Chapter 4

Scientific Exploration and Utilization of the Moon

UNDERSTANDING THE MOON

Except for the Sun, the Moon is humanity's most familiar celestial object. Following a complicated apparent path through the night sky, waxing and waning on a 29-day cycle, urging Earth's tidal ebb and flow, the Moon has been the subject of sacred and poetic wonder and scientific examination for millennia. Ancient astronomers tried but despaired of satisfactorily characterizing its complex motions analytically. Galileo contributed to the scientific revolution of the early 17th century by noting from telescopic observations that the Moon had mountains and craters. Because these forms threw shadows as the relative position of the Sun changed, Galileo deduced that the Moon was composed of Earthlike materials[1] — in other words, it could and should be studied like the Earth.[2] Galileo also noted later that although the Moon constantly keeps the same face toward Earth, it also appears to wobble slightly from moonrise to moonset, enabling Earth observers to see somewhat more than 50 percent of the surface.

Through the 18th and 19th century, astronomers examined the Moon with ever greater resolving power as telescopes grew in capability. Early observers took Galileo's suggestion that the Moon was analogous to Earth to the point that they thought it might be habitable and concluded that the Moon might have an atmosphere, great seas, and riverbeds. They named the broad dark places on the lunar surface "Maria," thinking they contained water.

By the 20th century, astronomers understood that Earth's companion had little or no atmosphere and was incapable of sustaining life without major support systems. Beyond generating maps of the visible surface, their primary activity was to catalogue and closely examine lunar craters. Some scientists felt that the many lunar craters resulted from volcanic activity. Others, who argued that the craters came from outside bombardment, saw the heavily cratered Moon as possessing along-term record of asteroidal and cometary bombardment of the Earth-Moon system. Most astronomers ignored the Moon until the prospect of reaching it with spacecraft became a reality in the 1960s. Not only could astronomers and geologists then view it close up from lunar orbit, including the mysterious farside, but they could look forward to the return of samples for detailed laboratory study on Earth. The geological structure, formation, and evolution of the Moon soon became of great interest, in part because scientists began to recognize that asteroidal or cometary impacts played a significant role in Earth's geological history.[4]

Between 1%1 and 1%8, the United States sent 28 automated spacecraft to study the Moon, and to select landing sites for automated and piloted landers. Thirteen of these proved unsuccessful. The Soviet Union launched 23 lunar spacecraft between 1959 and 1975 (table 4-l). A Soviet spacecraft, ***Luna 2,*** became the first to reach the lunar surface on September 12, 1959. ***Luna 3*** made the first photograph of the farside of the Moon. Although the photograph was extremely crude and indistinct, it and the other Soviet firsts

[1]Galileo, "The Starry Messenger," in Stillman Drake, Jr., Discoveries *and Opinions of Galileo (New* York, NY: Anchor Books, 1957).

[2]Ray A. Williamson *and* Philip Chandler, *III,* "The Promise of Space and the Difference It Makes: The Search for Golden Age," *Cultural Futures Research,* vol. II, No. 2, 1983.

[3]The world's space programs have made possible, among others, the development of the scientific specialty of planetary geology.

[4]This interest accompanied a fundamental change in the scientific understanding of Earth's geological processes with the development of plate tectonic theory.

Table 4-1 -Successful Soviet Lunar Missions

Spacecraft	Encounter Date	Mission	Event
Luna 2	Sept. 12, 1959	Moon strike	Struck Moon at 1 W, 30N.
Luna 3	Oct. 10, 1959	Moon flyby	Photos of farside after flyby at 6,200 km.
Zond 3	July 20, 1965	Moon	Passed Moon at 9,200 km. System test; taking pictures, then flew as far as orbital path of Mars.
Luna 9	Feb. 3, 1966	Moon	Soft landed on Moon at 7.1 N, 64.3 W; returned pictures.
Luna 10	Apr. 3, 1966	Moon orbiter	First object to orbit Moon; studied lunar magnetism and radiation.
Luna 12	Oct. 25, 1966	Moon orbiter	Transmitted 15 m resolution pictures of portions of the Moon.
Luna 13	Dec. 24, 1966	Moon	Soft landed on Moon at 18.9 N, 62 W; returned pictures.
Luna 14	Apr. 10, 1968	Moon orbiter	Studied lunar gravitational field.
Zond 5	Sept. 18, 1968	Moon	Circumlunar, recovered, landed Indian Ocean. Man precursor.
Zond 6	Nov. 13, 1968	Moon	Circumlunar, 2,420 km from Moon, Man precursor.
Zond 7	Aug. 11, 1969	Moon	Circumlunar, 2,200 km from Moon, Aug. 11. Man precursor.
Luna 16	Sept. 20, 1970	Moon	Automated return of soil sample to Earth.
Zond 8	Oct. 24, 1970	Moon	Circumlunar, passed 1,120 km of Moon. Man precursor.
Luna 17	Nov. 17, 1970	Moon lander	Landed Lunokhod roving surface vehicle 756 kg, after orbiting Moon.
Luna 19	Oct. 1, 1971	Moon	Orbiter Only. Returned pictures.
Luna 20	Feb. 18, 1972	Moon	Orbited Moon, then soft landed. Sample returner.
Luna 21	Jan. 16, 1973	Moon	Orbited Moon, landed Lunokhod 2 roving laboratory (840 kg) at 26.5 N, 30.6 E.
Luna 23	Nov. 2, 1974	Moon	Orbited Moon, landed at 13.5 N, 56.5 E to drill for soil sample. Sample return failed to launch because drill damaged.
Luna 24	Aug. 19, 1976	Moon	Orbited Moon, landed at 21.7 N, 62.2 E to drill sample. Sample return.

SOURCE: National Aeronautics and Space Adminlstratlon

made an important political point and spurred U.S. efforts to best Soviet accomplishments. The first U.S. spacecraft to come near the Moon was ***Pioneer 4,*** which passed within 37,300 miles in March 1959, but the United States proved unable to reach the Moon with a functioning spacecraft before Ranger 7[5] returned more than 4,000 photographs of the lunar surface before crash landing in the Ocean of Storms on July 28, 1964.

