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Introduction to Space

The Science of Spaceflight

Thomas D. Damon

THOMAS L. O'KUMA



INTRODUCTION TO SPACE:

The Science of Spaceflight

by
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Pikes Peak Community College

with Foreword by
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To Jimmie . . . may he one day walk on Mars.

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Foreword

This time we've really gone and done it!

Regardless of the means—feet, horse, boat, covered wagon, car, or plane—we humans have always felt compelled to push outward, to take that next step, to surge into the space around us, to explode into every fresh frontier that offers growth and challenge. But this time, with the technology of the rocket, we've pierced gravity's cocoon, stepped outward and come face to face with our ultimate frontier, an insatiable frontier—the remainder of our universe.

True, so far we've made just a small, tentative step, maybe even just a shuffle. Yet, make no mistake about it, our first step into space is as important as those first steps we've made onto land, across mountains, over oceans, and into air. For we've just made that first step that must precede the strides and dashes to planets, the marathons between stars and that matter-of-fact galactic travel that someday will fill eons yet to come. No longer just observers of the heavens, we can now leave Earth and in only minutes become participants.

Intimidating? No doubt about it.

For after looking back at Earth from the Moon, we've responded by pulling back to regroup, to sort out the motives, methods, and timing of our next steps. Before beginning Tom Damon's clear, concise, and exciting presentation of the science of spaceflight, let's raise some key issues.

In every venture into a new frontier, we humans always benefit by proceeding in the same orderly manner: explore, develop, and use. Is space to be the same?

Yes. With manned and unmanned spacecraft we've explored the edge of our new frontier—low Earth orbit—and have now developed the most logical means to use it—space stations. The United States is planning to end its visitor status in space with its Space Station, as the Soviet Union has already done, and to reap the benefits of a permanent presence.

In the short term, Space Station provides a Space Research Center for science and technology, as well as for the development of new commercial products and industries. Occupancy in low Earth orbit provides researchers and entrepreneurs with an environment unequaled in any earthbound facility: near zero gravity, near perfect vacuum, and a vantage point from which to study Earth as well as the undistorted image of the universe.

In the long term, Space Station will be an assembly base, a stepping stone, a central gateway in an evolving infrastructure that enables our future expeditions to the Moon, Mars, and farther out. Behind our expeditions, colonies will spread permanent human presence throughout the Solar System. We can feel confident that with time, modest upgrades to our technology, and our permanent presence on space stations, this next outward surge will occur.

But let's be "prudent and economical" about this new frontier. Let's just develop it remotely from the ground or dart back and forth to it now and then and avoid the expense of a space hotel. We don't really have to stay on-board Space Station day after day, do we?

Yes! In earthbound research and industrial facilities, our human perception, logic, creativity, and dexterity are, without question, unique and indispensable. The value of this hands-on direction and support is undiminished by the relocation of our facilities into space. In truth, it is our continuous presence that permits us to most profitably operate, repair, maintain, and upgrade every facility and gives us the time and experience to evolve every concept, design, instrument, and operation to its fullest potential.

Sould we do anything more now than give space token attention?

Yes! The time for space is now. At any time in the past, only a few nations have had the strength and opportunity to shape

human history. Not so today. Many nations are strong and have access to space. Those nations who do shape our future and, indeed, those who remain free of military or economic domination will be those who understand that response to challenge enhances strength and that, from this time onward, strength in space is closely tied to strength on Earth. Our decision can be delayed, our future cannot.

But didn't we say that once we've left gravity's cocoon behind we'd be ready for "our entire universe"? That's a bit pretentious. What about the distances and the technology required to cover them? Sure, new frontiers have always shocked us with their remoteness, until technology advancements reduce this to inconvenience. But beyond our Solar System loom invincible expanses that take years to travel, even at light speed. Can interstellar distance also be overcome?

Yes! But here our confidence requires more than a direct extrapolation of today's technology and time; it also requires a faith inspired by the history of human achievement and an awareness of what shaped it—humanity's expanding intellect and incessant drive.

Lastly, let's go back to the basic premise: ". . . compelled to push outward, to take that next step, to surge into the space around us. . . ." All froth and no substance? Do we need to allow anything other than economics, politics, or other concrete intellectual considerations to enter our deliberations on space?

Once again—yes! In the exploration and development of previous frontiers, we humans have always been obsessed with lists of scientific objectives and practical benefits. Yet when we look back, we realize that our rationalizations, often even our imaginations, fell far short of predicting the frontier's true importance. We really accepted the challenge for more basic reasons.

So it is now with our presence in space. We may underestimate its importance to us and our descendants as well as our basic motivation. Data, information, pictures, or other nourishments of the mind, by themselves, ring hollow. They can only thicken our intellectual shell, only toughen our educated hide. Inside us, as always, the essential spark resides, alive and well with all the primordial drives and desires, itches and urges. In time, we must break the physical limits of our turf and go there, to see and feel the new territory up close, to take physical measure of it with our own person before it can become a true part of our world. To deny this drive is to deny our humanity.

Tom Damon provides for you, the reader, a lucid understanding of the science and technology of entering space, what we are finding, and some of our plans for the future. Enjoy it! It is an extraordinary treatment of an exciting subject, an outstanding introduction to mankind's greatest, open-ended adventure.

