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THE FUTURE OF HUMANITY

TERRAFORMING MARS, INTERSTELLAR TRAVEL, IMMORTALITY, AND OUR DESTINY BEYOND EARTH

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PROLOGUE

One day about seventy-five thousand years ago, humanity almost died.

A titanic explosion in Indonesia sent up a colossal blanket of ash, smoke, and debris that covered thousands of miles. The eruption of Toba was so violent that it ranks as the most powerful volcanic event in the last twenty-five million years. It blew an unimaginable 670 cubic miles of dirt into the air. This caused large areas of Malaysia and India to be smothered by volcanic ash up to thirty feet thick. The toxic smoke and dust eventually sailed over Africa, leaving a trail of death and destruction in its wake.

Imagine, for a moment, the chaos caused by this cataclysmic event. Our ancestors were terrorized by the searing heat and the clouds of gray ash that darkened the sun. Many were choked and poisoned by the thick soot and dust. Then, temperatures plunged, causing a "volcanic winter." Vegetation and wildlife died off as far as the eye could

see, leaving only a bleak, desolate landscape. People and animals were left to scavenge the devastated terrain for tiny scraps of food, and most humans died of starvation. It looked as if the entire Earth was dying. The few who survived had only one goal: to flee as far as they could from the curtain of death that descended on their world.

Stark evidence of this cataclysm may perhaps be found in our blood.

Geneticists have noticed the curious fact that any two humans have almost identical DNA. By contrast, any two chimpanzees can have more genetic variation between them than is found in the entire human population. Mathematically, one theory to explain this phenomenon is to assume that, at the time of the explosion, most humans were wiped out, leaving only a handful of us—about two thousand people. Remarkably, this dirty, raggedy band of humans would become the ancestral Adams and Eves who would eventually populate the entire planet. All of us are almost clones of one another, brothers and sisters descended from a tiny, hardy group of humans who could have easily fit inside a modern hotel ballroom.

As they trekked across the barren landscape, they had no idea that one day, their descendants would dominate every corner of our planet.

Today, as we gaze into the future, we see that the events that took place seventy-five thousand years ago may actually be a dress rehearsal for future catastrophes. I was reminded of this in 1992, when I heard the astounding news that, for the first time, a planet orbiting a distant star had been found. With this discovery, astronomers could prove that planets existed beyond our solar system. This was a major paradigm shift in our understanding of the universe. But I was saddened when I heard the next piece of news: this alien planet was orbiting a dead star, a pulsar, that had exploded in a supernova, probably killing everything that might have lived on that planet. No living thing known to science can withstand the withering blast of nuclear energy that emerges when a star explodes close by.

I then imagined a civilization on that planet, aware that their mother sun was dying, working urgently to assemble a huge armada of spaceships that might transport them to another star system. There would have been utter chaos on the planet as people, in panic and des-

peration, tried to scramble and secure the last few seats on the departing vessels. I imagined the horror felt by those who were left behind to meet their fate as their sun exploded.

It is as inescapable as the laws of physics that humanity will one day confront some type of extinction-level event. But will we, like our ancestors, have the drive and determination to survive and even flourish?

If we scan all the life-forms that have ever existed on the Earth, from microscopic bacteria to towering forests, lumbering dinosaurs, and enterprising humans, we find that more than 99.9 percent of them eventually became extinct. This means that extinction is the norm, that the odds are already stacked heavily against us. When we dig beneath our feet into the soil to unearth the fossil record, we see evidence of many ancient life-forms. Yet only the smallest handful survive today. Millions of species have appeared before us; they had their day in the sun, and then they withered and died. That is the story of life.

No matter how much we may treasure the sight of dramatic, romantic sunsets, the smell of fresh ocean breezes, and the warmth of a summer's day, one day it will all end, and the planet will become inhospitable to human life. Nature will eventually turn on us, as it did to all those extinct life-forms.

The grand history of life on Earth shows that, faced with a hostile environment, organisms inevitably meet one of three fates. They can leave that environment, they can adapt to it, or they will die. But if we look far enough into the future, we will eventually face a disaster so great that adaptation will be virtually impossible. Either we must leave the Earth or we will perish. There is no other way.

These disasters have happened repeatedly in the past, and they will inevitably happen in the future. The Earth has already sustained five major extinction cycles, in which up to 90 percent of all life-forms vanished from the Earth. As sure as day follows night, there will be more to come.

On a scale of decades, we face threats that are not natural but are largely self-inflicted, due to our own folly and shortsightedness. We face the danger of global warming, when the atmosphere of the Earth

itself turns against us. We face the danger of modern warfare, as nuclear weapons proliferate in some of the most unstable regions of the globe. We face the danger of weaponized microbes, such as airborne AIDS or Ebola, which can be transmitted by a simple cough or sneeze. This could wipe out upward of 98 percent of the human race. Furthermore, we face an expanding population that consumes resources at a furious rate. We may exceed the carrying capacity of Earth at some point and find ourselves in an ecological Armageddon, vying for the planet's last remaining supplies.

In addition to calamities that we create ourselves, there are also natural disasters over which we have little control. On a scale of thousands of years, we face the onset of another ice age. For the past one hundred thousand years, much of Earth's surface was blanketed by up to a half mile of solid ice. The bleak frozen landscape drove many animals to extinction. Then, ten thousand years ago, there was a thaw in the weather. This brief warming spell led to the sudden rise of modern civilization, and humans have taken advantage of it to spread and thrive. But this flowering has occurred during an interglacial period, meaning we will likely meet another ice age within the next ten thousand years. When it comes, our cities will disappear under mountains of snow and civilization will be crushed under the ice.

We also face the possibility that the supervolcano under Yellowstone National Park may awaken from its long slumber, tearing the United States apart and engulfing the Earth in a choking, poisonous cloud of soot and debris. Previous eruptions took place 630,000, 1.3 million, and 2.1 million years ago. Each event was separated by roughly 700,000 years; therefore, we may be due for another colossal eruption in the next 100,000 years.

On a scale of millions of years, we face the threat of another meteor or cometary impact, similar to the one that helped to destroy the dinosaurs 65 million years ago. Back then, a rock about six miles across plunged into the Yucatán peninsula of Mexico, sending into the sky fiery debris that rained back on Earth. As with the explosion at Toba, only much larger, the ash clouds eventually darkened the sun and led temperatures to plunge globally. With the withering of vegetation, the

food chain collapsed. Plant-eating dinosaurs starved to death, followed soon by their carnivorous cousins. In the end, 90 percent of all life-forms on Earth perished in the wake of this catastrophic event.

For millennia, we have been blissfully ignorant of the reality that the Earth is floating in a swarm of potentially deadly rocks. Only within the last decade have scientists begun to quantify the real risk of a major impact. We now know that there are several thousand NEOs (near-Earth objects) that cross the orbit of the Earth and pose a danger to life on our planet. As of June 2017, 16,294 of these objects have been catalogued. But these are just the ones we've found. Astronomers estimate that there are perhaps several million uncharted objects in the solar system that pass by the Earth.

I once interviewed the late astronomer Carl Sagan about this threat. He stressed to me that "we live in a cosmic shooting gallery," surrounded by potential hazards. It is only a matter of time, he told me, before a large asteroid hits the Earth. If we could somehow illuminate these asteroids, we would see the night sky filled with thousands of menacing points of light.

