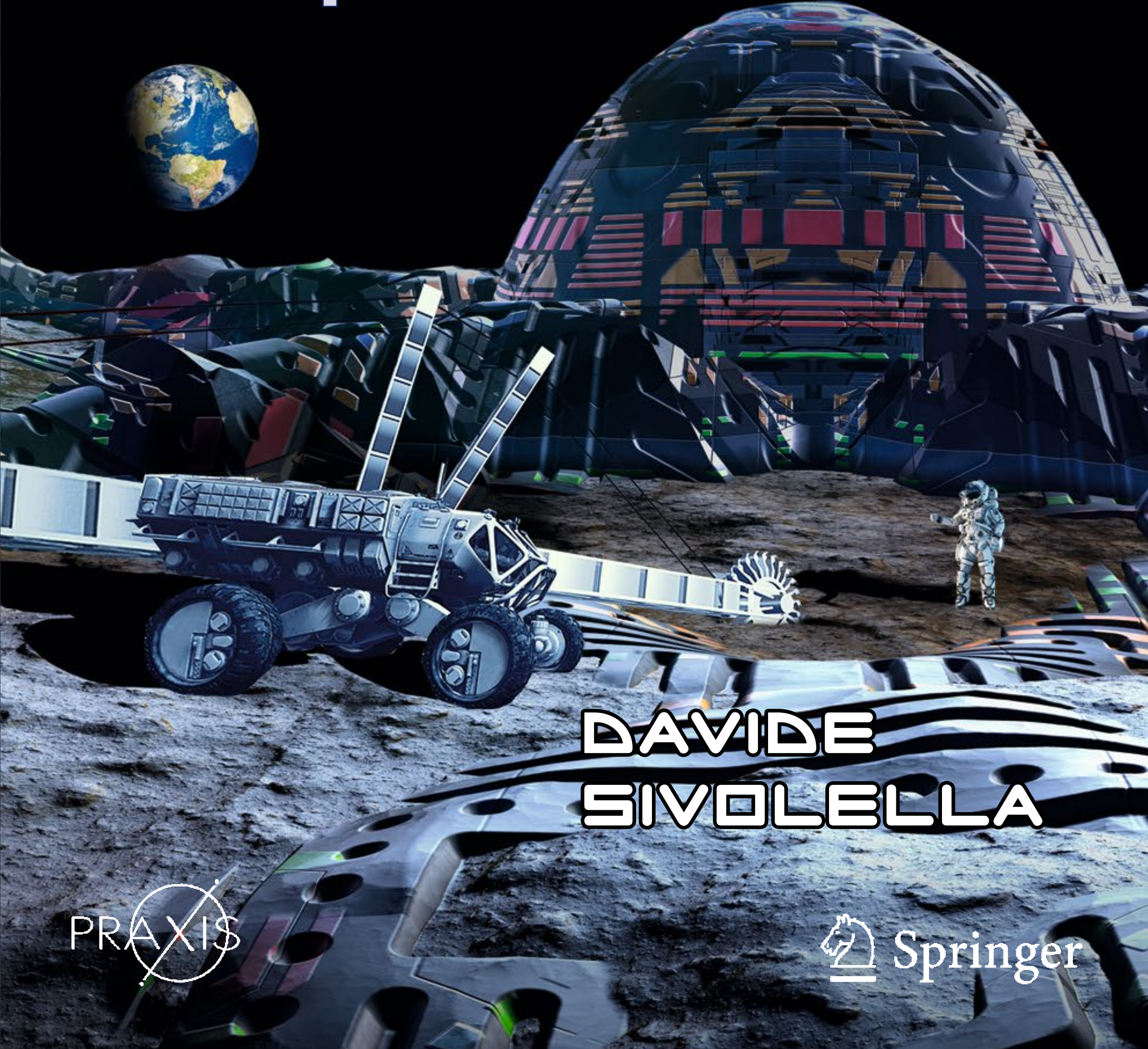
SPACE MINING AND MANUFACTURING

Off-World Resources and Revolutionary Engineering Techniques



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Preface

In 2019 we celebrated the 50th anniversary of Apollo 11. What a truly outstanding achievement it was! In less than 70 years, human society saw the first flying machines evolve into spaceships capable of delivering two individuals to the surface of the Moon, possibly the most inhospitable environment to life humans have ever ventured into. Even more remarkable is that Apollo 11 came less than 12 years after Sputnik, the first satellite in space, and less than 9 years after Yuri Gagarin became the first person in space.