THE APOLLO PROGRAM

The U.S. lunar research effort carried out as part of the Apollo program has provided lunar scientists with a rich source of data about the Moon and its physical processes that enhance our scientific knowledge of the origins and evolution of the solar system (box 4-A). These data have vastly improved our scientific understanding of

[5]*Ranger 1* through *Ranger* 6 failed for a variety of reasons. See R. Cargill Hall, *Lunar Impact: A History of Project Ranger* (Washington, DC: U.S. Government Printing Office, 1977), for a detailed history of these spacecraft and their builders.

the Moon and its evolution. The United States had planned from the first years of National Aeronautics and Space Administration (NASA) the Ranger series of automated lunar probes to photograph the Moon's surface up close and the Surveyor series to make soft landings, photograph their surroundings and return data on the surface properties. When President John F. Kennedy announced the Apollo program in May 1%1, NASA restructured these science programs to support the effort to place humans on the Moon. Robotic spacecraft prepared the way for the first footprints on the Moon.

Robotic Spacecraft

- ***Ranger – The*** Ranger series[6] was designed to photograph selected areas of the Moon at many different resolutions as the spacecraft sped toward a crash landing on the lunar surface. After a long string of launch and other failures, Rangers 7,8, and 9 took thousands of images of the Ocean of Storms, the Sea of Tranquility, and the Crater Alphonsus (table 4-2).

Box 4-A-Science Accomplishments of the Apollo Program

- Carried out in situ geological and geophysical exploration at six landing sites.
- Returned 385 kilograms of rock and soil samples from six landing sites.
- Emplaced six geophysical instrument stations that carried out measurements of seismicity, heat flow, crustal properties, local fields and particles, and other phenomena.
- Carried out orbital remote sensing experiments, collecting data on crustal composition, magnetic fields, gas emission, topography, subsurface structure, and other properties.
- Obtained extensive photographic coverage of the Moon with metric, panoramic, multispectral, and hand-held cameras during six landing and three nonlanding missions.
- Carried out extensive visual observations from lunar orbit.
- Visited and retrieved parts from Surveyor III, permitting evaluation of the effects of 31 months' exposure to lunar surface conditions.
- Carried out extensive orbital photography of the Earth with hand-held and hard-mounted multispectral cameras, providing verification of LandSat multispectral concept.
- Emplaced laser retroreflectors at several points on the lunar surface, permitting precision measurement of lunar motions with an accuracy of several centimeters.
- Emplaced first telescope on the Moon, obtaining ultraviolet photographs of the Earth and various celestial objects.
- Obtained samples of the Sun by collecting solar wind-implanted ions with surface-emplaced aluminum foil.
- Carried out astronomical photography from lunar orbit.
- Carried out cosmic ray and space physics experiments on lunar surface, in lunar orbit, and in Earth-Moon space.

SOURCE: Paul D. Lowman, Jr., NASA Goddard Space Flight Center, 1991.

[1]Includes only Apollo missions; Gemini, Skylab, and Apollo-Soyuz mission results not included.

[6]*Ranger 3* through *Ranger 9*. NASA designed *Rangers 1* and *2* to go well beyond lunar orbit to accumulate various data about the space environment between the Earth and the Sun.

Table 4-2-Summary of Ranger Missions

Spacecraft	Launch date	Comments
Ranger I	Aug. 23, 1961	Intended to fly out beyond Moon's orbit for particle and field studies (to 804,500 kilometers). Launch vehicle malfunction placed it in low-Earth orbit (180 kilometers), but spacecraft functioned properly.
Ranger II	Nov. 18, 1981	Identical to Ranger I, with same results.
Ranger III	Jan. 26, 1982	Designed to return pictures of the Moon. Missed Moon and went into heliocentric orbit.
Ranger IV	Apr. 23, 1962	Mission same as Ranger III. Struck back side of Moon; returned no data.
Ranger V	Oct. 18, 1982	Mission same as Ranger II and IV. Missed Moon and entered heliocentric orbit.
Ranger VI	Jan. 30, 1964	Mission to return closeup photos of Moon before crashing into surface. No pictures returned.
Ranger VII	July 28, 1984	Mission to return closeup pictures of lunar surface; 4,304 pictures of lunar surface; 4,304 pictures returned of Sea Clouds. First successful Ranger.
Ranger VIII	Feb. 17, 1983	Returned 7,137 pictures of Seas of Tranquility and high land area west of the sea.
Ranger IX	Mar. 21, 1983	Returned 5,814 pictures of Crater Alphonsus and vicinity.

SOURCE: National Aeronautics and Space Administration

- ***Surveyor — The*** Surveyor program was designed to test the technology for soft lunar landings, survey potential future landing sites, and return scientific data about surface properties of the Moon. Five out of seven Surveyor spacecraft successfully reached the lunar surface, photographed their surroundings, and, using a teleoperated scoop to acquire surface samples, carried out measurements on chemical composition and mechanical properties of the lunar soil (table 4-3). Among other things, the Surveyor spacecraft tested the bearing strength of the soi1[7] and demonstrated that it would support a crew-carrying lander.

- ***Lunar Orbiter —*** Five Lunar Orbiters provided nearly 100-percent" photographic coverage of the Moon at surface resolutions of 1 to 500 meters (table 4-4). Photographic data from the Lunar Orbiters ruled out several sites thought possible for an Apollo landing, as they revealed far too many craters. Precise tracking of the orbiters also yielded measurements of the nearside lunar gravity field, demonstrating the existence of dense concentrations of mass below the lunar surface. These "mascons," as they were dubbed, later had to be taken into account in calculating the orbit of the Apollo lunar landers.

Astronauts on the Moon

Apollo astronauts, supported by extensive geological training[8] and a team of professional geologists in Mission Control, conducted field studies on the Moon, bringing back samples of particular interest for study in laboratories on Earth. The six lunar missions returned a total of 385 kilograms of lunar material.

Astronauts collected surface rocks, but also brought back cores of subsurface lunar material, made by pushing a coring tube into the surface and mechanically drilling to depths of 3 meters at three different places. Analysis of the lunar samples, which are basically similar to rocks on Earth, has shown that some rocks are as old as 4.6

Y&t ronomer Thomas Gold had postulated that the Moon's constant bombardment by micrometeoroids might have created a thick lunar dust that would make travel by humans or rovers extremely difficult or even impossible. Although the lunar surface contains a significant dust layer, it is compact enough to pose no major hindrance to navigation.

[8]Astronaut Harrison Schmidt, who roamed the Moon on the Apollo 17 mission, holds a Ph.D. in geology. Other astronauts received field training prior to flight.

