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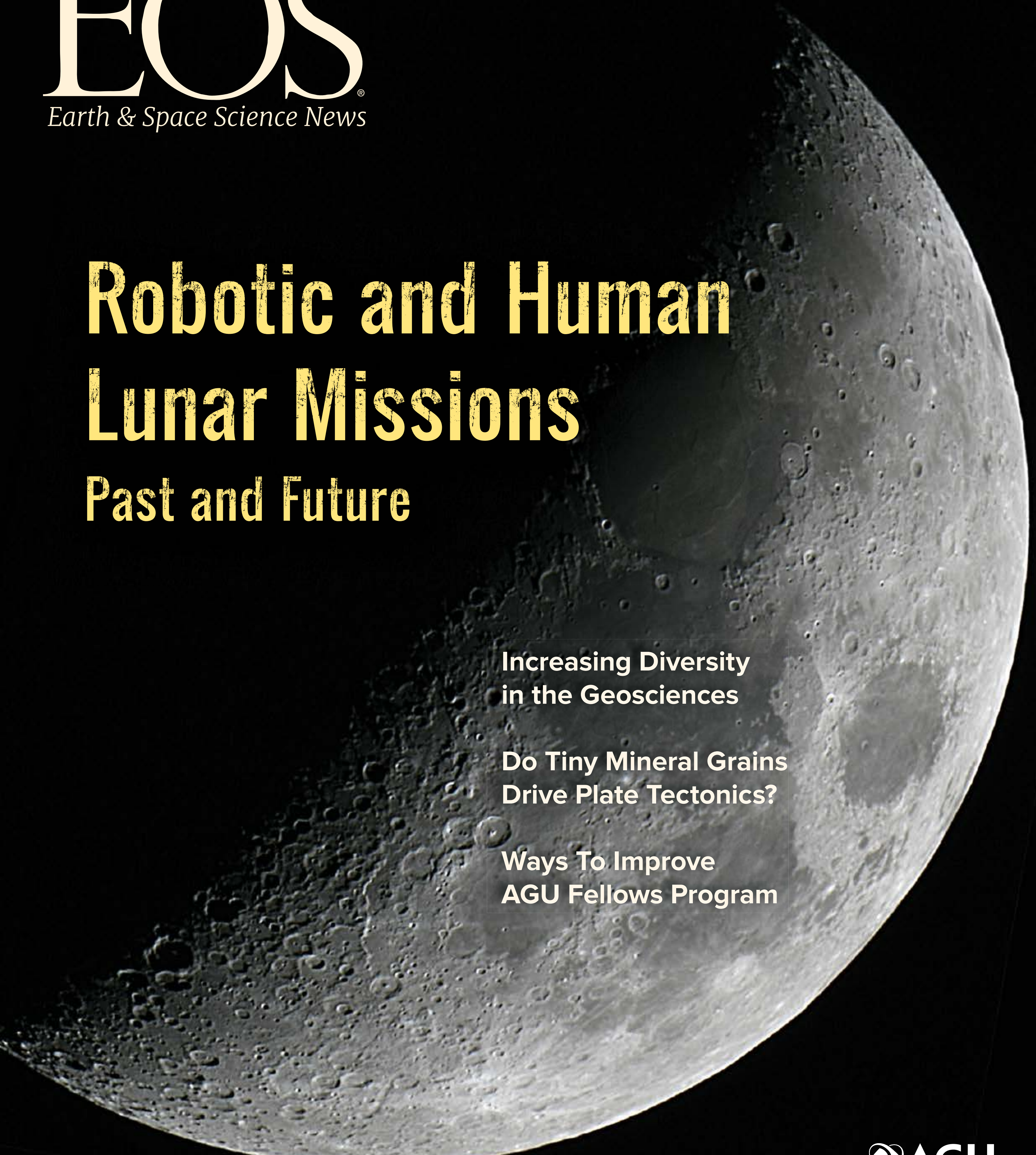

