THE VALUE OF THE MOON

How to Explore, Live, and Prosper in Space Using the Moon's Resources

Paul D. Spudis

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PREFACE

Twenty years ago, I wrote *The Once and Future Moon* (Smithsonian Institution Press, 1996). That bo described the field of lunar science for the interested nontechnical reader and explained what we h learned about the processes and history of the Moon from robotic and human missions. We were acquiri some tantalizing hints that the Moon was *useful*—that it contained the material and energy resour necessary for a sustained human presence there. In the decades since then, exploration by robotic spacecra has shown us more about the nature of these resources, confirming that the Moon is a more compelli destination than we had previously thought.

Regrettably, strategic confusion currently abounds in the American civil space program. Despite the hyp and disprovable propaganda that we are preparing to conduct human missions to Mars, such an effort is fa away technically, politically, and especially fiscally. A program to extend human reach beyond low Eart orbit (LEO) was arbitrarily terminated in 2010, and no rational program was offered by the administratio as a replacement. Into this leadership vacuum, Congress stepped forward with a makeshift program to bui a heavy lift launch vehicle (the Space Launch System) along with a human spacecraft designed for missio beyond LEO. No mission for these two items has been articulated. We will soon have some nice hardwar but no place to go.

In part, this policy chaos resulted from a misguided attempt to re-create the Apollo program. Apollo, no almost a half-century in the past, was the national effort that sent humans to the Moon. Contrary to th belief of many, the Apollo program was not about space exploration—it was about beating the Soviet Unio to the Moon by landing a man there first. The entire Apollo program was a Cold War battle, and the Unite States won. Afterward, we stopped going to the Moon. The wartime setting of Apollo dictated that it conducted along the lines of a wartime program: with urgency, marshalling the best technology an industrial capacity we could muster, and with cost as a secondary consideration.

Since then, we have repeatedly failed to achieve sustainable space exploration beyond LEO by trying shoehorn it into the Apollo template. After landing American astronauts on the Moon in a highly visible an successful manner, perhaps it was natural to assume that this approach should be the configuration f future space endeavors. But after continually trying to re-create the Apollo experience by focusing on similar human mission to Mars, with all pieces launched entirely from the Earth, we are little closer to th goal today than we were fifty years ago. The Apollo template, applied to the even greater technical challen of a Mars mission, is enormously difficult and thus, enormously expensive, requiring tens to hundreds billions of dollars to conduct a single mission.

A slower but affordable approach to the problem of a human Mars mission would be to gradually an incrementally increase the range of spaceflight. To do this, we would need several technical developmen including reusable vehicles based in space, staging nodes at strategic space locations, and the ability provision ourselves for the trip from non-Earth resources, especially with high-mass, low-information densi items, such as life-support consumables and rocket propellant. To our great good fortune, nature ha provided us with a readily available source for this materiel—the Moon.

We can use the Moon to create new spaceflight capability. Water ice, the most useful material in space occurs in abundance at the poles of the Moon. We can access and extract these valuable deposits because th poles also possess areas where we can generate electrical power nearly continuously. The polar “oases” of th lunar desert allow us to live on the Moon and learn how to use off-Earth material and energy resources. Th effort will create a new paradigm of spaceflight: to use what is available in space instead of launching it a from the deepest gravity well in the inner solar system, the Earth's surface. Such a development w revolutionize space travel.

Of critical importance to achieving this revolution is working out how to affordably establish a presen on the Moon. We have limited time and money to spend on space. I believe that there is a path to the Moo one that accommodates the needs of federal, international, and commercial interests, a visionary scheme th will open up the solar system to economic development.

Modern technical civilization depends on a variety of assets in space. These machines monitor our weath and environment, provide instant global communications, permit precision navigation anywhere in th world, and secure our nation and the world with strategic surveillance. Satellites are vulnerable, and national presence in cislunar space—the space between Earth and the Moon—is essential to guarantee o continued and uninterrupted access to these assets. A robust presence by the United States in cislunar space necessary to assure the future emergence of free markets and to promote the growth of a pluralistic, politic system on the new frontier.

This book tells the story of how we once went to the Moon, what we found as a result, our various effor to return there, and especially why and how we should go back. We go to the Moon to create ne capabilities. It is the next logical step in space beyond LEO.

I thank my colleagues who critically read and reviewed all or parts of the manuscript: Sam Lawren (Arizona State University), John Greuner (NASA–Johnson Space Center), Jack Frassanito (Frassanito an Associates, Inc.), Tony Lavoie (NASA–Marshall Space Flight Center), and Ben Bussey (Johns Hopkin University Applied Physics Laboratory, currently detailed to NASA Headquarters). Some figures wer provided by Dennis Wingo (Skycorp, Inc.), Mark Robinson (Arizona State University), and Jack Frassanit As always, my wonderful wife, Anne, is my most insightful critic, merciless editor, and best friend; especially thank her for editing multiple versions of this manuscript and for general inspiration.

Luna: Earth’s Companion in Space

Humans dreamed of touching the Moon for millennia. It was only within living memory that v actually left our planet and stepped upon the strange new world that lies on our celestial doorste Recently, an international flotilla of robotic probes mapped the properties and determined the processes this lunar world. Amazingly, it found that the Moon contains the material and energy resources needed establish a permanent, sustained human presence there. Water ice was found near the poles of the Moon- billions of tons of ice, trapped in its cold, dark regions. Areas close to these ice deposits are bathed in sunlig for most of the lunar year. Water and light are two resources that permit us to use the Moon to create ne capabilities for spaceflight. Thus, the Moon is an object of great utility that offers us strategic and operation possibilities that other destinations in space do not.

Because the Moon is close, we can access it easily and continuously, unlike virtually any other deep spa destination. The Moon’s nearness means that much of the initial work of producing water and preparing t surface for habitation can be done remotely with robots under the control of human operators on Eart Unique among space destinations, the proximity of the Moon allows us to begin its development befo sending people, making the lunar surface the most inexpensive space goal beyond low Earth orbit, whe significant progress can be attained early. The low gravity of the Moon (one-sixth that of Earth) enables us use its resources to provision ourselves with the air, water, and propellant needed for the interplaneta journeys that humanity will undertake in the future.

The Moon is a small, complex satellite with a protracted and fascinating history and evolution. The ear history of the solar system, a distant age when planets collided, globes melted, and crusts were formed a bombarded by impacts of leftover debris, are recorded in the rocks and soil of the Moon. The Moon has core, a mantle, and a crust. Giant impact craters and basins have excavated thousands of cubic kilometers rock and then crushed, melted, and reassembled it into complex forms. Internal melting generated magma which were released onto the surface as massive outpourings of lava, flooding large regions of the lun surface. Following this period of violent geological events, near quiet has presided over the last billion yea The fossilized world of the Moon intrigues us, challenging our understanding of how the universe works.

All of these attributes place the Moon in the high-value column when selecting future strategic directio for humans in space. We went there half a century ago largely because a human lunar landing was dramatic space goal achievable within a reasonable amount of time. Now, this same proximity, coupled wi the Moon’s intrinsic interest and resources, again makes it an attractive destination. As we consider this, it important to know how we went before, what we learned and why the Moon is the logical next strateg goal for the American space program. I will relate the history of our efforts to return to the Moon and t multiple starts and stops of that effort. Like Sisyphus and his stone, each time we thought we were on t road back to the Moon, we seemingly rolled back to the beginning. But unlike Sisyphus, each failed attem to restart lunar spaceflight resulted in the acquisition of new data and information that has shown us that t Moon is an even more useful and inviting destination than we had thought. It is a wandering and compl (but fascinating) story involving geopolitics, government spending, big science and technology, and nation greatness.