Even assuming we avoid all these dangers, there is another that dwarfs all the others. Five billion years from now, the sun will expand into a giant red star that fills the entire sky. The sun will be so gigantic that the orbit of the Earth will be inside its blazing atmosphere, and the blistering heat will make life impossible within this inferno.

Unlike all other life-forms on this planet, which must passively await their fate, we humans are masters of our own destiny. Fortunately, we are now creating the tools that will defy the odds given to us by nature, so that we don't become one of the 99.9 percent of life-forms destined for extinction. In this book, we will encounter the pioneers who have the energy, the vision, and the resources to change the fate of humanity. We will meet the dreamers who believe that humanity can live and thrive in outer space. We will analyze the revolutionary advances in technology that will make it possible to leave the Earth and to settle elsewhere in the solar system, and even beyond.

But if there is one lesson we can learn from our history, it is that humanity, when faced with life-threatening crises, has risen to the

challenge and has reached for even higher goals. In some sense, the spirit of exploration is in our genes and hardwired into our soul.

But now we face perhaps the greatest challenge of all: to leave the confines of the Earth and soar into outer space. The laws of physics are clear; sooner or later we will face global crises that threaten our very existence.

Life is too precious to be placed on a single planet, to be at the mercy of these planetary threats.

We need an insurance policy, Sagan told me. He concluded that we should become a "two planet species." In other words, we need a backup plan.

In this book, we will explore the history, the challenges, and the possible solutions that lie before us. The path will not be easy, and there will be setbacks, but we have no choice.

From near extinction approximately seventy-five thousand years ago, our ancestors ventured forth and began the colonization of the entire Earth. This book will, I hope, lay out the steps necessary to conquer these obstacles that we will inevitably face in the future. Perhaps our fate is to become a multiplanet species that lives among the stars.

If our long-term survival is at stake, we have a basic responsibility to our species to venture to other worlds.

—CARL SAGAN

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'll serve us right.

—LARRY NIVEN

INTRODUCTION TOWARD A MULTIPLANET SPECIES

When I was a child, I read Isaac Asimov's Foundation Trilogy, which is celebrated as one of the greatest sagas in the history of science fiction. I was stunned that Asimov, instead of writing about ray gun battles and space wars with aliens, asked a simple but profound question: Where will human civilization be fifty thousand years into the future? What is our ultimate destiny?

In his groundbreaking trilogy, Asimov painted a picture of humanity spread out across the Milky Way, with millions of inhabited planets held together by a vast Galactic Empire. We had traveled so far that the location of the original homeland that gave birth to this great civilization was lost in the mists of prehistory. And there were so many advanced societies distributed throughout the galaxy, with so many people bound together through a complex web of economic ties, that, with this huge sample size, it was possible to use mathematics

to predict the future course of events, as if predicting the motion of molecules.

Years ago, I invited Dr. Asimov to speak at our university. Listening to his thoughtful words, I was surprised at his breadth of knowledge. I then asked him a question that had intrigued me since childhood: What had inspired him to write the Foundation series? How had he come up with a theme so large that it embraced the entire galaxy? Without hesitation, he responded that he was inspired by the rise and fall of the Roman Empire. In the story of the empire, one could see how the destiny of the Roman people played out over its turbulent history.

I began to wonder whether the history of humanity has a destiny as well. Perhaps our fate is to eventually create a civilization that spans the entire Milky Way galaxy. Perhaps our destiny is truly in the stars.

Many of the themes underlying Asimov's work were explored even earlier, in Olaf Stapledon's seminal novel *Star Maker.* In the novel, our hero daydreams that he somehow soars into outer space until he reaches faraway planets. Racing across the galaxy as pure consciousness, wandering from star system to star system, he witnesses fantastic alien empires. Some of them rise to greatness, ushering in an era of peace and plenty, and some even create interstellar empires with their starships. Others fall into ruin, wracked by bitterness, strife, and war.

Many of the revolutionary concepts in Stapledon's novel were incorporated into subsequent science fiction. For example, our hero in *Star Maker* discovers that many superadvanced civilizations deliberately keep their existence a secret from lower civilizations, to prevent accidentally contaminating them with advanced technology. This concept is similar to the Prime Directive, one of the guiding principles of the Federation in the *Star Trek* series.

Our hero also comes across a civilization so sophisticated that its members enclose their mother sun in a gigantic sphere to utilize all its energy. This concept, which would later be called the Dyson sphere, is now a staple of science fiction.

He meets a race of individuals who are in constant telepathic contact with one another. Every individual knows the intimate thoughts

of the others. This idea predates the Borg of *Star Trek,* where individuals are connected mentally and are subordinate to the will of the Hive.

And at the end of the novel, he encounters the Star Maker himself, a celestial being who creates and tinkers with entire universes, each with its own laws of physics. Our universe is just one in a multiverse. In total awe, our hero witnesses the Star Maker at work as he conjures up new and exciting realms, discarding those not pleasing to him.

Stapledon's trailblazing novel came as quite a shock in a world where the radio was still considered a miracle of technology. In the 1930s, the idea of achieving a space-faring civilization seemed preposterous. Back then, propeller-driven airplanes were state-of-the-art and had hardly managed to venture above the clouds, so the possibility of traveling to the stars seemed hopelessly remote.

Star Maker was an instant success. Arthur C. Clarke called it one of the finest works of science fiction ever published. It fired up the imagination of a whole generation of postwar science fiction writers. But among the general public, the novel was soon forgotten amidst the chaos and savagery of World War II.

FINDING NEW PLANETS IN SPACE

Now that the Kepler spacecraft and teams of Earth-bound astronomers have discovered about four thousand planets orbiting other stars in the Milky Way galaxy, one begins to wonder if the civilizations described by Stapledon actually exist.

In 2017, NASA scientists identified not one but seven Earth-sized planets orbiting a nearby star, a mere thirty-nine light-years from Earth. Of these seven planets, three of them are close enough to their mother star to support liquid water. Very soon, astronomers will be able to confirm whether or not these and other planets have atmospheres containing water vapor. Since water is the "universal solvent" capable of being the mixing bowl for the organic chemicals that make up the DNA molecule, scientists may be able to show that the conditions for life are common in the universe. We may be on the verge of

finding the Holy Grail of planetary astronomy, a twin of the Earth in outer space.

Around the same time, astronomers made another game-changing discovery, an Earth-sized planet named Proxima Centauri b, which orbits the star closest to our sun, Proxima Centauri, which is just 4.2 light-years away from us. Scientists have long conjectured that this star would be one of the first to be explored.

These planets are just a few of the recent entries in the huge Extrasolar Planets Encyclopaedia, which has to be updated practically every week. It contains strange, unusual star systems that Stapledon could only have dreamt of—including systems where four or more stars rotate among one another. Many astronomers believe that if you can imagine any bizarre formation of planets, then it probably exists somewhere in the galaxy, as long as it doesn't violate some law of physics.

