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Space Invaders:
How Robotic Spacecraft Explore
the Solar System
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INTRODUCTION

IN our modern high-tech world we very much depend on the unique benefits of space, although we often do not realize it. Satellites broadcast a television news program to us, including a report from Moscow sent to the news studio by a journalist via a satellite link. The report concerns the latest international agreements to limit the production of CFC-chemicals, which, when they escape into the atmosphere, can destroy the ozone layer. Earth-observing satellites helped to reveal the extent of the problem over Antarctica, and detected the smaller ozone holes over the Arctic. This new knowledge convinced us that we must prevent further damage to this precious atmospheric shield, which protects us against the harmful ultraviolet radiation of the Sun. Without continuous monitoring from space, it would have been impossible for scientists and politicians to appreciate the scale of the ozone problem. Without urgent action, the ozone holes could have grown much larger, considerably increasing our chances of developing skin cancer or cataracts.

Another news item is about the International Space Station, where astronauts are investigating the effects on the human body in microgravity conditions. This will help us to plan and design future crewed expeditions to the Moon and Mars. The astronauts were recently joined by a so-called Flight Participant – a rich person who bought a ticket on board a Russian Soyuz spacecraft to visit the space station. Thanks to space technology, it is now possible for non-professional astronauts to experience the thrill of a launch, weightlessness, and the magnificent view of the Earth from orbit. It is still very expensive, but ticket prices may come down in the future and allow more and more people to take their holiday of a lifetime.

The weather forecast following the news is based on pictures made from orbit by meteorological satellites. We pick up the phone and within seconds, using satellite telephone links, we talk to friends and family on the other side of the planet. We learn that an adventurous relative narrowly escaped drowning when his yacht sank in a storm in the Pacific Ocean. He was rescued by a Navy ship that received a distress and location signal from a transmitter on his life raft. The signal had been forwarded to them by a Search and Rescue radio system on board a satellite. We browse the Internet and, via an orbital connection, check how the stock exchange is doing in Tokyo. Next, we go to visit a colleague who wants to show his new house, which has advanced solar arrays on the roof that are based on solar cells developed for spacecraft. The navigation system in our car accurately guides us to his place using GPS signals from positioning system satellites.

Meanwhile, we are curious about the endless Universe around us and send space probes to the planets and beyond. We are discovering the magnificence and the unbelievable diversities of the new worlds we explore, and at the same time start to understand how unique our own Earth really is. The exploration of the Solar System is a marvelous, inspiring adventure, and the science, the technology and the challenges involved make it an endeavor like no other.

The quest for scientific knowledge is a worthy goal in its own right, but the exploration of the Solar System has direct uses as well. For instance, what the investigation of the planets tell us about the runaway greenhouse effect on Venus and the thin, ozone-less atmosphere of Mars helps us to make better predictions about what is happening to our own atmosphere here on Earth.

We are used to all these space applications, which have been seamlessly integrated into our daily lives to such an extent that we hardly think about them any more. However, until 50 years ago this was all pure science fiction; there were simply no satellites and no interplanetary probes flying through the Solar System.

From the Ground Up

The sky at night has fascinated us for as long as we can look back. Early man thought that the Earth was the center of everything, and that the stars were mere points of light hanging overhead. Most stars appeared to be fixed forever in the same patterns or constellations, and by drawing lines between stars appearing close together we could picture animals and gods in them.

A few stars, however, moved differently around the sky, and the ancient Greek called these objects "planets," meaning "wandering stars." At first we thought the Sun, Moon and planets all revolved around us, until Copernicus revived a long forgotten idea of the Greek philosopher Aristarchus of Samos that the Sun was actually the queen of the Solar System and that the planets, including Earth, were orbiting her. The movements in the sky made much more sense this way.

Planets nevertheless remained mysterious specs of light until the telescope was invented. Galileo Galilei used the new instrument to discover that the Moon was scarred by thousands of large craters, and that the planet Jupiter had four large moons of its own. As telescope technology advanced, the amazing rings of Saturn were observed, and the outer planets Uranus, Neptune and Trans-Neptunian objects such as Pluto were discovered. (It now appears that there are many more small Pluto-type planets beyond Neptune.)

We discovered that the Sun is only one of 200 billion stars in a disk-shaped system we see edge-on as the Milky Way, and that there are an uncountable number of other galaxies. The planets proved to be more than points of light; Venus was found to have a thick atmosphere, Mars had polar caps, and Jupiter was surrounded by ever-changing bands of clouds.

Telescopes grew larger and larger, but we always had to remain on Earth and could never actually visit the planets to inspect them close-up. Because of this limitation, misconceptions arose that could not be proven false, such as the idea that the craters on the Moon had a volcanic origin (while they are in fact created by the impacts of comets, asteroids and meteorites), or that Mars was covered with long, possibly artificial, channels or canals and intriguing changing patterns of vegetation (the canals later proved to be an optical illusion of vague features together appearing as lines, and the changing spots of vegetation were shown to be dark rock plateaus that are sometimes partly covered by lighter colored dust). However, in the mid-twentieth century the state of technology offered us a way to visit these mysterious places – in person or using remotely operated automatic probes.

