The New Moon

BY PAUL D. SPUDIS

Recent lunar missions have shown that there is still much to learn about Earth's closest neighbor

THE MOON does not yield her secrets easily. Although Earth's airless satellite was the first planetary object to be explored by spacecraft and the only body ever visited by astronauts, scientists still have many unanswered questions about its history, composition and internal structure. In recent years, researchers have called for renewed exploration of the moon; the European Space Agency and Japan are planning to send probes into lunar orbit, and NASA is considering landing an unmanned spacecraft on the moon's far side. By studying the moon, these missions may also illuminate the history of all the rocky planets in the inner solar system: Mercury, Venus, Mars and especially Earth. Because the moon's surface has remained relatively unchanged for the past three billion years, it may hold the key to understanding how the inner planets formed and evolved.

When astronomers first gazed at the moon through telescopes 400 years ago, they found that its surface consists of two principal types of terrain: bright, rugged, heavily cratered highlands and dark, more sparsely cratered lowlands. Galileo Galilei, the 17th-century astronomer, called the lowlands *maria*—Latin for "seas"—because of their smooth, dark appearance. One of the biggest surprises of the space age came in 1959, when the Soviet spacecraft Luna 3 photographed the moon's far side, which had never been seen before because it is always turned away from Earth. The photographs showed that it almost completely lacks the dark maria that are so dominant on the near side. Although scientists now have some theories that could explain this dichotomy of terrain, it remains an unsolved puzzle.

Analysis of the lunar rocks and soil brought back to Earth by the Apollo astronauts and by unmanned Luna landers allowed researchers to get a glimpse of the moon's evolution. The evidence suggests that the moon was created about 4.5 billion years ago when a Mars-size body hit the early Earth. This collision sent a spray of vaporized rock into orbit around Earth, and these small bodies rapidly coalesced into the moon. They accumulated so quickly that the heat generated by the process melted the outer portion of the nascent moon and formed a global ocean of liquid rock, or magma. The

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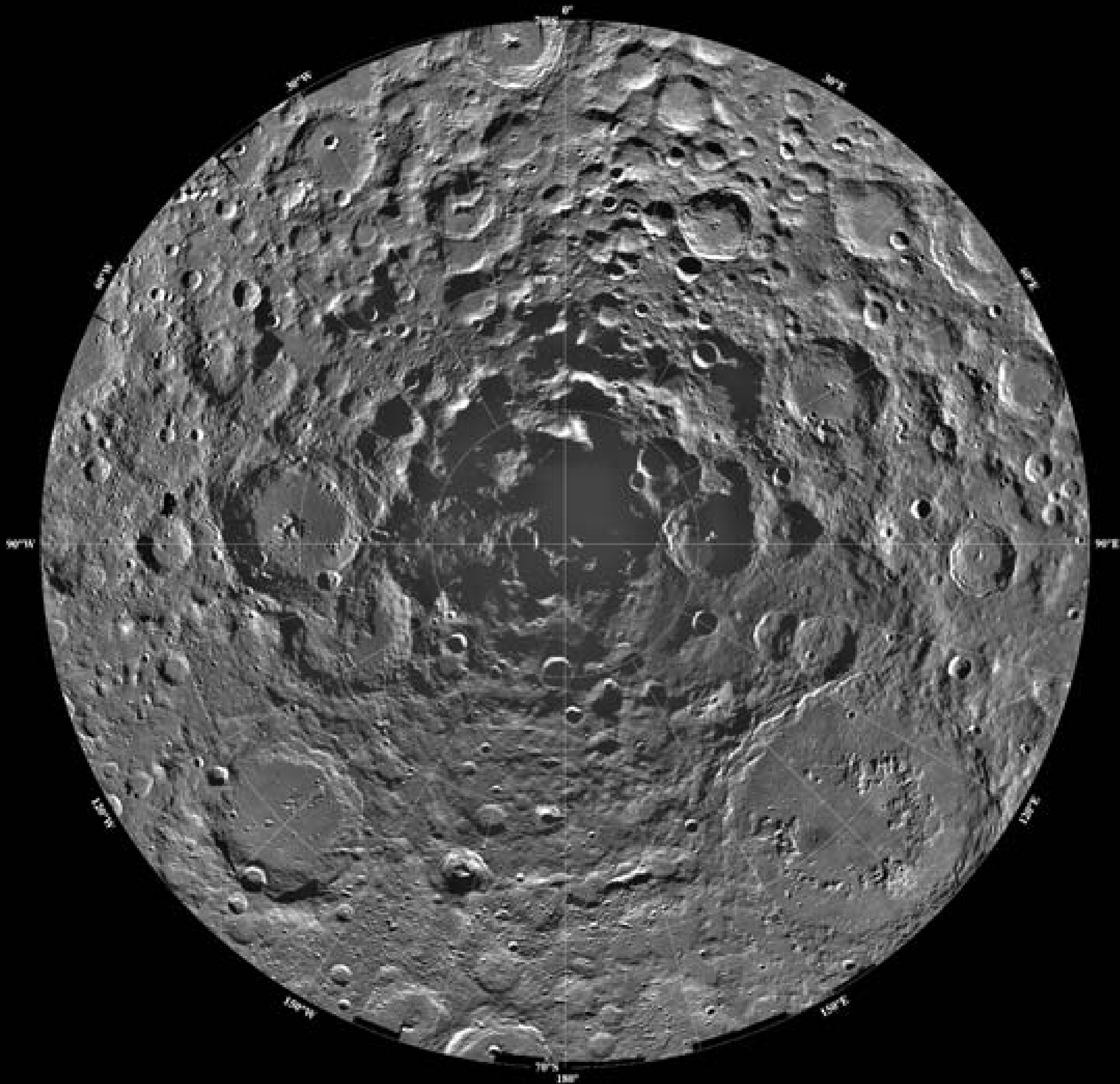
MOON'S SOUTH POLE is shown in this mosaic of 1,500 images taken by the Clementine spacecraft's ultraviolet/visible camera in 1994. The pole is at the center of the mosaic; the lunar latitude of 70 degrees south is at the edge. Both Clementine and the Lunar Prospector orbiter found evidence of water ice in the permanently shadowed areas near the moon's poles.



