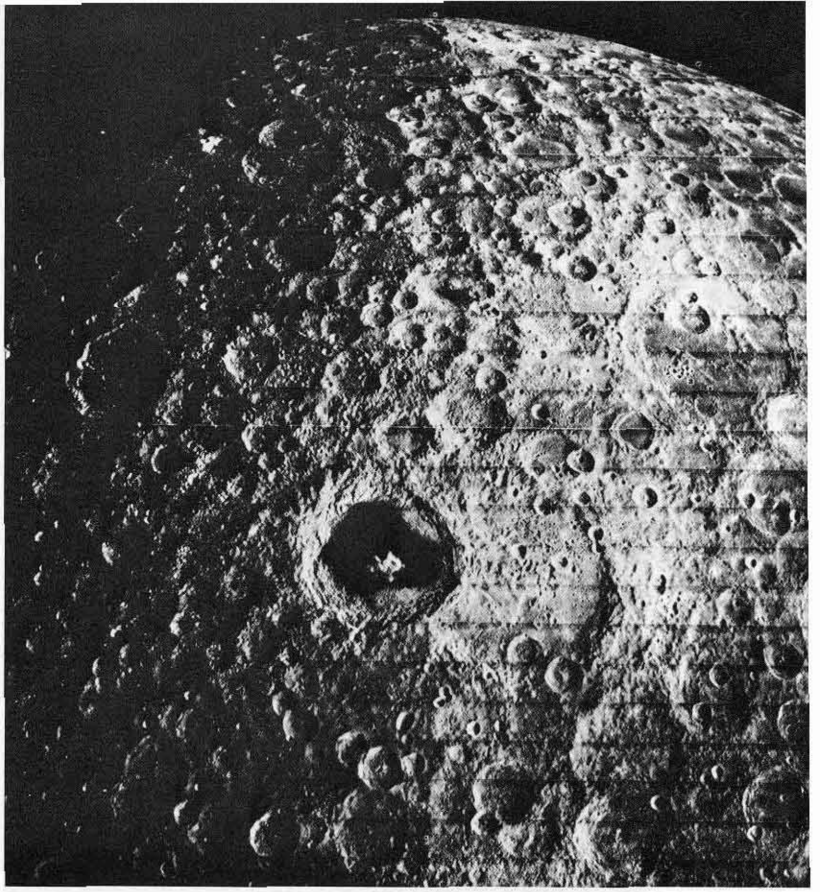
Seen relatively close up by the Apollo 15 Command Module, the 150-mile-wide crater Tsiolkovsky looks like a frozen lake with a high white peak rising from the center. The floor of the crater is of dark mare material, and it is one of the few scattered dark areas on the far side of the moon. The front side is nearly half covered with mare material.

The Moon and Beyond

by BEVAN M. FRENCH, MS '60

No longer just our satellite, the moon has become a base and a proving ground, no longer a destination but a way station on the road of continuing exploration



Photographed from an altitude of 900 miles by Lunar Orbiter III, Tsiolkovsky looks less like a frozen lake than a black eye in the relatively light-colored "face" of the back side of the moon. The crater was named after a Russian pioneer in rocketry.

In the centuries before the Apollo Program, we watched the moon as we might watch a stranger passing to and fro outside our house. Now we have gone outside to meet the stranger. The moon has become an acquaintance, and she has now revealed to us much of her own personal history.

The illumination of the moon's past is probably the greatest scientific triumph of the Apollo Program, for we now have the record of another world to compare with the history of our own planet.

Despite the flood of chemical and historical information obtained by the Apollo Program, we still do not have a single, universally accepted theory for the origin of the moon. Because scientific theories always die hard, the three pre-Apollo theories (double planet, fission, and capture) have all survived the Apollo results, though often with considerable modifications.