Chapter 1

ROCKETS AND SATELLITES

The history of satellites and space probes is directly linked to the history of the rocket, as this was the only machine that could achieve the extreme velocities and altitudes required to put objects into space.

The first to really understand that we would need to develop large rockets before we could even think of developing artificial satellites was a Russian schoolteacher by the name of Konstantin Tsiolkovsky (1857–1935). Born deaf, he was unable to attend normal elementary schools, but he taught himself physics and mathematics from books. His father sent him to Moscow to study further, but limited by his deafness he spent most of his time in the great Moscow libraries. Nevertheless, just as he had done before, he educated himself using the library books he found, and in 1882 he managed to get a job as a mathematics teacher in the town of Kaloega, south of Moscow.

Ever since Tsiolkovsky was 12 years old, he had been fascinated by rockets and their possibilities for the exploration of space. He understood that only rockets can still work in the vacuum that exists above the Earth's atmosphere; unlike, for instance, propeller engines, they do not need air because rockets produce their own gasses to propel themselves. Furthermore, unlike car engines and jet engines, rockets do not depend on atmospheric oxygen to sustain combustion since they carry their own oxidizers.

As the fuel and oxidizer (oxygen) mix in the combustion chamber and ignite, they form a fast expanding gas that is expelled at great velocity through the rocket nozzle. Following the "Action = Reaction" principle of Newton, the rocket itself will be thrust forward (the reaction) in the opposite direction to that in which the exhaust gases are going (the action). It is like standing on a skateboard and throwing rocks in the backward direction, which makes you move forward.

In his free time, Tsiolkovsky increasingly busied himself with the theories of spaceflight. He wrote about steerable airships, manned rockets, self-sustaining space stations and spacesuits. Since even motorized airplanes were still science fiction at the time, his fellow citizens considered him to be rather eccentric. However, Tsiolkovsky was far from mad. He understood the physics of rocketry and formulated the basic mathematical equations describing the workings of a rocket and the dynamics of its flight.

In 1903, the same year that the Wright brothers' first motorized plane took off, he invented a method of "staging": stacking series of rockets on top of each other. This method increases the efficiency of launchers, as

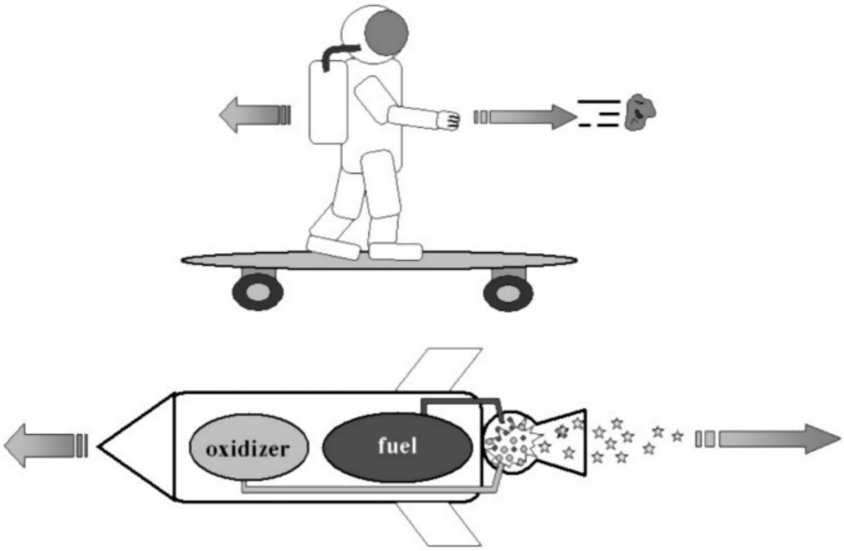

FIGURE 1.1 Both someone on a skateboard throwing rocks and a rocket creating thrust by burning oxidizer and fuel move forward because of Newton's Action = Reaction principle.

stages can be dropped off when their tanks run dry, ensuring that their useless empty mass does not have to be dragged all the way into orbit.

Under the Russian Tsar's regime Tsiolkovsky never enjoyed any government support, but this changed dramatically after the 1917 Revolution and the Soviets came to power. In 1919 he was even made a Member of the prestigious Academy of Sciences and between 1925 and 1932 no less than 60 of his papers were published.

Tsiolkovsky died in 1935, and although he never built any rockets himself, he inspired a number of young Russian rocket experimenters who, in the 1930s, began to build small experimental rockets based on liquid propellants. As a testimony to his vision, Tsiolkovsky's most famous words can be found on his gravestone: "The Earth is the cradle of mankind, but one cannot stay in the cradle forever."

Also in other countries scientists and engineers started to think about the possibilities for rockets to reach outer space. In 1918 American Robert Goddard had already built and launched an extensive series of small rockets, of which the largest measured 1.70 meters (5.1 feet) in length and weighed 20 kilograms (44 pounds). They were supposed to lead to rocket weapons that could be used in the First World War, but the fighting was over before Goddard's developments were finished and the military lost interest in his work.

Nevertheless, Goddard continued his research and experimentation,

FIGURE 1.2 Dr Robert H. Goddard with the world's first liquid propellant rocket, which he launched in 1926. Unlike in modern rockets, the nozzle is on top. [NASA]

and the following year he published a report called "A Method of Reaching Extreme Altitudes" in which he described how a rocket could reach the Moon and signal its arrival by use of flash powder igniting at impact. However, in spite of the scientifically sound basis of his proposals, Goddard's ideas were met with disbelief and ridicule.

