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CHAPTER 1

The New Space Race

> [Space travel] will free man from his remaining chains, the chains of gravity which still tie him to this planet. It will open to him the gates of heaven.
>
> —WERNHER VON BRAUN

> The ultimate purpose of space travel is to bring to humanity, not only scientific discoveries and an occasional spectacular show on television, but a real expansion of our spirit.
>
> —FREEMAN DYSON

The Past Half-Century

In 1961 President John F. Kennedy decided that the National Aeronautics and Space Administration (NASA) would land men on the Moon by the end of the decade. His decision was in part a reaction to the first space flight around the Earth by the Soviet cosmonaut Yuri Gagarin. The United States needed to counter. The Soviets already had made a head start in planning for a space station and orbital flights in space. A crewed lunar landing was the most feasible step that the United States could take to reinforce its superiority in space. And national security issues were certainly a factor in the president's decision.

Kennedy took up the gauntlet in an address to the nation a year later, on September 12, 1962:

> We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard; because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one we intend to win.

And so began the Apollo program, approved by the US Congress in 1963 to send American astronauts to the Moon. Kennedy, sadly, did not live to see his promise to the nation fulfilled.

Various US presidents had weighed in on space exploration before Kennedy. It was Dwight Eisenhower who initially responded to the surprise Soviet launch of Sputnik in 1957. He decided that US space activities should be administered by a civilian agency. Though he assured the public that Sputnik was but "one small ball in the air," Eisenhower nevertheless saw to it that NASA was established the following year. Spacecraft design and launch facilities were organized. The Mercury program was established to evaluate the feasibility of low near-Earth crewed orbits as a precursor to going further into space. The program culminated in the first crewed suborbital flights.

When Eisenhower set up NASA in 1958, the space race was on. Crewed low-Earth orbital flights would set the pace for human space travel. In 1961, Yuri Gagarin was the first man in space when his Vostok spacecraft took about 108 minutes to orbit the Earth once before landing by parachute in the Soviet Union. His flight was followed within a month by the first suborbital spaceflight by an American, Alan Shepard, in a Mercury capsule that flew for just 15 minutes.

In the words of the spacecraft pioneer Wernher von Braun: "To keep up, the USA must run like hell."

Mercury-boosted orbital flights soon followed. The Mercury missions led to Earth orbital crewed flights. The first flight was just three Earth orbits in 1962 by John Glenn, who would go on to serve for twenty-five years as a US senator for Ohio. The Mercury program culminated in 1963 with a daylong flight by astronaut Gordon Cooper. It was succeeded in 1965 and 1966 by the Gemini orbiter, which carried two astronauts in low-Earth orbit for prolonged space missions. Humanity was preparing to go beyond the Earth.

The United States was determined to catch up with and overtake the Soviet Union, and the Moon clearly was the next goal. Eisenhower was reluctant, however, to enter into a space competition with the Soviet Union. The space race only really began when President Kennedy laid down the challenge in 1961. His goal was clear: human landings on the Moon. The Moon had remained a distant dream for crewed missions until Kennedy's intervention, which led to the establishment of the Apollo program.

Of course, robotic space missions to the Moon came first. The Soviet Union flew the first sequence of robotic lunar landers, the Luna series, which ran from 1959 to 1976. In all, there were seven Luna soft landings. The Soviet space program did not culminate in crewed landings in large part because of the Soviets' failure to develop a heavy-load spacecraft in time to compete with NASA. The Soviet space agency had begun with a strong lead in low-Earth orbital space flights but could not keep pace with the Apollo landings between 1969 and 1972. As the technical gap between the two countries grew, political considerations in the Soviet Union became more important. Its crewed lunar program was closed down in 1974.

The US crewed lunar missions were carried out in several stages. First, a series of robotic missions were conducted to prepare the way. NASA's lunar Ranger program began in 1961 with a spacecraft equipped with television cameras to record possible landing sites. After a series of crash landings on the Moon, it was superseded five years later by the lunar Surveyor program. These spacecraft soft-landed on the Moon and studied its surface composition. A new series of lunar orbiters was launched, beginning in the same year, to search for possible landing sites for the upcoming crewed missions.[1]

The Apollo program achieved success in 1969 with the first crewed lunar landings. All Apollo landings were on Saturn V launch vehicles. The three-stage Saturn V spacecraft was 110 meters high, or 15 meters taller than Big Ben, and its total weight was 3,000 tons. More than 90 percent of the weight was liquid propellant fuel. The third stage was fired from low-Earth orbit, launching the Apollo spacecraft to the Moon. It carried a 50-ton deliverable payload, including the lunar lander. Also on board was the Command and Service Module, which remained in lunar orbit to return the astronauts safely to Earth. The highlight of the first phase of human lunar exploration was the 1969 landing of Apollo 11 in the Sea of Tranquility. Neil Armstrong and Buzz Aldrin performed the first moon walks before a worldwide audience.

In all, there were six crewed Apollo missions that landed on the Moon. Each carried three astronauts some 239,000 miles into space and then returned home safely. Although the United States would continue to dominate lunar space exploration for decades, the crewed lunar program was over in less than four years. The last crewed mission to the Moon was in 1972. Saturn V last flew in 1973, when it launched Skylab, a precursor to the International Space Station.