EDWARD G. GIBSON
ASTRONAUT, SKYLAB 4

Preface

Most of what the general public ''knows'' about space has been learned from watching *Star Trek, Star Wars,* and the evening news. Unfortunately, these sources of ''information'' often lead to misconceptions about the laws of nature with regard to what is scientifically and technically possible. For example, in a classroom discussion concerning the hazards of rocket debris and dead satellites that orbit the Earth, one student suggested that the Space Shuttle could simply fly around picking up the pieces of space junk, drawing them into the cargo bay with a tractor beam. The student seriously believed that the Star Trek tractor beam really exists.

Several colleges and universities around the country offer courses in space science and technology, heavy in math and oriented toward upper division or graduate students in science and engineering. Because of the high interest in space activities in Colorado Springs, we at Pikes Peak Community College felt the need for a general science, general education course primarily for liberal arts students who would like to know, among other things, how spacecraft get into orbit, why astronauts float, what satellites are doing up there, and if permanent colonies can be built in space.

We searched for an appropriate textbook, but none was available. Considerable effort has gone into space education curriculum development at the grade school and junior high level, but ours may be the only course of its kind for nonspecialist college students and adults. At first we assembled a collection of NASA pamphlets, government publications, and contractor reports, along with a few freshly written sections on basic science. As the course became more popular, the need for a more formal textbook became obvious. This book is the result.

I have tried to avoid writing a trivia reference book. This is, I hope, a book of scientific and technical substance, not just a collection of interesting facts. On the other hand, I have avoided any ''heavy'' math, but have included a number of MATHBOXES for those students and classes that can handle simple algebra. MATHBOXES are set apart from the rest of text and may be omitted without disrupting the continuity of the book.

The subjects included here are those that have been of greatest interest to my students. A brief history is summarized in Chapter 1. The basic science of propulsion, orbital mechanics, and the space environment is covered in Chapters 2, 3, and 4. These topics are fundamental to understanding the rest of the book. The next three chapters discuss unmanned spacecraft with particular emphasis on remote sensing. Chapters 8, 9, and 10 deal with man in space, particularly the Space Shuttle, our only manned space program. The final three chapters project into the future with solid facts and some speculation about humankind's ventures into the final frontier.

The thirteen chapters can be covered at the average rate of one per week during a 15 week semester, with time left for tests and other subjects. Some topics, particularly Chapters 2 and 3, may require more than a week; some others can be covered more quickly.

I must acknowledge the help of many people in this project. Particular thanks go to Dr. Mario Iona, Professor Emeritus of Physics at Denver University, and to Dr. William Bennington, PPCC biologist, for their review and critique of certain chapters. The numerous individuals and groups that provided background information, artwork, and photographs are mentioned by organization, if not personally, in the captions of the illustrations. This book could never have been completed without their assistance. Special thanks go to Mary Roberts, editor, whose words of encouragement always came when they were most needed, and to Robert Krieger for his willingness to venture into the unknown.

Chapter 1

History of Spaceflight

When the history of this time is written, which of the daily multitude of momentous events will characterize this era? When those future historians chronicle our most significant contribution, I believe they will say that this was the time when man took his first tentative steps out of the cradle, when he left Earth to seek greener pastures, to start anew, to try again. Space is the new and final frontier.

Americans have already impressed footprints in the dust of the Moon, put robots on the surface of Mars, launched spacecraft to fly past the other planets and moons in our Sun's family, and sent people commuting to work in orbit. The Soviet Union has also sent robot explorers to the far reaches of the solar system and has built a permanently manned space station where cosmonauts live in space for many long months. Only 66 years, less than an average lifetime, took us from the Wright brothers' first airplane flight in 1903 to a walk on the Moon in 1969.

The exploration and colonization of other worlds will be the most exciting undertaking of all time. It is inevitable, as inevitable as the discovery and colonization of America.

That is what spaceflight and this book are all about.

Rocketry: The Means of Getting There

The history of spaceflight begins with the history of rocketry; without rockets there would be no spaceflight.

The history of rocketry begins in China. The Chinese invented gunpowder which exploded violently when ignited in an enclosed space. If it were ignited in the open, however, it just burned rapidly. By putting the gunpowder into a chamber with one end open so the gases formed by the combustion could escape, the whole thing took off ''like a rocket'' instead of exploding. Indeed, it was a rocket. As early as 1212, Chinese armies fired rockets carrying flaming materials into Mongol encampments to start fires.

About the year 1500, according to legend, a Chinaman named Wan Hu made the first attempt to build a rocket-powered vehicle. He attached 47 rockets to some sort of cart and at a given signal 47 coolies lit the 47 rockets simultaneously. In the explosion that followed the entire vehicle disappeared in a cloud of smoke and Wan Hu was never seen in this world again.

Artillery rockets carrying bombs became highly developed in Europe by 1800. They had been used on a large scale against British troops in India, and in response, Sir William Congreve developed the modern stick-rocket in 1805. These new weapons of war were used by most world armies of that time. The British used them against Napoleon in Europe and against the newly organized United States of America. In 1814 during the 25 hour long British bombardment of Baltimore, Francis Scott Key, watching the action from a ship in Baltimore harbor, wrote a poem later to become our national anthem. ''And the rocket's red glare, . . . gave proof through the night that our flag was still there.''

Science fiction writers have long written stories about people traveling to far-off planets. Propulsion systems included flocks of birds, balloons, and just closing your eyes and wishing. A cannon was the choice of Jules Verne who gave us *From the Earth to the Moon and Around the Moon* in the mid-1800s.