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lunar crust then formed from low-density minerals that floated to the surface of this magma ocean.

This early phase was followed by a violent pelting of the moon's surface by comets, asteroids and meteoroids. Some of the larger objects blasted out enormous basins more than 2,000 kilometers in diameter. Most craters and basins, at least on the near side, were filled with iron-rich basaltic lava over the next 300 million to 400 million years, forming the dark maria seen today. As time went on, the bombardment eased, with impacts becoming less frequent and less powerful. This fact explains why the maria, which are younger than the highlands, have fewer and smaller craters. Little has occurred on the moon since about three billion years ago; after the volcanic fires died, the only activity has been the occasional formation of an impact crater, the constant rain of micrometeorites and the six blink-of-an-eye visits by a dozen astronauts more than 30 years ago.

Because the moon has experienced impact, volcanism and tectonic activity, it can serve as a touchstone for understanding those processes. In particular, the moon's companionship to Earth makes it an ideal place for studying the extraplanetary events that occurred in this part of the solar system during its early history. Nearly all traces of the asteroids and comets that struck Earth billions of years ago have been erased from our planet's geologically active surface. Yet this record is preserved on the moon, where it can be recovered and read.

Scientists learned much from the Apollo explorations, but many mysteries remained after that program ended. Researchers realized that they needed to map the moon globally with a variety of remote-sensing instruments. A hint of the fascinating discoveries awaiting global reconnaissance came from two flybys of the Earth-moon system in the early 1990s by the Jupiter-bound Galileo spacecraft. In the southern hemisphere of the moon's far side, mission scientists saw an unusual signature of high-iron rocks in the floor of the South Pole–Aitken (SPA) basin, the largest basin on the moon. Galileo also mapped some of the maria using spectral filters that provided information on surface composition; the results suggested that researchers could use remote spacecraft data to delineate the sequence of lava flows in the maria.

Maria and Highlands

IN 1994 the U.S. Department of Defense launched the Clementine spacecraft. Its goal was to test lightweight sensors developed for national ballistic-missile defense while traveling in a polar orbit of the moon. Clementine successfully orbited the moon for 71 days. It obtained a complete global map of the lunar surface in 11 wavelengths in the visible and near-infrared parts of the spectrum. The spacecraft also carried a laser ranger that allowed researchers to make a topographic map of the entire moon for the first time. In addition, radio tracking of the spacecraft's orbit provided better information on the moon's gravity field. And an improvised radar experiment uncovered tantalizing hints that water ice exists in the permanently shadowed areas near the lunar south pole.