Skylab's orbit slowly decayed and the space station disintegrated in 1979, on reentry to the Earth's atmosphere. The shower of debris covered western Australia and parts of the Indian Ocean. Its successor, the International Space Station, would not be launched into low-Earth orbit until 1998. The ISS features a still ongoing international collaboration. Russia launched the first module of the ISS on a Proton rocket from the Baikonur site in Kazakhstan, and months later the first crewed flight to ISS was made by the Endeavour orbiter, the fifth and last spacecraft of NASA's Space Shuttle Program. Long-duration visits began in 2000.

The Apollo program culminated with six successful lunar astronaut landings, but support for the program did not continue. Lyndon Johnson's Great Society Program trumped space spending, at least for any human lunar exploration, and the huge space budget could not be justified. With the end of the era of heavy lifters, Saturn V proved a hard and expensive act to follow. Nevertheless, only twelve years after Sputnik's low-Earth orbit, some 300 miles above the Earth, the United States had won the race to the Moon.

Return to the Moon

Today the major space agencies are gearing up to return to the Moon. They will spend decades surveying the surface and then move on to the deployment of resources. Will the enormous costs involved inhibit or limit the lunar exploration program? If there are cutbacks in government funding, are science projects doomed? Will military prerogatives hold sway? Commercial goals are likely to dominate, with lunar science inevitably suffering, but there is hope. Space is limited on the lunar surface, at least of the quality needed for major telescope projects, but the space available should suffice.

Plans to return to the Moon are now becoming serious thanks in large part to international competition for lunar resources.[2] An optimistic outlook on this competition is that science and activities such as tourist travel and mining will share lunar resources, and that science will benefit from the necessary infrastructure. For this complementarity to prevail, however, and for the pristine lunar environment to be preserved, international agreements will be needed.

Successive US presidents touted the value of space exploration but settled for robotic ventures that explored the solar system. Cost was an overriding issue. The situation was to change only when serious international competition came to the fore. Now, with that competition coming from China, there once more are military considerations, but they remain on a backburner, as commercial aspects loom large. The immense interest in space tourism and lunar mining ventures may seem futuristic, but the spoils may go only to the first arrivals.

There was a moment of real international collaboration in the decade following the Apollo years. The space shuttle was developed during the Nixon administration. Later, in 1984, under Ronald Reagan's leadership, planning and construction began on an orbiting space station. It would take more than a decade to complete.

As costs grew uncomfortably high by the early 1990s, the incoming administration of Bill Clinton and Al Gore had to make a difficult financial decision. To limit the drain on the NASA budget, they decided to bring in new partners, and the new orbiting space station became the International Space Station. Soviet and NASA astronauts shared the crewing and the transport costs, and other international agencies that nursed space ambitions joined as partners, including those in Europe, Canada, and Japan. The first joint US-Russian crew began living in the ISS in 2000, and it has been crewed ever since.

But the International Space Station, moving in near-Earth orbit, eventually must be superseded. It has always been an outstanding laboratory for training astronauts in preparation for more distant space exploits. After the Space Shuttle Program was phased out in 2011, NASA contributed to the space station servicing missions by purchasing space on Russian spacecraft. Then new plans were developed and US ambitions became grandiose. President George W. Bush announced in 2004 that NASA's human space flight program would start "with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations."[3]

With successive US administrations, the time line for human space flight has been prolonged. And as realism sets in, so has the time line for any final destination beyond the Moon. A major change has now come about with the development of commercial spacecraft. Elon Musk's SpaceX Falcon 9 was the first commercial spacecraft to service the International Space Station. Deployment of a cargo spacecraft containing some three tons of supplies and experiments soon followed. The Dragon crew spacecraft transported four astronauts to the ISS in November 2020. Commercial exploitation of human spaceflight has truly begun, and commercial missions to the Moon will surely follow.

At the same time, China has announced plans to build a new space station in near-Earth orbit. This is far from China's only goal. Its National Space Administration is pursuing a human outpost on the Moon, among other lunar projects. Not to be outmaneuvered, President Donald Trump declared that the next time US astronauts blast off, they would be headed to our rocky satellite. In 2021, his successor, Joe Biden, endorsed

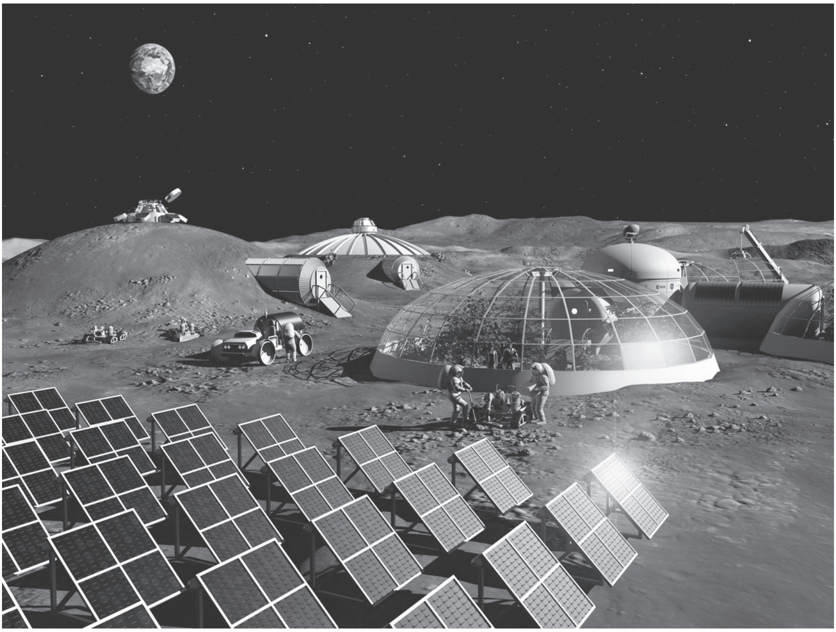

FIGURE 1. How light, water, and elevation will be provided at NASA's Artemis base camp on the Moon. American astronauts will take their first steps near the Moon's south pole, a land of perpetual light, extreme chill, darkness, and frozen water. NASA's next leap forward into interplanetary space will be fueled there, perhaps by 2026. Through the use of lunar rovers with 3-D printing capacity, power will be generated from solar cells and food will be produced in greenhouses.