The Moon as an Object of Wonder, Mystery, and Worship

As the largest object in our night sky, the Moon has always been an object of interest and awe. From our fir gaze overhead, we have wondered about and studied it, charting its path across the heavens. Because th Moon's shape and appearance changed with regularity, it suggested to early humans that there was order i the otherwise capricious and potentially dangerous unknown world around them. The Moon allowed th earliest life on Earth to measure the passage of time, predict the seasons, and plan ahead—survival ski important to all species. Early religious speculation involved the worship of nature. The Moon's changi appearance over the course of a month, along with the passing of days and seasons, became the natu timepiece whose rhythms and cycles helped humans regulate their lives. The coincidence of the duration the lunar cycle to human menses suggested a female presence in the heavens. In the pantheon of deiti Moon goddesses Artemis, Diana, and Selene oversaw the natural world.

Even after ancient nature worship had been largely abandoned in western culture, the Moon remained timekeeper and an object of intrigue. Both Judaic and Muslim religious calendars are lunar-based, not sola based. Because the lunar and solar cycles are not coincident, holidays such as Passover and Ramadan fall different dates every year. Aside from its early, practical use as a timekeeper, the Moon also influence culture. A full moon permitted considerable outdoor activity during preindustrial history, spawning tales an legends of werewolves and "lunacy"—the idea that a full moon (Luna) could induce unnatural a abnormal behavior and activity.[1]

We now know that Earth's Moon has been, and will remain, intimately tied to human origins, histor and development. The Moon's twenty-eight-day orbit around Earth acts as a stabilizing influence on th obliquity of Earth's spin axis, causing it to be stable for extended geological periods. Without th stabilization, rapid and chaotic changes in the orientation of its spin axis would make Earth oscillate wild between climatic extremes, as happened on Mars. The Moon's rotation around Earth causes tides on oceans and land, resulting in the development of periodically inundated coastal areas, sometimes belo water and sometimes above it. Such terrain fluctuation is believed to have facilitated the development land creatures, as marine species began to tolerate brief periods on dry land. Thus, because of gravitational influence, the Moon was a major driving force in the evolution of life on Earth.

Anaxagoras (500–428 BCE) was among the first of the early Greeks philosophers to examine the Mo scientifically. He believed that the Moon did not shine from its own light, but merely reflected the light the Sun. He also developed the first correct explanation of solar eclipses. Aristotle (384–322 BCE) believe that the Moon was a sphere, always showing the same hemisphere (the near side) to us. Aristarchus of Sam (310–230 BCE) calculated the distance between Earth and Moon at 60 Earth radii, an astonishingly goo estimate (in its elliptical orbit, the Moon actually varies in distance between 57 to 64 Earth radii, or betwe 363,000 to 406,000 km).[2]

During the Middle Ages, leading up to the Renaissance, or roughly the fifth to the sixteenth centuries, t Moon was simply another object to astronomers, but it did play a key role in the development and evolutio of modern physical science. Galileo (1564–1642), an Italian philosopher, physicist, and astronomer, not on observed the Moon with a primitive telescope but also conducted experiments on the laws of motion and w an early convert to the Copernican system of a heliocentric solar system. The recorded motions of the Mo and planets against a background of fixed stars by careful observers, such as the Danish court astronom Tycho Brahe (1546–1601), led German scientist Johannes Kepler (1571–1630) to formulate his three laws planetary motion. A key insight is that planets and moons orbit their primaries in elliptical paths, n circular ones, as Copernicus (1437–1543) had suggested. As the Renaissance gave way to the Age Enlightenment, English physicist Isaac Newton (1643–1727) synthesized the observations of Tycho, and t laws of planetary motion by Kepler, into a unified theory of gravitation. Once again, the Moon played criti~~cal role. As Newton observed an apple fall from a tree in his garden, he wondered if the force~~ acti upon the apple was the same force that kept the Moon in its orbit around Earth. From this simple musin he developed the laws of motion and universal gravitation, a mathematical system that explained t physical world in exquisite, clockwork detail.

Although the naked eye cannot resolve individual landforms on the Moon, patches of light and dark are on its visible disc have been discussed since antiquity, leading to fanciful Rorschach-like interpretation ranging from the famous "Man in the Moon" to rabbits, dogs, dragons, and a wide variety of other creatur or objects. The dark and light areas are caused by the Moon's two principal terrains: the dark, smooth *mar* (Latin for "seas") and the brighter, rougher *terra* ("land" or highlands). The association of the dark terra with seas has a muddled history. Galileo is often credited with it, but he didn't actually equate the dark area with water; he only suggested that some "might" be so. Using the newly invented telescope, Galileo mac drawings and wrote detailed descriptions of the complex landforms that make up the lunar surface.[3] I observing the Moon during different phases and surface illuminations, he saw that its surface was n smooth, as some of the classical philosophers had surmised, but rough and jagged, consisting of toweri mountains and most significantly, circular depressions in a wide variety of sizes. Even though the Moon near side had been thoroughly mapped and remapped by astronomers over the previous two hundred yea the use of the word "crater" (from the Greek word meaning cup or bowl) to describe these holes was n used until the late eighteenth century.

With the advent of increasingly more powerful telescopes, the landscape of the lunar near side becar known in much greater detail (figure 1.1). Astronomers now moved past the Moon to the more interestir stars, nebulas, and galaxies beyond. Lunar studies were left to a few diehards, mostly amateur astronome and rogue geologists. The vast bulk of work on the Moon in the nineteenth and early twentieth centur dealt with descriptions and studies of its surface features and history—most pressingly, the problem of t origin of craters. There were two opposing camps regarding craters. One group held that volcanic explosio and eruptions formed craters, while the other group believed that craters were made by the impact of sm bodies, such as asteroids and comets.[4] This debate grew to near religious intensity, often with more heat tha light being shed on the problem. The two proposed mechanisms had very different implications. Th volcanic hypothesis suggested that the Moon was an active body, with internal heat and ongoing volcanisn The impact idea suggested instead that the Moon was cold and dead and might never have had any intern activity. To support their arguments, each side marshaled the best examples they could; few analogues fron the study of Earth's landforms were of any help. Although Earth has many volcanoes that have been studi for years, at the beginning of the twentieth century, no recognized terrestrial impact feature had as yet bee described.

Figure 1.1. View of the waxing gibbous Moon generated from LRO WAC images. The dark, smooth plains (maria) are basaltic lava flows, most erupted before three billion years ago. The rough, heavily cratered highlands (terrae) are the remnants of the original lunar crust. Bright spots fresh craters. (Credit 1.1)

In 1892, Chief Geologist of the US Geological SurveyGrove Karl Gilbert, intrigued by the craters of t Moon, spent many nights studying the lunar surface through a telescope at Washington's Naval Observator Gilbert had heard a lecture about meteorite fragments that had been collected near a feature known as Co Butte in northern Arizona. Mineralogist Albert Foote described these iron meteorites and noted the proximity to Coon Butte, but did not go so far as to connect the two in origin. Gilbert decided to study Co

Butte as a possible impact crater. By carefully measuring the shape of the crater, he calculated the likely si of ~~an impacting iron meteorite. He postulated that the remnants of such an object must curren~~tly ex beneath the floor of the crater and used a magnetic dip needle (designed to show variations in Eartl magnetic field) to search for what he believed should be an enormous buried iron body below the surfac But after intensive mapping failed to reveal the buried meteorite, Gilbert reluctantly (and wrongl concluded that the Coon Butte crater must be a volcanic steam vent.[5] Today, Coon Butte is known as Mete Crater and is considered the world's first documented meteorite impact site. How did Gilbert get its origin wrong, especially since he had specifically tested the impact idea?