Following up on Clementine, NASA sent the Lunar Prospector spacecraft into a polar orbit of the moon in 1998. One of NASA's Discovery-class missions, Lunar Prospector mapped the moon's surface composition using gamma-ray and neutron spectroscopy. It confirmed Clementine's detection of ice near the south pole and discovered additional deposits at the north pole. An alpha-particle spectrometer measured gas emissions from the lunar interior while a magnetometer mapped the distribution of local surface magnetic anomalies. Additional radio tracking of the spacecraft improved our knowledge of the moon's gravity field. Finally, ground controllers deliberately crashed it into the moon in an attempt to induce a release of water vapor from the surface. Telescopes on Earth and in space were trained on the crash site to observe a vapor plume, but none was detected.

By putting the Apollo discoveries in a global context, the Clementine and Lunar Prospector measurements prompted scientists to revise their understanding of the moon and its history. For example, in the Oceanus Procellarum, a huge depression in the western part of the moon's near side, the astronauts of *Apollo 12* and *Apollo 14* found anomalous basaltic rocks that were rich in trace elements collectively known as KREEP ("K" for potassium, "REE" for rare-earth elements and "P" for phosphorus). Geologists refer to these trace elements as incompatible—that is, they do not fit well into the crystal structures of common rock-forming minerals. The presence of KREEP-rich rocks indicates that the early moon underwent intense melting and differentiation, a process in which the incompatible elements were concentrated in the molten part of an increasingly solid, crystallized system. Lunar Prospector revealed that the highest concentrations of KREEP occur in the Oceanus Procellarum, although the reason for this unusual distribution is not clear.

Furthermore, the lunar orbiters confirmed that the highlands of the moon are dominated by anorthosite, an igneous rock composed primarily of the mineral feldspar and rich in calcium and aluminum. These rocks were created early in lunar history, when the outer portion of the moon was completely molten; the low-density anorthosite floated to the sur-

Overview/*The Moon's Mysteries*

- In the 1990s the Clementine and Lunar Prospector spacecraft provided scientists with global maps of the moon's topography, surface composition, gravitational variations and magnetic anomalies.
- The findings gave context to the discoveries made by the Apollo missions but also raised new questions. In particular, researchers want to know more about the violent bombardment of the moon that occurred about four billion years ago.
- The European Space Agency, Japan and the U.S. plan to send more unmanned probes to the moon to solve some of the lingering lunar mysteries.

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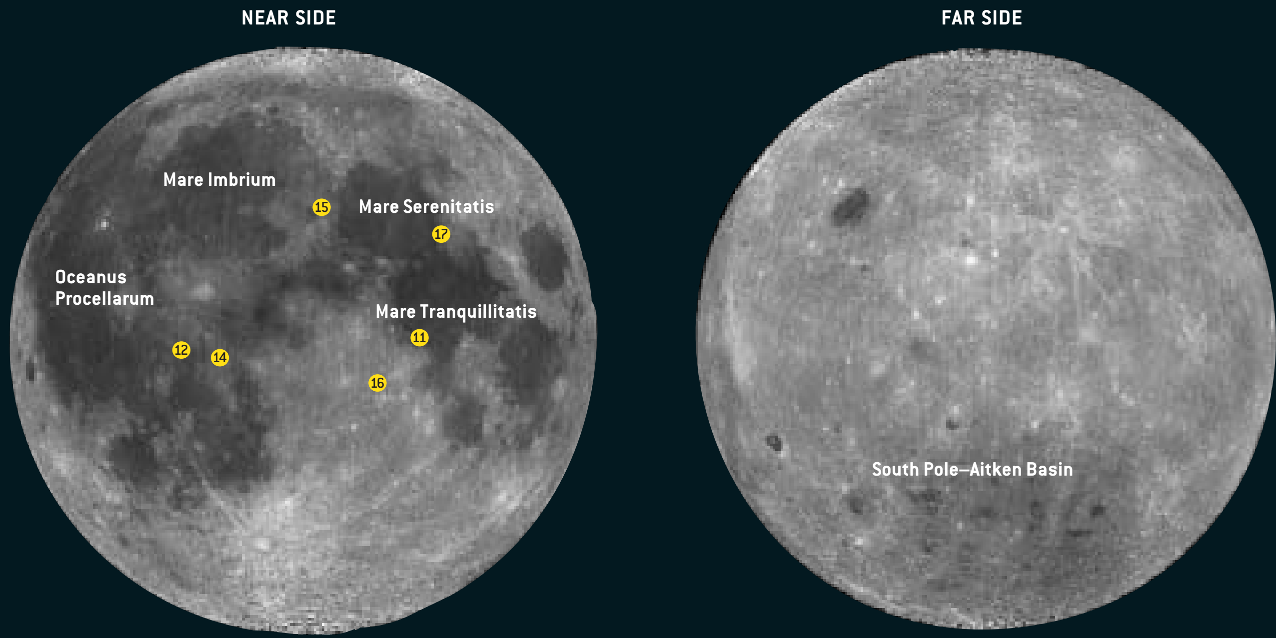
Light and Dark



CLEMENTINE'S IMAGES of the moon's near side show the two principal types of terrain: bright, heavily cratered highlands and dark, smooth lowlands called maria. In contrast, the far side almost completely lacks maria. Six Apollo missions visited the near side (the yellow circles show the landing sites and mission numbers). Now NASA wants to send a robotic lander to the far side.