Image credit: Image by P. Carril in European Space Agency, "ESA Opens Oxygen Plant—Making Breathable Air out of Moondust," January 17, 2020, https://scitechdaily.com/esa-opens-oxygen-plant-making-breathable-air-out-of-moondust/.

NASA's Artemis program to operate an orbiting space station along with lunar bases tapping the low gravity of the Moon. Artemis will be permanently crewed and is designed to facilitate space travel throughout the solar system. Biden also gave his support to the newest branch of the US armed forces, the United States Space Force.

Both China and private entrepreneurs in the United States are enthusiastic about mining minerals on the Moon. There are high-value resources to be extracted, including the rare earth elements and semiconductor materials for which terrestrial mining capacity is limited. One key project will be production of rocket fuel out of lunar ice, a prerequisite for further space exploration. Large lunar living habitats are being planned. The European Space Agency has called for the installation of a permanent, inhabited village at the lunar south pole. As a first step, a program has begun of synthesizing lunar construction materials with water and regolith, which is naturally available on the Moon.

What has happened post-Apollo? China is leading the current Moon rush. The first robotic Chinese probe to the Moon landed in 2013. Chang'e 3 carried a rover that operated briefly in Sinus Iridum, an area of dark lava flows in the lunar highlands. This area is being considered for future colonization in the nearby giant lava caves. The first landing on the far side occurred in January 2019. A lunar rover on board Chang'e 4 landed in the huge Von Kármán crater, which is some 186 kilometers across. This is part of the South Pole–Aitken Basin, which measures about 2,500 kilometers. As we will see, lunar polar craters especially have commercial and scientific potential.

Meanwhile, NASA has been scrupulously conserving frozen and vacuum-packed samples of retrieved lunar soil, but some of the Apollo-collected soil samples taken fifty years ago show some deterioration, likely caused by water vapor contamination. NASA has a monopoly on exploration of the lunar surface, but for how much longer? China is rapidly catching up. At the end of 2020, the Chang'e 5 mission conducted a sample return of lunar rocks to Earth. About 2 kilograms of rocks were delivered to a landing site in Inner Mongolia.

The lunar terrain covered in the early years by Apollo 15, 16, and 17 was limited. We need to sample new sites with more varied geological records. Pristine new samples are expected to help focus efforts to better understand the geological context and history of lunar soil and rocks. As we acquire new insights into how the Moon formed, we may incidentally learn about the potential for lunar mining.

The Next Stop for Humanity

There is a clear path forward for lunar exploration and exploitation.[4] It may take up to a century to get there, but the process has begun and all major space agencies are enthusiastically joining the race to the Moon. What should we do once we settle on the exploration program?

There are lunar resources to be mined. The Earth is exhausting its easily accessible supplies of ores such as rare earth metals, which play a crucial role in the electronics industry. There may well be centuries of reserves on Earth, but we should be taking the long-term view. Mines can be toxic environments. Avoiding pollution will be essential. The lunar resources offer other challenges, but environmental protection will play an important role if built in at the onset.

Our visions for future exploration of the Moon already include plans for industrial applications, ranging from manufacture in low-gravity environments to mining of rare earths and fuel production for interplanetary travel. There is a huge demand for lunar projects, in large part because the opportunities for entrepreneurship are unparalleled. These opportunities, pursued through both human and robotic exploration, will be realized by the mid-twenty-first century.

The Moon presents a potentially vast tourist industry. As humanity seeks new challenges, the Moon offers dazzling new horizons for leisure and sports activities. The commercial aspects of these activities will drive investment in them. Mass transportation for human lunar travel will not be offered in the first decades—not until the pent-up demand for luxury tourism is met. The Moon will initially be a playground for the rich, but change over time is certain once low-cost space transport systems are developed. Giant lunar parks for leisure and relaxation will be established, and low-cost housing will be designed to host the necessary support personnel to organize mass tourism. In the next half-century, the Moon seems destined for such activities, with commercial backing.

The Moon's low gravity and the presence of water ice have inspired designs for lunar habitations. The Moon may not be the ideal solution for the Earth's overpopulation problem, as much of the surface is a hostile environment. One cannot imagine that the lunar surface could accommodate large numbers of permanent inhabitants apart from key workers. However, it does offer some enticing pieces of real estate with relatively moderate climates, especially in the polar regions. And inevitably, the wealthiest segments of terrestrial society will find it hard to resist the attraction of the Moon as a new environment for developing secondary residences.

There is lots of lunar dust, accumulated by meteorite collisions over billions of years, and its abrasiveness creates an environment not ideal for the smooth running of machinery. Although the dust could be easily lifted above the surface by entrepreneurial activities, it makes for a potentially dangerous environment, especially with respect to the pulmonary health of long-term lunar residents. It will be essential to develop effective filtering once we build lunar telescopes.