Gilbert did not understand that an impact at extremely high velocities (greater than 10 km/secon produces such enormous energies that the projectile essentially vaporizes as a point-source release of ener left behind is a big hole with no buried iron body beneath the crater floor. An impact event is very similar the detonation of a nuclear bomb. In fact, the formation of Meteor Crater fifty thousand years earlier by t impact of an iron meteorite must have looked very much like a nuclear explosion, complete with blindi flash and subsequent mushroom cloud. Documentation that this crater formed by impact opened t floodgates to the recognition and cataloging of dozens of impact craters on Earth (a process that continues this day). Study of these features taught scientists to recognize the physical and chemical effects of hi velocity impact, knowledge that would become critical in future interpretations of samples from the Mo and for a startling new interpretation of Earth's history as well.

The Moon as Destination: The Space Race

The idea that we might someday travel to the Moon was often the subject of imaginative fiction, but such journey could not be seriously contemplated until Konstantin Tsiolkovsky, Hermann Oberth, and Robe Goddard had developed the basic principles of rocketry and spaceflight.[6] The technology of rockets ma great strides under the impetus of war, as Germany developed the world's first intercontinental ballis missile (ICBM), the A4 (or "V-2" as Hitler dubbed it). In the years following World War II, intensive wor toward the development of larger and better ICBMs as weapons of war led to the advent of Earthorbiti satellites (Soviet Sputnik in 1957 and American Explorer 1 in 1958) and ushered in the Space Age. War ar space were tightly coupled from the beginning, since the first use envisioned for space revolved around possible value as a battleground.

Given this background, it was inevitable that the Moon would emerge as a key object in the exploration space. Indeed, trips to the Moon began shortly after the beginning of the Space Age with the flight of Luna in 1959. This Soviet robotic probe hit the Moon after a three-day journey, making it the first man-ma object to reach another extraterrestrial body. Because of the Moon's prominence in the sky and its proximi to Earth, it quickly became the focus of the first race into space between the United States and the Sov Union. In May 1961, responding to a growing sense of geopolitical competition, President John F. Kenned declared a national goal of a human lunar landing by the end of the decade. It was widely assumed that t USSR had accepted America's challenge and that the "Race to the Moon" was on. A series of activities Earth orbit conducted by both nations soon followed, filling that decade with new space accomplishmen which included extravehicular activities (spacewalks), the rendezvous and docking of two orbital spacecra long-duration flights (up to two weeks), flights to extremely high altitudes in the hundreds of kilometers, ar the mastery of complex orbital changes. All of these techniques would be needed for a human mission to t Moon.

Meanwhile, the United States launched a series of robotic spacecraft to examine and scout the Mo These missions probed its surface, landed softly on it, examined the soil, took high-resolution images of surface features, and prepared the way for future human missions. The Ranger (impactors), Surveyor (sc lan~~ders), and Lunar Orbiter series gave us a first-order understanding of lunar surface features, process~~es ar history.[7] Scientists and engineers learned that the surface was dusty, yet strong enough to support the weig of a lander and astronauts. Craters covered every square millimeter of its surface, ranging in size fro microscopic to enormous basins spanning thousands of kilometers. The landscape of thefar side of the Mo turned out to be very different from its near side, with a near-absence of the dark, smooth maria that cov much of the Earth-facing hemisphere. Many unusual landforms of non-impact origin were found in t maria, strongly suggesting its origin as volcanic lava flows. Assuming that most craters were formed b impact, their density and distribution suggested that the Moon was an ancient world. Its surface told a sto of having being exposed to space for many millions to billions of years.

The results of the Apollo missions, along with 380 kg (842 pounds) of rock and soil samples returned Earth, largely confirmed and extended these inferences.[8] We found that the Moon is made up of some of t same rock-forming minerals widely found on Earth and that it formed almost 4.6 billion years ago, abo the same time as Earth. The samples suggested that the early Moon had been nearly completely molte covered by an “ocean” of liquid rock. After this magma solidified at 4.3 billion years, a barrage of asteroi and comets bombarded the Moon’s surface for the next 400 million years, mixing-up the crust and creating rough, heavily cratered surface. A final cataclysmic series of large impacts about 3.9 billion years ago forme the youngest basins, including the large, prominent Imbrium basin on the near side. The low areas of impa basins slowly filled with volcanic lava over the next 800 million years. For most of the last couple of billi years, the Moon has been largely inactive, with only the occasional large-body impact punctuating the slo and steady “rain” of micrometeorites that continue to grinds the surface into a fine powder.

This brief sketch of the history and evolution of the Moon describes a more complex planetary body th had been imagined before the Space Age. The Moon’s scarred, ancient surface records not only its ow history, but also that of impacts in the Earth-Moon system as well. Because the Moon has no atmosphere global magnetic field, the dust grains of the lunar surface also record the particle output of the Sun for t last three billion years. With the Moon as a “witness plate” to events in this part of the universe, this geolog time capsule remains virtually untouched, waiting to be recovered and read. Although we found that t Moon is depleted in volatile elements compared to Earth, we have only explored the lunar surface wi people at six sites, all relatively close to the equator and on the near side. One cannot help but wonder wh possible surprises await us at the regions near the poles or on the far side.

Most people are familiar with the political and pop-culture effects the Space Race had on the world, b they are not as well versed on the profound scientific impact of the Apollo missions. For the first time, v had collected samples from another world, taken from sites of known location and geological context. W took what we learned from these physical samples and coupled it with the global data gained from t robotic precursors. Added to this knowledge was information attained from regional areas through remo sensing. Combining all of these data allowed us to reconstruct the story of the Moon with a high degree fidelity. The most important discovery of the Apollo studies was recognition of the critical importance of t process of impact on the history and evolution of the solar system. From an elusive and questionable idea the pre–Space Age era, the collision of solid objects became recognized as *the* dominant, fundamental proce in planetary formation and evolution. Because we had learned to recognize the physical and chemical effec of hypervelocity impact through the study of the lunar samples, we soon recognized that large body impa had occurred on Earth in the distant past. In particular, the extinction of the dinosaurs 65 million years a was recognized to have happened simultaneously with the impact of an asteroid 10 kilometers in diamet This observation, suggesting that impacts might cause mass extinctions of life, was soon extended to oth extinction events evident in Earth’s fossil record.[9] Some scientists now think that mass extinctions caused b impact may be one of the principal drivers of biological evolution. Thus, because we went to the Moon mo than ~~forty years ago, we now understand something very profound about the history of life on our~~ hom planet—an understanding that holds clues about our past and poses some sobering implications for o future.