Table 4-3-Summary of Surveyor Missions

Spacecraft	Launch date	Comments
Surveyor I	May 30, 1966	Successful soft lunar landing in Ocean of Storms. Primarily on engineering test. Returned 11,237 pictures.
Surveyor II	Sept. 20, 1966	During midcourse maneuver, one of three engines malfunctioned, causing spacecraft tumbling. Communications lost 5-1/2 hours prior to impact on Moon southeast of Crater Copernicus.
Surveyor III	Apr. 17, 1967	Successful soft lunar landing in Sea of Clouds. Returned 6,315 pictures. First soil scoop.
Surveyor IV	July 14, 1967	All communications with spacecraft lost 2.5 minutes prior to lunar impact.
Surveyor V	Sept. 8, 1967	Successful soft lunar landing in Sea of Tranquility. Returned over 19,000 pictures. Alpha scattering experiment provided data on composition of lunar soil.
Surveyor VI	Nov. 7, 1967	Successful soft lunar landing in Central Bay region (Sinue Medii). Returned 30,065 pictures. First lift-off from lunar surface moved 2.5 meters to new location for continuing experiments.
Surveyor VII	Jan. 7, 1968	Successful soft lunar landing on ejecta blanket adjacent to Crater Tycho.

SOURCE: National Aeronautics and Space Administration.

Table 44-Summary of Lunar Orbiter Missions

Spacecraft	Launch date	Comments
Lunar Orbiter I	Aug. 10, 1966	Returned 207 frames of medium and high resolution of pictures. Commanded to impact Moon on Oct. 29, 1966.
Lunar Orbiter II	Nov. 6, 1966	Returned 211 frames, Commanded to impact Moon on Oct. 11, 1967.
Lunar Orbiter III	Feb. 5, 1967	Returned 211 frames; photographed Surveyor 1. Commanded to impact Moon on Oct. 9, 1967.
Lunar Orbiter IV	May 4, 1967	Returned 163 frames. Commanded to impact Moon on Oct. 6, 1967.
Lunar Orbiter V	Aug. 1, 1967	Returned 212 frames. Commanded to impact Moon on Jan. 31, 1968.

SOURCE. National Aeronautics and Space Administration.

billion years, or as old as Earth, but most formed from 4 to 3 billion years ago. Lunar rock samples contain ample oxygen bound in the silicate minerals that form them, but no hydrogen, except for solar-implanted atoms in the regolith. This means that the Moon likely contains very little water.[9] The lunar samples also contain relatively few mineral species compared to rocks on Earth. The astronauts' samples show that the predominant rock in the dark lunar maria is similar to basalt. Missions to the lighter-colored lunar highlands reveal that they contain an exceptionally high abundance (compared to Earth) of a calcium-rich rock called anorthosite, suggesting that the bulk composition of the upper lunar crust is quite unusual by terrestrial standards. The entire surface of the Moon is covered by a fine-grained, fragmented material called regolith, made from repeated meteoroid impacts, which have pulverized and mixed the upper surface. To date, the available data do not allow scientists to confirm or deny whether the Moon was formed at the same time as Earth but separately, or the Earth and Moon were once part of the same planetary body.[10] Study of existing lunar samples continues. As scientists examine the samples with ever more powerful techniques, the samples reveal additional details of the Moon's history.[11]

[9]The extreme shortage of water on the Moon could have important consequences for human crews, which would have to bring their own water, transport enough hydrogen to make water from oxygen extracted from lunar reeks and Earth hydrogen, or extract hydrogen from the regolith.

[10]Although the question of the origin of the Moon has not been definitively resolved, most lunar scientists favor the theory that the Moon was created when the Earth suffered an impact with a "planetesimal" body roughly the size of Mars, after separation of Earth's core and mantle.

[11]Stuart Ross Taylor, *Lunar* Science.- *A Post-Apollo View* (New York, NY: Pergamon press, Inc., 1975).

Photo credit: National Aeronautics and Space Administration

Apollo 16 on Moon. Apollo astronaut John W. Young works at Lunar Roving Vehicle on left. Lunar Module at right. Apollo 16 was the fifth NASA voyage to carry people to the Moon.

In addition to doing field geology, and returning lunar samples, each Apollo crew left an experiment package on the Moon[12] that returned data to Earth on lunar seismic activity, the solar wind, the Moon's magnetic field, the lunar atmosphere, and heat flow from the interior. Data from these instruments allowed scientists to detect thousands of moonquakes, measure heat flow, and to estimate the thickness of the lunar crust, but not to confirm the presence or absence of a metallic core.

The crews of Apollo 11, 14, and 15 left laser-ranging reflectors on the Moon that allowed scientists on the Earth to measure precisely the distance between the Earth and the surface of the Moon. Among other things, lunar laser-ranging provided data on the orbital dynamics of the Moon, and demonstrated that the distance between the Moon and Earth is slowly increasing.

Apollo astronauts also took thousands of photographs of the lunar surface from orbit with a variety of cameras. These high-quality photographs constitute some of the highest resolution images of the lunar surface. However, they did not provide complete coverage of the Moon, as they were taken from equatorial orbit. Only about 20 percent of the Moon was under the ground track of Apollo missions. None reached above 30

[12] The Lunar Surface Experiment Package (ALSEP).

degrees N (north) latitude. In addition, because Apollo crews focused their efforts on the illuminated portions of the Moon, most of which faced the Earth at the time, they made relatively few observations of the farside. The astronauts also initiated global geochemical/geophysical mapping from orbit, using instruments capable of remotely sensing a small number of elemental constituents and determining the Moon's magnetic properties.

The Apollo program provided one important but largely unanticipated benefit to the world–the views of Earth from lunar orbit—which showed it for the first time as a single system. Those photographs also emphasized how vulnerable our planet looks from the outside, and are often used today to convey a sense of Spaceship Earth and global unity.

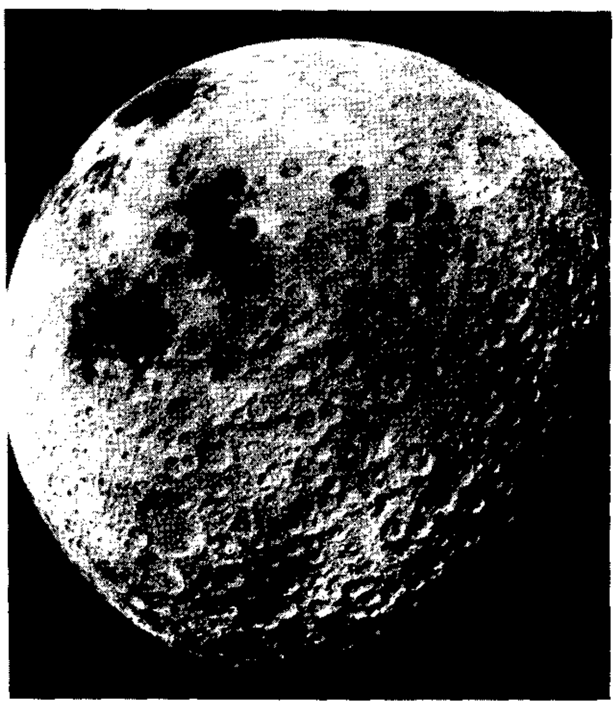

Photo credit: National Aeronautics and Space Administration

Apollo 16 view of a near full Moon on the far side, photographed by the Fairchild Metric Camera from the Apollo 16 Service Module, Feb. 28, 1972.