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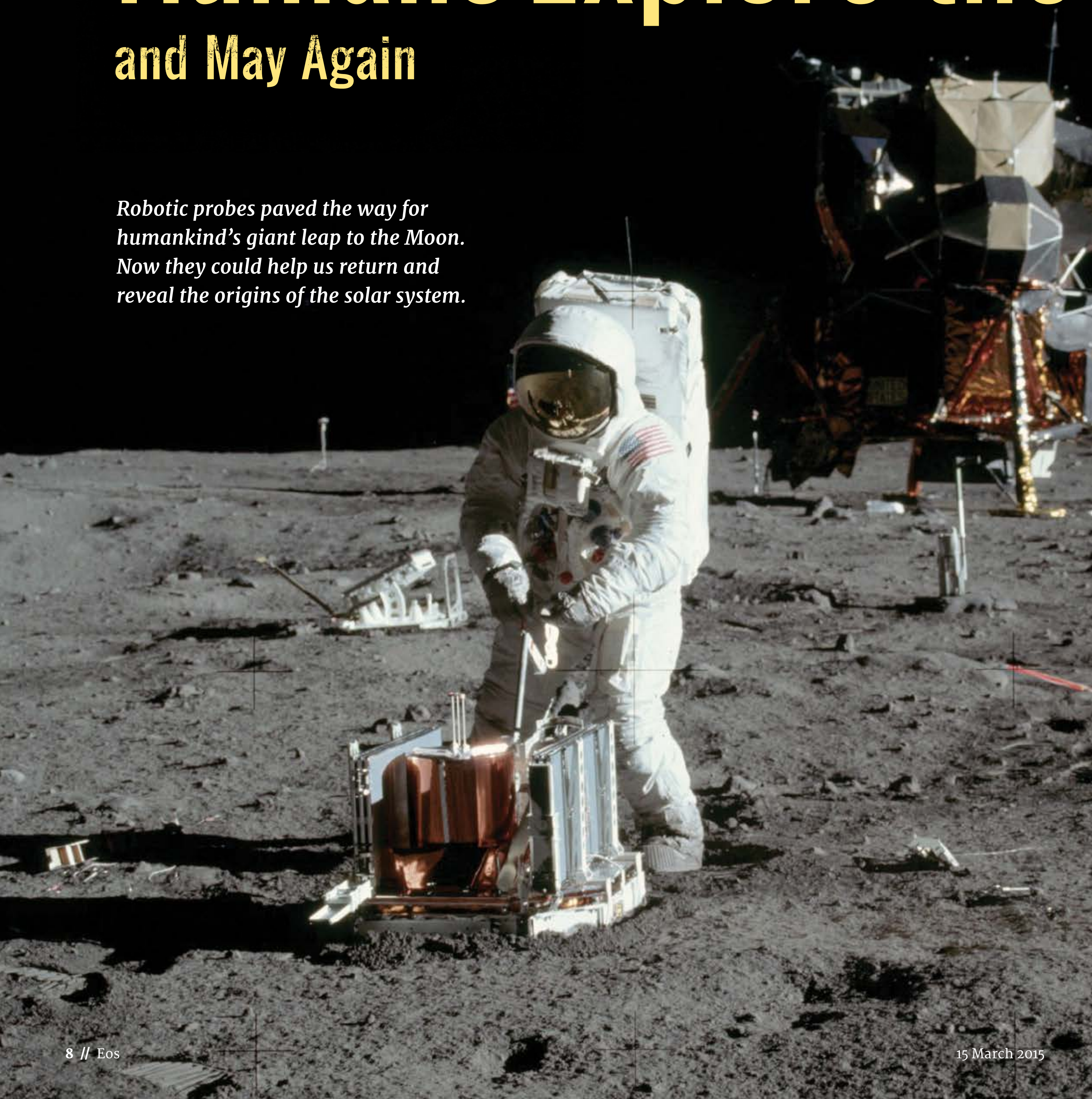
How Robotic Probes Helped Humans Explore the and May Again

Robotic probes paved the way for humankind's giant leap to the Moon. Now they could help us return and reveal the origins of the solar system.



Moon...

By David A. Kring

NASA/Apollo 11

Fifty years ago, on 17 February 1965, NASA launched the Ranger VIII robotic spacecraft toward the Moon. Three days later, the vehicle provided the world's first high-resolution glimpse of what would become Tranquility Base—the landing site of Apollo 11, where humans first stepped onto another planetary surface.

Together, the Ranger VIII results and subsequent Apollo 11 mission illustrate the tremendous value of an integrated robotic and human space exploration program. Uncrewed craft snapped pictures for mission planning and tested landing technologies. However, only Apollo's human crews could perform the intensive field work that paved the way for that era's scientific legacy.

These lessons may help guide the international scientific community as it considers future plans for lunar exploration. They point the way to a new series of lunar missions in which robotic spacecraft and humans could work together to solve the most pressing mysteries surrounding our solar system's formation.