The Moon as an Enabling Asset

For all of its impressive scientific and technical accomplishments, the Apollo program left many spa advocates wanting. Because it was primarily driven by geopolitical conflict and designed to demonstrate o technical superiority, once Apollo had achieved its objective of "landing a man on the Moon and returni him safely to Earth," as President Kennedy's proclamation put it, there was no longer any reason to continu returning to the Moon or to go beyond into the solar system. Thus, the program held within itself the seeds its own demise. The rates of expenditure acceptable during the Apollo program were simply not political feasible for any follow-on space program.[10] So the decision was made to make an attempt to lower the co of spaceflight via a reusable space shuttle. While this effort did not succeed in lowering costs, th development of the shuttle led to some significant and unique capabilities. More importantly, it pointed th way toward an alternative architectural template for spaceflight, one in which small pieces, incremental launched and then assembled in space and operated as a large system of systems, might multiply spacefli capabilities carried out over a longer, more sustainable period of time. This template of operations reach its acme with the completion of the International Space Station (ISS).

As for missions to the Moon, there was only silence and isolation. Several attempts to fly an unmann orbital mission to obtain additional global remote sensing data (which would permit better interpretation the superb Apollo sample database) were unsuccessful. With the focus of the human program centered the space shuttle and the subsequent building of a space station in low Earth orbit, little interest in addition lunar exploration was evident. Then, in the mid-1980s, a confluence of events occurred to focus attenti once again on the Moon, an interest that continues to the present. First came the realization that after t building of the space station, an orbital transfer vehicle designed to reach high orbits, such as geosynchrono (~36,000 km or 22,000 miles high), was the obvious next step. A vehicle that can reach geosynchronous Ear orbit (GEO) can also reach the Moon. Thus, a series of studies focused on the possibility of lunar return, wi an emphasis on longer, more permanent stays on the surface.

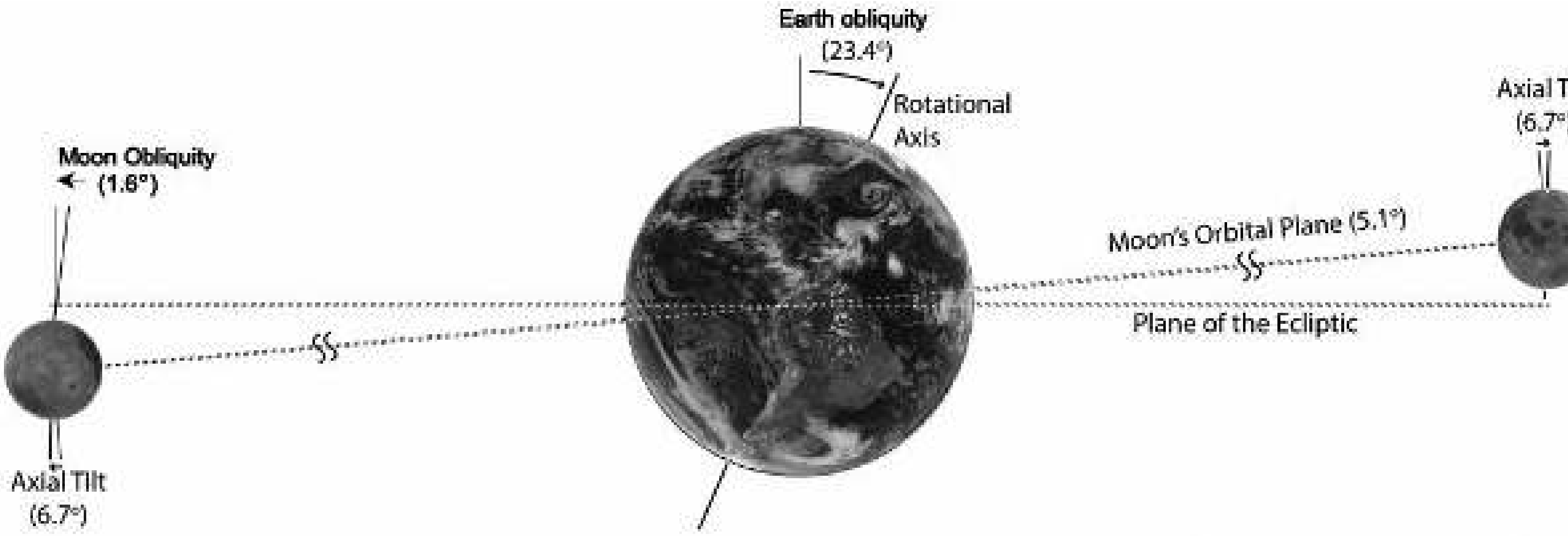

Figure 1.2. Orbital geometry of the Earth and Moon. The Earth-Moon system orbits the Sun within the plane of the ecliptic. The Moon's orb plane is inclined 5.1° from the ecliptic, and the Moon's spin axis is tilted 6.7°. This results in a nearly perpendicular orientation of the Moon's s axis to the ecliptic (called obliquity) of 1.6°. This is in contrast the Earth's obliquity of 23.4°.

The idea that we might want to remain on the Moon for longer periods of time inevitably led to t concept of obtaining some supplies locally, from the materials and energy found and available on the Moo This concept, called in situ resource utilization (ISRU), is an essential skill for humans to master if we are be significantly and permanently present in space and on other worlds.[11] That realization led to a renew interest in getting additional lunar data—most especially, data for the unique local environment found at t Moon's polar regions. Because the spin axis of the Moon is nearly perpendicular to the ecliptic plane (figu 1.2), the Sun is always on the horizon at the poles. Some areas are in permanent darkness and hence, ve cold. It was recognized that these "cold traps" might contain deposits of ice, along with other volat substances deposited over geological time as water-bearing comets and asteroids collided with the Moon surface. Additionally, other areas near the poles might be bathed in permanent sunlight. This nea continuous energy source allows for the generation of electrical power during the long, two-week lunar nigh At the time, we did not know the details of these hypothesized properties or even if they actually exist However, over the past twenty years, a number of lunar robotic missions have revolutionized our knowled of the Moon, and in particular the environment and deposits of the poles.

In 1994, the Department of Defense Clementine mission mapped the mineralogy and topography of t entire Moon from orbit. An improvised experiment on this flight used the spacecraft transmitter as a rad source to illuminate dark areas within craters near the poles. Analysis of radio echoes from the south po suggested the presence of water ice in the crater Shackleton. This discovery was confirmed a few years lat by the Lunar Prospector spacecraft, which found enhanced amounts of hydrogen at both poles. The discoveries stunned the lunar science community, since earlier results from the study of the Apollo sampl had suggested that the Moon was bone-dry and always had been. Now, that concept—and ou understanding of the Moon and its history—had to be reevaluated. Over the next few years, addition results from sample studies, remote sensing, and theoretical modeling culminated in the unequivoc detection of water vapor and ice during the impact of the LCROSS spacecraft, thus demonstrating beyo any doubt that significant deposits of water ice are present at both lunar poles. Conservative estimates of t amount of water ice run between several hundred million to more than a billion tons at each po Additionally, we have found that small areas near both poles are illuminated by the Sun for extende periods of time, some for more than nine-tenths of the year. All of this new lunar data has countries arou

the world planning ways to access the energy and resource bonanza at the poles of the Moon, available
those who arrive first.