Persevering, in 1926 he flew the first ever liquid-fueled rocket. Like Tsiolkovsky, he realized that rocket systems based on liquid propellant have a number of advantages over the simpler solid propellant (gunpowder) rockets used then for artillery and fireworks. Liquid propellant rockets have a lower mass relative to their thrust and, unlike solid propellant rockets, can be throttled up or down, or stopped entirely.

In 1935 Goddard's rockets had broken the sound barrier and reached a height of 1.5 kilometers (0.9 mile), but the US government did not seem to appreciate the possibilities of this technology. During the Second World War all they did was assign Goddard a contract for the development of a starting rocket to help carrier-based aircraft to take off from their ships.

In the meantime Germany had seriously started to develop rockets. In 1923 Hermann Oberth published his classic book *Die Rakete zu den Planetenräumen* ("The Rocket into Planetary Space"), stimulating young German engineers to experiment with rockets themselves. Oberth's own interest in rockets had been stimulated when, at the age of 12, his mother had given him a copy of Jules Verne's *From the Earth to the Moon*.

Oberth's inspiring book resulted in the launch of the first ever rocket-powered aircraft in 1928, while in the same year car manufacturer Fritz von Opel achieved 200 kilometers (124 miles) per hour in a rocket car and reached 153 kilometers (95 miles) per hour flying a glider fitted with solid propellant rockets. In 1931, Germany's first liquid propellant rocket left a proving ground near Berlin, while two years later Viennese Professor Eugene Sänger published a book called *Raketenflugtechnik* ("Rocketflight technology") that contained a concept for a high-speed rocket-propelled research aircraft.

Unlike in America, the developments in rocketry caught the serious attention of the military. German Army leaders saw the development of large, powerful rocket bombs as a way to circumvent the ban on the use of large cannons, as stipulated in the Treaty of Versailles, which Germany had been forced to sign after its defeat in the First World War.

The futuristic engineers were recruited by the military, and instead of reaching for space they found themselves developing ballistic missiles. However, both parties needed the same rocket technology to achieve their goals, and while the engineers had the brains, the military could provide the much-needed financial and logistical support.

Wernher von Braun, one of the group's younger spaceflight enthusiasts, greatly impressed the military leaders. Although he was only 20 years old, they appointed him to lead the technical part of their extensive rocket development.

Soon the development team's expanding activities required a dedicated development, production and launch center, and it was decided to create such a center in Peenemünde, a remote, sparsely inhabited place at the

Baltic Sea in the north of Germany, far from spying Allied eyes. Laboratories, wind tunnels, test stands, launch platforms and housing facilities for the 2,000 rocket scientists and 4,000 supporting workers, plus their families, were built there.

Until the Second World War rockets had been small and incapable of carrying much or going very high, but with the support of the Nazi war machine von Braun's team developed a 14-meter-high (46-foot-high) monster capable of launching a 738-kilogram (1,630-pound) warhead a distance of 418 kilometers (260 miles). In 1942 they launched their first rocket into space, reaching a height of 80 kilometers (50 miles), a distance of 193 kilometers (120 miles), and attaining a velocity of over 5,300 kilometers (3,300 miles) per hour.

The A4 rocket that the Peenemünde group created was soon renamed "Vengeance 2" by the Nazi government. Before the war was over, thousands of V2 rocket bombs were launched at London and liberated Antwerp, blowing away entire blocks of houses in an instant.

Fortunately, the V2 and the other "Wonder Weapons" of Nazi Germany were unable to turn the tide of the war, and in 1945 Germany

FIGURE 1.3 A Bumper V2, based on the German V2 rocket of the Second World War, leaves Cape Canaveral in 1950. [NASA]

surrendered. Understanding that ballistic missiles were going to play a major role in military power, a race developed among the Soviet, British and American military forces to find as many German rocket engineers and blueprints, and as much hardware, as they could get their hands on.

Located in what was soon to become East Germany, Peenemünde was destined to be under Soviet control. However, von Braun and most of the leading figures of the Peenemünde team had fled the rocket base, carrying as much documentation and hardware with them as they could. Convinced that their best chance for continuing rocket development lay with the United States, they surrendered to American forces.

They also gave them directions to find crucial documentation that they had hidden in an underground mine. Some 14 tons of design blueprints, test reports and other archive materials were transported to the American sector just before the British took control of the region, as agreed. The material would have become British property had it remained in the mine.

In another daring smuggling operation, the American Army managed to transport 341 rail carts of rocket equipment out of an underground factory in the Harz mountains, just before the area had to be turned over to the Soviets.

The Americans now had the best cards for the future: the rockets, the documentation and most of the German experts. Nevertheless, the Russians also managed to retain a few rocket experts and some rocket parts, while the British obtained some hardware. (Some of the V2s they "liberated" can still be seen in the Imperial War Museum and the Science Museum in London.)

America and Russia soon moved the German engineers to their own development centers and put them to work on new ballistic missile projects. With the Cold War just starting, the development of large rockets became a top priority in America and Russia. Once again, von Braun and his consorts found themselves working on military weapons instead of spacecraft.