This means that we can roughly calculate how many Earth-sized planets there are in the galaxy. Since it has about one hundred billion stars, there might be twenty billion Earth-sized planets orbiting a sun-like star in our galaxy alone. And since there are one hundred billion galaxies that can be seen with our instruments, we can estimate how many Earth-sized planets there are in the visible universe: a staggering two billion trillion.

Realizing that the galaxy could be teeming with habitable planets, you will never see the night sky in the same way again.

Once astronomers have identified these Earth-sized planets, the next goal will be to analyze their atmospheres for oxygen and water vapor, a sign of life, and listen for radio waves, which would signal the existence of an intelligent civilization. Such a discovery would be one of the great turning points in human history, comparable to the taming of fire. Not only would it redefine our relationship to the rest of the universe, it would also change our destiny.

THE NEW GOLDEN AGE OF SPACE EXPLORATION

All these exciting discoveries of exoplanets, along with the novel ideas brought about by a fresh new generation of visionaries, are rekindling

the public's interest in space travel. Originally, what drove the space program was the Cold War and superpower rivalry. The public did not mind spending a staggering 5.5 percent of the nation's federal budget on the Apollo space program because our national prestige was at stake. However, this feverish competition could not be sustained forever, and the funding eventually collapsed.

U.S. astronauts last walked on the surface of the moon about forty-five years ago. Now, the Saturn V rocket and the space shuttle are dismantled and rusting in pieces in museums and junkyards, their stories languishing in dusty history books. In the years that followed, NASA was criticized as the "agency to nowhere." It has been spinning its wheels for decades, boldly going where everyone has gone before.

But the economic situation has begun to change. The price of space travel, once so high it could cripple a nation's budget, has been dropping steadily, in large part because of the influx of energy, money, and enthusiasm from a rising cohort of entrepreneurs. Impatient with NASA's sometimes glacial pace, billionaires like Elon Musk, Richard Branson, and Jeff Bezos have been opening up their checkbooks to build new rockets. Not only do they want to turn a profit, they also want to fulfill their childhood dreams of going to the stars.

Now there is a rejuvenated national will. The question is no longer whether the U.S. will send astronauts to the Red Planet, but when. Former president Barack Obama stated that astronauts would walk on the surface of Mars sometime after 2030, and President Donald Trump has asked NASA to accelerate that timetable.

A fleet of rockets and space modules capable of an interplanetary journey—like NASA's Space Launch System (SLS) booster rocket with the Orion capsule and Elon Musk's Falcon Heavy booster rocket with the Dragon capsule—are in the early testing phase. They will do the heavy lifting, taking our astronauts to the moon, asteroids, Mars, and even beyond. In fact, so much publicity and enthusiasm have been generated by this mission that there is rivalry building up around it. Perhaps there will be a traffic jam over Mars as different groups compete to plant the first flag on Martian soil.

Some have written that we are entering a new golden age of space

travel, when exploring the universe will once again become an exciting part of the national agenda after decades of neglect.

As we look to the future, we can see the outlines of how science will transform space exploration. Because of revolutionary advances in a wide range of modern technologies, we can now speculate how our civilization may one day move into outer space, terraforming planets and traveling among the stars. Although this is a long-term goal, it is now possible to give a reasonable time frame and estimate when certain cosmic milestones will be met.

In this book, I will investigate the steps necessary to accomplish this ambitious goal. But the key to discovering how our future may unfold is to understand the science behind all of these miraculous developments.

REVOLUTIONARY WAVES OF TECHNOLOGY

Given the vast frontiers of science that lie before us, it may help to put the broad panorama of human history into perspective. If our ancestors could see us today, what would they think? For most of human history, we lived wretched lives, struggling in a hostile, uncaring world where life expectancy was between twenty and thirty years of age. We were mostly nomads, carrying all our possessions on our backs. Every day was a struggle to secure food and shelter. We lived in constant fear of vicious predators, disease, and hunger. But if our ancestors could see us today, with our ability to send images instantly across the planet, with rockets that can take us to the moon and beyond, and with cars that can drive themselves, they would consider us to be sorcerers and magicians.

History reveals that scientific revolutions come in waves, often stimulated by advances in physics. In the nineteenth century, the first wave of science and technology was made possible by physicists who created the theory of mechanics and thermodynamics. This enabled engineers to produce the steam engine, leading to the locomotive and the industrial revolution. This profound shift in technology lifted civilization from the curse of ignorance, backbreaking labor, and poverty and took us into the machine age.

In the twentieth century, the second wave was spearheaded by physicists who mastered the laws of electricity and magnetism, which in turn ushered in the electric age. This made possible the electrification of our cities with the advent of dynamos, generators, TV, radio, and radar. The second wave gave birth to the modern space program, which took us to the moon.

In the twenty-first century, the third wave of science has been expressed in high tech, spearheaded by the quantum physicists who invented the transistor and the laser. This made possible the supercomputer, the internet, modern telecommunications, GPS, and the explosion of the tiny chips that have permeated every aspect of our lives.

In this book, I will describe the technologies that will take us even farther as we explore the planets and the stars. In part 1, we will discuss the effort to create a permanent moon base and to colonize and terraform Mars. To do this, we will have to exploit the fourth wave of science, which consists of artificial intelligence, nanotechnology, and biotechnology. The goal of terraforming Mars exceeds our capability today, but the technologies of the twenty-second century will allow us to turn this bleak, frozen desert into a habitable world. We will consider the use of self-replicating robots, superstrong, lightweight nanomaterials, and bioengineered crops to drastically cut costs and make Mars into a veritable paradise. Eventually, we will progress beyond Mars and develop settlements on the asteroids and the moons of the gas giants, Jupiter and Saturn.

In part 2, we will look ahead to a time when we will be able to move beyond the solar system and explore the nearby stars. Again, this mission surpasses our current technology, but fifth wave technologies will make it possible: nanoships, laser sails, ramjet fusion machines, antimatter engines. Already, NASA has funded studies on the physics necessary to make interstellar travel a reality.

In part 3, we analyze what it would require to modify our bodies to enable us to find a new home among the stars. An interstellar journey may take decades or even centuries, so we may have to genetically engineer ourselves to survive for prolonged periods in deep space, perhaps by extending the human life span. Although a fountain of

youth is not possible today, scientists are exploring promising avenues that may allow us to slow and perhaps stop the aging process. Our descendants may enjoy some form of immortality. Furthermore, we may have to genetically engineer our bodies to flourish on distant planets with different gravity, atmospheric composition, and ecology.

Thanks to the Human Connectome Project, which will map every neuron in the human brain, one day we may be able to send our connectomes into outer space on giant laser beams, eliminating a number of problems in interstellar travel. I call this laser porting, and it may free our consciousness to explore the galaxy or even the universe at the speed of light, so we don't have to worry about the obvious dangers of interstellar travel.

If our ancestors in the last century would think of us today as magicians and sorcerers, then how might we view our descendants a century from now?

More than likely, we would consider our descendants to be like Greek gods. Like Mercury, they would be able to soar into space to visit nearby planets. Like Venus, they would have perfect immortal bodies. Like Apollo, they would have unlimited access to the sun's energy. Like Zeus, they would be able to issue mental commands and have their wishes come true. And they would be able to conjure up mythical animals like Pegasus using genetic engineering.