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face of the magma ocean. Although scientists had postulated this phase of lunar history based on the Apollo samples, the proof came from the Clementine and Lunar Prospector data, which indicated the global distribution and large abundance of anorthosite. Because the only source of heat that could melt the entire moon would be a very rapid accumulation of small bodies, the presence of large quantities of anorthosite in the lunar crust supports the theory that the moon coalesced from the debris of a planetary collision.

The lunar orbiters also explained one of the more puzzling discoveries of the Apollo missions: the unusually high content of titanium in the mare basalts collected by the *Apollo 11* astronauts during the first moon landing. Lunar geologists had been hard-pressed to explain how very high density, titanium-rich magmas could have ascended through the moon's low-density anorthosite crust. Clementine and Lunar Prospector showed that the high-titanium lavas found by *Apollo 11* are actually quite rare on the moon. Although mare basalts have a range of titanium concentrations, only a small fraction have the extreme compositions observed at the first landing site in the Sea of Tranquility. Lunar researchers learned a valuable lesson: samples from a single location on the moon are not necessarily representative of large regions.

Because lava flows typically have uniform and distinct compositions, the data from Clementine and Lunar Prospector can be used to map the flows that have occurred in the maria. The age of each flow can then be determined by measuring its density of impact craters. Older mare flows have been exposed to bombardment longer than younger flows, so they have higher crater densities. Scientists already know the ages of the mare flows at the Apollo sites from analyzing the radioisotopes in the rock samples, so they can estimate the ages of other flows by comparing their crater densities with those of the landing-site flows. The results show that although the moon has mare lavas of widely varying compositions and ages, the bulk erupted between 3.8 billion and three billion years ago.

Although maria are recognized by their dark color, certain areas of the highlands appear to be intermediate in reflectance and contain relatively high amounts of iron. Some of these surfaces are mare deposits that have been covered by blankets of highland debris—layers of ejected rock spread by the impacts that created the moon's basins. Because these mare lavas predate the highland debris layers, which were laid down during basin formation 3.8 billion years ago, they indicate that the eruption of lava onto the moon began well before the ages of the oldest mare flows sampled by Apollo. Global mapping has shown that these ancient mare flows are very widespread across the far side of the moon and the limb regions (the border between the near and far sides).

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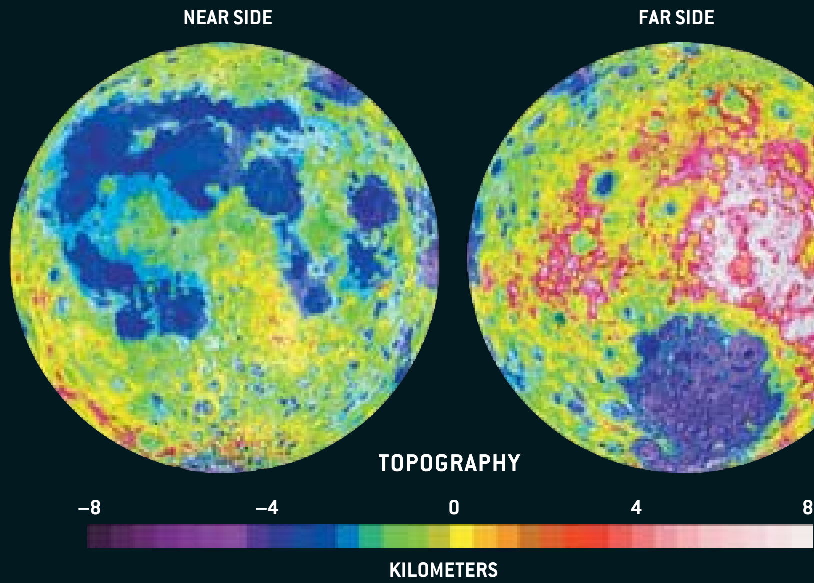
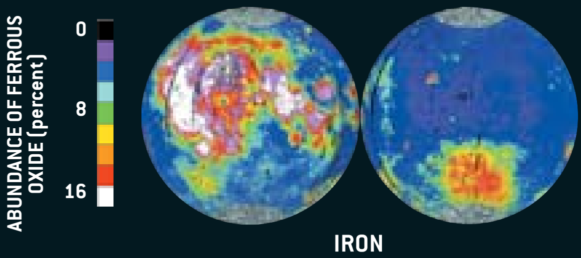
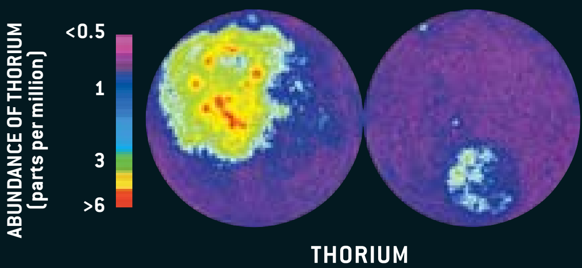
Moon Maps

