

Missing on the Moon for 42 years, the Lunokhod 1 lunar rover and the Soviet Luna 17 lander that carried it to the lunar surface in 1970 were found by LRO. Note the fork-like ramps on which the rover descended to the surface and the rover tracks surrounding the lander. LRO found Lunokhod 1 about 6.5 mi. from the lander near the center of the Imbrium Basin. Credit NASA Goddard/Arizona State.

The Soviet Luna 23 spacecraft was launched in November 1974 from the Baikonur Cosmodrome atop a large Proton booster. The spacecraft was a 6.5-ton, 12-ft-tall vehicle meant to land on the Moon and drill 7 ft into the lunar surface to obtain subsurface samples that it would then fire back to Earth.

Two earlier spacecraft, Luna 16 in September 1970 and Luna 20 in February 1972, had previously done this successfully, after 11 major failures.

Luna 23 maintained radio contact with Earth after touchdown on Mare Crisium, but ground controllers feared from telemetry that it had landed at too high a velocity.

It was to lower its sampling drill immediately, then transfer its precious load of lunar material to a basketball-sized, ablative-covered Earth reentry vehicle mounted atop the bright silver canister of electronics attached to a propulsion stage.

If all had gone as planned, it would have been fired back to Earth within about 24 hr. But after three days of communications and no sampling activities, Luna 23 went dead.

Two years later, in an impressive feat of targeting, the Soviets managed to command an identical Luna 24 sample return spacecraft to land within 1.5 mi. of the long-dead Luna 23 to sample the same area.

That ended the Soviet lunar program, and Luna 23 was forgotten—but not by the Goddard and Arizona State LRO camera team. They began to search high-resolution LRO images of Mare Crisium and found Luna 23—looking like new, but toppled over on its side. Mystery solved.

Its bright upper canister was unmistakable, lying crosswise atop the large mass of the lander and ascent propulsion system. LRO also found the successful Luna 24 descent stage, sitting upright, just 1.5 mi. to the northeast. Its upper stage and reentry vehicle had departed the Moon and delivered 170 g of lunar material to Earth in August 1976.

In another find, one of the biggest in its three years in lunar orbit, LRO solved another Soviet space mystery, and this time the result was important not just to Russian space history but also to continuing lunar and Earth studies: It discovered the USSR's missing Lunokhod-1 Moon rover, which Soviet ground controllers had lost 42 years ago after driving it 6.5 mi. onto the west side of the Imbrium Basin. (Viewed from Earth, the basin makes up the left eye of the 'man in the Moon.')

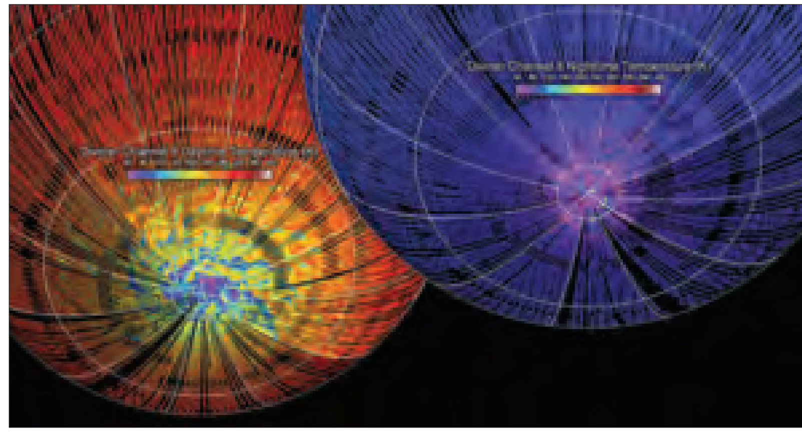
Lunokhod 1 weighs nearly a ton and is shaped like an eight-wheeled bathtub, standing 4.5 ft high and 5.7 ft long. The discovery will finally enable Earth-based lasers to use it as a target for ongoing geodetic and gravity measurement studies, including the validation of theories proposed by Albert Einstein.

The laser system at Apache Point Observatory in New Mexico has begun firing on Lunokhod 1 and receiving laser returns from its French-built retroreflectors.

Because of Lunokhod 1's location away from the Apollo retroreflectors, its discovery is especially important for lunar geophysical studies. Its position near the northwestern limb of the Moon and the ability to receive reflected-back laser light when the Moon is in daylight are special attributes of the big rover.

LRO also found the Luna 17 lander, whose ramps enabled Lunokhod 1 to descend to the surface. The imagery shows numerous wheel tracks around the lander made by the Soviet rover before it departed to explore the surface, where it was lost until its location was precisely pinpointed for the Apache Point geodetic researchers.

The primary objective of the original LRO mission was to enable safe and effective exploration of the Moon. "To do so, we needed to leverage the very best the science community had to offer," says Michael Wargo, NASA's chief lunar scientist. "By doing that, we've fundamentally changed our scientific understanding of the Moon." A



LRO's Diviner radiometer detects south polar temperature differences during the day (left) and at night where some north polar areas are found to be nearly -400F, the coldest place in the solar system. Image courtesy: NASA Goddard/UCLA.