In other words, our destiny is to become the gods that we once feared and worshipped. Science will give us the means by which we can shape the universe in our image. The question is whether we will have the wisdom of Solomon to accompany this vast celestial power.

There is also the possibility that we will make contact with extraterrestrial life. We will discuss what might happen were we to encounter a civilization that's a million years more advanced than ours, that has the capability to roam across the galaxy and alter the fabric of space and time. They might be able to play with black holes and use wormholes for faster-than-light travel.

In 2016, speculation about advanced civilizations in space reached a fever pitch among astronomers and the media, with the announcement that astronomers had found evidence of some sort of colossal

"megastructure," perhaps as big as a Dyson sphere, orbiting around a distant star many light-years away. While the evidence is far from conclusive, for the first time, scientists were confronted with evidence that an advanced civilization may actually exist in outer space.

Lastly, we explore the possibility that we will face not just the death of the Earth but the death of the universe itself. Although our universe is still young, we can foresee the day in the distant future when we might approach the Big Freeze as temperatures plunge to near absolute zero and all life as we know it will likely cease to exist. At that point, our technology might be advanced enough to leave the universe and venture through hyperspace to a new, younger universe.

Theoretical physics (my own specialization) opens up the notion that our universe could be just a single bubble floating in a multiverse of other bubble universes. Perhaps among the other universes in the multiverse, there is a new home for us. Gazing upon the multitude of universes, perhaps we will be able to reveal the grand designs of a Star Maker.

So the fantastic feats of science fiction, once considered the byproduct of the overheated imagination of dreamers, may one day become reality.

Humanity is about to embark on perhaps its greatest adventure. And the gap that separates the speculations of Asimov and Stapledon from reality may be bridged by the astonishing and rapid advancements being made in science. And the first step we take in our long journey to the stars begins when we leave the Earth. As the old Chinese proverb says, the journey of a thousand miles begins with the first step. The journey to the stars begins with the very first rocket.

PART I LEAVING THE EARTH

SUPERIOR
ESSENTIALS

Anyone who sits on top of the largest hydrogen-oxygen fueled system in the world, knowing they're going to light the bottom, and doesn't get a little worried, does not fully understand the situation.

—ASTRONAUT JOHN YOUNG

1 PREPARING FOR LIFTOFF

On October 19, 1899, a seventeen-year-old boy climbed a cherry tree and had an epiphany. He had just read H. G. Wells's *War of the Worlds* and was excited by the idea that rockets could allow us to explore the universe. He imagined how wonderful it would be to make some device that had even the *possibility* of traveling to Mars and had a vision that it was our destiny to explore the Red Planet. By the time he came down from that tree, his life had been forever changed. That boy would dedicate his life to the dream of perfecting a rocket that would make this vision a reality. He would celebrate October 19 for the rest of his life.

His name was Robert Goddard, and he went on to perfect the first liquid fueled multistage rocket, setting into motion events that changed the course of human history.

TSIOLKOVSKY—A LONELY VISIONARY

Goddard was one of a handful of pioneers who, despite isolation, poverty, and ridicule from their peers, forged ahead against all odds and laid the foundation for space travel. One of the first of these visionaries was the great Russian rocket scientist Konstantin Tsiolkovsky, who mapped out the theoretical basis for space travel and paved the way for Goddard. Tsiolkovsky lived in total poverty, was a recluse, and scraped by as a schoolteacher. As a youth, he spent most of his time in the library, devouring science journals, learning Newton's laws of motion, and applying them to space travel. His dream was to travel to the moon and Mars. On his own, without the help of the scientific community, he figured out the mathematics, physics, and mechanics of rockets, and he calculated the escape velocity of the Earth—that is, the speed necessary to escape the gravity of the Earth—to be twenty-five thousand miles per hour, which is far greater than the fifteen miles per hour one could attain with horses in his time.

In 1903, he published his famous rocket equation, which allows one to determine the maximum velocity of a rocket, given its weight and fuel supply. The equation revealed that the relationship between speed and fuel is exponential. Normally, one might assume that if you want to double the velocity of a rocket, you simply need to double the amount of fuel. Instead, the amount of fuel you need rises exponentially with the change in velocity, so that enormous amounts of fuel are needed to give an extra boost in speed.

This exponential relationship made it clear that you would need huge amounts of fuel to leave the Earth. With his formula, Tsiolkovsky was for the first time able to estimate how much fuel was necessary to go to the moon, long before his vision became reality.

Tsiolkovsky's guiding philosophy was, "The Earth is our cradle, but we cannot be in the cradle forever," and he believed in a philosophy called cosmism, which holds that the future of humanity is to explore outer space. In 1911, he wrote, "To place one's feet on the soil of asteroids, to lift a stone from the moon with your hand, to construct moving stations in ether space, to organize inhabited rings around the Earth, Moon and Sun, to observe Mars at the distance of several tens

of miles, to descend to its satellites or even to its own surface—what could be more insane!"

Although Tsiolkovsky was too poor to convert his mathematical equations into actual models, the next step was taken by Robert Goddard, who actually built the prototypes that would one day form the basis of space travel.

ROBERT GODDARD—FATHER OF ROCKETRY

Robert Goddard first became interested in science as a child witnessing the electrification of his hometown. He came to believe that science would revolutionize every aspect of our lives. His father encouraged this interest, buying him a telescope, microscope, and a subscription to *Scientific American.* First he began experimenting with kites and balloons. While reading in the library one day, he stumbled across Isaac Newton's celebrated *Principia Mathematica* and learned the laws of motion. His focus soon became the application of Newton's laws to rocketry.

Goddard systematically turned this curiosity into a usable scientific tool by introducing three innovations. First, Goddard experimented with different types of fuels and realized that powdered fuel is inefficient. The Chinese had invented gunpowder centuries earlier and used it for rockets, but gunpowder burns unevenly and hence rockets remained mainly toys. His first stroke of brilliance was to replace powdered fuel with liquid fuel, which could be precisely controlled so that it burned cleanly and steadily. He built a rocket with two tanks, one containing a fuel, such as alcohol, and the other tank containing an oxidizer, such as liquid oxygen. These liquids were fed by a series of pipes and valves into the firing chamber, creating a carefully controlled explosion that could propel a rocket.

Goddard realized that as the rocket rose into the sky, its fuel tanks were gradually depleted. His next innovation was to introduce multistage rockets that discarded spent fuel tanks and therefore could shed some dead weight along the way, vastly increasing their range and efficiency.

And third, he introduced gyroscopes. Once a gyroscope is sent

spinning, its axis always points in the same direction, even if you rotate it. For example, if the axis points toward the North Star, it will continue to point in that direction if you turn it upside down. This means that a spaceship, if it were to wander in its trajectory, can alter its rockets to compensate for this motion and return to its original course. Goddard realized he could use gyroscopes to help keep his rockets on target.

In 1926, he made history with the first successful launch of a liquid fueled rocket. It rose 41 feet into the air, flew for 2.5 seconds, and landed 184 feet away in a cabbage patch. (The exact site is now hallowed ground to every rocket scientist, and it has been declared a National Historic Landmark.)

In his laboratory at Clark College he established the basic architecture for all chemical rockets. The thundering behemoths we see blasting off from launchpads today are direct descendants of the prototypes he built.