THE OBSERVATIONS made by the Clementine and Lunar Prospector spacecraft enabled scientists to draw the first detailed global maps of the moon's surface. Clementine carried a laser ranger that measured the distance to the surface once a second during each polar orbit. The results showed the enormous extent of the South Pole–Aitken basin (*purple splotch on moon's far side*), an impact feature that stretches 2,600 kilometers across.

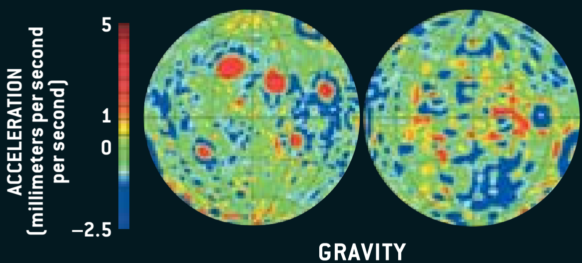




CLEMENTINE'S CAMERAS captured images in 11 wavelengths in the visible and near-infrared parts of the spectrum. Using data from two of those wavelengths (750 and 950 nanometers), researchers created a map showing the concentration of iron in the soils of the lunar surface. Iron levels are highest in the maria on the near side and lowest in the central part of the far side (above the South Pole–Aitken basin).

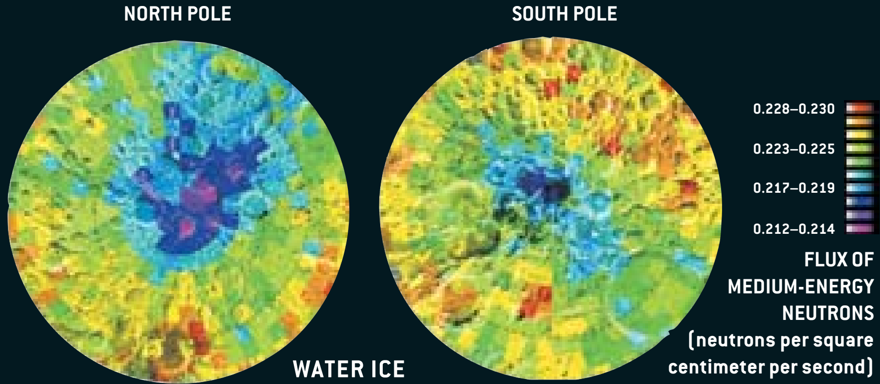


GAMMA-RAY SPECTROMETER was used by Lunar Prospector to measure the abundance of 10 elements in the moon's crust. One of those elements was thorium, which behaves much like the trace elements collectively known as KREEP—it does not fit well into the crystal structures of common rock-forming minerals. The highest levels of thorium occur in the Oceanus Procellarum on the near side, but the reason for this unusual distribution is not clear.



TRAVELING IN AN ORBIT that came as close as seven kilometers to the lunar surface, Lunar Prospector was able to precisely measure variations in the moon's gravity. Careful tracking of the spacecraft's orbit revealed stronger than expected gravity (*red areas*) above some of the youngest impact basins. One possible explanation is that plugs of dense rock from the lunar mantle may have risen toward the surface of the basins after impact.

LUNAR PROSPECTOR also discovered evidence of water ice at the moon's poles. The craft's neutron spectrometer found a lack of medium-energy neutrons bouncing off permanently shadowed areas (*purple*). Ice slows down neutrons because of collisions with hydrogen atoms in water molecules. The results confirmed Clementine's detection of ice in these dark areas.