The Apollo program was a victim of the particular historical context called the Cold War, in which what mattered most was to show technological superiority rather than a genuine motivation to undertake space exploration for the benefit of humankind. This explains why, fast forward to the present day, none of the grandiose plans of space exploration and development which so animated the 1960s and 1970s came to fruition. For the most part, space activities are dominated by political ideology and scientific curiosity, in particular in the context of human space exploration. A return to the Moon or a mission to the Red Planet are from time to time promoted by all the major space agencies. But until the financial support needed to back such ambitions is forthcoming, nobody is going to start cutting metal. Perhaps, even more demoralizing is the lack of endorsement from the general public. Sending people to the Moon or Mars, or sending robots to photograph alien worlds billions of kilometers from Earth can briefly capture public attention, but many people would gladly get rid of space exploration and divert financial assets and talent into solving the pressing issues affecting our society, notably climate change, environmental pollution, and the scarcity and control of resources.

I have been a life-long advocate for the development of space, but I must admit that since an early age I have always felt a pang of distress at seeing how space exploration seemed so far removed from assisting society in overcoming the predicaments that are increasingly threatening our future on this planet. Out of such dissatisfaction, I started to embrace the notion of moving our manufacturing industries into orbiting factories that draw their resources from the Moon or asteroids. Many studies dating back to the 1970s and 1980s have discussed off-world mining and manufacturing. Today they fall under the banner of "living off the land" and envisage permanent outpost on the Moon or Mars. This is a worthy notion, but it is a restricting way of thinking because there is so much scope for exploiting such research to the benefit of humankind here on Earth. Mining and manufacturing activities can produce waste products of such kinds and in such amounts that they cannot be metabolized and neutralized by the air, water, and soil in the environment. In exceeding the capability of the environment to absorb what we throw at it, we face long-term pollution. Factored across the whole globe, we have now created the conditions for climate change, endangering of animal species, and loss of human lives. Our frantic way of living is also exhausting the resources of the planet. Many conflicts between peoples arise from efforts to exert control over ever dwindling resources.

There is no danger of environmental pollution in space, since there is no biosphere. Water and minerals are available on the Moon and countless mountain-sized asteroids. We have grown familiar with such ideas in science fiction stories, but rest assured it is not beyond of the realm of real engineering. We are already extracting resources in the most inhospitable environments, such as the ocean floors for diamonds and fossil fuels. We have built prodigious infrastructures such as dams that halt the flow of some of the largest rivers in the worlds in order to produce electricity for whole countries. We have built pipelines crossing land and sea to pump fossil fuels between countries thousands of kilometers apart. In opencast mining we have dug pits so deep there are different microclimates at the top and bottom. Automation is allowing the extraction industry to work mines with completely automated machinery. Whenever there is a need, human ingenuity can achieve great things. The aim of this book is to show that space mining and manufacturing are within our current technological capabilities. If we implement a practical development strategy, such as that described here, we will gain a concrete opportunity to transform such thinking into reality.

Rest assured however, that unlike many fellow space advocates I am not preaching the development of space as a panacea that will enable us to write off environmental degradation, resource scarcity, and the like. Instead, I do believe that it has the potential to contribute to the mix of strategies available for tackling those issues. For the last 60 years of space exploration, we have been guilty of seeing space as a place for discovery and exploration. Now it is time to consider it also as a resource, and set a new space exploration and exploitation path that will genuinely benefit humankind.

I hope you find the material in this book sufficiently informative and convincing that you will join me in advocating to make such a vision a reality.

Acknowledgments

It seems to me that writing a book must be one of the loneliest projects an individual can undertake. It means spending countless hours researching and studying in advance of even drafting anything meaningful. As chapters are developed, they are periodically reviewed, rewritten, amended, or pruned until the quality of the content and narrative fulfill the master plan. It may take years before the manuscript of a 200-page book can be presented to the publisher. In all this time, the author has to spend hours at the desk, reading, note-taking, and typing. Inevitably, this entails subtracting precious time from family and friends, as writing demands a great deal of concentration and commitment. And the pressure only mounts as the deadline for submission to the publisher looms.

Nevertheless, an author is never truly alone. For instance, in my case, I am grateful to Clive Horwood of Praxis and Maury Solomon and her staff at Springer New York, who for the third time have entrusted their reputation to one of my writing proposals. I am also indebted to Dr. David M. Harland, who for the third time has turned my raw manuscript into a book. I must also mention Dr. Erik Seedhouse, Michel van Pelt, Dr. Philip T. Metzger, and Robert Zimmerman for expressing a positive recommendation to Springer for publication and for their counsel on layout and content. And, as usual, I thank Jim Wilkie for his eye-catching cover.

I cannot deny that I had several moments of frustration and doubt. My wife Monica was instrumental in dispelling them, even when she was busy earning her bachelor and master degrees. My parents, Pasquale and Maria, have always encouraged me in my various projects, particularly those concerning space exploration. In addition, by their interest and support, my friends, work colleagues, and acquaintances have all played a role in motivating me to write this book.