In Russia, chief designer Sergei Korolev was the driving force behind the Soviet rocket program. Originally a carpenter and slater turned aircraft designer, Korolev decided to pursue spaceflight after having met Tsiolkovsky. He started equipping gliders and other airplanes with rocket engines and even flew some of them himself.

In the 1930s Korolev grouped with a couple of other rocket fanatics and started GIRD, a Russian abbreviation for "Group for Research of Reactive Propulsion." Working without any financial support, they jokingly explained that their club's name meant "Group of Engineers Working without Money."

Nevertheless, in 1933 they managed to launch the first Soviet liquid propellant rocket, designed by rocket pioneer Fridrikh Tsander, to an altitude of 400 meters (1,300 feet). Now the military became interested, offered financial support and even founded a special institute for the development of rocketry.

However, the Soviet Union under Stalin was a dangerous place in which to live and work. Together with almost half the officer corps of the Red Army, the Field Marshal who supported Korolev and his colleagues was accused of conspiring with Nazi Germany and executed on Stalin's orders. Because of his link with the Marshal, even Korolev was arrested. According to the accusations, he was supposed to have tried to sabotage a rocketplane he was working on. Korolev narrowly escaped being shot, but was sentenced to 10 years of forced labor in the infamous Kolyma gold mines of Siberia.

However, when the Second World War broke out Stalin realized that he desperately needed technicians and Korolev was brought back to Moscow. Still under custody, he was put to work on military planes and rockets. After the war, Korolev continued his work on rocketry together with the captured German engineers and scientists of von Braun's Peenemünde team.

Taking advantage of the German experts' knowledge, Korolev and his group were soon building Russian copies of the V2 rocket. Unlike their colleagues in America, the German experts in Russia were dismissed and sent home after their V2 work was completed. Korolev's institute, now fully supported by Stalin, continued its work and started to launch rockets that were increasingly larger and more advanced. Soon they were capable of launching satellites in Earth orbit.

To put a satellite into orbit, you need to give it a very high velocity. Imagine a tower with a cannon on top of it, aimed horizontally to the horizon. The fired shell will be given a velocity in the horizontal direction, but as soon as it leaves the cannon's muzzle, gravity will start pulling it down. As a result the shell's trajectory is curved downward, and it hits the ground a certain distance from the cannon.

If you manage to put more gunpowder into your cannon and fire it again, the second shell will get a higher initial velocity, and therefore fly further before it impacts. Now imagine a truly huge gun, able to give a projectile the enormous velocity of 7.5 kilometers (4.7 miles) per second. Again, as soon as the shell is fired, gravity starts pulling it down into a curved trajectory. However, the shell now manages to fly very, very far in the horizontal direction before it falls to ground level. In fact, at this velocity it flies over the horizon and, as it falls down, the ground level also moves down because of the Earth's curvature.

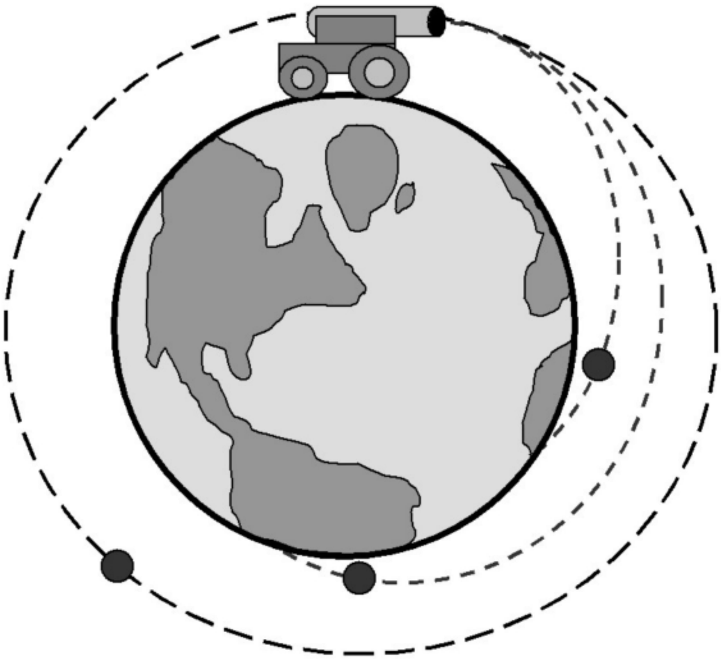

FIGURE 1.4 The faster a cannonball, the further it will fly. If shot at a high enough velocity and at sufficient altitude, the projectile could go into orbit.

At 7.8 kilometers (4.8 miles) per second the curvature of the projectile's trajectory is exactly the same as the curvature of the Earth. The shell thus never reaches the ground, but falls all the way around the Earth to hit the cannon in the back. If you could quickly remove the cannon, the shell would continue to fall around the planet in a circle. It would then be in Earth orbit and have become a satellite.

In reality this does not work, owing to the atmospheric drag that continuously slows down the projectile. To keep the projectile in orbit you would need to put it above the atmosphere, at least to an altitude of about 200 kilometers (130 miles).

Satellites are not launched by cannons, mostly because the enormous acceleration needed to bring them from 0 to 7.8 kilometers (4.8 miles) per second over the length of the cannon's barrel would be far too high for most on board equipment to survive.