PAUL D. SPUDIS AND LUNAR AND PLANETARY INSTITUTE (*topography, iron and thorium maps*); REPRINTED BY PERMISSION FROM A. S. KONOPLIV ET AL. IN *SCIENCE*, VOL. 281, PAGES 1476–1480, 1998 (*gravity map*), AND W. C. FELDMAN ET AL. IN *SCIENCE*, VOL. 281, PAGES 1496–1500; 1998 (*water ice map*); © 1998 AAAS

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Bumpy and Lumpy

THE MOON IS a very rough world. The difference in altitude from its lowest point (within the SPA basin) to its highest (on the rim of the Korolev basin on the far side) is more than 16 kilometers. On Earth, where the maximum altitude differential is about 20 kilometers, surface topography is the result of tectonic activity that creates high mountain belts and deep ocean trenches. The moon, in contrast, has a static outer shell; the lunar crust has been cold and rigid for at least the past four billion years. Topographic relief on the moon is entirely related to impact craters and basins. It is no accident that the largest basin on the moon is also the locale for the greatest extremes in altitude, although it is somewhat surprising that such a large and old feature still retains most of its original relief.

Internally, the moon also appears to be quite lumpy. Radio tracking of the trajectory of Lunar Prospector, which traveled in a low orbit that came as close as seven kilometers to the lunar surface, showed stronger than expected gravity above some of the youngest impact basins. Scientists do not think the mare basalts in the basins are the source of the gravity anomalies; individual lava flows appear to be quite thin—from a few meters to a few tens of meters—and total accumulations are typically 200 meters or less. Rather researchers believe the mass concentrations are plugs of dense rock from the lunar mantle that rose toward the surface of the basins after impact.

The moon's unusual dichotomy of terrain, with the near side dominated by dark maria and the far side by bright highlands, may also be explained by structural differences under the surface. Although scientists have not definitively resolved this problem, the most likely reason for the dichotomy is that the crust on the near side is relatively thinner, and therefore ascending magmas can reach and break through the surface more easily there than on the far side. The enormous SPA basin contains most of the mare lavas on the far side, yet even these deposits are very thin and of limited extent. The SPA basin as a whole is largely unfilled by mare lavas, whereas even the smallest basin on the near side tends to have copious lava fill.

The topographic map produced by Clementine's laser ranger revealed the astounding dimensions of the SPA basin, which stretches 2,600 kilometers across, making it the largest impact crater in the entire solar system. Clementine also documented the presence of numerous additional basins, some of which were unknown before the orbiter's flight. Researchers now estimate that the moon has more than 45 basins (defined as impact features with diameters greater than 300 kilometers). Based on crater densities within the basins, SPA appears to be the oldest and Orientale the youngest.

Scientists, however, know the absolute ages of only the basins that were visited by the Apollo and Luna missions. Radioisotope dating of the impact-melt samples—rocks that melted when an asteroid or comet struck the moon, therefore revealing when an impact occurred—shows that all these basins formed in a narrow interval between 3.9 billion and 3.8 billion years ago. This small range of basin ages has been interpreted to mean that the moon experienced a very high impact rate for a short period, which has been dubbed the lunar cataclysm.

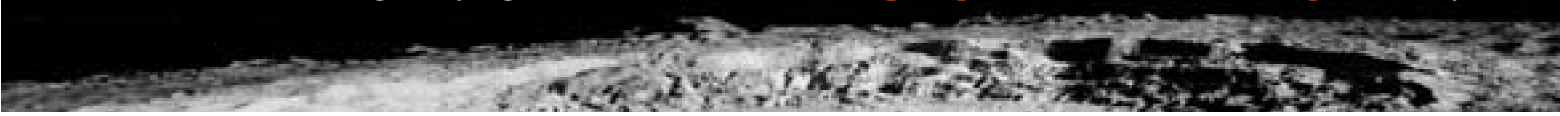
But how could such a deluge have occurred? Models of the solar system's early history posit that the frequency of impacts should have tapered off between 4.5 billion and four billion years ago because most of the planetesimals—the small rocky bodies that formed from the solar nebula—were gradually cast out of the inner solar system or absorbed by the outer planets. If researchers can confirm that the lunar cataclysm did indeed occur, the discovery would have profound implications for the history of all the inner planets. It is possible, for example, that a very large body in the asteroid belt broke apart about 3.9 billion years ago and that the debris was swept toward the Earth-moon system. If that is the case, it could mean that lunar cratering history is unique and cannot be used as a guide for dating features on other planets besides Earth.