Beginning with Impact

The U.S. government started the Ranger program in 1959 to conduct lunar science and compete with the Soviet Union's Luna program. However, in 1962, when President Kennedy announced plans to safely land astronauts on the Moon and return them to Earth, NASA redirected Ranger to support this effort, dubbed the Apollo program.

The Ranger program's primary objective involved characterizing the fine-scale structure of the lunar surface and thus determining if robotic and human missions could land on the surface safely [*Trask*, 1970]. The Ranger spacecraft did so by flying toward the Moon, taking photographs at ever-lower altitudes until they hit the lunar surface.

NASA/JPL

The Ranger VIII spacecraft.

Ranger VIII was the second successful mission in a series of nine spacecraft. It targeted one of the Moon's dark plains—formed by ancient lava flows since cooled into basalt—called Mare Tranquillitatis, Latin for the "Sea of Tranquility." Scientists studying lunar photographs, made with telescopes on Earth, found the plain alluring in part because it was relatively flat terrain close to the equator—attributes that made it more accessible for the first attempt at landing a crew on the Moon. The spacecraft carried six television cameras with different exposure times, fields of view, lenses, and scan rates.

In the 23 minutes before crashing into the lunar surface, Ranger VIII continually transmitted back to Earth full scans from its wide-angle camera A and narrow-angle camera B, providing 60 and 90 frames,

Apollo 11's mission to the Moon relied, in part, on data from Ranger VIII, its first robotic precursor.

LPI

A shaded relief chart made by Ranger VIII of the Sabine Region (roughly between 3.00°N and 1.00°S and 19.00°E and 24.00°E). The chart includes the area where Apollo 11's Eagle lander touched down, roughly near the center of the map's right edge. Scale is 1:250,000.

respectively, with about 5 seconds between frames on each camera. Camera B pointed farther south than camera A and captured several pictures of the terrain that would become Tranquility Base from an altitude as low as 229 kilometers. The spacecraft hit the lunar surface 68 kilometers north-northeast of what would later become Tranquility Base.

Scientists used the images to make a series of shaded relief charts with depths of impact craters estimated using shadow lengths. In parallel and with the same data, the U.S. Geological Survey (USGS) generated a series of geologic maps for the Moon.

Using Ranger VIII images, *Wilshire* [1967] completed a preliminary map of the Sabine Region, including the area where Apollo 11 would land, at a 1:250,000 scale. However, work on Ranger-based maps eventually slowed as personnel began shifting to NASA's next phase of robotic lunar exploration: sending craft to orbit and land on the Moon.

Orbiters and Landers

NASA began the Lunar Orbiter (LO) program in 1964, launching five spacecraft specifically designed to photograph potential Apollo landing sites. From the Lunar Orbiter images, officials selected eight sites for detailed study. The USGS assigned *Grolier* [1970a, 1970b] the task of unraveling the geology of the Mare Tranquillitatis site, also known as Apollo Landing Site 2. He based his map principally on seven high-resolution images that LO II acquired in November 1966.

The final phase of NASA's robotic Apollo preparations was to demonstrate landings themselves and test surface conditions. To do this, NASA initiated the Surveyor program while lunar photogeologic studies were under way. Within a year of the LO II flight, Surveyor V landed in a small 9 × 12 meter crater 25 kilometers northwest of what would become Tranquility Base.

Surveyor V survived three lunar nights (14 Earth-day periods without sunlight), finally succumbing and going dark after about 107 Earth days. Surveyor V, the first lunar lander to carry an alpha particle backscattering instrument, produced the first estimates of the lunar surface's chemical composition.

Excited, geologists confirmed that the maria were composed of basalt, meaning the Moon was a differentiated body with a crust derived by partial melting of a mantle with a low silica content.

Astronaut Harrison Schmitt used the last image taken from Ranger VIII to develop a hypothetical moonwalk route around a hypothetical lander in Mare Tranquillitatis.

Choosing Tranquility Base

After Surveyor V and the success of Apollo 8, the first human mission around the Moon, researchers still had not decided on the site for the first lunar landing. The Ranger VIII, LO II, and Surveyor V spacecraft had provided important precursor data for Apollo Landing Site 2, increasing its favorability. In addition, in 1966, astronaut Harrison Schmitt (who later flew on Apollo 17) had used the last image from camera B on Ranger VIII to develop a hypothetical moonwalk route around a hypothetical lander in Mare Tranquillitatis [*Schmitt*, 1966].