A completely successful theory of lunar origin must explain the evidence that the moon has been a separate and unique body since its formation. It also must account for significant differences in the chemistries of the earth and the moon. This chemical disparity is the major stumbling block of the "double planet" theory, which argues that the earth and moon were both formed together in the collapsing dust cloud that became the solar system. It is hard to believe that such major chemical differences could have been produced in two bodies that formed so close together. Consequently, most current explanations for the origin of the moon combine modifications of the other two traditional theories, fission and capture.

But the original version of the fission theory—that the moon spun off as a single body from a rapidly rotating earth—has also been undercut by the Apollo data. The chemical differences between the earth and moon, especially the absence of volatiles in the moon, are so profound that it is hard to argue that the earth and moon ever were part of the same body.

A newer variation of the fission theory suggests that the moon was built up gradually from a heated atmosphere that was thrown off a hot, rapidly spinning primordial earth. During its formation, the earth was heated up by collisions with small bodies until the temperature in its outer layers was over 2,000°C. At such a high temperature, both volatile materials and some less volatile elements like silicon, aluminum, and magnesium boiled off the primitive earth into a dense atmosphere around it. As this atmosphere cooled, the less volatile elements condensed into small rocky particles which were spun into orbit around the earth and then assembled to become the moon. The moon thus developed by separating from the earth atom by atom instead of by separation as a single mass. Since it holds that the moon formed from material whose volatile elements were removed by the intense heating, this theory does account for the different chemical compositions of the earth and moon; but, like the original fission theory, it still has a number of problems.

Apollo's confirmation of the chemical differences between the earth and moon has led still other scientists to argue that the moon formed somewhere else in the solar dust cloud and was then "captured" by the earth. However there is some disagreement as to *where* in the solar system the moon might have formed. The loss of volatile elements indicates a high temperature of formation, which prompts some scientists to place the origin of the moon near the center of the solar system, inside the present orbit of Mercury. But if it had originated there, it would have developed an enrichment in iron, as the dense planet Mercury apparently did. Unfortunately for this argument, the moon has a relatively low iron content. Another snag in the capture theory is that the captured body has to be slowed down in order to go into orbit around a planet like the earth. A possible explanation is that the moon was slowed down by crashing into a swarm of smaller bodies which circled the earth at that time.

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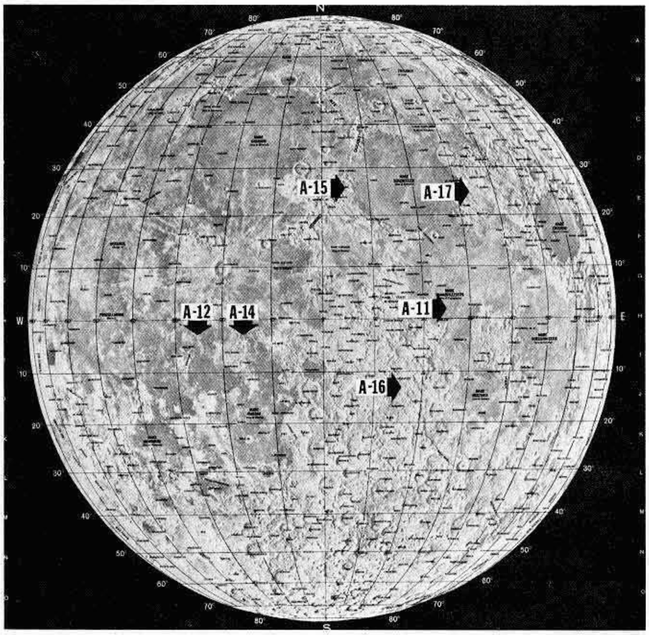


Like footprints, the locations of the six Apollo lunar landings mark the areas men have actually studied on the surface of the moon. The Apollo program has made man a space traveler, and space a permanent part of his environment.

All of these theories explain some of the data about the moon, and all of them run into difficulties trying to explain all of it; none of them can be conclusively proven or disproven. We will probably never understand the origin of the moon until we make progress in understanding the formation of the solar system itself. We have a great deal more to learn about the actual chemical processes that went on in the original dust cloud. We also need to know more about the mechanical processes which caused small particles to assemble into larger bodies and then brought these bodies together into moons and planets. When we understand these mechanisms better, we may be able to put more precise boundaries on where the moon actually originated. If it is proven that the moon originated inside the orbit of Mercury, then some kind of capture process must have occurred, no matter how unlikely it may seem. On the other hand, if new theories manage to explain how chemically different bodies could form close together, then the "double planet" origin may be correct after all.