Russian schoolteacher, Constantin Tsiolkovski, was a space dreamer. He first published some of his ideas in 1883 and in 1903 published a treatise ''Exploration of the Universe With Rocket Propelled Vehicles.'' By the time of his death in 1935 he had considered every aspect of spaceflight. Although he was considered mad by many during his lifetime, a monument to his memory now stands in Moscow.

Robert Goddard was the first to build successful liquid fueled rockets. The first flight was launched from a farm in Auburn, Massachusetts, on March 16, 1926. It lasted less than 3 seconds, covered a distance of 184 feet, reached an altitude of 41 feet, and a speed of 60 miles per hour. The rocket weighed less than 6 pounds.

Goddard was a quiet person and when he suggested that rockets would be the way to leave Earth and fly to the Moon and Mars, he met with such ridicule that he never sought public attention again. *The New York Times* said Goddard did not have the knowledge of a high school student. *The Times* printed a retraction 49 years later when Apollo 11

landed on the Moon. In 1930, with financial backing from Charles Lindbergh and from the Guggenheim Foundation, Goddard moved to New Mexico where he continued his experiments until 1941.

At Goddard's request, his papers describing interplanetary flight were held secret by the Smithsonian Institution until 1970, twenty-five years after his death. Four papers covered nearly all the basic science and engineering principles that were needed for flight to the planets. He held 214 patents for his many inventions. In 1960 the U.S. government agreed that the large military rocket engines used for intercontinental ballistic missiles infringed on Goddard's patents and paid his widow a million dollars in damages. She gave half of it to the Guggenheim Foundation.

In Europe, the story was different. Unlike Goddard's bad public experience in the United States, Germans were highly interested in rocketry and the prospect of space travel. Rockets were being built by German amateur rocket societies, especially Verein fur Raumschiffahrt (Society for Space Travel). Hermann Oberth in 1923 published a book, *The Rocket Into Interplanetary Space*. In Russia, Tsiolkovski's works were eagerly read and rocket societies were actively experimenting in the 1920s and 1930s. In England, the British Interplanetary Society did serious studies on all aspects of spaceflight. One of its early presidents was Arthur C. Clarke who later wrote *2001: A Space Odyssey*.

The technology needed to actually fly into space and return safely was the outgrowth of several technologies developed in the mid-twentieth century. The German military, limited by the World War I Treaty of Versailles, became interested in the rockets being built by amateur rocket societies. Military research with rocket-powered artillery led to the first ballistic missile in 1943 and culminated in the V-2 ''vengeance weapon'' that carried warheads from Peenemünde, along the Baltic coast of Germany, to England in the closing days of World War II. It was a fearful weapon because there was no sound, no forewarning before the warhead hit and exploded. The V-2 rocket boosted the one-ton warhead to 3,500 miles per hour and burned out. The warhead continued on a ballistic trajectory to a range of 200 miles and fell on its target. By contrast, there was some warning of an attack by airplanes and by the previous guided missiles whose engines continued running until they reached their targets. Fortunately, the V-2s came too late in the war to have any effect on the outcome.

While the Russian army was advancing across Germany at the end of the war, the German rocket scientists and engineers from Peenemünde sought out the American army and surrendered. Some were captured by the Russians and taken to the Soviet Union. The Americans confiscated some of the V-2 rockets and took them along with Wernher von Braun and co-workers to White Sands, New Mexico, where they continued their research and development work. When asked about the design of their V-2, the Germans said to ask Robert Goddard; it had been copied from a rocket Goddard flew in 1939.

By 1948 the German engineers in the United States had flown a two-stage rocket to an altitude of 244 miles. Von Braun dreamed of space travel. He knew that the work he and his colleagues were doing for the army could lead to rockets which could fly into orbit, but any time the subject came up it was vetoed. The army was not in the space business. Nonetheless, without the military rocket development programs, the advances in rocketry necessary for spaceflight would not have come about as they did.

While the U.S. Army was interested in artillery, the U.S. Air Force was working toward the development of very long range rocket-powered missiles. Both the United States and the Soviet Union saw rockets as a means to deliver nuclear weapons against an enemy. Successful development of intercontinental ballistic missiles (ICBMs) was dependent on three things: the perfection of reliable high powered rocket engines, guidance systems, and reentry vehicles. The problem of reentry into Earth's atmosphere was particularly important. Without protection from the searing heat of atmospheric friction, the nuclear weapons would melt and vaporize before reaching their targets.

At about the same time, jet aircraft were being perfected and experiments with rocket-powered aircraft were beginning (Figure 1.1). These craft were able to fly to the upper fringes of the atmosphere, where a human could not survive without special protective equipment, the forerunners of the modern space suit and life support equipment.

The center of aircraft research was at Edwards Air Force Base in the desert northeast of Los Angeles. There Chuck Yeager became the first man to fly faster than sound in the Bell X-1 rocket airplane. The X-1, shaped like a bullet, was powered by four liquid rockets and was carried to high altitude strapped under a B-29.

Further experiments with rocket airplanes led to the X-15 which flew 199 flights up to six times the speed of sound. Neil Armstrong, later to become the first man to walk on the Moon, was an X-15 test pilot.

Sputnik: Dawn of the Space Age

On October 4, 1957, the United States was shocked when the Soviet Union launched the first satellite into orbit. Sputnik I was a small sphere carrying a radio transmitter which ''beeped'' a signal for all the world to hear of the supremacy of Russian technology. A month later, on November 3, Sputnik II was orbited carrying the spacefaring dog, Laika.