Instead, rocket launchers are used to relatively slowly increase the velocity and bring the satellite above the atmosphere. This requires an enormous amount of propellant and supporting equipment. Typically, it takes 100 kilograms (230 pounds) of propellant and launcher hardware to place 1 kilogram of satellite in a low Earth orbit. Hence a satellite launcher needs to be very, very large.

In the 1950s Soviet nuclear technology was behind that of America, making Russia's nuclear bombs much heavier than those of its rival. The Soviets had to put much effort and money into building rockets that were large enough to be able to launch their weapons at the United States. The USA, with its more sophisticated and lighter nuclear bombs, only needed relatively small launchers. However, in spaceflight large launchers mean that you can put heavier satellites into orbit, and so the Russian military disadvantage soon turned into an unforeseen spaceflight advantage.

On October 4, 1957, a 58-centimeter (23-inch) polished metal sphere called "Sputnik" was put into orbit on top of one of Korolev's converted ballistic missiles. The instrumentation of this very basic satellite included a radio transmitter and devices for measuring the air density, temperature and electron concentrations in the uppermost part of the atmosphere. Using its four long antennas it continuously transmitted its coded "beep, beep" signal until its battery was empty 21 days later. Sputnik 1 remained in orbit for a total of 96 days, until the minute drag of the upper atmosphere slowed it down sufficiently to be pulled back to Earth. It burned up in the atmosphere after making 1,400 orbits around our planet.

The attention of the world for the Soviet success was overwhelming, enforced by the fact that on a clear night people could actually see Sputnik as a star-like point of light moving across the sky. Thanks to sunlight, it reflected back to the night side of the Earth (in fact, what people saw at the time was not the actual Sputnik satellite, but rather the much larger upper stage of the rocket orbiting close by).

Thinking that Russia was a backward country years behind in technology, America had been taken completely by surprise. Totally underestimating Soviet rocket power, some people even thought the comma in the published "83,6 kg" (184 pounds) mass of Sputnik 1 was wrongly placed and that the satellite actually weighed only 8.36 kilograms (18.4 pounds)!

However, the Soviets proved that they could launch even larger objects when only a month later they put Sputnik 2 into orbit. This satellite, weighing an incredible 508 kilograms (1,120 pounds), even carried a dog named Laika on board! Housed in a small, pressured container, Laika served as a test subject for obtaining data on the effects of microgravity on mammals.

As the satellite did not contain a return capsule, the unfortunate animal died seven days later when the oxygen supply ran out. Nevertheless, Laika's flight showed the Soviet's intention to launch people into space; it also showed that this would in principle be possible once a way was found to bring them back to Earth.

Nightmares of Soviet nuclear missile platforms in space and on the Moon made the USA scramble to get its own satellites into orbit. The problem was that the USA had only developed relatively small ballistic missiles for their relatively light nuclear bombs, and these were barely powerful enough to launch anything into orbit.

On December 6, 1957 the United States Navy's fragile Vanguard rocket with its puny Vanguard satellite (Russia's leader Khrushchev called it a "grapefruit") toppled over and exploded on its Cape Canaveral launch pad in front of the television cameras. America's pride was hurt deeply.

Fortunately, von Braun's team had not lost its vision of launching satellites while working on rockets for the US Army. Unofficially and secretly, the German experts had converted a ballistic missile into a satellite launcher. The USA could have had their satellite in orbit before Sputnik, but politics had assigned the space program to the Navy. Now, with the whole nation in a hurry to catch up with the Soviets, von Braun and his Army team were given the go-ahead to launch the Explorer 1 satellite with their Juno 1 rocket.

The launch on January 30, 1958, was a complete success and gave America back some of its confidence in its own technological capabilities. Instrumentation on board Explorer 1 even discovered large bands of charged particles from the Sun trapped by the Earth's magnetic field. These were later named the Van Allen radiation belts, after the American physicist James Van Allen who had designed the particle measurement equipment.

The next big step was to send a person into orbit. With the launch of Yuri Gagarin in 1961 the Soviets were first again, but the Russian cosmonauts were soon followed by NASA astronauts.

As launchers got bigger and satellite equipment technology advanced, Russia and America sent increasingly larger and heavier satellites into orbit. At first their purpose was only to measure the conditions in space, but soon they were also put to practical use such as relaying telephone and television signals and observing the Earth. This has in fact now become the commercially most important application of space.

The Soviet and US governments also soon recognized the military value of satellites, in particular for observing each other's military installations with large telescope cameras and for intercepting radio signals. As each side put ever larger numbers of nuclear missiles into operation and tightened security around them, satellites were the best, and often the only, way to monitor enemy rocket launches and atomic bomb