Materials and energy are available on the Moon, two critical requirements for extended human presenc
Water, in its decomposed form of hydrogen and oxygen, not only supports human life but is also the mo
powerful chemical rocket propellant known. Near-permanent solar energy is available proximate to th
water-rich cold traps at the poles. The previously misleading image of the Moon as a barren, usel
wilderness (as painted by Apollo results) has given way to a richer, more inviting, useful persona. The wor
now knows that the Moon is not simply another destination in space—but that it is an important enablin
asset for spaceflight. Our current understanding of the Moon is vastly different from those early humans w
first gazed up, grateful that they had the Moon to mark their calendars and chart the seasons. We no
understand that the Moon is a world in its own right, an object located in our cosmic backyard who
resources we can access and use to travel throughout the solar system.

Our Future on Luna

Space engineer and visionary Kraftt Ehricke once said, "If God had intended man to be a space fari
species, He would have given him a Moon."[12] This tongue-in-cheek statement is even more applicable toda
than when Ehricke first said it more than thirty years ago.

Why is the Moon a destination for humanity? Because it can be used to open up the frontier of spa
through the development of its material and energy resources. By harvesting the water ice and solar pow
available at the poles of the Moon, we create the ability for long-term human presence on the Moon and
near-Earth space. Water can fuel a permanent, reusable space transportation system that can access not on
the lunar surface but also every other point between Earth and Moon. This zone, called cislunar space,
where 95 percent of our satellite assets reside. The ability to reach these places with people and machines w
allow us to build space systems of extraordinary power and capability. Moreover, such a system can also tak
us to the planets beyond Earth and its Moon.[13]

We can use the Moon to learn how to live and work effectively and productively on another world. Th
goal requires us to learn how to build protective shelters, safe from the thermal and radiation extremes
deep space. To provision ourselves, we must learn how to extract our supplies from local resources, includin
life support consumables, and learn how to build infrastructure using local resources for constructio
materials. Once established on the lunar surface, we will use these new capabilities to explore our neare
neighbor in space as well as to build a "transcontinental railroad" in cislunar space and establish
permanent beachhead off Earth. On the Moon, we will learn how to explore a planet using the optimu
combination of people and robots, each doing the tasks at which they uniquely excel. Finally, we will reve
and decipher the record of planetary and solar system evolution recorded in the rocks of the Moon. Sor
mysteries uncovered by the Apollo explorations revolutionized Earth science. Additional exploration w
reveal even more startling secrets and continue to revolutionize our understanding of the world and univer
around us.

Why is it important for the United States to make the Moon a high priority goal? Because the Unite
States is not the only nation interested in it. This coin of international interest has two sides. On the positi
side, our partners in current space endeavors, such as the International Space Station, have expressed gre
interest in human missions to the Moon. Some have begun the process of gathering detailed informati
from precursor robotic missions to enable future human missions to the Moon. How can we proclaim wor
leadership in space if we ignore a prominent destination that so many other nations are anxious to visit a
exploit? Nations such as China have plans to explore and use the Moon with both robotic machines and wi

people. While their lunar intentions appear benign at present, they are developing capabilities now th could ~~pose a threat to the security of this nation and other countries in the near future. Thus, there~~ is strategic dimension to American lunar presence. It is vital to the security and economic health of t community of nations that future societies in space develop according to pluralistic, democratic princip and that commerce is open to free markets, with respect for property rights and contract law. Althoug American presence in cislunar space does not guarantee such an outcome, our absence from this theat could well result in the reverse.

What makes the Moon both important and unique? It is close, interesting, and useful. The close proximi of the Moon to Earth means that we can always and easily access it, unlike the limited and infreque launch windows to all other planetary targets. This nearness means that much of the early preparatory wo at the Moon can be done by robots on the lunar surface, as directed from Earth. Thus, the first humans return to the Moon can arrive at a fully functional, turnkey lunar outpost, assembled in advance by the teleoperated robots. Interest in the Moon derives from its role as a small planet of complex and interesti process and evolution. The Moon's environment permits unique and specialized scientific and engineeri experiments to be conducted—studies not possible anywhere else in the solar system. We will find th answers to questions surrounding our moon's complexity and gain a fuller understanding of our hom planet's early evolution. The utility of the Moon lies in its material and energy resources, the access to whi will allow us to acquire the knowhow and means for humanity to plant its first foothold on another world.

2

The Moon Conquered—and Abandoned

How is it that America went to the Moon, going from nearly zero space capability to the lunar surface less than a decade, and then rapidly left it? Why have we not been back since? Within that tale a important lessons, some never fully absorbed by either historians or our national leadership. Millennia befo we achieved it, humans dreamed about going to the Moon. The actual circumstances of our journey had n been imagined by science fiction authors and as a result, virtually all science fiction dealing with lunar trav made the first landing the beginning (not the end) of humanity's movement into space. Now, it remains be seen whether our first steps on the Moon really was an ending, or merely the prelude to a delayed gold age of spaceflight.

Journeys to the Moon in Fiction and Fact

The idea that some day we would be able to journey to the Moon is very old, conceivably going back as f as the early cave dwellers. The first literary description of trips to the Moon, Sun, and other heaven destinations was likely the work of Lucian of Samosota (125–180 CE). Johannes Kepler, the discoverer of t laws of planetary motion, wrote *Somnium* ("Dream," published posthumously by his son in 1634). In h novel, Kepler describes a trip to the Moon and the view of Earth and the solar system from its surfa English clergyman John Wilkins wrote several books about trips to the Moon, the most famous being *T Discovery of a World in the Moone* (1638). In it, he outlined the idea that someday people might inhabit t Moon. Included in Wilkins's work were exotic and infeasible techniques on how to get there, such transport by angels or with the help of harnessed fowl.

During the Industrial Age, authors of classic science fiction took more reasonable (if still fancif approaches to the problem of lunar flight. In Jules Verne's *From the Earth to the Moon* (1865), voyagers we shot from a huge cannon (the *Columbiad*) in order to reach escape velocity and land on the Moon. Ver skipped over how the acceleration from a cannon shot would create enormous g-forces that would kill h crew; he also misunderstood the nature of weightlessness by having his passengers experience it only when h moonship crossed the gravitational spheres of influence between Earth and Moon. Konstantin Tsiolkovsk the inventor of astronautics and the first to derive the rocket equation, was inspired by Jules Verne an penned his own novel, *On the Moon* (1893). The character in Tsiolkovsky's story wakes up on the Moon an experiences the unusual effects of being on an alien world. Curiously, considering his contributions to rock science, Tsiolkovsky does not record the details of the trip from Earth. The approach of H. G. Wells was ev more fantastic: A special substance called Cavorite (named for its inventor, a character in Wells's 1901 nov *First Men in the Moon*) cuts off the force of gravity, allowing his sphere to effortlessly travel to the Moo Once there, the voyagers find large insectlike creatures that live below the lunar surface.

The Moon was lifted out of the realm of fiction and fantasy and put back into the domain of science w the advent of modern rocketry (an outgrowth of the Second World War). Starting with a few eccentrics, t Moon once again became a topic for scientific inquiry. Ralph Baldwin, an astronomy student at t

University of Chicago, after noticing the spectacular series of telescopic photographs on display in the lob of t~~he Adler Planetarium, began cogitating about the origin of craters, basins, and the evolution of th~~e lun surface. He wrote down thoughts for a couple of articles before being pressed into war service, where helped develop the proximity fuse. After the war, Baldwin collected his lunar ideas into a book, *The Face the Moon* (1949).[1] This pre–Space Age synthesis was a fairly complete and accurate account of the Moo processes and history—how the craters and basins were formed by impact, that the dark smooth maria we volcanic lava flows (Baldwin correctly identified them as basalt), and that the Moon's surface was very o compared to that of Earth's. Baldwin's study of the Moon continued throughout his life, and he lived to s virtually all of his surmises validated through the exploration of the Moon by the Apollo missions.