Acronyms

AFM	Additive Manufacturing Facility
APIS	Asteroid Provided In-situ Supplies
ARM	Asteroid Return Mission
AU	Astronomical Unit
BEAM	Bigelow Expandable Activity Module
CCD	Charged Coupled Device
CDR	Computed Dental Radiography
CMOS	Complementary Metal Oxide Semiconductor
FDM	Fused Deposition Modeling
FMD	Forced Metal Deposition
FLNG	Floating Liquefied Natural Gas
GE	General Electric
GPS	Global Positioning System
GRASP	Grapple, Retrieve, And Secure Payload
IOSD	International Organization for Space Development
ISS	International Space Station
ITER	International Thermonuclear Experimental Reactor
JPL	Jet Propulsion Laboratory
KREEP	Phosphate, Rare Earth Elements, Phosphorous
KRUSTY	Kilopower Reactor Using Stirling Technology
MEB	Molecular Beam Epitaxy
MEMS	Micro Electro-Mechanical Systems
MIT	Massachusetts Institute of Technology
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NEA	Near Earth Asteroid
NEP	Nuclear Electric Propulsion

NTR	Nuclear Thermal Rocket
NIAC	NASA Innovative Advanced Concepts
OST	Outer Space Treaty
PEEK	Polyether Ether Ketone
RAP	Rapid Asteroid Prospector
SETI	Extraterrestrial Intelligence Institute
SLA	Stereolithography
SLS	Selective Laser Sintering
SMM	Small Manufacturing Machine
SMR	Small Modular Reactor
SPACE Act	Spurring Private Aerospace Competitiveness and Entrepreneurship Act
USSR	Union of Soviet Socialist Republics
VAD	Ventricular Assist Device
VASIMIR	Variable Specific Impulse Magnetoplasma Rocket
VICAR	Video Image Communication and Retrieval
WSF	Wake Shield Facility
WRANGLER	Weightless Rendezvous and Net Grapple to Limit Excess Rotation

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Space Exploration: What For?

WHAT FOR?

What is the purpose of space exploration? Why spend prodigious amounts of money to enable a few highly trained individuals to travel in space months for at a time in an inherently dangerous environment? Why devote taxpayer money just to send a small robot to snap pictures at the edge of the Solar System? Are not there more pressing, urgent conditions affecting human society that would benefit from such investments? You, or somebody you know – a family member, a colleague, an acquaintance – might have similar questions. They all hinge on determining whether space exploration is a worthy endeavor. If you are an advocate for space exploration, you might find these questions annoying. Why cannot people understand the importance of spaceflight, you might ask yourself? Why must they question it?

However, if we take an objective look at some numbers we might concur that these questions, and the detractors, might be onto something. Consider that, on average, a mission by the Space Shuttle cost some US$450 million; support and handling of the International Space Station costs between $3 and $4 billion per year; the New Horizons spacecraft that in 2016 showed us the jaw-dropping landscape of Pluto cost some $700 million; the car-sized Curiosity rover on Mars required some $2.5 billion to build, and more money is poured annually to continue its adventures on the Red Planet. Space exploration is clearly expensive, and perhaps the money could be put to better use in building hospitals and schools in developing countries, in eradicating cancer, and in obliterating plagues such as AIDS. Advocates of space do have an obligation to answer to these questions. Let us start therefore by analyzing the main rationales attributed to space exploration.

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Then we will weigh their value against our present reality and assess whether space exploration has any place in our society.

Rationales of Space Exploration: Geopolitics, Prestige, National Security

Ever since the Soviet Union orbited Sputnik on October 4, 1957, space exploration in general, and human spaceflight in particular, have portrayed a country's technological strength and manifesto for way of living. The race to the Moon is the perfect example. In the midst of the Cold War, President John F. Kennedy's call to reach our natural satellite was motivated more by a need to demonstrate that America was superior, in every way, to its rival on the other side of the "Iron Curtain".

In his Special Message on Urgent National Needs delivered to a joint session of Congress on May 25, 1961, shortly after the Russians flew Yuri Gagarin in orbit and America responded by sending Alan Shepard on a ballistic mission, Kennedy made this explicit: "If we are to win the battle that is now going on around the world between freedom and tyranny, the dramatic achievements in space which occurred in recent weeks should have made clear to us all, as did the Sputnik in 1957, the impact of this adventure on the minds of men everywhere, who are attempting to make a determination of which road they should take." He presented space exploration and its achievements as the yardstick to gauge the success of a nation's way of living. The "road" he referred to was the choice between freedom and tyranny, and that decision was to be based, among the other things, on the quality of a nation's space exploration program.

Kennedy continued: "Recognizing the head start obtained by the Soviets with their large rocket engines, which gives them many months of lead-time, … we nevertheless are required to make new efforts on our own. For while we cannot guarantee that we shall one day be first, we can guarantee that any failure to make this effort will make us last. … We go into space because whatever mankind must undertake, free men must fully share." Considering that there were only two contenders in the space exploration arena, the United States had better not be last, because that was what free men had to undertake. Nothing less than freedom was at stake.