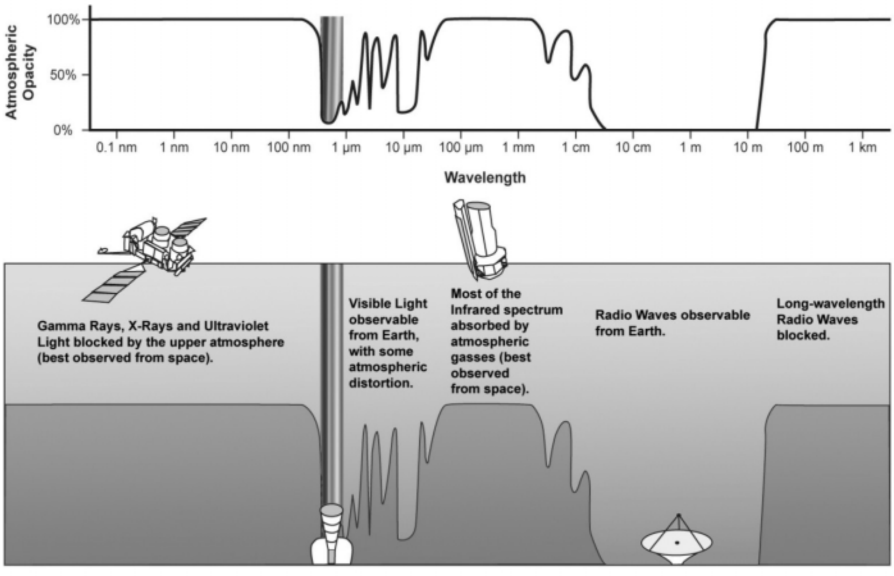

FIGURE 1.5 The atmosphere blocks much of the radiation from the Sun, planets, stars and other astronomical objects; only visible light, some infrared radiation and a large portion of radio waves get through. To see the rest of the spectrum, observations have to be done in space. [NASA]

tests. Increasingly powerful optical, radar and radio-receiving spy satellites are still being launched today, even though the Cold War is over. Many nations still want, and need, to know what their neighbors are building in their back yard.

Astronomy became another important occupation for satellites. High above the Earth's atmosphere – which filters out much of the spectrum of scientifically interesting radiation and disturbs light so that stars appear to twinkle – orbital observatories have an unprecedented clear view on the Universe.

Both the USA and the Soviet Union started to launch ever more sophisticated space observatories, detecting objects in the Universe that were completely unknown until then. The study of exotic objects such as black holes and gamma-ray bursts started entirely new branches of the ancient science of astronomy.

The pictures of the famous Hubble Space Telescope now frequently reach the front pages of the newspapers, but equally interesting data is sent to us by modern X-ray, gamma-ray and infrared observing satellites such as the XMM and Integral of ESA (European Space Agency), and NASA's Chandra Observatory and Spitzer Telescope. They have shown us a Universe that is even weirder than we ever imagined, with all kinds of peculiar star systems, mysterious black holes, gaseous nebulae where new stars are born, and old stars dying in gigantic explosions. However, even though they look at objects millions of light-years away, these satellites still remain relatively close to Earth.

To the Moon

From the point of velocity and energy, once you have the ability to reach Earth orbit you don't have to stretch too much to send a space probe further – to the Moon or to the other planets in the Solar System.

To stay in a low Earth orbit at an altitude of 200 kilometers (125 miles), a satellite needs to have a velocity of about 7.8 kilometers (4.8 miles) per second. To reach a much higher orbit at 36,000 kilometers (23,000 miles) requires a boost of only an extra few kilometers per second. This velocity increase is not too hard to achieve, as the difficult part of flying up through the atmosphere with all its problems of aerodynamic drag is already behind when you reach low Earth orbit. Moreover, as you get further from the Earth, the pull of its gravity weakens.

The 36,000-kilometer (23,000-mile) altitude orbit over the equator is a very popular one for television and communication satellites, because there they circle the Earth in 23 hours 56 minutes. (The circle around the Earth they have to cover is much larger than for a low Earth orbit satellite and, furthermore, their orbital velocity is lower; the net effect is that while it takes a low orbit satellite only 1.5 hours to go around once, it takes nearly 24 hours at 36,000 kilometers.) As the Earth also makes one complete rotation in 23 hours 6 minutes, it appears that the satellites are permanently hanging still over the same area, thereby acting as giant, stable antenna masts able to cover about a third of the planet per satellite. This 36,000-kilometer (23,000-mile) circular orbit over the equator is therefore called the "Geostationary Earth Orbit," or "GEO."

To completely escape Earth's gravity and go elsewhere in the Solar System, you'll need to achieve a velocity of 11.2 kilometers (7 miles) per second), starting from the Earth's surface. After achieving that, there is no need to keep the engine running as you would need to do with a vehicle on Earth; in space, once you achieve the right orbit, you cruise effortlessly along through the vacuum, unhindered by any braking friction. You are then in orbit around the Sun, only possibly disturbed by the gravity of other planets.

That is why as early as January 2, 1959, only one year and three months after the launch of Sputnik 1, Russia already managed to send a probe to the Moon. Luna 1 was meant to hit our rocky neighbor, but just missed it and went into orbit around the Sun instead. On September 15, its successor, Luna 2, hit its target spot-on. Crashing into an area called the "Sea of Rain," the metal ball showered the lunar surface with small emblems of the Soviet Union.

Only a month later Luna 3 zoomed behind the Moon, taking the first ever pictures of the part of the lunar surface that is always turned away from us. As the electro-optical systems we have nowadays did not exist at the time, Luna 3 carried a conventional camera with rolls of film. Following exposure, the film had to be developed on board, then scanned by a kind of television camera system. The gray-scales of the scanned picture were coded into radio signals and sent to Earth, where they could be translated back into an image.