FACING RIDICULE

Despite his successes, Goddard proved to be an ideal whipping boy for the media. When word leaked out in 1920 that he was giving serious thought to space travel, the *New York Times* published scathing criticism that would have crushed any lesser scientist. "That Professor Goddard," the *Times* snickered, "with his 'chair' in Clark College ... does not know the relation of action and reaction, and of the need to have something better than a vacuum against which to react—to say that would be absurd. Of course he only seems to lack the knowledge ladled out daily in high school." And in 1929, after he launched one of his rockets, the local Worcester newspaper ran a degrading headline: "Moon Rocket Misses Target by 238,799 1/2 Miles." Clearly the *Times* and others did not understand Newton's laws of motion and incorrectly believed that rockets could not move in the vacuum of outer space.

Newton's third law, which states that for every action, there is an equal and opposite reaction, governs space travel. This law is known

to any child who has ever blown up a balloon, released it, and watched the balloon fly in all directions. The action is the air that suddenly rushes out of the balloon, and the reaction is the forward motion of the balloon itself. Similarly, in a rocket, the action is the hot gas ejected out of one end, while the reaction is the forward motion of the rocket that propels it, even in the vacuum of space.

Goddard died in 1945 and did not live long enough to see the apology written by the editors of the *New York Times* after the Apollo moon landing in 1969. They wrote, "It is now definitely established that a rocket can function in a vacuum as well as in an atmosphere. The *Times* regrets the error."

ROCKETS FOR WAR AND PEACE

In the first phase of rocketry, we had the dreamers, like Tsiolkovsky, who worked out the physics and mathematics of space travel. In the second phase, we had people like Goddard, who actually built the first prototypes of these rockets. In the third phase, rocket scientists caught the eye of major governments. Wernher von Braun would take the sketches, dreams, and models of his predecessors and with the support of the German government—and later the United States—would create gargantuan rockets that would successfully take us to the moon.

The most celebrated of all rocket scientists was born an aristocrat. Baron Wernher von Braun's father was the German minister of agriculture during the Weimar Republic, and his mother could trace her ancestry to the royal houses of France, Denmark, Scotland, and England. Von Braun was an accomplished pianist as a child and even wrote original works of music. At one point, he might have become a renowned musician or composer. But his destiny changed when his mother bought him a telescope. He became fascinated by space. He devoured science fiction and was inspired by the speed records set by rocket-propelled cars. One day, when he was twelve, he unleashed chaos in the crowded streets of Berlin by attaching a series of fireworks to a toy wagon. He was delighted that it took off like, well, a rocket. However, the police were less impressed. Von Braun was taken into

custody but released because of his father's influence. As he recalled fondly years later, "It performed beyond my wildest dreams. The wagon careened crazily about, trailing fire like a comet. When the rockets burned out, ending their sparkling performance with a magnificent thunderclap, the wagon rolled majestically to a halt."

Von Braun confessed that he was never good with mathematics. But his drive to perfect rocketry led him to master calculus, Newton's laws, and the mechanics of space travel. As he once told his professor, "I plan on traveling to the Moon."

He became a graduate student in physics and earned his Ph.D. in 1934. But he spent much of his time with the amateur Berlin Rocket Society, an organization that used spare parts to build and test rockets on a deserted three-hundred-acre piece of land outside of the city. That year, the society successfully tested a rocket that rose two miles into the air.

Von Braun might have become a professor of physics at some German university, writing learned articles about astronomy and astronautics. But war was in the air, and all of German society, including the universities, was being militarized. Unlike his predecessor, Robert Goddard, who had requested funding from the U.S. military but was turned down, von Braun got an entirely different reception from the Nazi government. The German Army Ordnance Department, always searching for new weapons of war, noticed von Braun and offered him generous funding. His work was so sensitive that his Ph.D. thesis was classified by the army and wasn't published until 1960.

Von Braun, by all accounts, was apolitical. Rocketry was his passion, and if the government would fund his research, he would accept it. The Nazi Party offered him the dream of a lifetime: directorship of a massive project to build the rocket of the future, with a nearly unlimited budget, employing the cream of German science. Von Braun claimed that being offered membership in the Nazi Party and even the SS was a rite of passage for government workers rather than a reflection of his politics. But when you make a deal with the devil, the devil always asks for more.

RISE OF THE V-2

Under von Braun's leadership, the scribblings and sketches of Tsiolkovsky and the prototypes of Goddard became the Vengeance Weapon 2 rocket, an advanced weapon of war that terrorized London and Antwerp, blowing up entire city blocks. The V-2 was unbelievably powerful. It dwarfed Goddard's rockets, making them look like toys. The V-2 stood forty-six feet tall and weighed 27,600 pounds. It could travel at a blazing speed of 3,580 miles per hour and it achieved a maximum altitude of about sixty miles. It hit its targets at three times the speed of sound, giving no warning apart from a double cracking noise as it broke the sound barrier. And it had an operational range of two hundred miles. Countermeasures were futile since no human could track it and no airplane could catch it.

The V-2 set a number of world records, shattering all past achievements in terms of speed and range for a rocket. It was the first long-range guided ballistic missile. It was the first rocket to break the sound barrier. And most impressively, it was the first rocket ever to leave the boundary of the atmosphere and enter outer space.

The British government was so flummoxed by this advanced weapon that they had no words for it. They invented the story that all these explosions were caused by faulty gas mains. But because the agent of these horrific explosions clearly came from the sky, the public sarcastically referred to them as "flying gas pipes." Only after the Nazis announced that a new weapon of war had been unleashed against the British did Winston Churchill finally admit that England had been attacked by rockets.

Suddenly, it appeared as if the future of Europe, and Western civilization itself, might hinge upon the work of a small, isolated band of scientists led by von Braun.

HORRORS OF WAR

The successes of Germany's advanced weapons came at a tremendous human cost. More than three thousand V-2 rockets were launched

against the Allies, resulting in nine thousand deaths. It is estimated that the death toll was even higher—at least twelve thousand—for the prisoners of war who built the V-2 rockets in slave labor camps. The devil wanted its due. Von Braun realized too late that he was in way over his head.

He was horrified when he visited the site where the rockets were built. A friend of von Braun's quoted him as saying, "It is hellish. My spontaneous reaction was to talk to one of the SS guards, only to be told with unmistakable harshness that I should mind my own business, or find myself in the same striped fatigues! . . . I realized that any attempt of reasoning on humane grounds would be utterly futile." Another colleague, when asked if von Braun had ever criticized these death camps, replied, "If he had done it, in my opinion, he would have been shot on the spot."

Von Braun became a pawn of the monster he helped to create. In 1944, when the war effort was in trouble, he got drunk at a party and said that the war was not going well. All he wanted to do was work on rocketry. He regretted that they were working on these weapons of war instead of a spaceship. Unfortunately, there was a spy at the party, and when his drunken comments were relayed to the government, he was arrested by the Gestapo. For two weeks, he was held in a prison cell in Poland, not knowing if he would be shot. Other charges, including rumors that he was a communist sympathizer, were brought to light as Hitler decided his fate. Some officials feared he might defect to England and sabotage the V-2 effort.

Eventually, a direct appeal from Albert Speer to Hitler spared von Braun's life because he was still considered too crucial to the V-2 effort.