This mapping exercise provided a measure of mission reality that did not exist for any other landing site. Schmitt used it to argue that the simulated landing of the lunar module (LM) in the upcoming Apollo 10 mission should be above that site. Schmitt won his case, and Apollo 10 performed a dress rehearsal for Apollo 11 landing over Apollo Landing Site 2.

In June 1969, map makers with the U.S. Army delivered to NASA 116 charts and geologic maps, complete with NASA's robotic images and the USGS's geologic interpretations [*U.S. Army Topographic Command*, 1969]. The Apollo 11 astronauts carried these with them when they launched the following month.

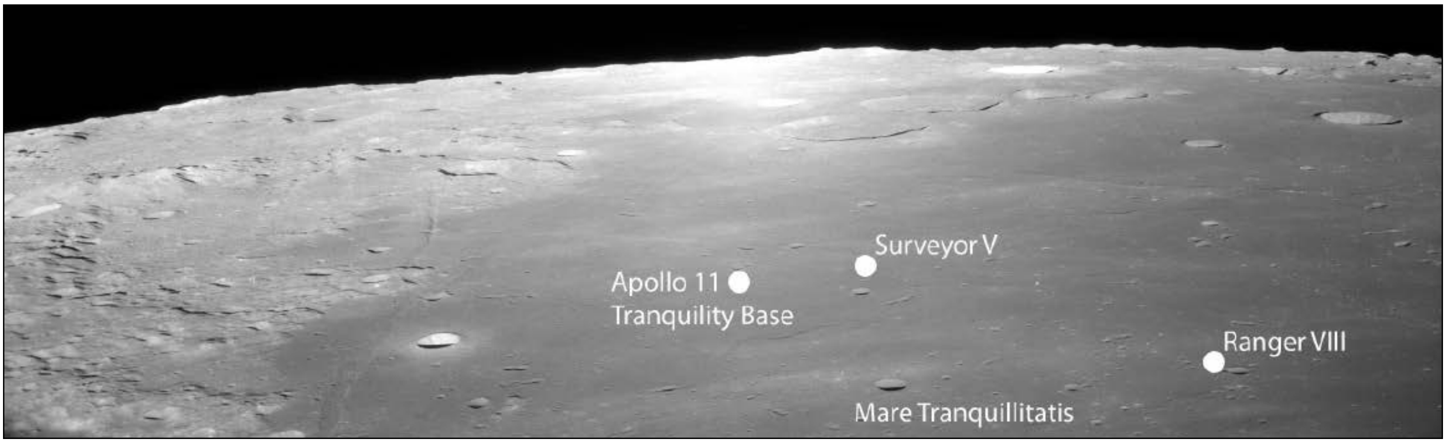
The charts and photogeologic maps of the landing area included maps at 1:100,000 and 1:25,000 scales that mapped out the anticipated landing zone and the boulders and craters that Apollo 11's lander would have to dodge.

The Eagle Has Landed…Where?

As Apollo 11's "Eagle" LM descended toward the lunar surface on 20 July 1969, carrying Neil Armstrong and Edwin "Buzz" Aldrin, a cascade of factors knocked the Eagle off course. These included the initial jolt of undocking from Apollo 11's Command Service Module (CSM), a series of test firings of the Eagle's thrusters, and variations in the Moon's gravity field encountered during the descent [*Mission Evaluation Team*, 1971].

Although the Eagle was flying over the geology mapped on the 1:25,000 charts, the crew did not know where they were on those charts. Occupied by resolving multiple alarms during the descent, they did not have an opportunity to monitor the landscape until they found themselves less than 600 meters above the surface [*Mission Operations Branch*, 1969]. By that point, Armstrong and Aldrin were not where they expected to be, and their trajectory would take them beyond the LO II high-resolution photographic coverage that had been used to certify safe landing sites.

Armstrong and Aldrin landed several kilometers west and south of their target, about 1.5 kilometers beyond the geology mapped on the 1:25,000 charts created from LO II data. They ended up in the older of two mare surfaces shown on the 1:100,000 geology map. At the time, however, they had no landmarks to place themselves. Michael Collins in the orbiting CSM could not locate the Eagle either.



NASA AS11-41-6091

Mare Tranquillitatis (the Sea of Tranquility), showing the crash site of Ranger VIII, the landing site of Surveyor 5, and Apollo 11's Tranquility Base.

A Scientific Bonanza

Despite the initial uncertainties in the LM's position, the value of a sample return mission involving a crew soon became obvious from the scientific bonanza that followed. This value only grew with each subsequent Apollo mission.