Luna 3 showed that there were fewer "lunar seas" (the dark, relatively smooth areas on the Moon we can see with the naked eye) on the farside than on the nearside. As a bonus propaganda caper for the Soviet Union, Luna 3 also broadcast the Socialist International hymn from space. As with Sputnik 1, America was beaten once more.

An even worse propaganda disaster for the USA occurred on April 12, 1961, when Russia managed to launch the first human into orbit. Cosmonaut Yuri Gagarin made one circle around the Earth in 108 minutes and landed safely on the deserted steppe of Kazakhstan. At that time, NASA was still only planning its first sub-orbital, parabolic "hops" with its Mercury capsule and low-power Redstone rocket combination. On May 5, astronaut Alan Shepard became the first American in space, although not in orbit, using this system.

It took almost a year for America to catch up and equal Gagarin's flight; on February 20, 1962, John Glenn rode his Mercury capsule into orbit on top of a more powerful Atlas rocket, and completed three orbits. However, by that time Russian cosmonaut Gherman Titov had already circled the planet no less than 17 times during a flight lasting 25 hours 18 minutes.

Tired of seeing the USA being second in all major space achievements until then, President Kennedy, in his famous speech of May 25, 1961, proclaimed that America should aim at landing a man on the Moon before the end of the decade. Apart from major advances in manned spaceflight, the ensuing "Moon Race" resulted in whole armadas of unmanned lunar orbiters and landers.

The American Ranger spacecraft were first sent on kamikaze missions, aiming straight at points on the lunar surface while taking as many pictures as possible before impacting. Next came the soft-landing Surveyors, meant to determine what the surface of the Moon looked like. Some scientists argued that billions of years of meteorite impacts and unfiltered radiation had pulverized the lunar surface to a depth of possibly many meters; astronauts attempting to land would surely sink into thick layers of dust. Fortunately they were wrong. Digging with their small scoops and making small jumps on their landing gear to be able to observe the depth of their footprints, the Surveyors showed that the dust was only a few centimeters deep at most.

In the meantime, NASA's Lunar Orbiters accurately photographed the surface from lunar orbit to find the most suitable landing spots for the upcoming manned Apollo missions.

The Soviets had already confirmed their unmanned exploration prowess by being the first to softly land a probe on the surface with Luna 9, which made panoramic images of its surroundings. Their next spacecraft, Luna 10, became the first satellite of the Moon.

Nevertheless, the Soviet Union was falling behind in the crewed part of the space race, as unmanned prototypes of its giant N-1 moonrocket consistently blew up shortly after leaving the launch pad. Without a proper heavy launcher, their large lunar capsules and landers were grounded.

The giant Saturn V rocket developed by von Braun and his team was much more successful. After only two test flights, the second of which was only partly successful, the machine was deemed to be ready for operational duty. NASA wanted to use the Saturn V as soon as possible to launch a crewed flight around the Moon before the Russians. The gamble paid off: in 1968 the enormous rocket engines pushed the first Americans in an orbit around the Moon on Apollo 8.

The following year the crew of Apollo 11 thundered off the launch pad. Even as Neil Armstrong, Edwin Aldrin and Michael Collins were heading to the Moon to deliver on Kennedy's promise, Russia desperately sent the uncrewed Luna 15 to land. Its mission was to quickly scoop up some grams of surface samples and return them to Earth before the American astronauts arrived with their load of moonrocks. However, while Apollo 11's crew prepared to leave the Moon and head back home, Luna 15's mission ended with an inglorious crash on the lunar surface. The Soviets had failed to snatch some lunar dust before the American astronauts, leaving them unable to even slightly dim the blazing glory of Apollo 11.

Chapter 1

HUMANS VERSUS ROBOTS

During the "Moon Race" of the 1960s, astronauts and cosmonauts captured the hearts of the public much more than any robotic spacecraft ever could, and proved to be far more flexible in adapting mission operations and handling emergency situations.

Even in comparison with today's advanced robotic Marsrovers, the Apollo lunar astronauts were much more efficient in collecting surface samples and covered far more terrain in less time. The two NASA rovers that were landed on Mars in January 2004 have driven less than 10 kilometers (6 miles) in two years of operation. The record distance for one rover in a Mars day (24 hours 37 minutes) was 220 meters (720 feet). Obviously a person in a spacesuit on Mars could do much better than that.

An astronaut may need a minute to spot an interesting rock, walk to it, grab the stone and inspect it from all sides. For an unmanned rover the same process may take several days.

Moreover, a human may see that the soil under the rock that has just been picked up has a strange color and decide to take a sample of it, while an automatic rover would not detect such a thing unless it was specifically instructed to look for it. A robotic probe can basically only perform tasks it has been built to do before launch, while people are inventive and able to make creative use of what is at hand.

An astronaut may decide to use a spade to break a small piece of a rock from the wall of a canyon a few meters high. Unless a rover has been equipped with a hammer and a long arm, it would not be capable of doing the same.

For a robot, a rock is either an object to avoid or an object to push an instrument against. It is incapable of seeing the rock as a piece of a geological puzzle, or imaging flows of water shaping it into peculiar forms. Computers do not have imagination and creativity, and they are generally incapable of learning by themselves; they literally cannot think "out of the box."