The V-2 rocket was decades ahead of its time, but it didn't enter full-time combat until the end of 1944, which was too late to stem the collapse of the Nazi empire, as the Red Army and Allied forces converged on Berlin.

In 1945, von Braun and one hundred of his assistants surrendered to the Allies. They, along with three hundred railroad cars of V-2 rockets and parts, were smuggled back to the U.S. This was part of a pro-

gram, called Operation Paperclip, to debrief and recruit former Nazi scientists.

The U.S. Army scrutinized the V-2, which eventually became the basis of the Redstone rocket, and von Braun and his assistants had their Nazi records "cleansed." But von Braun's highly ambiguous role in the Nazi government continued to haunt him. The comedian Mort Sahl would summarize his career with the quip, "I reach for the stars, but sometimes I hit London." Singer Tom Lehrer penned the words, "Once the rockets are up, who cares where they come down? That's not my department."

ROCKETRY AND SUPERPOWER RIVALRY

In the 1920s and 1930s, U.S. government officials missed a strategic opportunity when they did not recognize the prophetic work being done in their own backyard by Goddard. They missed a second strategic opportunity after the war, with the arrival of von Braun. In the 1950s, they left von Braun and his assistants in limbo, without giving them any real focus. Eventually, interservice rivalry took over. The army, under von Braun, created the Redstone rocket, while the navy had the Vanguard missile and the air force the Atlas.

Without any immediate obligations for the army, von Braun began to take an interest in science education. He created a series of animated TV specials with Walt Disney that captured the imagination of future rocket scientists. In the series, von Braun painted the broad outlines of a massive scientific effort to land on the moon as well as to develop a fleet of ships that would reach Mars.

While the U.S. rocketry program proceeded by fits and starts, the Russians moved ahead rapidly with theirs. Joseph Stalin and Nikita Khrushchev grasped the strategic importance of the space program and made it a top priority. The Soviet program was put under the direction of Sergei Korolev, whose very identity was kept top secret. For years he was only referred to mysteriously as "Chief Designer" or "the Engineer." The Russians had also captured a number of V-2 engineers and moved them to the Soviet Union. With their guidance, the

Soviets took the basic V-2 design and quickly built a series of rockets based on it. Essentially, the entire U.S. and USSR arsenals were based on modifying or lashing together the V-2 rockets, which in turn were based on Goddard's pioneering prototypes.

One of the major goals of both the United States and USSR was launching the first artificial satellite. It was Isaac Newton himself who first proposed the concept. In a now-famous diagram, Newton noted that if you fire a cannonball from a mountaintop, it will fall near the base of the mountain. Following his equations of motion, however, the faster the cannonball travels, the farther it will go. If you fire the cannonball fast enough, it will circle completely around the Earth and become a satellite. Newton made a historic breakthrough: if you replace this cannonball with the moon, then his equations of motion should be able to predict the precise nature of the moon's orbit.

In his cannonball thought experiment, he asked a key question: If an apple falls, does the moon also fall? Since the cannonball is in free fall as it goes around the Earth, the moon must also be in free fall. Newton's insight set into motion one of the greatest revolutions in all of history. Newton could now calculate the motion of cannonballs, moons, planets—almost everything. For example, using his laws of motion, you can easily show that you must fire the cannonball at eighteen thousand miles per hour in order to have it orbit the Earth.

Newton's vision became a reality when the Soviets launched the world's first artificial satellite, Sputnik, in October 1957.

SPUTNIK AGE

The immense shock to the American psyche upon learning of Sputnik cannot be underestimated. Americans quickly realized that the Soviets led the world in rocket science. The humiliation was made worse when, two months later, the navy's Vanguard missile suffered a catastrophic failure on international TV. I vividly remember, as a child, asking my mother if I could stay up and watch the missile launch. She reluctantly agreed. I was horrified to witness the Vanguard missile rise four feet into the air, then drop back down four feet, tip over,

and destroy its own launchpad in a huge, blinding explosion. I could clearly see the nose cone at the top of the missile, which contained the satellite, topple over and disappear in a ball of flames.

The humiliation continued when the second Vanguard launch a few months later also failed. The press had a field day, calling the missile "Flopnik" and "Kaputnik." The Soviet U.N. delegate even joked that Russia should give aid to the United States.

Trying to recover from this huge media blow to our national prestige, von Braun was ordered to quickly launch a satellite, Explorer I, using the Juno I missile. The Juno I was based on the Redstone rocket, which in turn was based on the V-2.

But the Soviets had a series of aces up their sleeve. A sequence of historic "firsts" dominated the headlines for the next several years:

1957: Sputnik 2 carried the first animal, a dog named Laika, into orbit
1957: Lunik 1 was the first rocket to fly past the moon
1959: Lunik 2 was the first to hit the moon
1959: Lunik 3 was the first rocket to photograph the back side of the moon
1960: Sputnik 5 had the first animals returned safely from space
1961: Venera 1 was the first probe to fly past Venus

The Russian space program reached its crowning achievement when Yuri Gagarin safely orbited the Earth in 1961.

I distinctly remember those years, when Sputnik spread panic throughout the United States. How could a seemingly backward nation, the Soviet Union, suddenly leapfrog ahead of us?

Commentators concluded that the root cause of this fiasco was the U.S. education system. American students were falling behind the Soviets. A crash campaign had to be mounted so that money, resources, and media attention could be devoted to producing a new generation of American scientists who could compete with the Russians. Articles at the time declared that "Ivan can read, but Johnny cannot."

Out of this troubled time came the Sputnik generation, a cohort of students who considered it their national duty to become physicists, chemists, or rocket scientists.

Under enormous pressure to let the military wrest control over the U.S. space program from seemingly hapless civilian scientists, President Dwight Eisenhower bravely insisted on continued civilian oversight and created NASA. Then President John F. Kennedy, responding to Gagarin's orbital trip, called for an expedited program to put humans on the moon by the end of the decade.

This call galvanized the nation. By 1966, an astounding 5.5 percent of the U.S. federal budget was going into the lunar program. As always NASA moved cautiously, perfecting the technology needed to bring a moon landing about in a series of launches. First, there was the one-manned craft called Mercury, and then the two-manned Gemini, and finally the three-manned Apollo. NASA also carefully mastered each step in space travel. First, astronauts left the safety of their spaceships and made the first spacewalks. Then astronauts mastered the complex art of docking their spaceship with another ship. Next, astronauts orbited completely around the moon but did not land on the surface. Then, finally, NASA was ready to launch astronauts directly to the moon.

Von Braun was called in to help build the Saturn V, which was to be the biggest rocket ever built. This rocket was a truly marvelous engineering masterpiece. It stood sixty feet taller than the Statue of Liberty. It could lift a payload of 310,000 pounds into orbit around the Earth. Most important, it could send large payloads past twenty-five thousand miles per hour, which is the escape velocity of the Earth.

The possibility of a fatal disaster was ever on the minds of NASA. President Richard Nixon had two speeches prepared for his TV announcement of the results of the Apollo 11 mission. One speech was to report that the effort was a failure and that American astronauts had died on the moon. This scenario actually came very close to happening. In the final seconds before the Lunar Module was to land, computer alarms went off inside the capsule. Neil Armstrong manually took control of the spacecraft and gently landed it on the moon.