New questions are constantly arising to complicate any single explanation of the solar system. If the formation of large moons was a normal phenomenon when our solar system formed, where are the large moons that we would expect to circle Mercury, Venus, and Mars? It could be that tidal forces on the sun have destroyed any original moons of Mercury and Venus. However, this explanation will not work for Mars, which has only two tiny captured asteroids instead of a full-fledged moon, because it is farther from the sun than the earth.

Another important post-Apollo question is whether the moon is chemically unique. Six large moons, about the same size as ours, circle the giant planets of our solar system—four around Jupiter, one around Saturn, and one around Neptune. We do not know yet whether these other moons share the high-temperature history and other chemical peculiarities of our own moon, or whether they are mostly condensed ice like the planets they accompany. An unmanned space mission to Jupiter's moons could answer this question.

THE MOON AND THE EARTH

What we have learned about the moon has also revamped our thinking about the earth. Although the earth and moon have different chemical compositions and different histories, the moon is still an important model of what the primitive earth may have been like. The moon clearly records a primordial melting and widespread chemical separation that produced a layered internal structure almost immediately after it had formed. It is likely that the present internal structure of the earth, including its iron core, also developed very early in its history, perhaps as a result of the accretion process that formed it.

The intense early bombardment recorded by the moon more than 4 billion years ago may be a general characteristic of the solar system too. If a similar intense bombardment struck the earth at this time, it would help explain why no terrestrial rocks older than 4 billion years have been found.

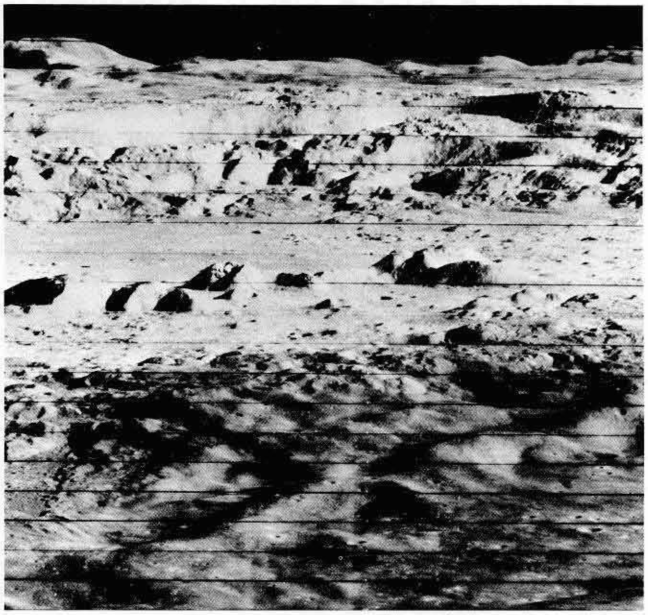
The discovery of ancient rocks on the moon has also generated a new enthusiasm for probing the ancient history of our own planet. Some of this excitement derives from the discovery of rocks about 3.8 billion years old in Greenland. These unusually old terrestrial rocks were found at about the same time that the Apollo 11 mission was collecting lavas of the same age from Mare Tranquillitatis. Moreover, the surprising discovery that the lunar highlands are composed of plagioclase-rich rocks such as anorthosites and gabbros promptly spurred a renewed interest in a group of similar terrestrial rocks which occur only in minor amounts in geologically old regions. The origin of these terrestrial anorthosites is an old unresolved geological problem. Comparative studies of terrestrial and lunar anorthosites may help explain the origin of both types of rocks as well as explaining why a rock that is a minor curiosity on earth is one of the fundamental building blocks of the moon.