Because they need to be severely modified to survive in space, the computer technology flown in modern space probes is some 10 to 15 years behind what is used in a typical office or at home. With respect to a modern PC, space robots are rather backward. Moreover, even the most modern terrestrial supercomputer is barely able to approach the intelligence of a frog. They may be great in mathematics and even beat us in chess, but reasoning and making decisions in novel situations is not their strong point.

However, the disadvantages of human spaceflight soon showed as well.

To begin with people require a certain minimum amount of living volume, food and oxygen that do not need to be included in robotic spacecraft. People want windows, want to sleep, want to interact with other human beings and have many more physical and psychological demands that are not an issue for robotic space exploration.

People are also continuously "on," whether they are needed or not. During the long flights to their destination, robots can simply shut down or be put in hibernation mode. People need food and oxygen even if there is nothing for them to do and are really not needed for that part of the mission.

Furthermore, people cannot be productive all the time. They need about a third of an Earth day to sleep, and also some time to wash, eat and relax. In principle, robots can work around the clock, day after day, week after week. They do not have holidays and they do not have unions.

Human crewmembers can forget their training and make mistakes. They need to practice just to keep the skills they started with and perhaps improve on them. Robots never forget anything and they do not need to train (although there are now some experiments with "learning" robots that program themselves through experience). Once rightly programmed, robot computer brains are able to refer to the right lines of software at any time. Improvements are possible by uploading updated software, with instant results.

Robots are entirely reproducible; if one fails, you can send an exact copy to take over and you can even skip all the development that was necessary for the first model. In contrast, each person is unique and can never be truly replaced. People cannot simply "download" the training of their colleagues; for each new person you have to start all over again. Robots are expendable; people are not.

Human crews also need to be brought back home after some time. This requires rockets and a lot of propellant, especially when they need to take off from another planet or moon; they require a heatshield for protection against the fierce heat caused by the collision with the atmosphere during re-entry, and parachutes for the final deceleration before landing. Space robots, generally, are simply left at their last destination.

Another disadvantage is that people can die; we have to limit risks for human missions to levels far lower than what would be acceptable for a robotic mission. This involves the duplication of critical equipment, extra design evaluations and tests, and very large ground support teams for monitoring all the systems all the time. For human missions, "failure is not an option," while for unmanned missions risk is just another parameter that can be traded for lower costs and less complex designs.

All this means that even the smallest crewed spacecraft is rather large, heavy, complex and thus expensive compared to an unmanned satellite with a similar amount of scientific equipment on board. To launch heavier and larger crewed spacecraft also requires larger and more expensive rockets.

A typical Space Shuttle mission may cost as much as $500 million, just to send eight astronauts and some experiments in a low orbit around the Earth for less than two weeks. For about the same amount of money you can develop and launch a medium sized robotic orbiter, and investigate the surface of another planet for a couple of years. For about $800 million, less than the price of two Space Shuttle missions, NASA was able to sent two landers, each with a golf cart sized rover, to Mars and operate them for a couple of months. These MER rovers actually lasted well beyond their design lifetime, and for a modest increase in budget they were operated for an even longer period.

The result of all this has been that manned spaceflight has become somewhat stuck in low Earth orbit after the Apollo Moon landings ended. Since the last few astronauts gathered their Moon samples and stepped into their lunar module to return home, we have been operating the Space Shuttle and Soyuz vehicles, as well as several space stations, but gone no higher than a couple of hundred kilometers above the atmosphere. For the last 30 years, flying any further has simply been deemed too difficult, too risky and too costly.

Robotic space probes, however, have long since visited all the eight major planets, flown through comet's tails, landed on asteroids, driven over the surface of Mars and explored the edges of the Solar System. It is a matter of fact that, until now, unmanned spacecraft have taught us far more about the Universe than human missions.

Nevertheless, there are good reasons for sending humans to Mars and beyond, such as the fact that people always want to visit places themselves and that crewed space flights are better than robotic missions for inspiring young people to study sciences. Looking at pictures from Mars taken by unmanned rovers is like having a look at the Grand Canyon through a webcam on the Internet; it is easy, relatively cheap and safe but does not offer the same experience as actually being there.

In the future, some of us may even choose to live on Mars: to increase the survival of our species in case of a global disaster on our mother planet; to expand our civilization; to gain access to the raw materials available on the planets and asteroids; to push our technological capabilities; or just to have the adventure.

In such cases, we should regard our robotic probes as scouts that tell us what lies ahead and can go where we yet fear to tread. They can test technologies that are currently too novel and too risky for integration in crewed spacecraft design.

ESA's Aurora program provides a good example. It is a roadmap that involves a series of increasingly complicated robotic Mars missions, starting with relatively simple demonstration landers and orbiters and evolving to a Mars Sample Return mission that brings Martian soil back to Earth. Each mission will result in more scientific knowledge about the red planet, but moreover will be part of a technology development plan leading to a human mission to Mars sometime around 2035.

Human and robotic space exploration should not be in competition, but rather be regarded as complementary elements of the same push of humanity into space.

FIGURE 1.6 A future astronaut finds her robotic predecessor on Mars. [ESA]

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