Having charged his audience with pride, and appealed to the ideology of freedom so dear to any American citizen, Kennedy was now ready to deliver the final blow: "I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth." How could anybody refuse such a commitment now that it was linked to everything that American society stood for! On July 20, 1969, Neil Armstrong, an American citizen, became the first man to set foot upon the Moon.

The example set by Kennedy would be followed by a number of his successors. For instance, despite an ever decaying public and political support for human-crewed spaceflight which curtailed the Apollo program and ended NASA's dreams of lunar exploration, President Richard M. Nixon made sure that approval for the Space Shuttle would be given. In fact, in August 1971, Caspar W. Weinberger, Director of the Office of Management and Budget, wrote a memorandum to Nixon expressing his concern "that our best years are behind us, that we are turning inward, reducing our defense commitments, and voluntarily starting to give up our super-power status, and our desire to maintain world superiority" and that hence "America should be able to afford something besides increased welfare, programs to repair our cities, or Appalachian relief, and the like." And the Space Shuttle was expected to enable America to reassert its superiority among nations and surge ahead in the exploration of space.

When NASA Administrator James M. Beggs met with President Ronald Reagan on December 1, 1983, he showed him a photo of a Soviet Salyut space station against the backdrop of the USA. At the State of the Union Address delivered before a joint session of Congress on January 25, 1984, another Kennedy moment was about to take place. The words would be different but the structure of the script remained the same. Reagan first appealed to the greatness of his nation: "Nowhere do we so effectively demonstrate our technological leadership. … Our progress in space, taking giant steps for all mankind, is a tribute to American teamwork and excellence." There was a nod to the values of the Free World relative to the closed communist Soviet Union: "And we can be proud to say: We are first. We are the best. And we are so because we are free." With his audience prepped for the next commitment in space, he said: "We can reach for greatness again. … Tonight, I am directing NASA to develop a permanently manned space station and to do it within a decade." Once again, national pride was a potent ally in initiating a complex and rather contested space program.

However, it would be more than 20 years before the assembly of the space station would start. And when on November 20, 1998, the first component was orbited it was not American but a Made-in-Russia module named Zarya. The political climate was profoundly different. The Soviet Union had ceased to exist in December 1991, and the need to demonstrate the superiority of the Free World over communism was irrelevant. With the fall of the USSR, the Russian space program was plunged into an existential financial crisis and the concern in America was that the cash-strapped engineers would offer their undoubted talents and capabilities to countries hateful of the United States. With the space station program running way over budget and teetering on the brink of cancelation, in his State of the Union Address on January 25, 1994, President Bill Clinton tackled the need to keep the Russian space workforce busy: "Russian scientists will help us build the International Space Station." Therefore, it is not surprising that since its inception the ISS has been criticized for being primarily a tool to maintain the post-Cold War détente and to showcase goodwill in international relations. Indeed, it is not uncommon at times of crisis for this multi-billion dollar collaboration at 400 km altitude to be hailed as evidence the two superpowers *can* still cooperate.

Consider the events involving the Russian annexation of Crimea in 2014. Despite the condemnation by the US and the European Union, and the economic sanctions that they then applied, Russia remains a partner in the ISS and routinely delivers supplies and personnel.[1]

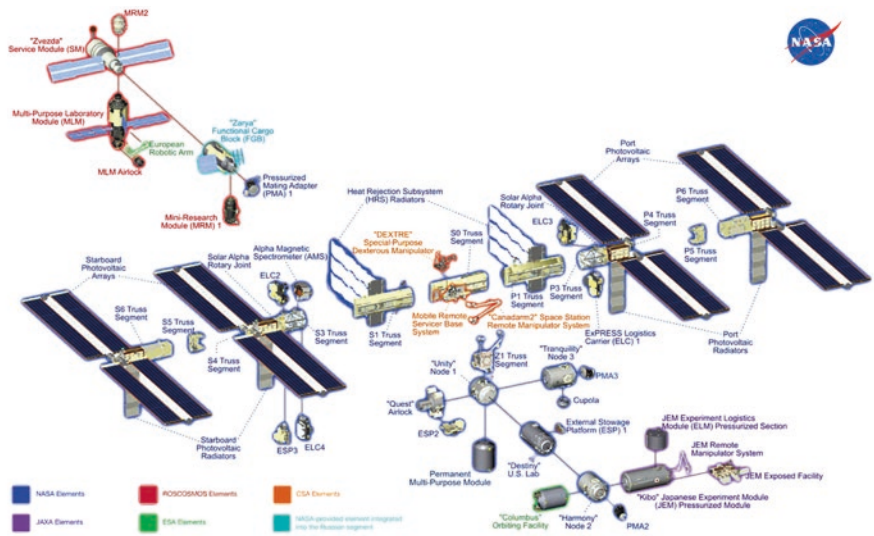

Figure 1.1 An exploded view of the International Space Station showing the individual components color coded by national contribution. The international cooperation in this venture is evident.