The earth and moon provide two contrasting examples of how differently planets can develop, and in their contrast we can see some of the factors that control the evolution of planets. Size is important. A large planet can hold volatile materials like water, and it can also retain more internal heat to produce continuous geological changes. Chemical composition is also important; a planet without water, no matter how large, lacks the one substance that is essential for the only kind of life we know. The presence or absence of radioactive elements determines whether a planet will be hot or cold during its lifetime, and the amount of iron in a planet determines whether it can ever develop a strong magnetic field. The first two bodies we have explored, the earth and its moon, show two different lines of development. Although we think that the planets all formed in the same general way, it is almost certain that we will find further different planetary histories as we explore the solar system.

AND THE LANDS BEYOND

The planets have suddenly become familiar too, for the manned exploration of the moon has gone hand in hand with the unmanned exploration of the solar system. In the five years between 1968 and 1973, scientists launched 17 heavily instrumented spacecraft to investigate every one of the five planets known to ancient astronomers. Mariner 9 went into orbit around Mars in November, 1971, circling the planet like a tiny third moon and radioing back to earth over 7,000 pictures of craters, volcanoes, canyons, and sand dunes on the Martian surface. Two years later, in December, 1973, Pioneer 10 passed safely through the Asteroid Belt, carried its instruments in a sharp turn around the giant planet Jupiter, and then sped away to become the first manmade object to leave the solar system. A sister spacecraft, Pioneer 11, made the same trip successfully a year later, swinging around Jupiter in December, 1974, and then heading outward on a path that will bring its instruments and cameras close to the ringed planet Saturn in September, 1979.

Mariner 10 was launched in the other direction, inward toward the sun. It passed close to Venus in February, 1974, and then settled into an orbit around the sun so well planned that the spacecraft has already been able to make three close approaches to the planet Mercury, taking pictures of that planet that are as good as our best views of the moon through earthbound telescopes.



An Orbiter's-eye view of the crater Copernicus, the huge feature that dominates the upper left quadrant of the moon as seen from the earth. Copernicus is 56 miles wide and more than 2 miles deep—twice the distance from the top to the bottom of the Grand Canyon.

We can now apply the lessons from the moon to other planets. We have learned, for example, that the early period of intense bombardment and cratering observed on the moon seems also to have been general throughout at least the inner part of the solar system. Mercury has revealed a battered surface that is virtually identical to the lunar highlands. The surface of Venus is shrouded in clouds, but earth-based radar, probing through its atmosphere, has detected a number of large circular depressions that are almost certainly craters. Mars exhibits two kinds of terrain. Half its surface is heavily cratered, while the other half is covered with younger features that seem to be volcanic lavas, windblown dust, and possible river channels.

Furthermore, the processes of chemical separation, melting, and volcanism also seem to have occurred on the other planets. Mercury has a detectable magnetic field, indicating the existence of an iron core. Photographs of the surface show units that resemble volcanic

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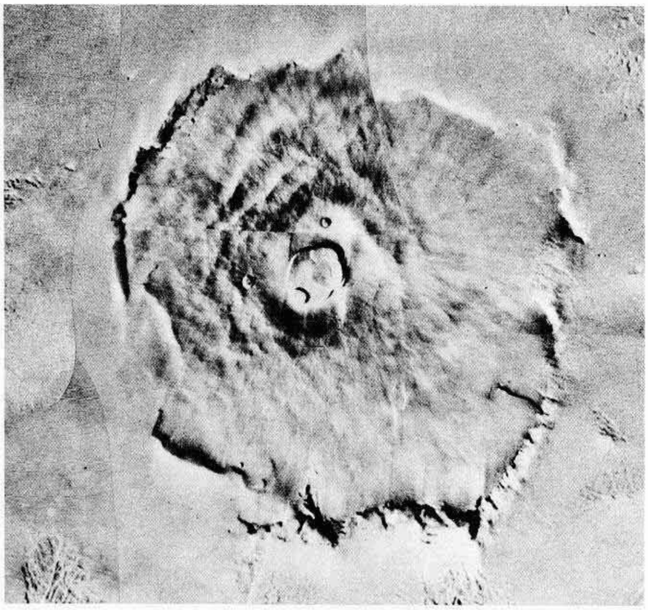