Shortly after this work appeared, the noted science fiction author Arthur C. Clarke published *T Exploration of Space* in 1951.[2] Clarke outlined an expansive vision of the future, including rockets into Ear orbit, trips to the Moon, and voyages to the planets. Interestingly, he made some careful and prescie observations about the issues of landing and sustaining a permanent human presence on the Moon. Clar considered the Moon an essential way station on the road to the planets. Here humans would learn t techniques of exploring and living on an alien world. Clarke specifically recognized that using the mine resources of the Moon to support human presence and create new capabilities was essential. He pointed o that, at least in the early phases of operation, centralizing operations at a single site on the Moon wou permit concentration of resources to maximize capabilities quickly. Thus, Clarke advocated building a bas not multiple sortie missions to many different locations. After the establishment of a presence at a base, v would be able to explore the entire Moon at our leisure.

Accounts hold that Nobel Prize–winning chemist Harold Urey became engrossed by *The Face of the Mo* when, by chance, he picked up the book at a party. Baldwin's description of the lunar landscape and t impact origin of its craters convinced Urey that the primitive, ancient Moon held secrets to the origin of t solar system. He went on to lead an effort that applied the basic principles of chemistry and physics to t origin and evolution of the Moon and planets.[3] Another astronomer, Gerard Kuiper, held the "heretica view that the Moon and the planets were worthy objects for observation and scientific study. For furth study and mapping, he collected the best telescopic images of the Moon at the Lunar and Planeta Laboratory that he established in 1960 at the University of Arizona in Tucson. Geologist Eugene Shoemak who was mapping uranium deposits in northern Arizona for the US Geological Survey in the 1950s, decid to reexamine the geology of Coon Butte, the feature dismissed by G. K. Gilbert as not being an impa structure sixty years earlier. Using the geology of the crater to unravel the mechanics of hypervelocі impact, including the discovery of forms of silica created only under extremely high pressures, Shoemak decided that Coon Butte was an impact crater. It has been known as Meteor Crater ever since.[4]

But Gene Shoemaker did more than just document the impact origin of Meteor Crater. In 1960, he ma the first geological map of the lunar surface, showing the basic sequence of events that had occurred there. brief, this technique involves using overlap and superposition relations to classify laterally continuous ro units, including sheets of crater ejecta and lava flows. These properties can be determined directly fro visual observations and photographs. Shoemaker mapped the region near the crater Copernicus on the ne side, working out the basic framework of lunar stratigraphy—that is, the sequence of layered rocks.[5] He th used this information to estimate the time correlation between events on the Moon and those on Eart concluding that the Moon preserved an ancient surficial record, which holds part of the early geological sto missing from the eroded and dynamic surface of Earth.

These scientists and their research, each in their own way, made the study of the Moon and its process scientifically respectable. After the launch of the first Earth-orbiting satellite Sputnik 1 in October 1957, was reasonable to imagine that spacecraft might be sent to the Moon. Soon, observations of the Moo surface through telescopes, the mapping of terrestrial impact craters, and compositional studies of rocks fro terr~~estrial impact craters and meteorites (rocks from space) became part of cutting-edge lunar sci~~ence. gradual but perceptible momentum began to formulate a conceptual model that would allow us to explo the Moon effectively and give us an understanding of its history. Some dreamed that they might live to s people travel to the Moon in their lifetimes (and Shoemaker planned on being one of them). Shoemake dream would come true in part, but under circumstances that no one foresaw.

The Apollo Program

In a series of articles published in *Collier's* in the 1950s, rocket scientist Wernher von Braun outlined a plan send people to the Moon and to Mars.[6] Accompanied with colorful illustrations by space artists such Chesley Bonestell, von Braun's articles caught the imagination of the public, including a very imaginati Walt Disney, who went on to feature von Braun's ideas in a series of programs as part of his new televisio series *Disneyland* (1954). Viewers were treated to a four-program series outlining the basic von Brau architecture: rocket to Earth orbit, space station, Moon tug, and human Mars spacecraft. This steppingston approach made both logical and programmatic sense. Each piece enabled and supported the next step in space. Although some technical details in von Braun's plan were out of date before they were realized—f example, von Braun had electrical power in space generated by solar thermal power alternately vaporizi and condensing mercury to drive turbines, a technology made obsolete with the advent of solar photovolta cells—major parts of his scheme enabled the establishment of a robust and permanent spacefaring system.

However, international events soon intervened on von Braun's orderly approach. The advent of the Apol program altered what was to have been a logical, incremental, and thoughtful space plan into a race on competition with the Soviet Union became our overriding concern. The slow approach had to be accelerate once President Kennedy committed the nation to a decadal deadline. Under ordinary technical developmen each piece would be designed, built, flown, and modified according to its performance. But with schedulin pressure designed to beat the Soviets to the Moon, a much faster approach was required. This caused vo Braun and others at the newly created National Aeronautics and Space Administration (NASA) to reexamin the problem of sending people to the Moon. Did we really need a space station first? Or was it possible build a launch vehicle big enough to send an entire expedition to the Moon in one fell swoop?

Although the space agency had already begun planning for the development of a new super heavy l rocket and had done some preliminary studies of manned missions to the Moon, the announcement of lunar landing goal by President John F. Kennedy in May 1961 shocked many at NASA. It was one thing t daydream about sending people into deep space and to the Moon, but quite another to actually be given th task to do so—and then bring them back safely to Earth, a stipulation of Kennedy's declaration. When th commitment to go to the Moon was made, the total manned spaceflight experience of the United Stat consisted of Alan Shepard's fifteen-minute-long suborbital hop. A lunar voyage would require the mastery a variety of complex spacefaring skills, including precision navigation and maneuvers necessary to chan orbit in flight.

The design or "architecture" for a manned lunar mission was debated extensively before the "mo decision." Initial plans called for either a direct ascent to the lunar surface or a rendezvous of two launch spacecraft in Earth orbit. Both approaches called for the development of a "super" heavy lift launch vehic Nova, a rocket capable of launching up to 180 metric tons to low Earth orbit.[7] John Houbolt, an engineer Langley, advocated instead for something called lunar orbit rendezvous.[8] This called for a small vehicle th would land on the lunar surface, then return to rendezvous with the Apollo spacecraft that had remained orbit around the Moon. Although this mission profile was thought to be very risky (a rendezvous had nev been accomplished in space, let alone one involving two separate spacecraft orbiting the Moon), it did enab the ~~voyage to be launched "all up" on a single heavy lift rocket. This design became the Saturn V, a~~ rock capable of launching 127 metric tons to low Earth orbit.

With the principal design features of Apollo outlined, the American space program next undertook a seri of manned and unmanned missions in preparation for a lunar landing. While human missions practice specific techniques (including rendezvous and docking), robotic missions gathered information about t Moon's surface conditions and environment and sought to identify a smooth, safe landing site. In preparatio for the Moon, we flew six single-man Mercury missions, ten two-man Gemini missions, and four three-ma Apollo rehearsal flights. There were thirteen successful robotic precursor missions to the Moon: three har landers, five soft-landers, and five orbiters. All this occurred within the eight years between Kennedy's spee and the landing of Apollo 11, a span of time that included the assassination of President Kennedy November 22, 1963, and a twenty-two-month stand-down after the tragic fire on Apollo 1 of January 2 1967, which killed astronauts Virgil "Gus" Grissom, Ed White, and Roger Chaffee.