In November 1957, President Eisenhower went on television and showed the first U.S. man-made object that survived the heat of reentry and had been recovered. The



Figure 1.1 A research rocket plane is dropped from a B-29 as a jet fighter chase plane follows.
Courtesy of NASA; artist William F. Phillips.

solution to that problem was one of the main keys to successful manned spaceflight as well as successful ballistic missiles. Eisenhower emphasized that although we were preparing to launch a satellite, our major effort focussed on development of ballistic missiles, not on space. In 1958 the president established a civilian space program and created the National Aeronautics and Space Administration (NASA) to oversee it.

American incentive was spurred and, after several spectacular failures of the Vanguard project, Explorer 1 was successfully launched on January 31, 1958. It was a 30 pound steel cylinder containing two detectors for micrometeoroids and one for high energy particle radiation. Their information was transmitted to the ground until May 23. Although small and simple, Explorer 1 made a major discovery, the Van Allen radiation belts around Earth.

Man in Space: A Russian

The Soviets also beat the Americans in putting a man into space. Yuri Gagarin orbited Earth in a Russian spacecraft on April 12, 1961. Soviet preeminence in these space spectaculars can be attributed to their very large rockets which had been built to carry heavy hydrogen bombs. In the United States a breakthrough in nuclear weapons technology by Dr. Edward Teller made possible the construction of relatively lightweight warheads. Thus, American ICBM booster rockets were not large enough to carry heavy loads into orbit.

Mercury: Man in a Can

The first U.S. manned spaceflight program was called Mercury. Flights of chimpanzees preceded manned flights; Ham was the first passenger in the Mercury capsule on January 31, 1961. The first astronauts were all military test pilots, some of them from the rocket aircraft research at Edwards AFB. Alan Shepard became the first American in space when he flew a 15 minute 22 second suborbital flight on May 5, 1961 (Figure 1.2). He reached an altitude of 116.5 miles and a maximum speed of 5,180 miles per hour. He landed in the Atlantic Ocean, 302 miles from his starting point at Cape Canaveral, Florida.

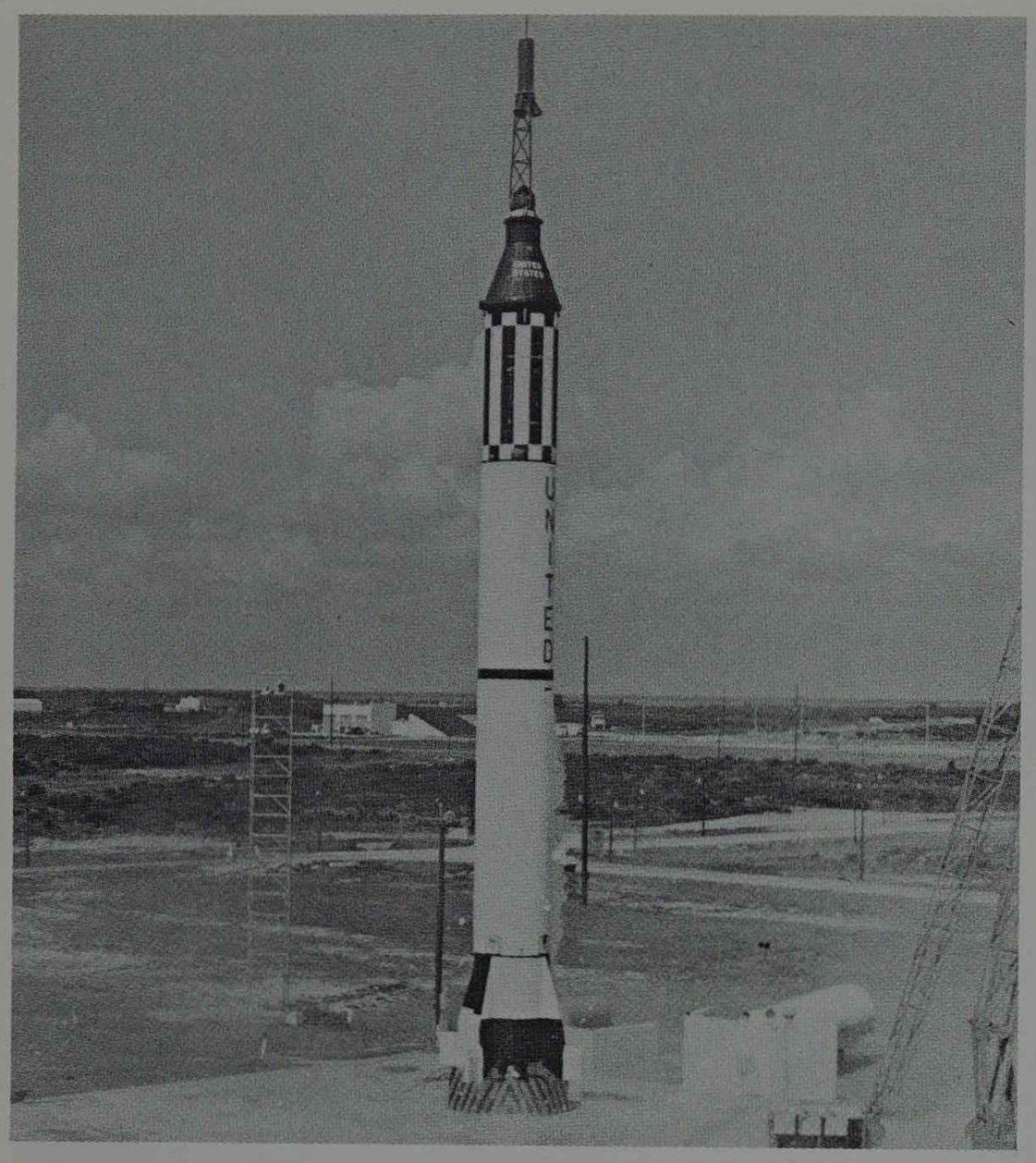


Figure 1.2 Mercury capsule, Freedom 7, sits atop the Redstone booster rocket to carry Alan Shepard on the first American flight into space. The towerlike structure at the top is equipped with small rockets which would pull the capsule away from the booster in case of an emergency. The rocket tower was jettisoned if everything was operating properly. *Courtesy of NASA.*