Analysis later showed that they had only fifty seconds of fuel left; the capsule might have crashed.

Fortunately, on July 20, 1969, President Nixon was able to deliver the other speech, congratulating our astronauts for their successful landing. Even today, the Saturn V is the only rocket ever to carry humans beyond near-Earth orbit. Surprisingly, it performed flawlessly. A total of fifteen Saturn rockets were built, and thirteen were flown, without a mishap. Altogether, the Saturn V sent twenty-four astronauts to either land on or fly by the moon, from December 1968 to December 1972, and the Apollo astronauts were rightly hailed as heroes who had restored our national reputation.

The Russians were also heavily involved in the race to the moon. However, they ran into a number of difficulties. Korolev, who had directed the Soviet rocket program, died in 1966. And there were four failures of the N-1 rocket, which was to take Russian astronauts to the moon. But perhaps most decisive was the fact that the Soviet economy, already stretched by the Cold War, could not compete with the U.S. economy, which was more than twice its size.

LOST IN SPACE

I remember the moment that Neil Armstrong and Buzz Aldrin set foot on the moon. It was July 1969, and I was in the U.S. Army, training with the infantry at Fort Lewis, Washington, and wondering if I would be sent to fight in Vietnam. It was thrilling to know that history was being made right before our eyes, but it was also disconcerting to know that if I died on the battlefield, I would not be able to share my memories of the historic moon landing with my future children.

After the last launch of the Saturn V in 1972, the American public began to be consumed with other matters. The War on Poverty was in full swing, and the Vietnam War was devouring more and more money and lives. Going to the moon seemed like a luxury when Americans were starving next door or dying abroad.

The astronomical cost of the space program was unsustainable. Plans were made for the post-Apollo era. Several proposals were on

the table. One prioritized sending unmanned rockets into space, an effort led by the military, commercial, and scientific groups that were less interested in heroics and more interested in valuable payloads. Another proposal emphasized sending humans into space. The harsh reality was that it was always easier to get Congress and the taxpayer to fund astronauts into space, rather than some nameless space probe. As one congressman summed up, "No Buck Rogers, no bucks."

Both groups wanted quick and cheap access to outer space rather than costly missions that were years apart. But the end result was a strange hybrid that pleased no one. Astronauts would be sent along with freight and cargo.

The compromise took the form of the space shuttle, which began operating in 1981. This craft was an engineering marvel that exploited all the lessons and advanced technologies developed over the past decades. It was capable of sending sixty thousand pounds of payload into orbit and then docking with the International Space Station. Unlike the Apollo space modules, which were retired after each flight, the space shuttle was designed to be partially reusable. It was capable of sending seven astronauts into space and then flying them back home, like an airplane. As a result, space travel gradually started to seem routine. Americans became accustomed to seeing astronauts waving at us from their latest visit to the International Space Station, which itself was a compromise between the many nations paying the bills.

Over time, problems emerged with the space shuttle. For one, although the shuttle was designed to save money, costs nevertheless began to soar, so that each launch consumed about $1 billion. Sending anything into near-Earth orbit on the shuttle cost roughly $40,000 per pound, which was about four times the cost of other delivery systems. Companies complained that it was much cheaper to send their satellites using conventional rockets. Secondly, flights took place infrequently, with many months between launches. Even the U.S. Air Force was frustrated by these limitations and eventually canceled some of its space shuttle launches in favor of using other options.

Physicist Freeman Dyson of the Institute for Advanced Study in

Princeton, New Jersey, has his own thoughts on why the space shuttle failed to live up to expectations. When we look at the history of the railroad, we see that it initially started as a carrier for all goods, including humans and commercial products. The commercial side and consumer side of the industry each had their own distinct priorities and concerns, and they eventually split apart, increasing efficiency and lowering costs. The space shuttle, however, never made this split and remained a cross between commercial and consumer interests. Instead of being "everything to everyone," it became "nothing to nobody," especially with its cost overruns and flight delays.

And matters worsened after the *Challenger* and *Columbia* tragedies, which cost the lives of fourteen brave astronauts. These disasters weakened public, private, and government support for the space program. As physicists James and Gregory Benford wrote, "Congress came to see NASA primarily as a jobs program, not an exploratory agency." They also observed that "very little useful science got done in the space station . . . The station was about camping in space, not living in space."

Without the wind of the Cold War in its sails, the space program rapidly lost funding and momentum. Back in the heyday of the Apollo space program, the joke was that NASA could go to Congress asking for funds and say just one word: "Russia!" Then Congress would whip out its checkbook and reply, "How much?" But those days were long gone. As Isaac Asimov said, we scored a touchdown—and then we took our football and went home.

Things finally came to a head in 2011, when former President Barack Obama ordered a new "Valentine's Day massacre." In one sweeping gesture, he canceled the Constellation program (the replacement for the shuttle), the moon program, and the Mars program. To relieve the tax burden on the public, he defunded these programs in hope that the private sector would make up the difference. Twenty thousand veterans of the space program were suddenly laid off, throwing away the collective wisdom of NASA's best and brightest. The greatest humiliation was that American astronauts, after going toe-to-toe with Russian astronauts for decades, would now be forced to hitchhike on Russian

booster rockets. The heyday of space exploration, it seemed, was over; things had reached rock bottom.

The problem could be summed up in one four-letter word, *c-o-s-t.* It takes $10,000 to put a pound of anything in near-Earth orbit. Imagine your body made of solid gold. That's roughly what it would take to put you into orbit. To put something on the moon can easily cost $100,000 per pound. And to put things on Mars costs upward of a million dollars per pound. Estimates of putting an astronaut on Mars are often between $400 and $500 billion in total.

I live in New York City. For me it was a sad day when the space shuttle came to town. Although curious tourists lined up and cheered as the shuttle came rolling down the street, it represented the end of an era. The ship was put on display, eventually resting off the pier on Forty-Second Street. With no replacement in sight, it felt as if we were giving up on science, and hence our future.

Looking back at those dark days, I am sometimes reminded of what happened to the great Chinese imperial fleet in the fifteenth century. Back then, the Chinese were the undisputed leaders in science and exploration. They invented gunpowder, the compass, and the printing press. They were unparalleled in military power and technology. Meanwhile, medieval Europe was wracked by religious wars and mired in inquisitions, witch trials, and superstition, and great scientists and visionaries like Giordano Bruno and Galileo were often either burned alive or placed under house arrest, their works banned. Europe, at the time, was a net importer of technology, not a source of innovation.

The Chinese emperor launched, under the command of Admiral Zheng He, the most ambitious naval expedition of all time, with twenty-eight thousand sailors on a fleet of 317 huge ships, each one five times longer than the ships of Columbus. The world would not see anything like it for another four hundred years. Not once, but seven times, from 1405 to 1433, Admiral Zheng He sailed across the known world, around Southeast Asia and past the Middle East, eventually ending up in East Africa. There are ancient woodcuts of the strange animals, like giraffes, that he brought back from his voyages of discovery being paraded before the court.