One positive aspect of dust is that it furnishes an ideal material for developing robust building materials. With its unique reservoir of rare elements, lunar dust allows unique commercial mining ventures to become feasible. Unique science projects should accompany them.

Power is a crucial accompaniment to surface development. One advantage of the lunar surface is the abundance of solar power it can provide. Perhaps the first sites for development will be the polar craters, whose high rims are permanently illuminated by sunlight. Polar craters are the preferred sites for developing the first lunar bases because many of them are in permanent shadow—which also makes them attractive sites for telescopes—yet have an inexhaustible supply of nearby solar power on the high crater rims where the sun never sets, and their polar ice deposits enable in situ construction facilities.

Moonquakes are caused by a slight shrinking of the lunar crust over millions of years, along with the buildup of stresses by the action of the Earth's and Sun's competing tidal forces on the stretching of the lunar crust. Perhaps the crust stretches one-tenth of a meter over 100 years, but that is enough to produce wrinkle-like faults on the surface as well as shallow moonquakes. Their strength, which ranges up to 5 on the Richter scale for earthquakes, can be measured by seismometers laid out by the Apollo astronauts.

Major lunar quakes seem to be rare. There are hundreds of weak moonquakes per year—down to 2 on the Richter scale—but there are millions of similar-strength earthquakes every year. The lack of extensive tectonic lunar activity means that the surface is seismically stable. That is good news for the construction of large telescopes.

The Moon has many advantages for astronomy over a free-flying telescope in space. The large, cold, and dark polar craters are preferred sites for infrared astronomy because the lunar atmosphere does not degrade the spectral and seeing capabilities of telescopes. The entire electromagnetic spectrum is available for exploration, from the ultraviolet to the far-infrared bands. The lunar environment, with its low lunar gravity, provides an ideal platform for constructing a new generation of really large telescopes.

The ionosphere is a tenuous layer of ionized gas in the Earth's outer atmosphere. It presents a huge distraction for radio waves, especially at the lowest frequencies, which is where we expect the most interesting signals from the very early Universe. Low-frequency radio waves are deflected and scattered by the ionosphere. The Moon has a negligible atmosphere. The far side of the Moon, shielded from the Earth, is an ideal site for radio telescopes and opens up a new window on the Universe because it allows us to do very low-frequency radio astronomy that is unfeasible from the Earth.

Let's go back to the Moon! Our space agencies are intent on developing lunar bases to support activities ranging from mining to spaceports, but building telescopes to explore the beginning of the Universe could be done at a modest fraction of the lunar infrastructure cost. Not only could we view the cosmos in a way that is currently unimaginable from the Earth, or even from space, but lunar platforms also have the potential to be immensely rewarding for fundamental physics goals. However, the planning must begin soon.

The race to the Moon is opening up as different space agencies join the rush. The first evidence for water on the Moon was discovered by a US-built experiment on the Indian Space Research Organization's Chandrayaan-1 spacecraft, launched in 2008. Planetary geologist Carle Pieters of Brown University led a team that detected infrared signatures of water molecules in the sunlit lunar soil. They mapped hydroxyl molecules—building blocks for water—that most likely had dispersed from layers of ice in cold, dark craters near the poles.

This lunar orbiter gave a huge boost to India's autonomous space program. ISRO scientists led by Ashutosh Arya also carried out 3-D surface imaging and discovered an empty giant lava tube (or cave), two kilometers long and some 160 meters below the lunar surface. The opening of the cave, which is 120 meters high and 360 meters wide, formed from the uncollapsed remains of an ancient volcanic lava flow. The 40-meter-thick roof of the lava cave offers protection from ultraviolet radiation, dust, micrometeorites, and extreme temperature variations, at a temperature of minus 20 degrees Centigrade. Lava tubes are naturally protected environments that are potential sites for future lunar bases.

In the United States, lunar space activity saw a revival in 2009, when a reconnaissance lunar orbiter was launched by NASA on the two-stage, 600-ton, medium-lift vehicle Atlas V. The impact of the accompanying module lifted plumes of crater debris miles above the surface. These plumes were found to be rich in volatile ices, including water, thus confirming the evidence for water that was earlier reported by the Chandrayaan space mission. More recently, in 2021, the SOFIA airborne far-infrared telescope found evidence of water molecules most likely dispersed throughout the regolith. In fact, these water molecules were detected in one of the largest visible craters and amounted in concentration to a bottle of water trapped in a cubic meter of soil spread over the surface. The fraction of water observed was only a percentage of the water detectable in the Sahara Desert, but there is far more desert on the Moon.

There had already been hints of lunar ice a decade earlier. One of the instruments on board the NASA Lunar Prospector spacecraft, a neutron monitor, scanned many craters around the lunar south pole. The idea was to look for neutrons produced by cosmic ray bombardment of the surface. The detected deficiency of neutrons is considered to be a proxy for hydrogen atoms—which of course do not contain neutrons—and hence water. It seems that there is abundant water ice on the Moon in the polar craters, which act as cold traps for impinging material from cislunar space.

The Lunar Gateway

Humans will certainly return to the Moon in great numbers, and an ultra-heavyweight launcher will be crucial for crewed landings. The huge cost of Saturn V ($50 billion in 2021 dollars) explains why half a century has passed before we are on the verge of flying comparable lunar payloads. The United States and China are currently leading the way, and Russia and India are also planning crewed missions to the Moon. Of course, the United States has other priorities much closer to home. The Apollo space program amounted to about 4 percent of the US annual federal budget at the time. One cannot imagine a comparable effort today.