THE SOVIET LUNAR PROGRAM

In the 1960s and 1970s, the Soviet Union had a strong robotic program aimed at achieving several spaceflight firsts and in gathering scientific data. In addition to launching the first spacecraft to reach the Moon and to photograph the farside of the Moon, the Soviet Union made the first soft landing on the Moon and launched the first lunar orbiter. In 1970, more than a year after the United States landed men on the Moon, the Soviet spacecraft, ***Luna 16,*** returned soil samples to Earth. Later that year, Soviet engineers successfully landed the Lunokhod rover on the Moon, which became the first rover on a planetary body to be operated from Earth.

The Soviet Union also expended major efforts to land cosmonauts on the Moon, but failed in building the necessary heavy-lift launcher to accomplish the task. Its last mission to the Moon was August 1976, when ***Luna 24*** landed, drilled a sample of the lunar surface, and returned to Earth with the sample. Although a number of Soviet scientists would like to continue the scientific study of the Moon, study of Venus and Mars have received greater priority in recent years.

SCIENTIFIC OBJECTIVES

Despite the substantial gains made in lunar science during the Apollo program, scientists still have a relatively rudimentary understanding of the Moon, its origins and evolution. Only about 40 percent of the Moon has been imaged at sufficient resolution for scientific study.[13]

The Moon is worth studying for its own sake. But because a substantial portion of Earth's history is closely tied to the history of the Moon, and because Earth and Moon share the same solar system neighborhood, detailed study of the Moon would also assist in understanding the geologicall[14] and climatological history of Earth. The Lunar Exploration Science Working Group

[13]When Mars Observer completes its mission in the mid-1990s, Mars will be more completely mapped geochemically than the Moon.

[14]See, e.g., Paul D. Lowman, Jr., "comparative Planetology and the Origin of Continental Drift," *Precambrian Research,* vol. 44, 1989, pp. 171-195.

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(LExSWG)[15] has developed a broad science strategy for the Moon.[16] The following briefly summarizes these scientific themes:

- ***Formation of the Earth-Moon system*** — Determining the chemical composition of the Moon in comparison to the composition of Earth's mantle would help solve the question of whether the Moon formed from the impact of a giant body with Earth or directly from accretion out of the primordial material. That in turn will affect scientists' understanding of Earth's early history.

- ***Thermal and magmatic evolution of the Moon*** — ***The*** Moon evolved quickly after formation. The Apollo data revealed that the Moon melted early in its history. When it cooled, it formed a low-density crust atop a denser mantle. Some scientists believe that a small metallic core may be present. Because the Moon's volcanic, tectonic, and other geological activity was not vigorous enough to erase the evidence of the Moon's early formation, the lunar crust is likely to provide important clues to the early evolution of Earth, and also Mars and Venus. These planets have experienced enough weathering and geologic activity to erase many obvious signs of their early evolution.

  A survey from orbit using high-resolution spectroscopic sensors will provide estimates of the composition of the lunar crust and its spatial diversity, but understanding its origins will require obtaining samples from the Moon's ancient highlands. Returning samples from the youngest lava flows, as determined by the count of lunar craters in these flows, would provide information about their ages. Seismometers, heat flow probes, and magnetometers on the surface would help determine the Moon's internal structure and thermal properties.

- ***Bombardment history of the Earth-Moon system*** — Mars, Venus, the Earth, and the Moon all display evidence of bombardment by large and small external objects (meteoroids, comets, and asteroids). Once volcanism ceased on the Moon, bombardment became the primary agent of surface change. Hence, the Moon contains a nearly complete record of its impact bombardment history, from the micrometeoroids that continually pound the surface, to the asteroids that formed the largest craters. Overlapping by the ejected material from successive volcanoes may also have preserved an undisturbed record of the early micrometeoroid influx. In addition to providing insights concerning the numerical density and range of sizes of bombarding objects, the lunar surface contains a statistical record of the like bombardment of Earth.[17] Hence such studies might assist in understanding the periodic extinctions of some species of life on Earth, which some scientists believe result from cometary or asteroidal impacts.[18] Observations from orbit and rock samples from many relatively young craters would provide the necessary data.

- ***Nature of impact processes*** — Despite considerable progress in studying how and why craters and their deposits form, scientists lack a complete understanding of the dynamics of cratering. High-resolution reconnaissance data from orbit would allow lunar scientists to formulate working hypotheses about the geological evolution of a region, which could be used to guide future sampling studies.

- ***Regolith formation and evolution of the Sun*** — Regolith, the blanket of broken rock and soil that covers the Moon, results from the impact of external objects with the lunar surface. The impacts both dig up the origi-

[15] LExSWG is composed of scientists from NASA, the U.S. Geological Survey, and the universities.

[16] Lunar Exploration Science Working Group, *A Planetary Science Strategy for the Moon*, draft, Sept. 28, 1990.

[17] Richard A.F. Grieve, "Impact Cratering on the Earth," *Scientific American*, April 1990, pp. 66-73.

[18] Walter Alverez and Frank Asaro, "What Caused Mass Extinction?" *Scientific American*, October 1990, pp. 78-84.

nal surface and redistribute previously created regolithic material. Charged particles from the solar wind and galactic cosmic rays continuously strike the regolith, embedding themselves in it. Thus, the regolith carries a historical record of the Sun and cosmic radiation. Regolith would also provide the material for building a lunar base. Detailed study of the regolith from many different locations at different depths would therefore provide scientists with data about the history of the Sun and add to their understanding of the regolith's potential for use as a construction material. All of the lunar samples returned by the Apollo flights are from the regolith. Although these samples have contributed immeasurably to our knowledge of the lunar surface, they provide only a glimpse of the history of the Sun and of the complicated processes that produce the regolith.

More complete understanding will depend on gathering large-scale chemical composition data from a lunar orbiter and detailed chemical and physical study of samples from a variety of sites at several depths. Because the uppermost layers of the regolith react strongly with foreign material e.g., gases, properties of these layers change as soon as they are placed in a spacecraft, which carries with it a variety of gases or gas-producing materials. To study the processes that produce these reactive grains, scientists will likely have to study them in situ at a lunar outpost, where contact with nonlunar gases and other materials can be closely controlled.