The Apollo spacecraft was extensively redesigned and modified after the Apollo 1 fire. Following a high successful checkout of the newly refurbished Command-Service Modules in Earth orbit on Apollo 7, a eleven-day mission in October 1968, the planned journey of Apollo 8 to orbit the Moon seemed to be a bo even reckless move. After all, a spacecraft sent to the Moon without any rescue capability using a lun module (LM) could have ended in tragedy, as was demonstrated a few years later during the Apollo 1 mission. We now know that there was a reason, one that was withheld from the public at the time, f sending Apollo 8 on a lunar journey. The CIA had intelligence that the Soviets were planning a manne flight around the Moon by the end of 1968. They had just completed a circumlunar mission with th unmanned Zond 8, which demonstrated that the pieces for such a flight were ready. It was believe probably correctly, that if the Soviets were able to pull this off, they would then claim to have won the Mo race, making an actual lunar landing irrelevant.[9] This possibility lent urgency to flying a manned lun mission as soon as possible, even one that simply orbited, rather than landed on, the Moon. So, just befo Christmas in 1968, Apollo 8 orbited the Moon carrying Frank Borman, Jim Lovell, and Bill Anders. Althou it was not evident at the time, the flight of Apollo 8 effectively won the Moon race for the United States.

The next two missions qualified the Apollo lunar module in Earth orbit and in lunar orbit. Then, on Ju 20, 1969, Apollo 11 landed two men on the Moon. There were a few heart-stopping moments when the shi computer sent the Apollo 11 LM *Eagle* toward a large, block-strewn lunar crater, but astronauts N Armstrong and Buzz Aldrin successfully overrode the automatic system and landed safely. Initial concer about possible dangerous surface conditions were soon dispelled as the crew conducted a successful 2.5-ho exploration of their immediate landing site. They collected rock and soil samples, laid out experiments, a verified that the surface was both strong enough to support the considerable mass of the LM as well as oth equipment. The world watched as they demonstrated what it was like to move around on the Moon in on sixth the gravity of Earth. Armstrong made an unreported traverse to a blocky crater that he had flown ov during his landing approach and observed the bedrock in the crater floor. Twenty-two hours later, the two man crew blasted off the Moon's surface to rendezvous with Mike Collins, orbiting the Moon in t Command Module *Columbia*. With the crew's safe return to Earth a few days later, Kennedy's darin challenge to America eight years earlier was fulfilled.

Next came the question of what to do with the remaining Saturn rockets and Apollo hardware, t surplus equipment that had been procured in the event that more than a single attempt would be needed successfully land on the Moon. Initially, Apollo engineers planned for more lunar missions and ultimately human mission to Mars. However, it soon became apparent that the national will was not inclined towa additional human exploration beyond the Moon—or even to it. An ambitious program to push t boundaries of human reach into space was shelved.[10] Apollo continued for a few more flights, but lun base~~s and Mars missions were not in the cards. Our focus shifted to completing the Apollo program,~~ then developing a reusable transport-to-orbit vehicle for people and cargo—the flight program that designe built, and operated the space shuttle.

Despite the political decision to abandon the capabilities of the Apollo-Saturn system, NASA was able t wrangle permission to fly out part of the remaining original plan for Apollo lunar exploration. Sever interesting landing sites were selected for these missions, most of which had advanced capabilities and too for exploration. Even with some notable mission problems, flight and surface operations steadily improve Despite being struck twice by lightning during liftoff, Apollo 12 successfully landed on the Moon November 1969. This mission validated the technique of pinpoint landing by setting the LM *Intrepid* dow within a hundred meters of Surveyor 3, a previously landed robotic probe. This technique allowed us safely land at future sites of high scientific (but dangerous operational) interest. After the disaster and nea loss of the Apollo 13 mission, following the explosion of an oxygen tank in its Service Module, whi cancelled its landing on the Moon, the Apollo 14 crew traveled to the highlands of Fra Mauro in early 197 Here it was expected that they would find material thrown out from the largest, youngest impact basin, t Imbrium Basin. From this site, the astronauts returned complex, multigenerational fragmental rocks call breccias, parts of which dated to the earliest era of lunar history.

On the final three Apollo missions (15, 16, and 17), the astronauts spent longer times on the surface a possessed greater capability for exploration.[11] The first three lunar landings had no surface transport, so t crews had to stay within a few hundred meters of their LM and could not remain outside the spacecraft f more than four to five hours at a time. The next three landings used more capable spacecraft and eac mission carried a surface rover—a small electric cart strapped to the outside of the LM. Once they were the surface, the cart was taken off, unfolded, and then driven by the crew to locales several kilometers awa from the landing points. In addition, a redesigned spacesuit allowed moonwalks of up to eight hou duration. Consequently, an extraordinary amount of high-quality exploration was conducted on these latt missions. Each subsequent mission improved upon the total distance traveled, the amount of sampl collected, the experiments performed and the data gathered. These were the “J-missions,” and because them, the Apollo program wrote great chapters in the history of human exploration.