Future lunar science, exploration, and utilization will build on current and upcoming automatic and planetary robotic missions. A flotilla of lunar orbiters has been deployed by several countries for science and reconnaissance in the past decade. The orbiting robotic spacecraft are providing new views of the Moon, as well as its environment and resources. Several international space agencies are pursuing lunar mapping programs. The main aim is to prepare for crewed missions a decade from now whose goals will include reconnaissance of future landing sites. Prospecting for mineral resources is the likely endgame.

Competition is energizing future plans, and transport to the Moon is a crucial factor in carrying them out. NASA has announced plans for commercial development of crewed launch vehicles that will transport construction materials to the Moon, and it is actively seeking private companies to build future launch vehicles and lunar landers. Three companies were selected in 2020 to compete for contracts worth $1 billion to develop the hardware for crewed landers, and Elon Musk's SpaceX was retained in 2021. Developers of commercial transport, which could prove profitable over the long term, are raring to go to the Moon.

The immediate future in crewed space missions to the Moon lies with NASA's Space Launch System. SLS is intended to be the first launch vehicle in half a century to have a liftoff weight comparable to that of Saturn V. The first crewed flight of the new heavy launch vehicle should occur in 2026. Astronauts will arrive at the lunar outpost in a crew capsule being built by Lockheed Martin. The European Space Research Organization will deliver the service module, all to be piggybacked onto the launch spacecraft.

Adequate launch capability for ultraheavy loads is a prerequisite for establishing the infrastructure for lunar base construction. Many launches will be needed to put the essential infrastructure in place so that human activities on the Moon can be developed over the next decades.

An early step will be to install the Lunar Gateway, the orbiting lunar space station that is a key component of NASA's Artemis program. Starting in the late-2020s, the Lunar Gateway will support a succession of crewed lunar launches and landers. The space station will initially have a minimal number of modules, sufficient to send shuttles to the surface, ensure a safe lunar landing, and return.

A long-term goal of the Lunar Gateway will be to send crewed probes to Mars. In view of the technical difficulties for human travel that are anticipated for prolonged space trips (described later), such crewed probes are certainly decades away. In the meantime, the Lunar Gateway will focus on lunar exploration.

Within the following few years, NASA expects to develop an enlarged lunar space station capable of deploying many astronauts to the lunar surface. The Lunar Gateway is intended to be a space traffic hub with multiple docking ports to launch crewed lunar landers. Astronauts will work on the surface and return to the lunar space station as their residential base. A permanent and sustainable human presence in lunar orbit is expected soon after 2028.

The orbiting station will also serve as a spacecraft refueling station to facilitate travel back to Earth and beyond. Crewed missions to the lunar surface will build outposts, laboratories, and surface observatories in order to develop the extensive infrastructure needed for local construction, transport, and deployment of activities on the lunar surface.

The International Competition

NASA is not the only player in the race to land humans on the Moon. Various national space agencies are vigorously carrying out plans to go to the Moon, most notably the Chinese space agency, the China National Space Administration (CNSA). The first Chinese post-Apollo astronauts are likely to land on the surface near the lunar south pole in 2030. NASA has announced that the lunar astronauts will include a woman and also a person of color. Meanwhile, the European Space Agency has announced its goal of further diversifying the future astronaut pool with a disabled candidate.

NASA clearly has competition. Since the Apollo era, the United States has been relatively cautious in reinvigorating the planning for crewed lunar missions, and that has provided a window of opportunity for its rivals—most notably China—to catch up. China is the third country to have sent humans into near-Earth space, beginning with Yang Liwei's successful twenty-one-hour flight in 2003 on the Shenzhou 5 launcher. No doubt an element of healthy competition will arise between China and other countries now that it has announced its intention to place the first woman on the Moon before 2030.

An ambitious lunar exploration program is being undertaken by the Chinese space agency, which is currently designing an ultraheavy-load spacecraft to go to the Moon. The first flight of Long March 9, with a 50-ton payload capacity, is scheduled for 2030. A crewed mission is planned in 2036, to build an outpost near the lunar south pole.

Russia is intent on overcoming any lingering inferiority complex from the Apollo decade by fully engaging in the new space race to the Moon. Moscow had several breakthroughs to its credit in the early days of the space race, including the launch in 1957 of the first artificial earth satellite and Yuri Gagarin making the first journey into space in 1961. Of course these achievements were overshadowed by NASA's landing of the first men on the Moon in 1969.

To facilitate future lunar landings, Russia is also preparing superheavy launchers. The Russian program will culminate sometime in the 2030s with crewed flights to the Moon. If the early results from the Indian Space Research Organization (ISRO) and from NASA on ice deposits are promising, this could be an initial step toward developing an ice-mining facility near the lunar south pole. Such an installation could provide a source of water and of hydrogen and oxygen with which to make rocket fuel.

It's not just the major space powers that are planning to robotically explore the Moon. Among the many robotic rovers planned for the early 2020s are missions from India and Japan. Even countries that have no launching capability of their own are involved in the lunar space race. On a smaller scale, Israel and the United Arab Emirates are joining in the challenge of the Moon as the emerging space agencies in those countries are intent on lofting spacecraft to the Moon via commercial providers. One example is the first privately funded lunar mission, the Israeli spacecraft Beresheet (or Genesis), which was launched on a SpaceX Falcon 9 rocket from Cape Canaveral. It crash-landed on the Moon in 2019. A successor mission planned for 2025 will include an orbiter and two lunar landers. One common goal of these missions is to measure the composition of soil samples from diverse regions.