The umbrella of geopolitics has enabled defense and national security to become effective motivators for activities in space. Civilizations of any type, place, and time have recognized the benefit of being able to observe the movements of an approaching enemy. In fact, castles and villages, whenever possible, were built on cliffs, high hills, and mountains tops. And as soon as we began to master the art of flight, balloons and airplanes were used for reconnaissance of the enemy lines, and indeed far beyond. And in addition to determining the next defensive or offensive maneuver, an elevated point also allows the delivery of bombs, missiles and the like for a greater destructive impact. It is therefore easy to appreciate how space became the ultimate "high ground" for the observation of the enemy and formulating offensive actions. As early as 1951, Werner von Braun proposed a bomb-dropping space station, saying that a nation orbiting such a platform "might be in a position virtually to control the Earth". Perhaps he struck a chord with the US military, as on 16 March 1955 the United States Air Force officially ordered the development of an advanced reconnaissance satellite to

[1] With the advent of commercial service providers such as SpaceX and Boeing, which are both developing spacecraft for crew transportation, the status quo might change radically.

provide continuous surveillance of "preselected areas" "to determine the status of a potential enemy's war-making capability". Not surprisingly, when Sputnik was launched 2 years later, the US military, as well as the general public, were swift to grasp the implications of that tiny sphere emitting a faint radio signal; namely that the Soviet Union might now have the unhindered capability to drop weapons, possibly nuclear, anywhere on Earth without warning.

Luckily, bombs have not yet been dropped from space, and no satellite has carried weapons.[2] However, flotillas of so-called spy satellites have been launched with ever-increasing capabilities in photo surveillance, early warning of missile launch, detection of nuclear explosions, electronic reconnaissance, and radar imaging. Such skills are no longer exclusive to the United States and Russia. These capabilities have proved their worth in conflicts or situations involving national security for the past six decades.

Rationales of Space Exploration: The Frontier

Throughout history, "the frontier" has been a potent lure motivating people to explore what lies beyond their comfort zone. This spirit has been present everywhere, from the mythological account of Ulysses, to the Far West, to the exploration of the poles just a century ago. As the acclaimed astronomer and science communicator Carl Sagan wrote: "We're the kind of species that needs a frontier – for fundamental biological reasons."

The online Oxford Dictionary defines "frontier" as "a line or border separating two countries" and also as "the extreme limit of settled land beyond which lies wilderness". With this explanation, it is easy to appreciate how space can be considered a frontier. It is the opposite of a life-laden settled planet. It is vast, lifeless, and wild. As the most difficult to reach and subject to our own will, space is the *ultimate* frontier. It is not by accident that in the 1950s, and for some time after that, you would hear and read about "the conquest of space". Compared to the more politically-correct "space exploration" a conquest did indeed instill feelings of dominating the harshest of the frontiers in the same manner that the western part of the United States was colonized.

The iconography of the frontier goes well beyond physical places, and penetrates deeper into the human psyche. The same Oxford Dictionary offers an additional telling interpretation: "the extreme limit of understanding or achievement in a particular area". Space exploration has furthered our comprehension of the most disparate mysteries of the Solar System and the Universe. For instance, it was the American-born physicist Lyman Spitzer who first proposed the carrying out of astronomical observations from orbit when in 1946 he published an intriguing

[2] An interesting exception are the Soviet Almaz space stations designed for reconnaissance-gathering missions. They even had a small, fixed cannon that the cosmonauts would have used in the case of being approached by an enemy spacecraft.

scientific article entitled ‘Astronomical Advantages of an Extra-Terrestrial Observatory’. He explained how the atmosphere hinders astronomical observation by absorbing most of the electromagnetic spectrum apart from that to which our eyes are sensitive. Furthermore, even the quality of optical observations is drastically affected by the daily and local changes of the atmosphere’s physical properties, referred to by astronomers as ‘seeing’ conditions. The scheme that Spitzer concocted was to put a telescope in orbit around Earth to perceive the Universe at never-before-seen wavelengths. Sure enough, the first satellite applications, by both superpowers, were for astronomy. Since then, there have been a steady stream of ever-sophisticated space-borne telescopes.

At the same time, robotic probes have been posted to every major body of the Solar System, revealing alien vistas that had previously only been imagined in the pages of science fiction publications. In some cases, robots have even provided an up-close in-situ studies of such landscapes. However, the only celestial body to have been visited by humans is the Moon, by the Apollo astronauts. Thus far, all efforts to renew human exploration have failed the funding hurdle. Since the tragic loss of the Space Shuttle Columbia in February 2003, every major space agency has been trying to initiate plans for either a return to the Moon or to achieve the first boot prints on Mars. Among the top reasons presented to justify such ventures is the need to improve our understanding of these alien worlds.