Analysis of the returned samples showed Mare Tranquillitatis to be volcanic, composed of at least two relatively iron- and titanium-rich basalts that were very old (3.6–3.9 billion years old). The regolith—lunar "soil"—also contained igneous dust and loose rocks characterized by plagioclase feldspar. Distant impact cratering events in the highlands likely kicked up this anorthositic material.

Petrological and geochemical analysis of this material led to the completely novel idea that an extensive magma ocean covered the early Moon and that the lunar crust formed from material floating to the top of this rapidly solidifying ocean.

Finally, several key studies of Apollo 11 samples and photography strongly suggested that most craters on the Moon formed from impacts, not from volcanic eruptions.

Geologists generated these big ideas of the Moon's evolution after analyzing samples collected from only 2.2 hours of astronauts' field work. In addition, during that time, Armstrong and Aldrin also managed to deploy a television camera, an experiment to measure solar wind composition, seismic monitoring instruments, a lunar dust detector, and a mirror for Earth-based laser ranging experiments, the latter of which remains in use.

To the Moon Again and Beyond

On 5 December 2014, NASA launched the first test flight—uncrewed—of its next-generation Orion crew vehicle. It was propelled to an altitude about 15 times higher than the International Space Station. Orion then returned to Earth at 80% of the speed of a spacecraft returning from the Moon. The success of the mission, including Orion's atmospheric reentry and recovery, provides an opportunity to revitalize an integrated robotic and human exploration program to the Moon and beyond.

Exploration of the Moon will address fundamentally important scientific questions, according to a broad international consensus of scientists [e.g., *National Research Council* (NRC), 2007], while also providing a credible path to carry humanity beyond low-Earth orbit [e.g., *International Space Exploration Coordination Group* (ISECG), 2013]. Toward that goal of renewed lunar exploration, scientists have accumulated new insights from a new generation of robotic spacecraft sent to the Moon. These spacecraft include the United States's Clementine, Lunar Prospector, Lunar Reconnaissance Orbiter, Gravity Recovery and Interior Laboratory (GRAIL), and Lunar Atmosphere and Dust Environment Explorer (LADEE); Europe's Small Missions for Advanced Research in Technology (SMART-1); China's Chang'e series of orbiters; Japan's Kaguya; and India's Chandrayaan-1.

Orbital spacecraft, supplementing the insights from Apollo and the missions before it, indicate the Moon is the best and most accessible place to evaluate the origin and evolution of the entire solar system. This evaluation could include new insights on the earliest evolutionary phases of our own planet, which through plate tectonics, crustal recycling, and constant weathering, have since been erased from Earth's rock record.

The Moon contains evidence of how it formed through accretion and differentiated into layers of crust, mantle, and core, which is a model for the origin and evolution of other solar system planets. It also records the history of asteroid and comet impacts on that crust, which is essential to evaluating the environmental and biological consequences of such events, both on Earth and on other potentially habitable worlds such as Mars.

Target: South Pole–Aitken Basin?

A 2007 report from the U.S. National Research Council—one of the most comprehensive studies of lunar exploration objectives—outlined 35 prioritized investigations. A global landing site study [*Kring and Durda,* 2012] concluded that the majority of the objectives could be addressed in the Moon's South Pole–Aitken basin.

At 2500 kilometers across, South Pole–Aitken is one of the largest impact basins in the solar system. Within it, the 320-kilometer-wide Schrödinger basin holds the most promise for finding scientific pay dirt. A sample return mission to Schrödinger has the potential to address the two highest science priorities from the *NRC* [2007] report. First, it could determine the length of the basin-forming epoch—the geological period in the Moon's early history when objects that formed enormous basins like South Pole–Aitken smashed to the surface. Second, samples from Schrödinger could help determine the age of South Pole–Aitken.

In addition, because the basin is so well preserved, it is a perfect target for discerning the geological processes of such impacts. Those processes also uplifted material from great depth, producing a ring of crystalline massifs. These exposed layers of rock may date back to when, according to a prevailing hypothesis, the Moon was covered by a magma ocean (before South Pole–Aitken formed).

That material, when combined with material exposed in the basin walls, can be used to reconstruct a cross section of the lunar crust. The melted rock on the floor of Schrödinger basin can be used to derive the bulk composition of that crust.