Twenty days later President Kennedy stated the national goal of placing a man on the Moon and returning him safely to Earth before the end of the decade. Nearly a year went by before the first American orbited Earth. John Glenn made a three orbit flight on February 20, 1962.

The Mercury capsule, shown in Figure 1.3, was crowded with only one person inside. The astronaut barely had room to turn his head and move his arms. It measured only 6 feet 10 inches long and 6 feet 2-1/2 inches in diameter at its base. An escape tower was attached to the top to pull the capsule off the booster rocket in case of emergency. It was jettisoned if it was not needed. Two different rockets carried the Mercury capsule: Redstone, a modified Army missile, and Atlas, an Air Force ballistic missile.

A retro-rocket motor slowed the vehicle to take it out of orbit and return it to Earth. Attached to the blunt end of the capsule was a heat shield which absorbed the 3,000 °F heat generated by atmospheric friction during reentry. The capsule landed in the ocean, its descent slowed by parachutes, and was recovered by ships waiting at the site. Each capsule was used only once. Six successful manned flights were made; the final one flew 22 orbits in more than 34 hours on May 15 and 16, 1963.

Gemini: Twins in Orbit

Named for the constellation of stars which includes the twins Castor and Pollux, the Gemini spacecraft, Figure 1.4, was a two man capsule with a volume about the size of the front part of a compact car. It measured 19 feet long and 10 feet in diameter and had the same basic design as the Mercury capsule. Equipment and expendables that were not needed for the return to Earth were put outside and left behind, providing more room in the cabin. As with Mercury, the capsule was designed for one-time use and landed at sea. Although development of a capability for landing the spacecraft on land was begun in the United States, it was never completed. The Soviets, on the other hand, recovered their manned spacecraft on land right from the beginning.

Titan, a modified Air Force ballistic missile, carried Gemini spacecraft to orbit. Ten flights were made in 1965 and 1966. In those cramped quarters, one of the flights spent just a few hours short of two weeks in orbit, a world record at that time. Gemini astronauts learned how to maneuver, change orbit, and rendezvous and dock with other spacecraft. Gemini VI launched on December 15, 1965, and accomplished the first space rendezvous with Gemini VII which had been launched on December 4, seen in Figure 1.5. They flew together for over five hours at distances of 1 foot to 295 feet.

The first space walk was on June 5, 1965, when Edward White opened the hatch and floated into space, attached to Gemini IV by a 23 foot tether line.

Apollo: To the Moon

Apollo was the project that took men to the Moon and back. To meet President Kennedy's challenge, dozens of technological breakthroughs had to be made. The spacecraft carried three men in a space about the size of the inside of a small van. It contained a shirtsleeve environment, so the astronauts could take off their space suits and move around a bit. They also had hot water aboard to prepare meals.

The huge Saturn V rocket which launched the Apollo spacecraft on its trajectory to the Moon is shown in Figure 1.6 with the previous manned space vehicles drawn to the same scale. Saturn V stood 363 feet high and weighed 6.5 million pounds. It burned liquid oxygen and kerosene, 15 tons per second at liftoff. The second and third stages used liquid hydrogen and liquid oxygen propellants.

The Apollo spacecraft itself is shown in Figure 1.7 compared to Gemini. The cone-shaped command module in the center carried the astronauts. It was 10 feet 7 inches high and 12 feet 10 inches in diameter. The cylindrical service module at the top carried electrical equipment, oxygen tanks, and the rocket engine for leaving lunar orbit to return to Earth. The spider-like 23 foot tall lunar module (LM) at the bottom was the vehicle that descended from lunar orbit