Nature of the lunar atmosphere — contrary to popular belief, which holds that the Moon has no atmosphere at all, the Moon possesses an extremely rarefied atmosphere. Its density, composition, and possible origin are poorly known. The lunar atmosphere is extremely fragile and could be destroyed by significant robotic or human activity.[19] Hence, if this atmosphere is to be studied at all, it will be important to characterize it very early in a program to return to the Moon.

FUTURE ROBOTICS MISSIONS

The Galileo Spacecraft

On its way to make extensive observations of Jupiter, the ***Galileo*** spacecraft has recently provided stunning observations of parts of the farside of the Moon. ***Galileo*** was launched toward Jupiter on October 18, 1989, from the shuttle ***Columbia.*** Because the upper-stage engine used to boost ***Galileo*** from low-Earth orbit to Jupiter is not powerful enough to take a more direct route, mission scientists have routed Galileo past Venus and the Moon and Earth[20] to benefit from a so-called gravity assist.[21] Galileo passed the Moon on December 8, 1990, allowing mission engineers to check out its sensors and other systems and to provide new data about portions of the lunar surface never examined with multispectral data (box 4-B). Galileo's sensors, which include ultraviolet, visual, and infrared sensors, examined the Orientale Basin, only a portion of which can be seen from Earth, and confirmed the existence of a large farside basin, called the South-Pole Aitken Basin, which could only be inferred from previous data.

Lunar Observer

The first detailed plans for a polar-orbiting spacecraft to survey and analyze the chemical and physical properties of the Moon were developed at the Goddard Space Flight Center[22] and

19 Richard R. Vondrak, "Creation of an Artificial Lunar Atmosphere," *Nature, vol.* 248, No. 5450, Apr. 19, 1974, pp. 657,659.

20 Galileo will pass near Earth again on Dec. 8, 1992.

21 Charlene M. Anderson, "Galileo Encounters Earth and Venus," *The Planetary Report*, vol. 11, March/April 1991, pp. 12-15.

22 Goddard Space Flight Center, *Lunar Polar Orbiter Interim* Technical *Report,* GSFC Report No. X-703-75-141, May 1973.

the Jet Propulsion Laboratory[23] in the 1970s. A Lunar observer spacecraft received further impetus in the reports of the Space Science Board's Committee on Planetary and Lunar Explora-

Box 4-B—Return to the Moon With Robotic Advanced Sensors: Lessons From Galileo

In December of 1990, the ***Galileo*** spacecraft completed its first flyby of the Earth-Moon system to acquire part of the necessary energy boost for its journey to Jupiter. Although Galileo instruments are optimized for the environment of the outer solar system, and lunar science was not included in original mission objectives, it was recognized that the fly-by geometry would allow several sensors to provide new and unique lunar data. In particular, digital multispectral images could be obtained for the first time for portions of the unexplored lunar farside and the western limb. The scientific focus was expected to center on the multi-ring Orientale Basin, the youngest and exceptionally well-exposed 900-km impact basin on the western limb.

Galileo carries a Solid State Imaging (SSI) camera that uses a CCD (charge coupled device) array detector with seven filters covering the extended visible spectral range (0.4 to 1.0 microns). Even though the fly-by period was brief and relatively small amounts of lunar data were obtained, the Galileo encounter with the Moon had two distinct advantages that allowed this small amount of new data to provide important discoveries. First, from the Apollo and Luna missions we have samples of lunar rocks and soil to analyze in our laboratories. From this "ground truth," we know the composition of several sites on the lunar near side and have identified diagnostic properties of materials that space-borne instruments can detect to provide compositional information for unexplored areas. Second, the geometry of the encounter allowed multispectral images to be obtained for the western nearside, the western limb, and half of the farside. This sequence provided nearside calibration with a direct link to "ground truth" compositional information, which in turn provided a solid interpretative foundation for farside data.

Several surprises were apparent even in preliminary analyses of the Galileo SSI images. The synoptic image of the western limb shown in the opposite photo illustrates one of the most obvious. The Orientale Basin is near the center of the image, the nearside is on the right, the farside on the left. Even the raw data provide evidence for the remarkable basin of the southern farside that is estimated to be twice the size of the Orientale Basin. Two sets of concentric basin rings can be seen on the western edge of the image. The interior of the basin extends to the south pole and is dark, which subsequent photometric analyses show to be due to an inherently low albedo of basin materials. The existence of this huge basin, called the "South-Pole Aitken Basin," was suspected from fragments of earlier information obtained largely during Apollo. The SSI images provide significant new evidence for what is now the largest documented basin on the Moon. Furthermore, compositional analysis of the SSI multispectral data indicates a distinct mineralogical anomaly (enrichment of minerals) associated with the entire South-Pole Aitken basin of the farside.

As the scientific content of these data is analyzed in more detail, some of the obvious lessons of the Galileo encounter are that the lunar crust is quite heterogeneous at all scales and that the lunar samples provide an immense advantage in using data returned from remote sensors with confidence. A more sublime result is that the post-Apollo Moon still contains many surprises waiting detection and recognition with more advanced detectors on robotic spacecraft.

SOURCE: Prepared by Carle Pieters, Brown University, 1991. Authors include M. Belton [Team Leader], C. Anger, T. Becker, L Bolef, H. Breneman, M. Carr, C. Chapman, W. Cunningham, M. Davies, E. DeJong, F. Fanale, E. Fischer, L. Gaddis, 1? Gierasch, R. Greeley, R. Greenberg, H. Hoffmann, J. W. Head, I? Helfenstein, A. Ingersoll, R. Jaumann, T. V. Johnson, K Klaasen, R. Koloord, A. McEwen, J. Moersch, D. Morrison, S. Murchie, G. Newkum, J. Oberst, B. Paczkowski, C. Pieters, C. Pilcher, J. Pluchak, J. Pollack, S. Postawko, S. Pratt, M. Robinson, R. Sullivan, J. Sunshine, and J. Veverka.