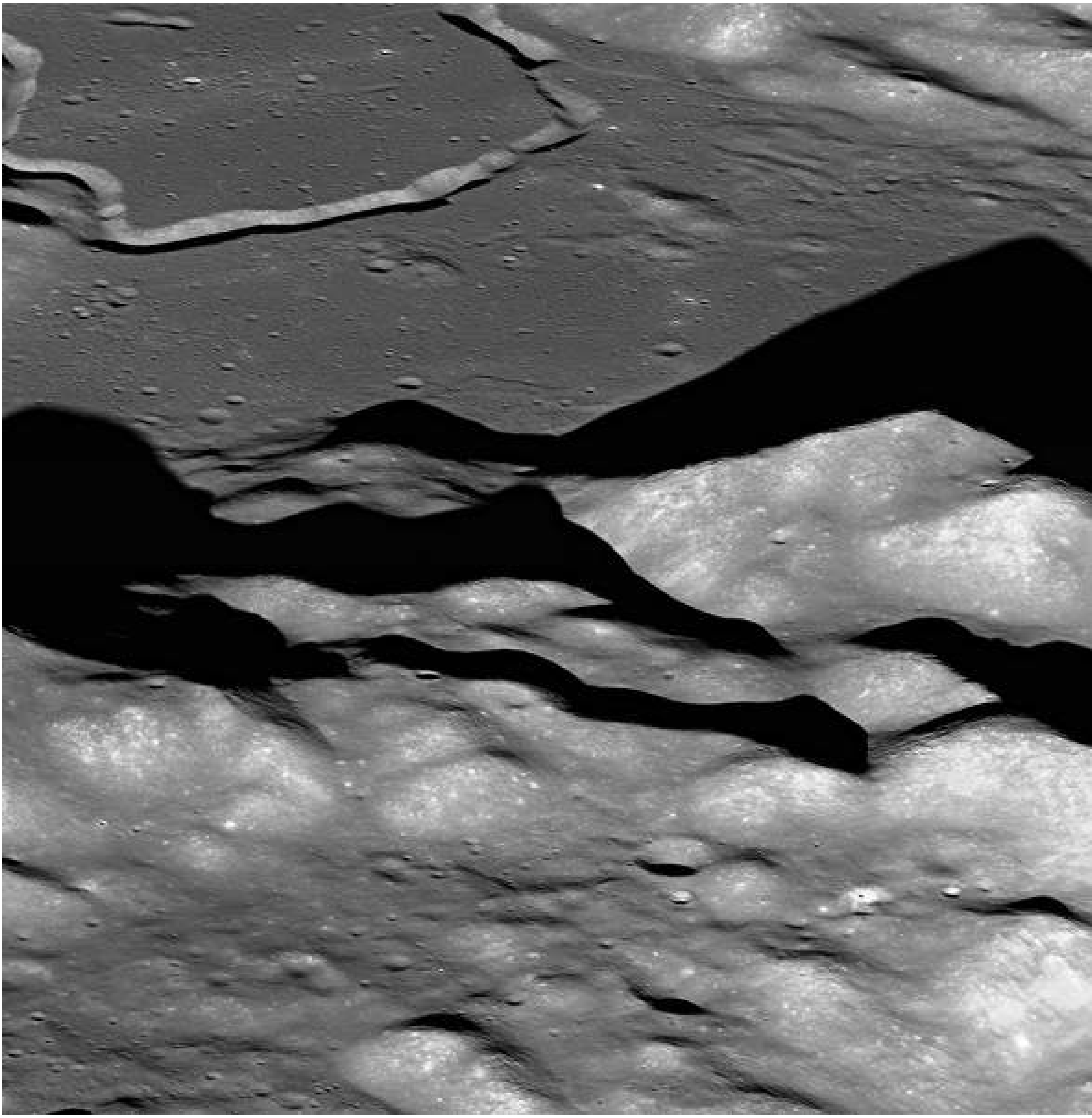

Figure 2.1. Oblique view of the Hadley-Apennine region, landing site of the Apollo 15 mission in 1971. The site is at top left; the sinuous chan
near the top is Hadley Rille, a channel carved by flowing lava. (Credit 2.1)

Apollo 15, the fourth manned lunar landing, was sent to the rim of the Imbrium basin, at the base of enormous mountain range called the Montes Apenninus (Figure 2.1). The mission occurred between July 2 and August 7, 1971. Astronauts Dave Scott and Jim Irwin spent three days exploring the mountains and t mare plain that surrounded them. The landing site was also near Rima Hadley, a winding, sinuous canyo believed to have been carved by flowing lava. With the Apollo 15 astronauts well trained in the science especially field geology, this mission demonstrated a new and growing sophistication in lunar exploratio

The astronauts found and returned a fragment of the original lunar crust, the “Genesis Rock,” and a unu~~sual emerald green glass, created by volcanic fire fountains erupting more than three billion yea~~rs ag
They also used a power drill to recover a core of the upper three-meters of the regolith at the landing site.

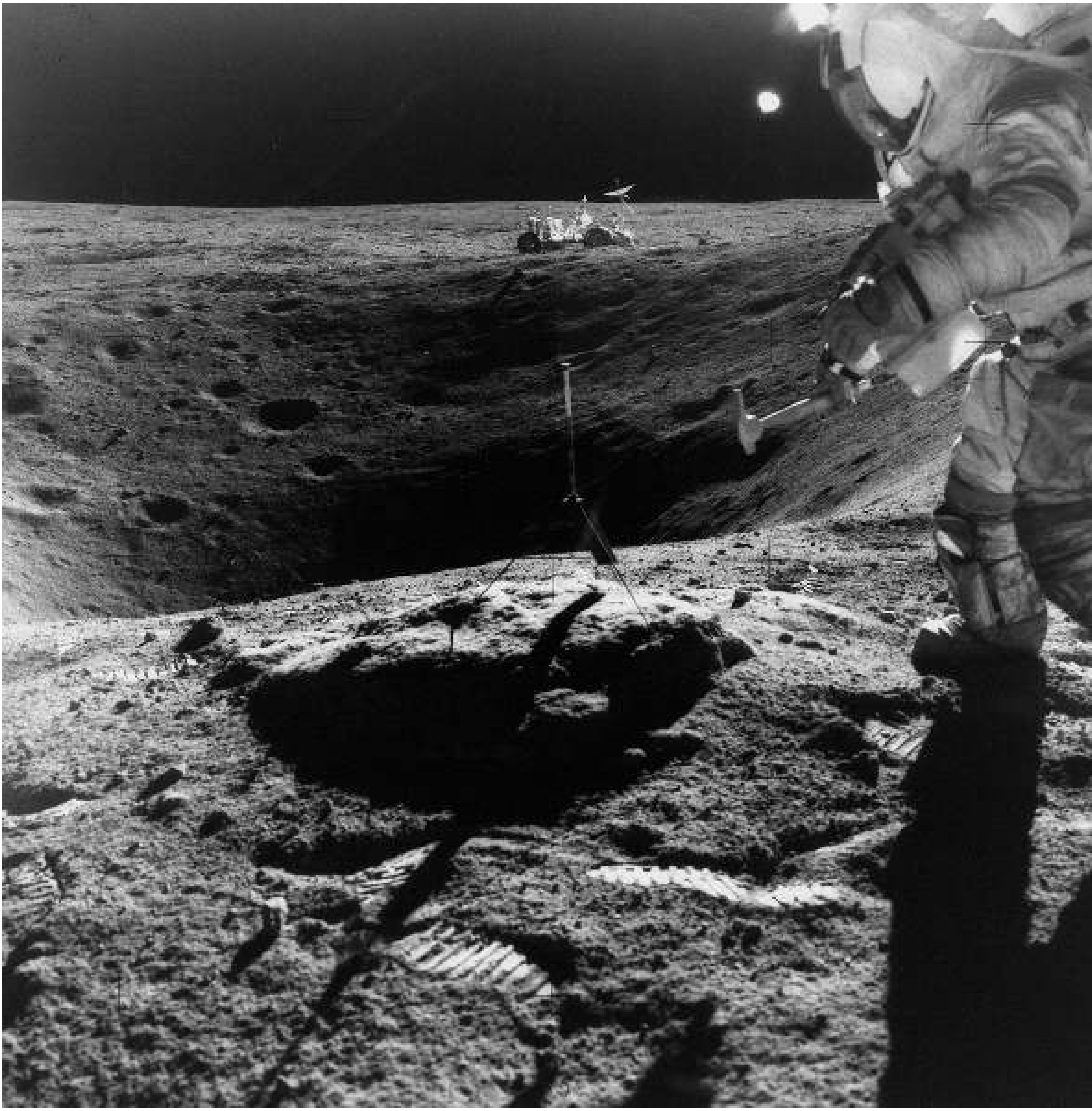

Figure 2.2. Apollo 16 Commander John Young explores the geology of the Descartes Highlands landing site. The samples and data returned fro the Apollo missions are the principal sources of detailed information on lunar history and processes. (Credit 2.2)

Continuing in this mode of surface exploration, the Apollo 16 mission visited the central lunar highlands April 1972. Veteran astronaut John Young (Figure 2.2) and rookie Charlie Duke explored two large impa craters situated in the mountainous Descartes highlands region, northwest of Mare Nectaris. Again expectations of finding volcanic ash flows, the crew discovered instead that the highlands are made up ancient rock debris, shattered and broken by eons of cataclysmic, large-scale impacts. Although t astronauts did not find the expected volcanic rocks, the results of this mission led us to a better understandi