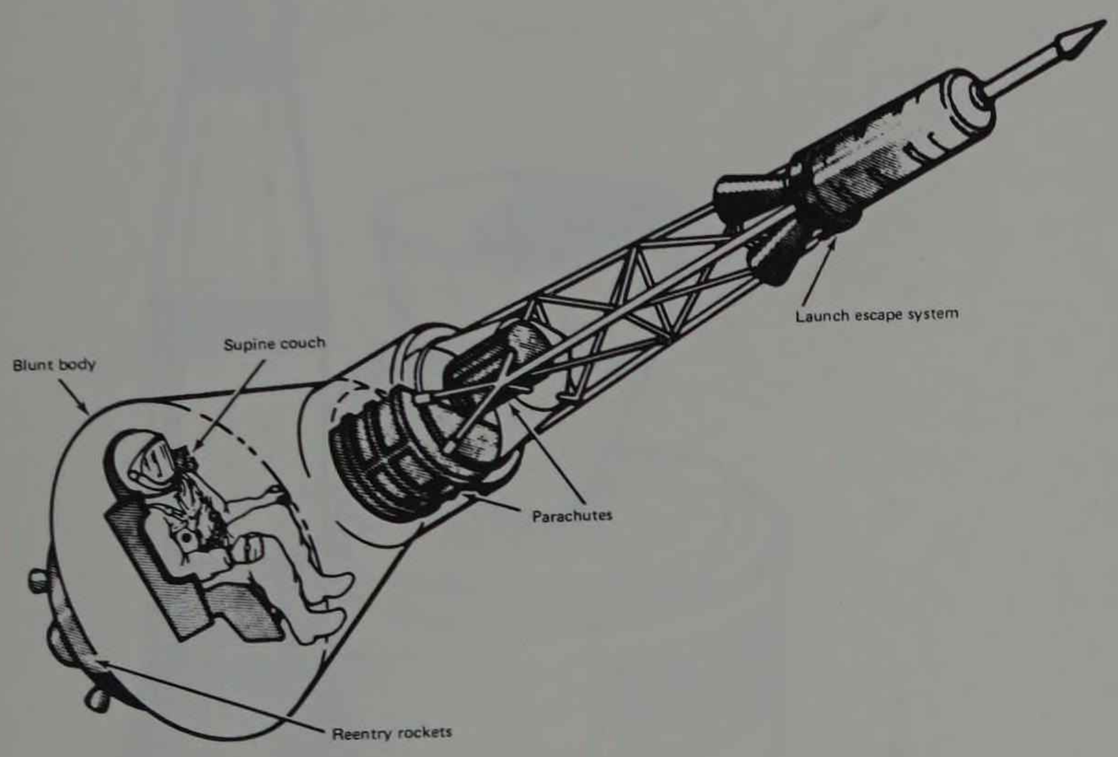


Figure 1.3 Diagram of Mercury capsule. *Courtesy of NASA.*



Figure 1.5 The Gemini VII spacecraft as seen through the window of Gemini VI during the first space rendezvous. *Courtesy of NASA.*