The long-term aim is to develop bases and habitats on the Moon. Of course reaching this goal will take decades. If plans for an inhabited base are to succeed, choosing a location with abundant natural resources will be key. The preferred places currently envisaged for bases are near the lunar poles, where the climate is not extreme and water ice is most likely to be found in deep craters.

A new hydrogen economy beckons us to the Moon. The stakes are large, and the major rival space agencies are eager to establish priority. There are potentially enormous commercial benefits from lunar development. Tourist resorts would inevitably be developed in response to huge public interest. The developments under study range from tourist activities to mining and manufacturing under low gravity, and inevitably to rocket fuel depots and spaceports.

A combination of human and robotic assets will be needed to support science goals and should become integral to future lunar exploration. The will to pursue those goals is there, and the commercial aspects of lunar exploration are under intense study. I turn now to a discussion of the desirability of incorporating science into lunar exploration and its potential rewards for humanity.

Beyond the Moon

With the international space race underway, humans will certainly go to the Moon, whatever the cost. A lunar spaceport will serve as a gateway to the solar system for pursuing the long-term aim of exploring the solar system with crewed missions. Beyond the Moon, the primary target is Mars, which may be hiding clues to the origin of life, from a bygone era when its surface had flowing oceans. We need to dig deep on Mars to reveal clues to its past. Current robotic missions to Mars are planning to do precisely this, and the first major step is being taken by NASA's Perseverance rover. Perseverance landed in an ancient Martian river delta in February 2021 and continues to survey the surface to search for microbial fossils in ancient rocks.

Of course the human aspiration to explore the solar system demands that we ultimately go beyond robotic missions. Mars is a challenging goal for crewed missions. Going there will inevitably be a risky endeavor. The Moon is only a three-day trip, and that path has already been navigated by the twelve Apollo astronauts who walked on the Moon, as well as by the six other astronauts who stayed in orbit on each landing. They too played indispensable roles in organizing the safe return to Earth.

Space planners are enthusiastic about the lunar sequel—a crewed trip to Mars. For the moment, a seven-month trip to

Mars, with a safe return, is currently beyond our capability for human space flight. Life support and indeed survival are among the unsolved problems. Exposure to galactic cosmic rays is one of the prime risks.[5]

Most cosmic rays are energetic protons capable of ionizing anything in their path. They are potential causes of gene mutations and cancers. To list just a few hazards of a trip to Mars, astronauts would be subject to vital organ deterioration, bone marrow damage, stem cell destruction, and tissue necrosis. Assisted only by current technology, astronauts would arrive on Mars saddled with muscular atrophy and riddled with cancers.

The dangers of radiation exposure depend on age and gender. The typical dosage is low on the Earth, where we are protected by the atmosphere. The average natural dosage per person corresponds to the biological effect of the deposit of some 30 ergs of X-rays in a kilogram of human tissue every year. One of the principal calibrations in risk estimation has been the survival rate of Japanese atom bomb survivors. The maximum limit by international standards is about 100 times the natural exposure limit. Adhering to this limit is required, for example, for individuals required to work with radioactive materials.

Our views have evolved on X-ray exposure. When I was a child, the best shoe stores in London routinely used X-ray machines for measuring shoe sizes. These delivered exposures of about one-tenth of the annual limit, typically in twenty seconds. And the wooden machines failed to protect the sales staff. Chest X-rays, by contrast, are well shielded and deliver typically about one-thirtieth of the natural limit.

The international regulatory limit is set by the estimate that cancer risk is doubled over a period of twenty years after exposure. Of course, such limits change with time and generally are lowered as more data become available. NASA's limit for low-Earth orbit trips to ISS is currently about five times higher than the current international limit on radioactive exposure, partly because astronauts are expected to take higher risks.

A recent report by the National Academies of Sciences, Engineering, and Medicine suggested that the lifetime maximum for a permissible dose should be reevaluated and recalculated to an even more conservative value for the highest lifetime risk to a healthy astronaut. The problem facing future space exploration is that a trip to Mars would greatly exceed this exposure. Meanwhile, traveling to the Moon should be safe.

Unshielded and prolonged space travel is dangerous, but most likely the risks will be manageable with enough spacecraft shielding and a correspondingly ultraheavy payload. The heavy-load spacecraft currently under development represent just the first steps toward developing the capacity that would be needed for a crewed Martian lander mission. When can we expect this to happen? NASA has announced plans to send a crewed mission to Mars in the 2030s. Such a mission would need to make use of lunar fuel resources. Launch of the necessary heavy payload would be achievable from a circumlunar space station.

Wealth in Asteroids

Meteorites and asteroids, which contain valuable natural resources that are rare or even nonexistent on Earth, have been bombarding the lunar surface over billions of years. The rain of cosmic debris was especially intense during the first few hundreds of millions of years after the Moon formed. The lunar regolith, at least 1 percent of which comes from ancient asteroids, is expected to be a rich source of rare elements. It promises to be a treasure trove for mining a century from now.

In the meantime, space agencies are exploring asteroids for extraction of samples to be returned to Earth. The study of asteroid surfaces provides a direct glimpse into the past, and asteroid mining is likely to be one of the long-term goals. Asteroids, which have no significant atmosphere, have much in common with the Moon. Asteroids and meteorites shaped the lunar surface over billions of years as meteoritic debris accumulated far more than on the surface of the Earth. In competition with ancient volcanic flows, asteroid debris covered the Moon. The buried layers lying deep under the lunar surface must contain huge amounts of asteroid debris.