23 Jet Propulsion Laboratory, *Mission Summary for Lunar Polar Orbiter*, JPL Dec. 660-41, September 1976.

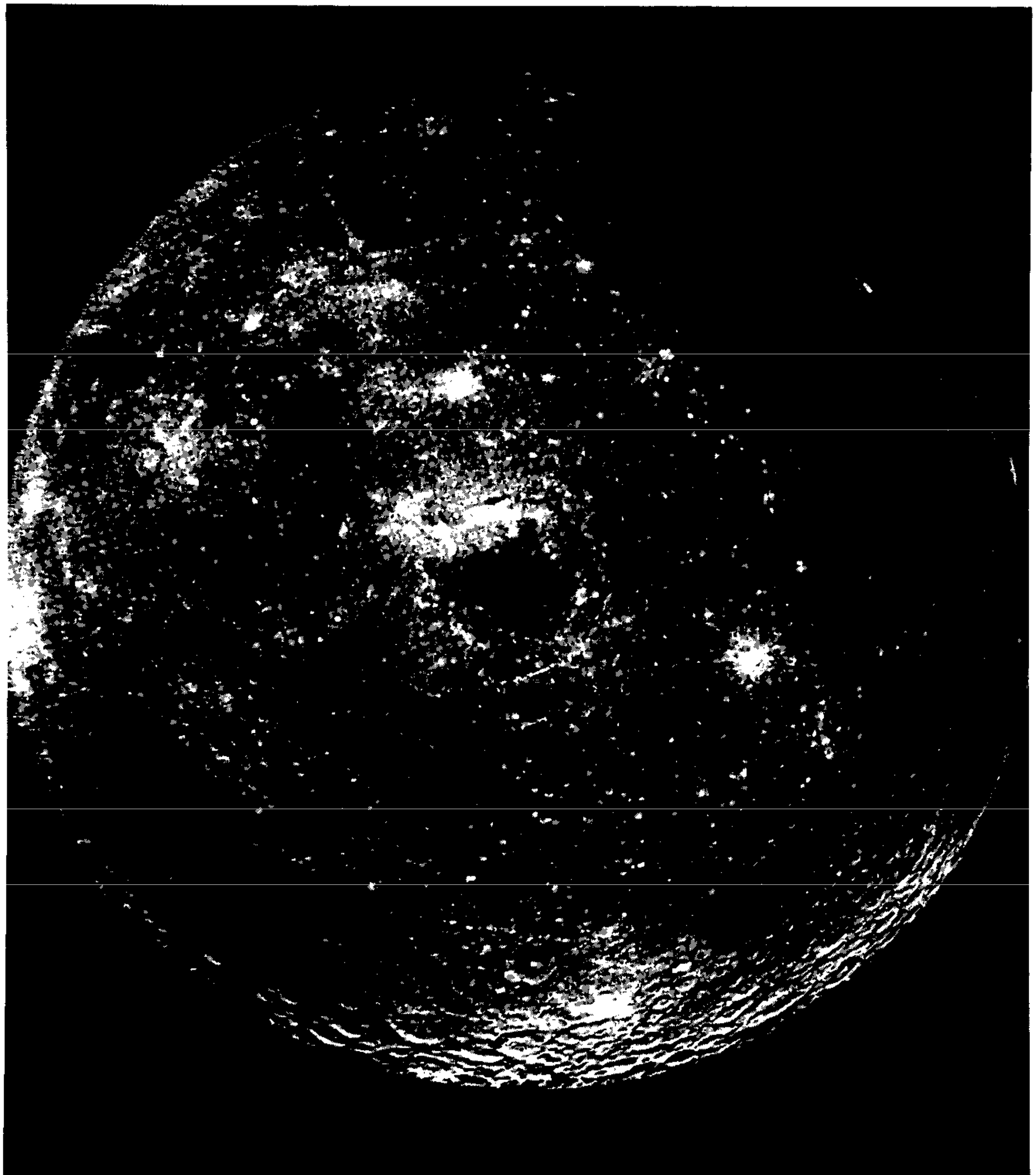

Photo credit: Jet Propulsion Laboratory

Image of the western hemisphere of the Moon taken through a green filter from the *Galileo* spacecraft, Dec. 9, 1990.

tion[24] and the NASA Advisory Council's Solar System Exploration Committee.[25]

The focus of scientific objectives and the capabilities of instrumentation for a polar orbiting lunar spacecraft have evolved substantially since the spacecraft was first proposed. Technologies developed over the last two decades allow far more sophisticated global, regional, and local questions to be addressed with advanced sensors. Some of the greatest technical advancements have been in detector technology and electronics. Lunar science provides an excellent application for these technologies—the lunar environment is static and the Apollo samples on Earth provide important "ground truth" information for several areas studied remotely.

NASA had planned to start design work on the Lunar Observer spacecraft (box 4-C) in fiscal year 1991. However, as a result of severe budget pressures, Congress removed $15 million for advanced studies related to Lunar Observer from NASA's planetary exploration budget for fiscal year 1991. NASA used about $1 million to complete spacecraft studies of the relative benefits and drawbacks of using various instruments and configurations for a lunar orbiter.

Other Possible Missions

Various robotics missions to the Moon are now under consideration. These include a network of small instruments, similar to the MESUR probes being studied for Mars, both small and large

Box 4-C—Lunar Observer

Lunar Observer is a proposed spacecraft designed to make detailed compositional and geophysical observations of the Moon's surface from a lunar polar orbit. Data from this spacecraft would constitute the first global assessment of the Moon's composition and surface properties and form the foundation for scientific exploration of the Moon. In addition, data from the Lunar Observer could assist in selecting the best sites for establishing a lunar base or for siting a prototype lunar observatory.

Science Objectives

The following science objectives could be met with the appropriate complement of scientific instruments aboard an orbiting spacecraft:

- estimate the composition and structure of the lunar crust in order to model its origin and evolution;
- determine the origin and nature of the lunar magnetic field and estimate the size of the core;
- estimate the refractory element content of the Moon by measuring the mean global heat flow;
- determine the nature of impact processes over time and how they have modified the structure of the lunar crust;
- determine the nature of the lunar atmosphere and its sources and sinks; and
- assess potential lunar resources.

SOURCE: Lunar Exploration Science Working Group, A *Planetary Science Strategy for the Moon,* draft, Sept. 28, 1990; G.L. Parker and KT. Neck, "Lunar Observer: Scouting for a Moon Base," presented at the Space Programs and Technology Meeting, Sept. 25, 1990; AIAA paper 90-3781; Office of Technology Assessment.

[24] National Research Council, Space Science Board Committee on Planetary and Lunar Exploration, *Strategy for Exploration of the Inner Planets: 1977-1987* (Washington, DC: National Academy of Sciences, 1978), pp. 71-74. This study noted the following primary scientific objectives for a lunar polar orbiter: 1) determine global and regional chemistry of the lunar surface; determine global and regional heat flow through the surface; 3) determine whether the Moon has a metallic core and explore its nature.