There is another area of the frontier definition that we must reflect on: “the extreme limit of … achievement in a particular area”. This is a frontier in what we, as a species, can do. Humans have always striven to accomplish ever grander projects and we have used them as yardsticks in demonstrating our ability to tame nature to our goals. The same attitude is also experienced on an individual scale, as most of us feel the need to embark on projects or hobbies that give us a sense of accomplishment and provide the confidence that we are capable of doing even better. It is not surprising that President Kennedy said: “We choose to the go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because the goal will serve to organize and measure the best of our energies and skills.” The exploration of space is difficult and challenging. It does require an extraordinary effort to concoct complex machinery to harness in a controlled manner the equivalent energy of an atomic bomb, or to precisely arrange for a space probe to rendezvous with a small body billions of kilometers away after a journey lasting years. Consider the fly-by of Pluto by NASA’s New Horizons spacecraft, the European Space Agency’s Rosetta mission’s encounter with the 67P/Churyumov-Gerasimenko comet, and more recently the Japanese Space Agency’s Hayabusa 2 probe which landed two small hopping rovers on the surface of the asteroid 162173 Ryugu. Another good example is the intricate sky-crane apparatus devised to safely and precisely land NASA’s Curiosity rover on Mars, something never previously attempted, difficult to test on Earth, and had only one chance to work upon reaching its target. Even for the layman such accomplishments raise awe, marvel, and a sense of pride at what humans can achieve.

At times, it can inspire action. It frequently gives us confidence that we can resolve thorny and demanding problems. It is not unusual to hear expressions such as "if they were able to go to the Moon then they can also [substitute a problem familiar to you]". Time and again, the public relations departments of the national space agencies levy heavily on our natural desire to seek a grand challenge as a reason for a return to the Moon or to send people to Mars. Quotations from Werner von Braun such as: "I have learned to use the word 'impossible' with the greatest caution" or Robert H. Goddard's "It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of tomorrow" really do nurture such spirit.[3]

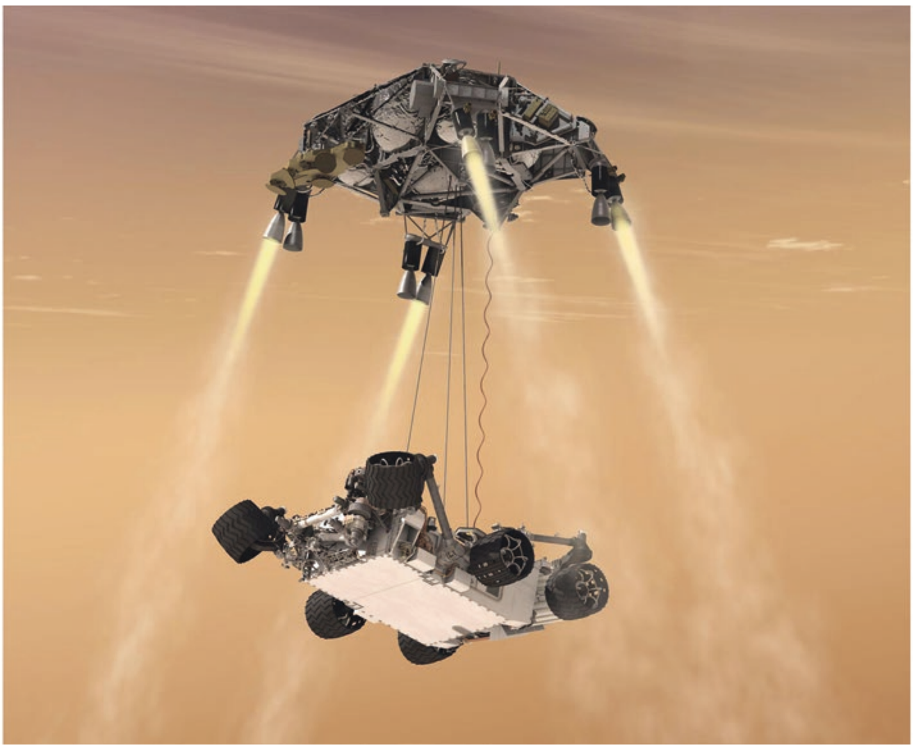

Figure 1.2 An artist's impression of the final moment before touchdown of the Curiosity rover on Mars. The so-called sky-crane consisted of a platform that was stabilized by four clusters of small rocket thrusters which fired just above the surface, while a winch lowered the rover gently to the surface at the end of a rope.

[3] It is worth recalling that both men are considered the fathers of modern rocketry in Germany and the United States, respectively.

The need to explore and advance the frontier has repeatedly protected our species from events that might otherwise have placed its survival at risk. There is abundant archaeological evidence of how large and small groups have undertaken migrations beyond their frontiers to find better places to settle. Often it was in response to natural events or human-made circumstances, such as war or over-exploitation of resources as a result of runaway population growth (more on this at the end of the chapter).