Asteroid missions are expected to set the scene for a better understanding of the lunar composition. Heavy-load carriers are optimally launched from geostationary orbits rather than from the Earth. The low escape velocity to leave the Earth gives a huge fuel advantage. Launching facilities on such orbits are required to effectively mine asteroids and eventually tap the much larger resources of the Moon. It will be much easier to construct orbiting space stations using building materials brought in from low-gravity environments.

We know something about the composition of asteroid rocks because many meteorites are thought to be fragments of an asteroid parent body. The asteroid belt between Mars and Jupiter is a dangerous environment. Asteroids occasionally crash into each other and shatter, the debris dispersing throughout the solar system. Some debris reaches Earth, and the largest fragments survive the impact and are found as meteorites. But contamination by our atmosphere prevents us from having pristine samples of asteroid rock that survive impact. Going to an asteroid would allow the ultimate retrieval of rocks in space.[6]

Asteroid rock samples were first directly returned to Earth by the two Japanese Hayabusa missions. The minuscule samples collected during these missions were mere specks of rock, culminating with a 5-gram haul recovered when Hayabusa 2 landed in the Australian outback in late 2020. A more substantial sample was gathered by NASA's OSIRIS-REx spacecraft from an asteroid known as 101955 Bennu. A near-Earth asteroid discovered in 1999, Bennu is named after the ancient Egyptian mythological bird associated with creation, rebirth, and the Sun. After a seven-billion-kilometer round trip lasting seven years, the NASA spacecraft delivered a capsule to Utah in September 2023 with some 70 grams of asteroid rock samples.

Understanding the feasibility and profitability of asteroid mining is one of the ultimate goals of rock sample return missions. Also beckoning, however, are lunar resources, which, because of eventual in-situ manufacturing possibilities, could be far more cost-effective.

Lunar Mining

The international space agencies envisage many commercial activities on the Moon. China is developing plans to mine the Moon, and other countries will not lag far behind. The lunar surface is likely to be a unique site for mining rare elements,[7] including rare earth elements such as europium. The terrestrial supply of some of these key elements is likely to be exhausted over the next hundreds or thousands of years.

The applications of rare earth elements are legion. The many industrial applications include the manufacture of superconductors, smartphones, electronics, flash drives, light bulbs, camera lenses, computers, electric vehicles, catalysts, magnetic resonance imaging, and high-power magnets, as well as clean energy technologies, wind turbine dynamos, medicine, X-ray tomography, and cancer treatments. Some rare earth elements are crucial to military applications, including laser weapons, radar, and sonar.

Rare earth elements are mined on the Earth, but only through environmentally polluting operations. Indeed, mining rare earths is such a toxic process that extraction is highly restricted. Economically viable deposits are limited to certain areas of the Earth. China is the site of the largest accumulation of rare earths.

Indeed, China dominates the limited world supplies of rare earth elements. Total world resources are 140 million tons, with more than one-third of these resources in China. The United States has 13 million tons of rare earths. Brazil and Vietnam combined have a reserve comparable to China's but currently are minor producers. At current extraction rates, some key rare earths are projected to be exhausted on the Earth in less than 1,000 years. The reserves of many rare elements face exhaustion within 10,000 years. These are short timescales for the terrestrial future. Of course, not all rare earth elements are rare—nearly all of them are more abundant than gold. But the extractable supply of rare earths is limited.

We will need a supply of the crucial rare earth elements for millions of years. Of course, further into the future, though it's impossible to reliably predict, humanity will surely have discovered new technologies that are less rare earth–dependent. Between then and now, lunar resources may bridge the gap. Based on analysis of the Apollo lunar samples, lunar reserves of rare earths approach a trillion tons—or 10,000 times more than the terrestrial reserves.

In light of how central rare earth elements are to present and future technologies, it will be hard for mining companies to resist the challenge of lunar extraction. The potential rewards are enormous, and the supply virtually inexhaustible. We will not run down the lunar reserves for a very long time.

Lunar extraction will be achieved robotically, and the environment will be closely controlled. Lunar habitats will be enclosed areas located near the polar regions or in giant lava tubes. There will be few local inhabitants to worry about. The toxic byproducts could be shipped to the nearest and most efficient giant incinerator—the Sun.

Mining water will also be a major lunar activity. Liquid oxygen and hydrogen are derived from breaking down ice, and a by-product will provide reservoirs of rocket fuel for Earth transportation use and beyond. Lunar resources can serve us for millions of years. They represent the future for our planet.

A Fusion Future

One of the more intriguing mining resources will be the isotope of helium that has a mass of three atomic units.[8] The prevalent type of helium, Helium-4, is rare on the Earth. Helium-3 is thought to be primordial, its formation having preceded the solar system. Small amounts are found in the Earth's mantle, above the core and below the crust. Helium-3 is in high demand on the Earth for its cryogenic properties. It is the coldest refrigerant that exists. Because a helium-3 refrigerator cools down to 300 millidegrees Kelvin, it is extremely useful for industrial and scientific applications that require very low temperatures.

Helium-3 has been widely exploited in astronomy to build extremely sensitive cold detectors. These instruments search for tiny fluctuations in the cosmic microwave background, itself a radiation field that is at the equivalent of 3 degrees Kelvin.

Mapping these fluctuations with an ultracold detector has transformed the science of cosmology.