Scientists think that long after the impact melt solidified, magmas rose through the basin and erupted on its floor, producing mare basalt flows and an immense vent spewing hot rock and gas. The basalt and pyroclastic vent can also be used to probe the thermal evolution of the lunar interior. The

New lunar landers have yet to be designed, meaning that the world no longer has the capability to land crew on the Moon's surface. To accomplish sound science without this capacity, researchers are seeking to combine robotic and human capabilities.

pyroclastic vent may also yield deposits of volatiles (such as sulfur and water) and fine-grained material that can easily be excavated, transported, and processed for use on the Moon to support a sustainable exploration effort.

Toward Sample Return Missions

To adequately address the *NRC* [2007] lunar objectives, sample return missions are required. The best results and those that maximize the advantages of an integrated robotic and human exploration program would be obtained by a trained crew on the lunar surface.

In pursuit of that type of integrated program, robotic efforts from many nations are under way. China recently landed a robotic spacecraft in Mare Imbrium as a precursor to a human landing scheduled for 2025–2030. Russia is planning a series of five robotic spacecraft, including a sample return mission that may involve the European Space Agency. Those efforts are part of an international community road map [*ISECG*, 2013] that includes a human-assisted robotic sample return mission circa 2024 and a human lunar surface mission circa 2028.

Unfortunately, new lunar landers have yet to be designed, meaning that the world no longer has the capability to land crew on the Moon's surface. To accomplish sound science without this capacity, researchers are developing plans for an alternative (and hopefully interim) solution combining robotic and human capabilities.

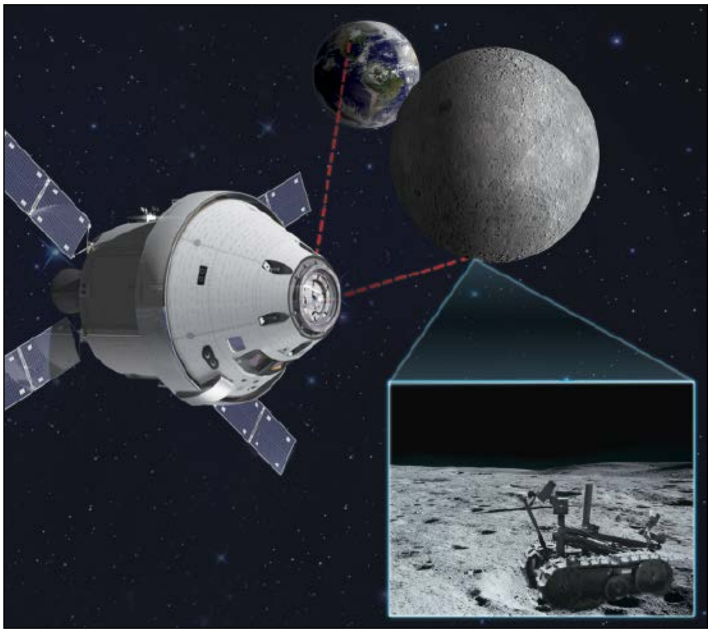
A Robotic Moon Lander Complemented by a Hovering Orion?

Burns et al. [2013] outlined a plan to deploy robotic vehicles—a Moon lander—to Schrödinger basin that could be operated remotely by a crew in the Orion spacecraft. In this plan, Orion would hover above the Moon's farside around Earth-Moon Lagrange position L2.

Candidate landing sites with traverses, along which a rover would collect samples and return them to the ascent vehicle, have already been identified [*Potts et al.*, 2015]. This vehicle would then rendezvous with Orion so that crew could return the samples to Earth.

This mission would present technical challenges that scientists and engineers will need to solve as part of the redevelopment and expansion of capabilities to explore beyond low-Earth orbit. It would also demonstrate Orion's capabilities to conduct long-duration operations, traveling 15% farther than Apollo and spending 3 times longer in deep space. It would practice teleoperation of rovers, which is an anticipated skill for future missions to Mars. It would also simultaneously address a majority of the *NRC* [2007] science objectives.

This mission or a similar one could deploy an astrophysical observatory, another high-priority *NRC* [2010] objective, and a communications satellite for future robotic and human missions. Joint scientific and engineering studies continue with the hope that this integrated robotic and human mission will be the first of many milestones that enhance our ability to explore space.



LPI/David A. Kring

In a concept using NASA's new Orion crew vehicle, astronauts would orbit above the lunar farside and remotely operate a robotic vehicle while maintaining communication with Earth. Samples collected by a rover would be launched to Orion, where they would be stowed before the crew returned to Earth.

Acknowledgments

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Author Information

David A. Kring, Lunar and Planetary Institute, Universities Space Research Association, Houston, Texas; email: kring@lpi.usra.edu