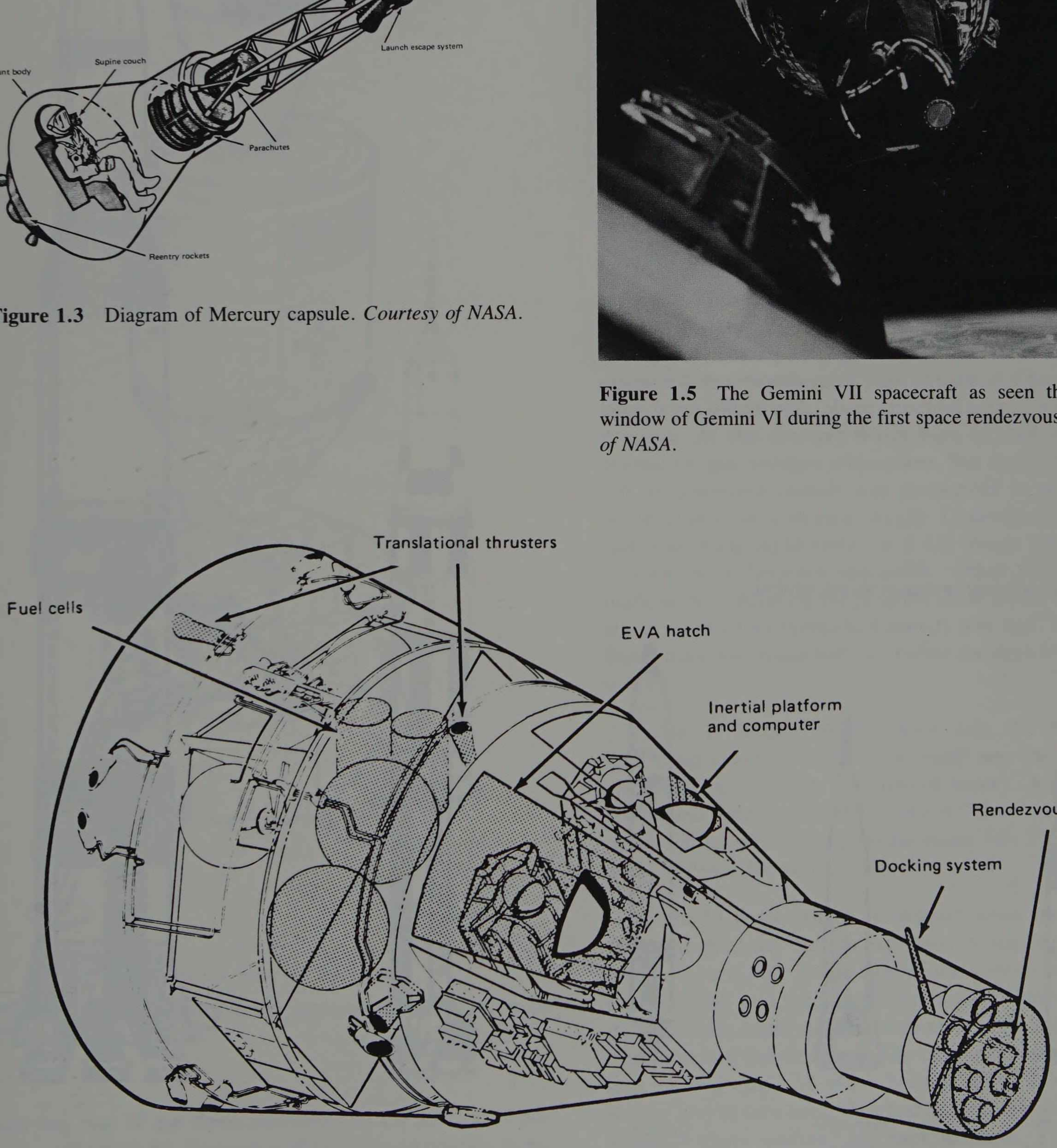
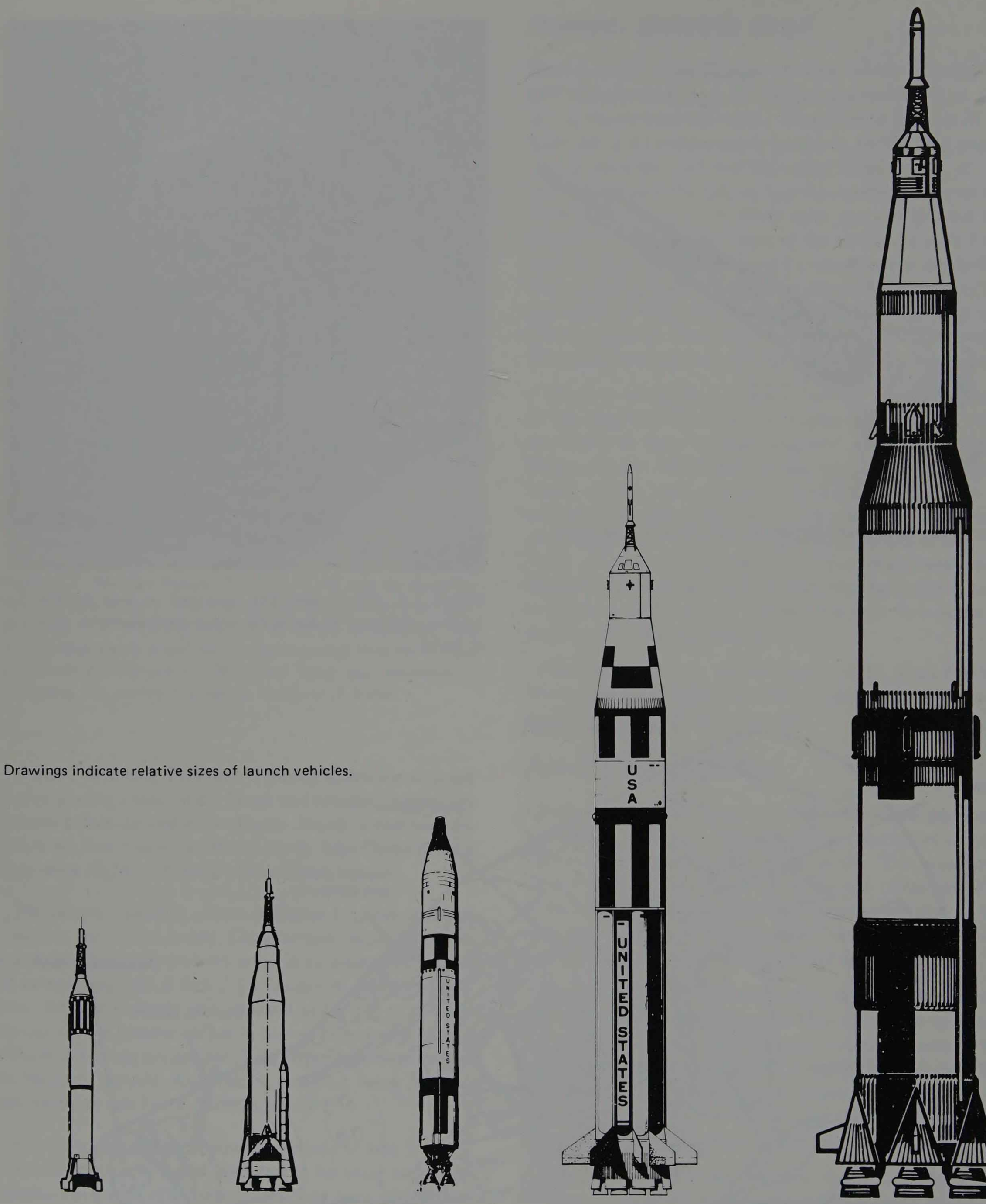


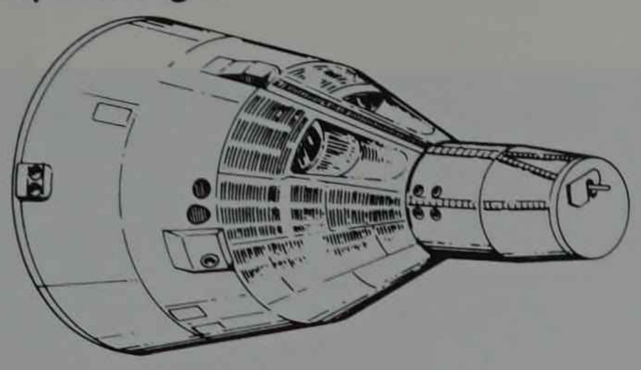
Figure 1.4 The Gemini spacecraft had a crew of two. Fuel cells generated electricity to power the craft. Astronauts could exit the vehicle on a "space walk" through the EVA hatch. Thrusters allowed the spacecraft to maneuver, rendezvous, and dock with other spacecraft. *Courtesy of NASA.*

Drawings indicate relative sizes of launch vehicles.