Olympus Mons may be the largest volcanic mountain in the solar system. This giant Martian peak, which was photographed by Mariner 9 in January 1972, is 310 miles in diameter and rises about 15 miles above the surrounding plain—three times the height of Mt. Everest.

deposits. However, the moon has taught us to be cautious about interpreting photographs too quickly. There was a time before the Apollo 16 landing when most scientists thought that the Cayley Formation was volcanic too, and it turned out to be composed of impact-produced breccias.

The occurrence of chemical separation on Venus has been demonstrated only by a single analysis of the surface made by a Russian lander, Venera 8, in July, 1972. The lander survived for nearly an hour on the surface and sent back an analysis resembling the composition of granite, a rock that requires considerable chemical processing to produce, at least on earth.

Mars provides unquestionable evidence of chemical evolution and volcanism. The lightly cratered half of the planet contains numerous structures that are undoubtedly volcanoes. They resemble the volcanic peaks of the Hawaiian Islands, but on a much greater scale. Mars' largest volcano, Olympus Mons, is 600 kilometers in diameter—about the size of the State of Nebraska—and rises about 25 kilometers above the surface of the planet.

Not only have we discovered that the moon is not a primordial object, but our exploration of the solar system has already shown that none of the small planets is likely to be an unaltered sample of the solar system. Perhaps we will have to search for original solar system material in Jupiter, in its icy moons, or in the bodies of comets that occasionally pass by us. We may even discover that the evolution of the solar system has so altered all the matter in it that there is nothing left of the original ingredients.

Our view of the distant universe also changed radically during the decade we spent exploring the moon. The same technology that carried man to the moon also invented new optical and radio telescopes to study the far corners of the universe from the surface of the earth. From new observations, and from unexpected discoveries of strange objects like quasars and pulsars, astronomers have recently been able to put boundaries on the size and age of the known universe. The universe seems to have an edge, or a boundary, at the unimaginable distance of about 15 billion lightyears away from us. Ages calculated for the universe fall in the range of 10 to 15 billion years; it is somewhat surprising that the universe seems to be only three or four times as old as the earth.

ROBOT ASTRONAUTS OF THE FUTURE

The next machine to go to the moon will probably be a Lunar Polar Orbiter, a spacecraft designed to observe and analyze the whole surface of the moon from lunar orbit. It would be placed so that its orbit passes over the north and south poles of the moon instead of being limited to the region around the lunar equator analyzed by the Apollo missions.

The Lunar Polar Orbiter will make it possible to extend the scientific measurements that so far have been made over only about 20 percent of the moon's surface. In a polar orbit around the moon, the spacecraft would eventually pass over its entire surface, because the moon rotates on its axis once every month while the Orbiter is passing over it.

Lunar samples have already been obtained by mechanical means. On September 20, 1970, an unmanned Russian spacecraft called Luna 16 landed in Mare Fecunditatis. Using a hollow drill, the spacecraft collected a 100-gram (3½-ounce) sample of lunar soil and returned it to earth. In an important step in international cooperation in space, some of the Luna 16 material was given to American scientists in exchange for Apollo 11 and 12 soil samples.

The instruments available for analysis of lunar samples are so sensitive and so precise that the small amount of Luna 16 material obtained from the Russians (about 3 grams—the weight of ten aspirin tablets) yielded an impressive amount of information. Scientists discovered that the surface of Mare Fecunditatis was covered by titanium-poor basalt lavas about 3.4 billion years old. The lavas were similar to, but slightly older than, the rocks returned from Oceanus Procellarum (Apollo 12). Even at a considerable distance from the Apollo landing sites, the lavas still seem to be about 3½ billion years old. The Luna 16 soil had also been heavily exposed to cosmic and solar atomic particles while on the moon, but it is hard to interpret the effects because there is so little material available for study.