One way to tell whether the lunar cataclysm actually occurred would be to determine the absolute age of the SPA basin. Scientists know that SPA must be older than any other lunar basin, and the oldest of the basins that can be reliably dated from impact-melt samples is Mare Serenitatis, which is estimated to be 3.87 billion years old. The impact that created SPA clearly happened after the lunar crust solidified, which occurred about 4.3 billion years ago. The age of SPA must therefore fall between these dates, but nearer to which end?

If SPA is found to be close in age to the other basins, then scientists would have a strong argument for the lunar cataclysm. On the other hand, if SPA's age is determined to be close to the solidification age of the lunar crust, there would be no need to postulate a lunar cataclysm. The moon's cratering history could be seen as evidence of an exponentially declining frequency of impacts. In this case, the lunar record could indeed serve as a guide to the interpretation of cratering on inner planets such as Mars. To date the SPA basin, however, researchers would need to obtain samples of its impact melt.

Perhaps the most exciting result of the Clementine and Lunar Prospector mis-

The moon may hold the key to understanding how the INNER PLANETS FORMED AND EVOLVED.



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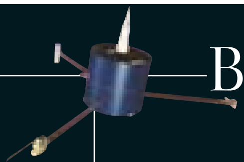
sion was the evidence of water ice at the lunar poles. Because the moon's spin axis is inclined just 1.5 degrees—that is, its axis is almost perpendicular to the plane of Earth's orbit around the sun—the sun is always at or near the horizon when viewed from the lunar poles. (In contrast, Earth's axis is tilted about 23 degrees.) If a place near the lunar pole is about 600 meters above the average surface elevation, it is in permanent sunlight; if it is at least 600 meters below the surface, it is in perpetual shadow. In the latter areas, the only sources of heat would be the meager amount of radioactive decay from the lunar interior and the feeble cosmic radiation. Scientists estimate that these permanently dark regions, which have existed for two billion to three billion years, are extremely cold—on the order of –223 to –203 degrees Celsius. These cold traps could accumulate water ice derived from comets and meteorites hitting the moon, because the ice would never be vaporized by sunlight.

Although Clementine did not carry any instruments specifically designed to search for polar ice, the mission's science team was able to improvise an experiment using the radio transmitter onboard the spacecraft. Whereas rocky surfaces scatter radio waves randomly, ice partly absorbs the waves and reflects some of them coherently. When Clementine directed radio waves at permanently shadowed regions near the moon's south pole, the reflected signals were characteristic of an icy surface. Four years later the neutron spectrometer carried by Lunar Prospector showed large amounts of hydrogen in the dark regions of both poles; the most likely explanation is that the craft detected the hydrogen in water ice. Current estimates indicate that more than 10 billion tons of ice exist within the upper foot or so of the surface at both poles. Researchers do not know, however, the physical state of this material, its exact composition, purity or accessibility. This knowledge can be acquired only by future missions to the moon.

The images from Clementine also showed that some regions near the moon's poles appear to be in near-constant sunlight. An area near the rim of Shackleton crater, for example, is illuminated for more than 75 percent of the lunar rotation period. These areas have a relatively benign thermal environment, with surface temperatures ranging from –60 to –40 degrees C. (In contrast, temperatures near the lunar equator swing from –150 to 100 degrees C.) Locating an unmanned or manned outpost in one of the sunlit areas near the poles would greatly ease the challenge of designing equipment to survive the temperature extremes of the lunar surface. And if ice could be retrieved from a permanently



Back to the Moon

The resurgence of scientific interest in the moon has inspired space agencies to plan new lunar missions.

Spacecraft	Country	Launch Date	Mass without Fuel (kilograms)	Lunar Research
PAST AND PRESENT MISSIONS				
Clementine	U.S.	Jan. 25, 1994	227	Used cameras and laser ranger to map surface composition and topography. Radar experiment found first evidence of water ice at the lunar poles.
Lunar Prospector	U.S.	Jan. 7, 1998	158	Spectrometers revealed abundance of elements in the crust and detected further evidence of ice. Magnetometer and electron reflectometer measured magnetic fields.
SMART-1	European Space Agency	Sept. 27, 2003	280	On arrival at the moon in early 2005, camera and spectrometers will chart the moon's minerals and peer into dark craters to search for ice.
FUTURE MISSIONS				
Lunar A	Japan	Aug.–Sept. 2004	520	The orbiter will drop two penetrators that will burrow into the surface on opposite sides of the moon. Seismometers and heat-flow sensors will probe the lunar interior.
SELENE	Japan	2005	1,600	Large array of cameras, spectrometers and other instruments will map the moon's surface composition, topography, gravity and magnetic fields in even greater detail.
South Pole–Aitken Basin Sample Return	U.S.	Before 2010	To be determined	Robotic lander will collect samples of rock and soil from the basin floor and rocket them to Earth for analysis of age and composition.