[25] NASA Advisory Council, Solar System Exploration Committee, *Planetary Exploration Through Year 2000: A Core Program* (Washington* DC: U.S. Government Printing Office, 1983); NASA Advisory Council, Solar System Exploration Committee, *Planetary Exploration Through Year 2000: Scientific Rationale* (Washington, DC: U.S. Government Printing Office, 1988).

rovers, and the emplacement of small astronomical telescopes.

WORKING ON THE LUNAR SURFACE

In his speech of July 20, 1989, President Bush proposed that the Nation return to the Moon "to stay." In other words, the United States should establish a permanently staffed lunar base. Proponents of a lunar base suggest various uses for it:

- ***Conduct continued scientific exploration of the Moon –*** A lunar laboratory would allow scientists to continue their study of the Moon.[26] Working in the lunar environment would allow much more flexible study of lunar geology and the lunar atmosphere. As noted earlier, scientists on the Moon could use robotic rovers to conduct field research while they supervise the rovers' activities from a protected, underground laboratory.
- ***Use the Moon as an astronomical platfonn – The*** Moon would provide a stable, nearly atmosphere-free platform for conducting astronomical research (box 4-D).
- ***Use the Moon to learn about living and working in space –*** Administration policy calls for expanding the human presence into space. As Earth's nearest neighbor, the Moon provides a stepping stone to Mars and the rest of the solar system.

  On the Moon, scientists could learn more about the human reaction to long-term low gravity (about one-sixth Earth gravity). They could also learn how to work in an extremely hostile environment, building habitats and laboratories, and conducting scientific research about human reactions to lunar conditions. They might also investigate the properties of plants and small animals raised on the lunar surface.
- ***Exploit resources found on the lunar surface*** — Several individuals have suggested mining the lunar surface for resources to use either in near-lunar space, or to return to Earth. For most resources, the costs of mining the Moon and returning them to Earth would be prohibitive. However, for a resource such as Helium-3,[27] which might eventually find use infusion reactors, if they ever prove economical,[28] lunar mining might prove worthwhile.[29] If substantial infrastructure were to be placed on the Moon or in near-lunar space, lunar mining would likely be economically preferable to launching material from Earth's surface.[30] However, for the foreseeable future, lunar mining does not seem to be cost-effective.

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[26] G. Jeffrey Taylor and Paul D. Spudis, Geoscience *anda Lunar Base,* NASA Conference Publication 3070 (Washington, DC: National Aeronautics and Space Administration, 1990).

[27] Helium atoms with one less neutron than the vastly more common Helium-4.

[28] U.S. Congress, Office of Technology Assessment, *Star power: The U.S. and International Quest for Fusion Energy, OTA-E-338 Washington,* DC: U.S. Government Printing Office, October 1987).

[29] J.F. Santarius and G.L. Kulcinski, "Astrofuel: An Energy Source for the 21st Century," *Wisconsin Professional Engin eer, September/October 1989,* pp. 14-18.

[30] For example, th e production of oxygen o n the Moon to breathe and to use for propellant would quickly become cost+ ffective for long-term human stays on the surface.

Box 4-D-Advantages and Drawbacks of Using the Moon for Astronomy

Advantages

Compared to sites on Earth or in Earth orbit, the Moon possesses several advantages as a base for pursuing observational astronomical research. The following summarizes the most important ones for optical and radio astronomy. In order to determine the effectiveness of any particular lunar observatory, astronomers would have to make a detailed comparison of advantages, drawbacks, and costs of each proposed system compared to Earth- or space-based alternatives.

- ***Ultra-high vacuum.*[1] *The virtual absence*** of an atmosphere on the Moon means that the many atmospheric distortions caused by dust, aerosols, refraction, and scintillation that limit the resolving power of Earth-bound telescopes do not occur. In addition, the near vacuum of the lunar surface would allow telescopes to observe the entire electromagnetic spectrum unencumbered by the absorbing qualities of Earth's atmosphere.

- ***Stable solid surface. The*** rigidity of the lunar surface and its low incidence of seismic activity (10^{-8} that of Earth) allow relatively simple, low-cost telescope mountings to be used. Those same qualities make possible the construction and operation of interferometers involving many independent radio and optical telescopes. This is particularly important for optical telescopes, as the stability requirements vary inversely with the wavelength of light.

- ***Dark sky*** [1] Even the darkest terrestrial night reveals some air glow, which degrades the most sensitive optical measurements. When the Moon is in the night sky, light scattered by Earth's atmosphere interferes markedly with optical observations. Because the Moon has no scattering atmosphere, with proper optical shielding, it should be possible to observe even when Earth and/or the Sun are above the horizon. In contrast, terrestrial telescopes, and those in low-Earth orbits (e.g., the Hubble Space Telescope), collect data only about one-fourth of the time.

- ***Cold sky.*** [1] Not only does Earth's atmosphere scatter visual light, causing, for example, the sensation of blue sky, it also scatters infrared radiation, including the very long wavelength radiation known as the thermal infrared. This region of the electromagnetic spectrum has become extremely important in recent years, especially for detecting hot regions of star formation, and for very cold stars that are reaching the end of their evolutional path.

- ***Absence of wind.***[1] Protective structures surrounding earthly telescopes must be rigid enough to stand high winds. The absence of wind on the Moon means that structures need carry only static and thermal loads, which would make them much lighter and easier to construct. The lunar equivalent of telescope domes might simply be lightweight, movable foil shades to protect from dust, and from Sun and Earth light.

- ***Low gravity.*** Because the Moon only has one-sixth of Earth's gravity, lunar structures can be much less massive to carry the weight than Earth-bound structures. The presence of some gravity means that debris and dust fall quickly to the surface rather than tagging along, as they would do in space.

- ***Rotation.*** The lunar "day," its period of full rotation, lasts approximately 30 Earth days. Such a slow rotation rate allows observers to keep telescopes pointed in the same direction for long periods and permits the long integration rates required for extremely faint sky objects.

- ***Distance from Earth.*** *The* 400,000-kilometer distance between the Earth and the Moon weakens the electromagnetic noise generated on Earth by a factor of 100 compared to a radio observatory in geosynchronous orbit. Radio observations on the Moon will be very little affected by radio emission from Earth.

- ***Lunar farside.*** Despite the distance from Earth, reception in some radio frequencies would nevertheless be affected by noise generated by activities on Earth. The farside of the Moon is permanently oriented away from Earth. Siting a radio telescope on the lunar farside would permit the reception and discrimination of very faint radio signals in some critical radio bands.

[1] Telescopes in geostationary orbit also share in these advantages.