The same rationale applies to space exploration, particularly in terms of a human presence in space. The renowned sci-fi writer Larry Niven once said: "The dinosaurs became extinct because they didn't have a space program. And if we become extinct because we don't have a space program, it will serve us right!" This might sound like a joke, but the demise of these giant reptiles has been attributed to an asteroid striking our planet. As we track more and more such rocks passing by, the risk of another such cataclysmic event is no laughing matter. Recall the 2,000 square kilometers of Eastern Siberia where some 80 million trees were razed on June 30, 1908, by either an asteroid or a comet exploding with the force of a large nuclear bomb over the Stony Tunguska River area. On February 15, 2013, another space rock detonated with a much smaller blast over the Chelyabinsk area in the Southern Urals of Russia. Although neither event produced human casualties, the destruction they unleashed are stark reminders that we cannot dismiss such threats. It is therefore not surprising that expanding our capability to detect and chase what lies out there is gaining traction both within and beyond the space community.

Others have taken a more aggressive stand by proposing a modern version of our ancestors' migrations: the colonization of space. Two movements share the same goal with different destinations in mind. The first one was started by Gerard K. O'Neill, a physicist at Princeton University, New Jersey. In the mid-1970s, O'Neill called for a program to build vast cylinders in space to sustain millions of people in conditions not dissimilar to a typical American suburb. Such colonies would draw electrical power from the inexhaustible energy of the Sun and would gain independence from Earth by developing their own industries using lunar or asteroidal resources. In fact, they would sell their own products once full self-sufficiency was achieved. Since then, colonies in space in every sort of shape and size have been subject to serious consideration, at least from a technical perspective.

The alternative is to create an artificial habitat on the surface of a celestial body. Although the Moon is the closest, and we have already shown that we can reach it, the destination that space agencies, individuals, and space advocacy societies yearn for is Mars. For example, one of the most prominent individuals actively championing Mars is Elon Musk. He has used his personal fortune to create SpaceX, a rocket company whose stated purpose is to make humankind a

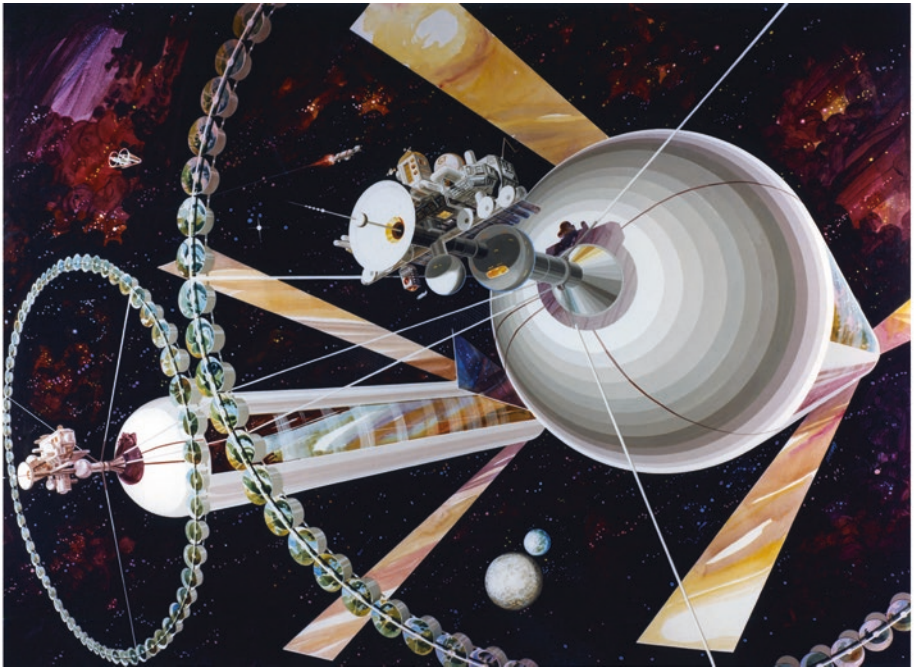

Figure 1.3 An artist's depiction of a pair of O'Neill cylinders, each capable of housing millions of people.

multi-planetary species. As of writing, SpaceX has already begun construction of a massive rocket ship with the objective of sending the first humans to Mars. Robert Zubrin, the founder of the Mars Society, has been strongly advocating for a Mars mission for several decades now. The work of the Mars Society to experiment with available technology in order to make a Mars mission feasible is both admirable and inspiring.

A major asteroid impact is not the only extinction risk facing the human species. A nuclear war, use of biological weapons, dwindling of resources due to overpopulation, societal collapse, and so on, are all reasons for a human migration into space. And in a few billion years our Sun will evolve into a 'red giant' star. Its inflated surface will swallow up the inner planets and the resulting conditions on Earth will render all life impossible. Thus, irrespective of the type of threat, the human colonization of space is heralded as an insurance policy against extinction. Furthermore, it can also provide the opportunity to give humankind a chance to develop a better society, opportunities for experiments in cultural diversity, even Utopian, as envisioned by science author T. A. Heppenheimer. As he wrote in his book *Colonies in Space*: "Some of these people will form specialized communities and will develop (or bring with them from Earth) their own characteristic ideas of how life should be lived, how a community should be organized. On Earth it is difficult for these people to form new nations or regions for themselves. … But in space it will become easy for ethnic or religious groups, and for many others as well, to set up their own colonies. … Those who wish to found experimental communities, to try new social forms and practices, will have the opportunity to strike out into the wilderness and establish their ideals in cities in space. This, in the long run, will be one of the most valuable results from space colonization: the new social or cultural forms people will develop."