But when the emperor passed away, the new rulers decided that they had no use for exploration and discovery. They even decreed that a Chinese citizen could not own a boat. The fleet itself was left to rot or allowed to burn, and records of Admiral Zheng He's great accomplishments were suppressed. Succeeding emperors effectively cut off contact between China and the rest of the world. China turned inward, with disastrous results, eventually leading to decay, total collapse, chaos, civil war, and revolution.

I sometimes think about how easy it is for a nation to slip into complacency and ruin after decades of basking in the sun. Since science is the engine of prosperity, nations that turn their backs on science and technology eventually enter a downward spiral.

The U.S. space program similarly fell into decline. But now the political and economic circumstances are changing. A new cast of characters is taking center stage. Daring astronauts are being replaced by dashing billionaire entrepreneurs. New ideas, new energy, and new funding are driving this renaissance. But can this combination of private funds and government financing pave the way to the heavens?

NOTES

PROLOGUE

1 **One day about seventy-five thousand years ago:** A. R. Templeton, "Genetics and Recent Human Evolution," *International Journal of Organic Evolution* 61, no. 7 (2007): 1507–19. See also *Supervolcano: The Catastrophic Event That Changed the Course of Human History; Could Yellowstone Be Next?* (New York: MacMillan, 2015).

2 **Stark evidence of this cataclysm:** Although there is universal agreement that the eruption of the supervolcano at Toba was a truly catastrophic event, it should be pointed out that not all scientists believe it altered the direction of human evolution. One group, from Oxford University, analyzed sediments in Lake Malawi in Africa going back tens of thousands of years into the past. By drilling into the lake bottom, one can retrieve sediments that were deposited in the ancient past and hence re-create ancient weather conditions. Analysis of this data from the time of the Toba volcano showed no significant sign of permanent climate change, which casts doubt on the theory. However, it remains to be seen if this result can be generalized to other areas besides Lake Malawi. Another theory is that the bottleneck in human evolution about seventy-five thousand years ago was caused by slow environmental effects rather than a sudden collapse of the environment. Further research is required to definitively settle the question.

CHAPTER 1: PREPARING FOR LIFTOFF

20 **As a youth, he spent most of his time:** Newton's three laws of motion are:

- An object in motion stays in motion, unless acted on by an outside force. (This means that our space probes can reach the distant planets with minimal fuel once they are in space, because they basically coast their way to the planets, since there is no friction in space.)
- Force equals mass times acceleration. This is the fundamental law behind Newtonian mechanics, which makes possible the building of skyscrapers, bridges, and factories. At any university, a first-year course in physics is basically solving this equation for different mechanical systems.
- For every action, there is an equal and opposite reaction. This is the reason why rockets can move in outer space.

These laws work perfectly well when shooting space probes throughout the solar system. However, they inevitably break down in several important domains: (a) extremely fast velocities approaching the speed of light, (b) extremely intense gravitational fields, such as near a black hole, and (c) extremely small distances found inside the atom. To explain these phenomena, we need Einstein's theory of relativity and also the quantum theory.

20 **"To place one's feet on the soil of asteroids":** Chris Impey, *Beyond* (New York: W.W. Norton, 2015).

22 **"That Professor Goddard":** Impey, *Beyond,* p. 30.

23 **Wernher von Braun would take the sketches, dreams, and models:** Historians still debate precisely how much cross-fertilization there was between pioneers like Tsiolkovsky, Goddard, and von Braun. Some claim that each worked in near total isolation and independently rediscovered one another's work. Others claim that there was considerable interaction between them, especially because much of their work was published. But it is known that the Nazis made inquiries to Goddard, asking for his advice. So it is safe to say that von Braun, because he had access to the German government, was fully aware of the developments of his predecessors.

24 **"I plan on traveling to the Moon":** Hans Fricke, *Der Fisch, der aus der Urzweit kam* (Munich: Deutscher Taschenbuch-Verlag, 2010), pp. 23–24.

27 **"I reach for the stars, but sometimes I hit London":** See Lance Morrow, "The Moon and the Clones," *Time,* August 3, 1998. For more on the political legacy of von Braun, see M. J. Neufeld, *Wernher von Braun: Dreamer of Space, Engineer of War* (New York: Vintage, 2008). Also, parts of this discussion were based on a radio interview I conducted with Mr. Neufeld in September 2007. Many have written about this great scientist, who opened up the space age but did it using financial backing from the Nazis, and have come to differing conclusions.

27 **While the U.S. rocketry program proceeded by fits and starts:** See R. Hal and D. J. Sayler, *The Rocket Men: Vostok and Voskhod, the First Soviet Manned Spaceflights* (New York: Springer Verlag, 2001).

33 **"Congress came to see NASA primarily as a jobs program":** See Gregory Benford and James Benford, *Starship Century* (New York: Lucky Bat Books, 2014), p. 3.

CHAPTER 2: NEW GOLDEN AGE OF SPACE TRAVEL

43 **"The whole idea is to preserve the Earth":** Peter Whoriskey, "For Jeff Bezos, The Post Represents a New Frontier," *Washington Post,* August 12, 2013.

43 **In the 1990s, an unexpected discovery caught scientists by surprise:** See R. A. Kerr, "How Wet the Moon? Just Damp Enough to Be Interesting," *Science Magazine* 330 (2010): 434.

45 **The Chinese have announced that they will put their astronauts on the moon:** See B. Harvey, *China's Space Program: From Conception to Manned Spaceflight* (Dordrecht: Springer-Verlag, 2004).

46 **One factor that limits how long our astronauts can stay on the moon:** See J. Weppler, V. Sabathier, and A. Bander, "Costs of an International Lunar Base" (Washington, D.C.: Center for Strategic and International Studies, 2009); https://csis.org/publication/costs-international-lunar-base.

CHAPTER 3: MINING THE HEAVENS

58 **Planetary Resources estimates that the platinum:** See www.planetaryresources.com.

CHAPTER 4: MARS OR BUST

65 **"Failure is an option here [at SpaceX]":** For more quotes from Elon Musk, see www.investopedia.com/university/elon-musk-biography/elon-musk-most-influential-quotes.asp.

65 **"They say Mars is the new black":** See https://manofmetropolis.com/nick-graham-fall-2017-review.

65 **"I really don't have any other motivation":** *The Guardian,* September 2016; www.theguardian.com/technology/2016/sep/27/elon-musk-spacex-mars-exploration-space-science.

65 **"I'm convinced":** *The Verge,* October 5, 2016; www.theverge.com/2016/10/5/13178056/boeing-ceo-mars-colony-rocket-space-elon-musk.

66 **"I think it's good for there to be multiple paths to Mars":** *Business Insider,* October 6, 2016; www.businessinsider.com/boeing-spacex-mars-elon-musk-2016-10.

66 **"NASA applauds all those":** Ibid.

70 **Bill Gerstenmaier, of NASA's Human Exploration and Operations Directorate:** See www.nasa.gov/feature/deep-space-gateway-to-open-opportunities-for-distant-destinations.

CHAPTER 5: MARS: THE GARDEN PLANET

84 **"Actually, it was Sputnik":** Interview on *Science Fantastic* radio, June 2017.

86 **Another outlandish attempt to form an isolated colony:** See R. Reider, *Dreaming the Biosphere* (Albuquerque: University of New Mexico Press, 2010).