Seventeen months later, on February 21, 1971, Luna 20 landed in an area of the lunar highlands between Mare Fecunditatis and Mare Crisium. Samples of this soil, also exchanged with American scientists, proved to be made up of crushed plagioclase-rich rocks very similar to the breccias returned by the Apollo 16 mission from the highlands near Descartes.

The Russians are still continuing their sampling of the moon by robot spacecraft. On August 18, 1976, Luna 24 landed safely in Mare Crisium, a small circular mare on the eastern edge of the moon. The spacecraft drilled about 2 meters deep into the lunar soil, then returned safely with a core section of the soil layer that provides a unique sample of the nature and history of an unknown part of the moon.

Existing spacecraft or their more complex descendants, can easily return similar samples from the moon. Our analytical instruments make it possible to obtain a great deal of scientific information from a tiny sample, and our experience with the larger samples obtained by the Apollo missions provides a necessary check on our interpretations.*

In future missions, it will be possible to combine unmanned sample collection with a roving vehicle that moves over the lunar surface. So far, the Russians have the only experience with unmanned lunar roving vehicles. Some of their Luna missions, instead of returning samples, landed a wheeled vehicle called *Lunokhod* (roughly, "moon-walker"). Controlled from earth, the vehicle traveled over the lunar surface, transmitting back TV pictures and data about the physical and chemical nature of the surface.

Future roving vehicles may travel for hundreds of kilometers, measuring the chemistry, gravity, and magnetic properties of the surface as they go. Even more complex rovers, equipped with TV cameras and guided from earth, will be able to examine the local geology and collect samples. At the end of the trip, the cargo would be transferred to a small spacecraft for return to earth.

Where should we send these machines on future missions? Landings on the near side of the moon are easiest to control because the machines are always in sight of the earth and can receive instructions continuously. The search for young volcanic rocks in the maria is one of the most important things that could be done on the near side of the moon, because it would help establish new limits on the thermal history of the moon. Studies of the number and distribution of craters on the maria suggest that young volcanic rocks may be found in parts of Mare Imbrium and Oceanus Procellarum; ages as young as 2.5 to 1.7 billion years have been estimated for these rocks. If these ages could be verified from returned samples, the whole history of the moon would have to be revised. The Marius Hills, which have already been identified as some of the youngest volcanic features on the moon, are an obvious landing site for such a mission.

Another unmanned mission could try to determine the origin of lunar transient phenomena by landing where they have been most often seen, in the craters Aristarchus, Alphonsus, or Plato. In addition to collecting samples of possible recent volcanic rocks, the spacecraft could leave instruments behind to await the next "eruption"—a seismometer to detect moonquakes, a heat flow experiment, and an atmosphere detector to sample diffusing gases.

Much remains to be done on the near side of the moon, but the entire far side of the moon is practically unexplored, and scientists are eager to send instruments there and to obtain samples. The curious magnetic anomaly near the crater Van de Graaff is an obvious site to place an instrument package, and the mare-filled

*There is a continuing debate over whether the scientific results from the Apollo Program could have been obtained at much less cost with unmanned samplers similar to the Luna 16 and Luna 20 spacecraft. In many cases the answer is no. The unmanned samplers returned only a small amount of soil and no large rocks; the one formation age determined for the Luna 16 material was made possible by an incredibly painstaking analytical effort on a rock chip that weighed 0.062 gram. The larger samples returned by the Apollo missions were essential to learning about formation and exposure ages, highland breccias, microcraters, lunar magnetism, the nature of solar wind, cosmic ray particles, and the layering and history of the lunar soil. The formation ages measured on large lunar rocks were especially important; without these ages, we might have concluded that the model age of the lunar soil, about 4.6 billion years, was actually the age of the mare lavas. Without the large rocks from Apollo, on which the true formation ages could be determined, our whole view of lunar history might have gotten off to a very false start, and we might never have learned that the moon had been an active evolving planet for a billion and a half years.

crater Tsiolkovsky could provide samples of both the highland crust and of the dark mare material that for some reason is so scarce on the far side of the moon.