Thermonuclear fusion is another futuristic application of helium-3. Deuterium and tritium are currently the fuels of choice for ongoing experiments in energy generation by thermonuclear fusion. These elements are abundant on the Earth. However, their fusion produces neutrons, which interact with the containing device and create high levels of radioactive contamination. In contrast, helium-3 is a relatively clean fuel that undergoes thermonuclear fusion without generating neutrons. It would not produce dangerous radioactive waste products when burning in a thermonuclear fusion reactor.

Scientists believe that, in the long term, helium-3 could replace tritium and deuterium as a thermonuclear fuel source. There is a major problem, however, to be resolved. Fusion of helium-3 involves combining nuclei of relatively high atomic mass and nuclear charge, as compared to the usual deuterium-tritium mix in mainstream fusion technology. To overcome the charge barrier between helium-3 nuclei requires a much higher temperature than is needed for burning deuterium and tritium. This challenge presents a serious technological barrier.

The essence of fusion energy is extracting more energy from fusion than what is put in. Our current approach to controlled thermonuclear fusion has still not attained a sustainable supply of energy. It is difficult. The engineering requirements for successful nuclear fusion are considered extreme compared to our current generation of nuclear fission reactors. The timescale for achieving the first generation of controlled fusion reactors remains highly uncertain. The most optimistic estimates are for significant energy production by 2035. Others would argue for midcentury as more realistic.

Sustainable fusion, however, seems inevitable, and when we achieve it, our energy supplies will be revolutionized. But it's still relatively dirty energy, at least in the reactor vicinity. Once the national power grids are supplied with fusion energy, the race will commence to establish the next generation of cleaner fusion reactors.

While helium-3 may indeed be the cleanest possible fuel for unlocking controlled fusion, it is expensive. The terrestrial price exceeds tens of millions of dollars per kilogram. And a kilogram is about the total annual production on the Earth, where it is collected as a decay product of tritium. Terrestrial reserves amount to just a few tons.

The lunar regolith is estimated to contain millions of tons of helium-3. Most of it is the result of the helium-rich solar wind impacting the lunar surface over billions of years. The outermost layer of the Sun is a dilute hot gas or plasma of charged particles that is heated by coronal eruptions driven by magnetic storms. The particles are protons, electrons, and helium nuclei. Solar gravity does not contain the hot plasma, and a wind is produced that travels to the Earth and beyond. The solar wind is rich in helium, reflecting the composition of the Sun, and does not impact the Earth, where our atmosphere shields us from it. On the Moon, heating large quantities of lunar regolith will release vast amounts of solar-produced helium-3.

Helium-3 fusion is clean and green as an energy source. It is futuristic, but is under intensive study. The helium-3 recapture strategy is being led by the head of the Chinese Lunar Exploration Program, Professor Ouyang Ziyuan. Commercial investors are eagerly standing by to reap the rewards. Helium-3 is expected to be the element of choice for future thermonuclear fusion reactors, albeit not until a century from now. Lunar mining could help justify and even subsidize the development of lunar bases and lunar science.

A Moon Village

The European Space Agency has announced plans to build a lunar village for commercial activities, which are expected to include tourism as well as construction and mining.[9] Construction is especially feasible near the lunar south pole. Here both abundant ice on crater floors and continuous sunlight on crater rims are available. The temperature extremes are moderate. There is sufficient regolith and water to fabricate glassy bricks with which to construct dwellings. One current design study features a four-story building situated in a dark crater in permanent shadow.

Ambitious technologies are under development. State-of-the-art industrial complexes are capable of fabricating complex materials and machines out of the ambient lunar materials available—not just lunar regolith and water but also various other elements obtained from the lunar mining industry. The use of telerobotics will be central to extracting lunar resources and utilizing them.

A large construction industry will be developed, mostly run robotically with human supervision. Three-dimensional printing facilities will produce much of the material needed for local construction. The low-gravity environment will facilitate new manufacturing technologies that might be especially relevant for the biomedical and pharmaceutical industries. Local lunar industry is key, as transport from Earth is costly and limited to relatively small loads.

As the focus of international lunar activities, the lunar village is intended to serve a number of goals, including a sustainable human presence and activity on the lunar surface. Multiple users will carry out multiple activities. For so many reasons, the Moon represents a prime choice for pursuing political, programmatic, technical, scientific, operational, economical, and inspirational aims.

We can look forward to an era when human spaceflight has been developed for economic development and international cooperation. A key element will be innovation that will inspire and educate the workforce of the future. It is expected that the emerging lunar community will be the catalyst of new alliances between the public and private sectors.

As yet, little attention has been given to the unique advantages of a lunar platform for studying the Universe. Lunar telescopes should be a key component of a future Moon village. The science goals will enable advances in planetary science and our understanding of the origin of the Moon, and the astronomy goals will include the imaging of distant planets and the first stars. On this new frontier of exploration, we will probe the dark ages of the Universe, just as geologists study the origins of progressively older layers of rocks on Earth. We will do the same in space, where we will see that our "rocks" are the remote hydrogen clouds from which galaxies were assembled.

The lunar platform will facilitate novel applications of the life sciences so that we can better understand the importance of biological risk issues. If humans are to ever attain quasi-immortality, the lunar low-gravity environment will play a crucial role in developing the essential medical transplants. We will learn to replace all of our vital organs. As computers become ever more powerful, we may replace our brains as well—or at least upgrade their memory contents.

A new science vision needs to be implemented at this early stage of lunar planning. The possible discoveries from lunar

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