Such possibilities also occurred to O'Neill in his masterpiece *The High Frontier*: "What chances will we have, though, here on an Earth ever more crowded and hungrier for energy and materials, to allow for diversity, for experiment, for groups to try in isolation to find better lifestyles? What chances for rare talented individuals to create their own small words, of home and family, as was so easy a century ago in our America as it expanded into a new frontier? … The most chilling prospect that I see for a planet-bound human race is that many of these dreams would be forever cut off for us."

This comes full circle with the human need to reach and tame the frontier. Reaching and settling the frontier is what Robert Zubrin describes as "humanity's greatest social need. Nothing is more important … Without a frontier to grow in … the entire global civilization based upon values of humanism, science, and progress will ultimately die."

Answering the urge to conquer the frontier, an insurance policy for humankind, a chance to create a better society that has learned from the past, and infusing confidence in our ability to engage in seemingly impossible endeavors, are all tightly intertwined in bestowing a strong rationale for space exploration.

Rationales of Space Exploration: Searching for ET

"But where is everybody?" Italian physicist Enrico Fermi asked at a luncheon in Los Alamos in the summer of 1950. As recalled by his colleagues, Fermi was questioning the lack of evidence for extraterrestrial civilizations. Known as the Fermi Paradox, this has spurred many a debate about the existence of other intelligent forms of life in the galaxy. The Search for Extraterrestrial Intelligence Institute (SETI) was established in 1984. Far from being a laughable excuse to look for little green aliens, the institute is a serious "private, nonprofit organization dedicated to scientific research, education, and public outreach" with the mission "to explore, understand, and explain the origin and nature of life in the universe, and to apply the knowledge gained to inspire and guide present and future generations".

Among the original board of trustees was Dr. Frank Drake, a radio astronomer at the National Radio Astronomy Observatory in Green Bank, West Virginia. In 1961 he published an equation, known as the Drake Equation, which grouped those factors that should be appraised in estimating the number of civilizations in our galaxy capable of radio communications. As explained by the SETI Institute, the Drake Equation "is a simple, effective tool for stimulating intellectual curiosity about the universe around us, for helping us to understand that life as we know it is the end product of a natural, cosmic evolution, and for making us realize how much we are a part of that universe".

There is no doubt that we have become obsessed with the search for extraterrestrial life, be it intelligent or not. For instance, robotic exploration of Mars is predominantly focused on this topic. The two Viking probes landed on the Red Planet in the summer of 1975 and not only snapped panoramic vistas and close-up pictures of the soil, but also "conducted three biology experiments designed to look for possible signs of life". The Spirit and Opportunity rovers landed on Mars in early 2003 to carry out extensive soil sampling. In doing so, they unearthed "evidence of ancient Martian environments where intermittently wet and habitable conditions existed". These are circumstances considered suitable for the development of life. The small Phoenix lander spent three months on Vastitas Borealis, an arctic plains near the north pole, digging into a near-surface ice-rich layer looking for evidence "about whether the site was ever hospitable to life". The car-sized Curiosity rover is currently surveying Gale Crater to answer one question: "Did Mars ever have the right environmental conditions to support small life forms called microbes?" In 2020, a twin of Curiosity is scheduled for launch, and with additional tools such as a drill it will take "the next step by not only seeking signs of habitable conditions on Mars in the ancient past but also searching for signs of past microbial life itself".

The search for life has extended well beyond the confines of the Solar System, and is actively pursued both on the ground and in space. Most notably, the Kepler Space Telescope has discovered thousands of extra-solar planets. Thus far, no planets have been found to host all the conditions deemed necessary for life to occur or survive, but the search for a "second Earth" continues. There is no doubt that the search for another civilization, the quest for another Earth, and the desire to find out whether life on Earth is unique, all play major roles in assigning considerable human and financial resources to space exploration.

Rationales of Space Exploration: Spinoff and Satellite Applications

The use of space for applications directly affecting our daily lives is well documented, and perhaps the easiest to understand. Weather forecasting, telecommunications, and GPS-based services are among the most ubiquitous accomplishment of the Space Age, so much so that it is easy to forget they rely on multi-million dollar spacecraft orbiting Earth. Environmental monitoring conducted by satellites specialized in analyzing one or more peculiar aspects of our planet's environment are perhaps less popular in daily jargon, but they play a paramount role in understanding and better managing our world and its limited resources on behalf of future generations.