Landing spacecraft on the far side of the moon is a difficult problem. On the far side of the moon, the spacecraft is out of radio communication and cannot be controlled directly from earth. One solution is to build a complex spacecraft that can be programmed in advance to land and perform its tasks without any contact with earth. However, a simpler and less expensive solution is to put a relay satellite in orbit over the far side of the moon, where it can "see" both earth and the lunar far side at the same time. Fortunately, nature has done most of the necessary work for us. Some distance beyond the moon, there is a point where the gravity fields of the earth and moon combine in such a way that a satellite placed there will always stay there, remaining on the far side of the moon as the moon orbits.

With such a relay satellite in orbit, nearly continuous communication between the earth and instruments on the lunar far side would be possible, and more ambitious explorations can be planned. The most important scientific step will probably be the landing of a group of seismometers to explore the interior of the moon beneath the highlands. More complex instrument packages could measure chemical and magnetic properties as well.

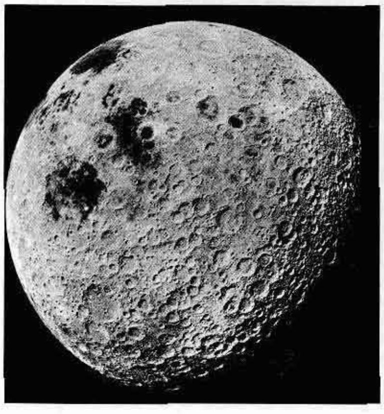
It may soon also be possible to put instruments on the far side to study things beyond the moon. The far side of the moon is an excellent place to do astronomy; it is entirely airless, utterly dark for half of the time, and shielded behind the entire mass of the moon from the lights and radio noises that make both optical and radio astronomy difficult on the earth. Small automatic telescopes placed there could make observations that are impossible for instruments on earth. They could observe the ultraviolet and infrared light of the stars; and seek new sources of radio waves, X-rays, and gamma rays in the sky; and possibly even find new examples of such puzzling objects as quasars, pulsars, and black holes.

The United States may not have to undertake these explorations alone. The new feasibility of international cooperation in exploring the moon is an important result of the Apollo Program. There is the precedent of Antarctica, where many nations, including the United States and Russia, have cooperated for over a decade in the scientific exploration of a continent about one-third the area of the moon itself. The more recent examples of the lunar sample exchanges and the joint Apollo-Soyuz mission are also encouraging indicators of future cooperation in space between the United States and Russia. It is possible now to plan a joint mission in which a Russian Luna spacecraft would descend to sample the crater Tsiolkovsky guided by an American relay satellite fixed above the far side of the moon. Geologists could easily plan voyages for a Russian Lunokhod that would collect samples along a trail a hundred kilometers long and then transfer them to an American robot spacecraft for return to earth. Or it could be an American rover and a Russian spacecraft. Neither the hazards of the moon nor the state of our technology is the factor determining whether such cooperative exploration takes place. We now know that such joint missions can be done if the governments and individuals involved decide that they should be done.

Another great gain from the Apollo Program is confidence. Already the exploration of the moon has changed from a great unknown challenge to a matter of relatively familiar engineering. What will determine the future exploration of the moon is no longer our ignorance and uncertainty about the universe, but the resources of desire, talent, and money that we ourselves provide.

In this post-Apollo period, the moon has become in some ways as familiar as the earth, and the other planets are becoming as familiar as the moon was a decade ago. No longer just our satellite, the moon has become a base and a proving ground, no longer a destination but a way station on the road of continuing exploration.

Despite our partial domestication of the moon it would be foolish to think that we have learned everything important or interesting about it. The Apollo Program has let us, as Newton put it, pick a few pebbles from the edge of the boundless ocean, but there is still much to be learned from studying the beach while we make plans to venture out onto the ocean itself. □



A farewell look at the far side of the moon was taken by the Apollo 16 astronauts on the way home to earth.