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dark area nearby, the base would have a source of water that could be used for life support as well as for rocket fuel (by breaking the water into liquid hydrogen and oxygen, the most powerful chemical propellants).

Return to the Moon

AS A RESULT of the successes of Clementine and Lunar Prospector, a spate of new lunar missions are in various stages of preparation. In September the European Space Agency launched the SMART-1 spacecraft, whose primary mission is to test an ion-propulsion engine during a 16-month journey to the moon. After entering lunar orbit, SMART-1 will use a camera and x-ray sensor to map the moon's surface. In 2004 Japan is scheduled to launch Lunar A, an orbiter that will drop two hard-landing probes, called penetrators, to the moon's surface. Equipped with seismometers and heat-flow sensors, the probes will gather information on the moon's interior and possibly map its core. And in 2005 Japan plans to follow up the mission with a larger orbiter called SELENE. This craft will map the moon in even greater detail using x-ray and gamma-ray spectrometers, a terrain camera, a laser altimeter and a radar sounder.

In addition, the newly appreciated significance of the SPA basin has revived the idea of landing a robotic probe there to collect samples and rocket them to Earth for analysis. A 2002 report by a panel of scientists sponsored by the National Academy of Sciences advocated such a mission. The primary goal of the effort would be to obtain samples of the SPA basin's impact melt. By revealing when the basin formed, these rocks could settle the question of whether there was a lunar cataclysm. Moreover, because the impact melt is a composite of all the rocks that were struck by the colliding asteroid or comet, studying it could reveal the composition and structure of the lunar crust in the basin target site. Some researchers suspect that the colliding object may well have penetrated the crust and exposed parts of the upper mantle, possibly from depths as great as 120 kilometers. If the impact melt contains some material from the mantle, scientists may be able to characterize in some detail the composition of the deep lunar interior.

A sample-return mission to the SPA basin is simple in concept but difficult to execute. Mission planners must select a landing site that would yield the proper samples to solve the scientific issues concerning the SPA's age and composition. Researchers can use existing remote-sensing information to identify areas that, by virtue of their composition and geologic setting, are good candidates to yield the desired rocks. Because the sites would be on the moon's far side, the lander would have to either operate autonomously or communicate with ground controllers through a relay satellite.

What is more, the spacecraft must obtain both rocks and soil from the landing site. Rocks are needed to analyze the mineralogy and date the samples, whereas the soil enables scientists to determine whether the collected rocks are actually representative of the area. (The soil may also contain small fragments of rare or exotic rock types.) The samples must be packed into a small Earth-return vehicle carried by the lander. This vehicle would then use a rocket engine to lift it off the moon and put it on a course back to Earth. After using Earth's atmosphere to decelerate, the vehicle would land in a remote area and turn on a radio beacon to attract the recovery team. All these elements make the mission ambitious and technically challenging, but it is well within our capabilities.

NASA has already requested proposals for a sample-return mission to the SPA basin, which could be launched before 2010. But when will astronauts return to the moon? There are numerous scientific reasons for human exploration. A manned mission would provide excellent opportunities for a whole range of studies, from planetary exploration to astronomy. And the existence of water ice at the lunar poles could make it much easier to establish a permanent human presence. NASA has recently sketched out proposals that would permit new human missions to the moon using existing launch and space transportation infrastructure, thereby saving billions of dollars in development costs.

But the return of astronauts to the moon requires a political rationale, not a scientific justification. It will never be undertaken solely for scientific purposes, nor should it. The missions must address a wide range of national concerns. Once we do return, though, new vistas of scientific possibilities will beckon. We have read part of the moon's story, but much is still murky. Future exploration will most likely show us that the history of our closest neighbor is more complicated and interesting than we ever imagined. SA

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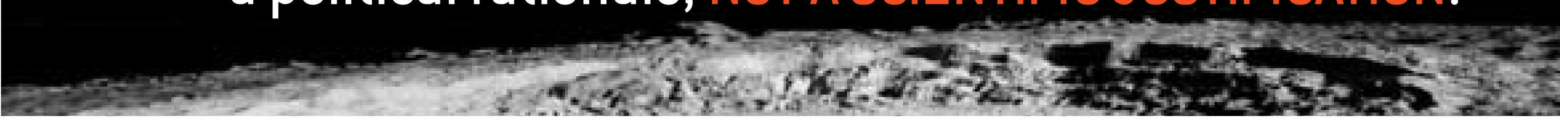

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MORE TO EXPLORE

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