Continued on next page

Box 4-D–Advantages and Drawbacks of Using the Moon For Astnonomy-Continued

- ***Useful landforrns. The*** surface of the Moon has numerous symrnetrical craters that would be suitable for use as astronomical telescopes, similar to the world's largest radio telescope-the 300-meter dish at Arecibo, Puerto Rico.
- ***Relative absence of competitive uses of the surface.*** For a long time, the surface of the Moon is likely to have few competing uses.

Drawbacks

Siting radio and optical telescopes on the lunar surface also possesses major disadvantages compared to space-based or Earth-based systems. Many of these disadvantages would fade away if a permanent lunar colony of sufficient size to support astronomy were established for other reasons, e.g., to study the long-term effects of low gravity conditions on humans, or to support lunar mining. In addition, if robotic emplacement were to prove cost-effective, these drawbacks would also diminish.

- ***Distance from Earth. The*** great distance from Earth to the Moon would make logistics and repair more difficult and therefore much more costly.
- ***High projected costs.*** Providing transportation to and from the Moon for people and equipment would be extremely costly. In addition, the costs of establishing a lunar base and constructing observatories in the hostile lunar environment would be great. As lunar crews became more accustomed to working on the Moon, the latter costs would likely decrease.
- ***Potential for competing systems.*** Some of the advantages of a lunar observatory also apply to telescopes situated in geostationary orbit. In addition, spacecraft designers have more than two decades experience designing and building spacecraft that operate in geostationary orbit. Telescopes located in geostationary orbit would likely compete economically with telescopes located on the Moon. The highly successful International Ultraviolet Explorer (IUE) provides a clear example of such economic competition. IUE was built at a cost (1991 dollars) of about $250 million and launched in 1978. It still provides high-quality ultraviolet data for hundreds of astronomers per year.
- ***Unknown practical details.*** Living and working in space has always been much more difficult and costly than foreseen when systems are planned. The lunar surface is unlikely to be different.
- ***Cosmic ray protection.*** Earth's magnetic field protects its surface and near-Earth space from cosmic rays and particles from the solar wind. The Moon has no such field. Hence, both instruments and humans need to have special protection from these highly damaging particles.[2]
- ***Micrometeoroid protection.*** Sensitive surfaces, e.g., optical mirrors, will have to be protected from the damaging impacts of micrometeoroids that constantly rain down on the lunar surface. However, spacecraft in low-Earth orbit suffer from the effects not only of micrometeoroid material, but also artificial orbital debris.[3]
- ***Need for substantial habitats for human operators.*** Humans will need pressurized quarters for living and working on the Moon. They will also need considerable protection from lethal doses of charged particles from cosmic rays and from the occasional solar flare.
- ***Lunar dust.*** Lunar observatories will need protection from Lunar dust, which, when disturbed, tends to adhere to surfaces with which it comes in contact.

SOURCES: Harlan J. Smith, "SomeThoughtson Astronomy From the Moon," in Michael J. Mumma, Harlan J. Smith, and Gregg H. Linebaugh, *Astrophysics from* the Moon, American Institute of Physics Conference Proceedings, vol. 207 (New York, NY: American Institute of Physics, 1990), pp. 273-282; Jack O. Bums, Nebojsa Duric, G. Jeffrey Taylor, and Stewart W. Johnson, "Observatories on the Moon," *Scientific American, vol.* 262, No. 3, 1990, pp. 42-49; Office of Technology Assessment.

[2]Observatories located in geostationary orbit, which is outside Earth's protective magnetic shield, also require such protection.

[3]U.S. Congress, Office of Technology Assessment, *Orbiting Debris: A Space Environmental Problem*, OTA-BP-ISC-72 *(Washington,* DC: U.S. Government Printing Office, September 1990).

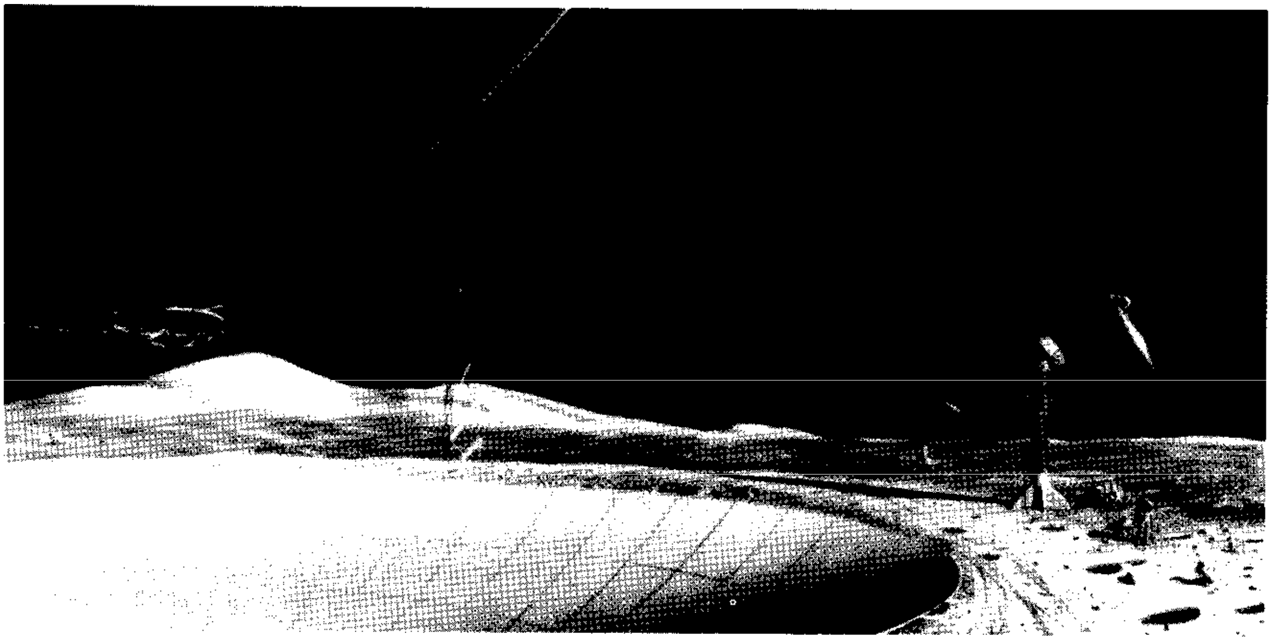

Photo credit: National Aeronautics and Space Administration

Artist's concept of a lunar observatory on the far side of the Moon. In the left foreground, a large radio telescope constructed from a lunar crater collects radio signals from space and focuses them on a collector suspended above the radio dish.