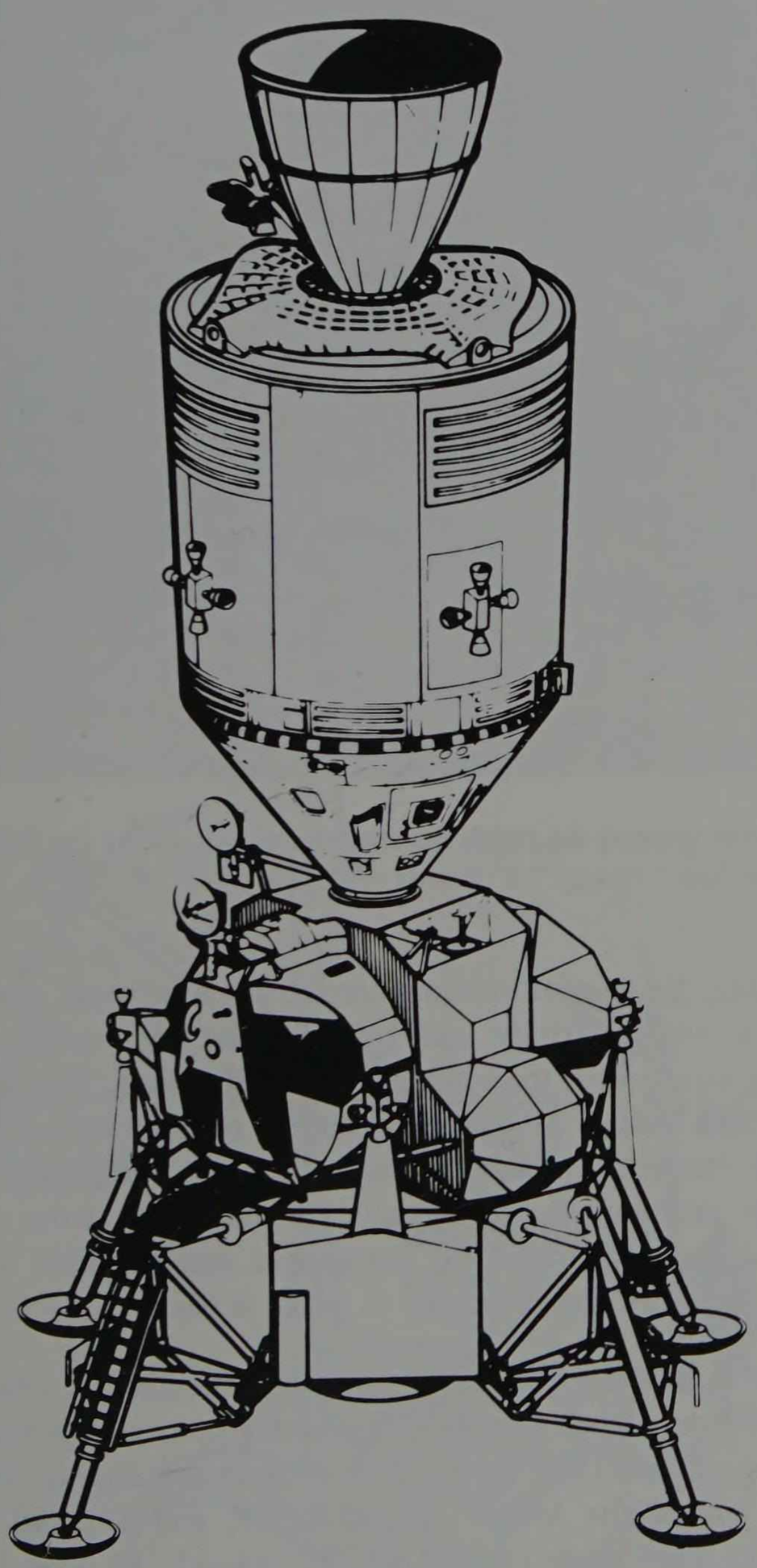


Mercury-Redstone | Mercury-Atlas | Gemini-Titan | Saturn IB | Saturn V

Figure 1.6. Comparison of manned launch vehicles. *Courtesy of NASA.*



Gemini



Apollo

Drawings indicate relative sizes of spacecraft.

Figure 1.7 Apollo and Gemini spacecraft drawn to the same scale. *Courtesy of NASA.*

carrying two of the three astronauts to the surface of the Moon (Figure 1.8). Because it didn't have to operate in the atmosphere (the Moon has none) it was not necessary to streamline it. It was actually the first true manned space vehicle. When the activity on the surface was finished, the lunar module rejoined the command and service modules, still in lunar orbit, for the return trip home. Only the command module with its three man crew landed back on Earth. As with Gemini and Mercury, Apollo landed in the ocean (Figure 1.9). Nothing, not even the command module, was reused.

An electric powered car, the lunar rover shown in Figures 1.10 and 1.11, was carried to the Moon on the last three flights so the astronauts had transportation while on the surface. For safety, landings had to be made on smooth, level terrain, often geologically uninteresting. The rover, with its range of up to 6 miles, allowed exploration of hills, cliffs, and craters to take photos and bring back samples. Each of the four wheels had its own electric motor so that if one or two failed the rover could still operate. Power was supplied by silver-zinc batteries. The astronauts drove a total of almost 60 miles on the three flights. The rovers were left behind along with just about everything else that was taken to the surface.

Disaster struck during the early days of the Apollo program. Three astronauts lost their lives in a launch pad fire on January 27, 1967, during preliminary checkout of the Apollo. During an actual flight, the command module contained an atmosphere of pure oxygen at a pressure of 5 pounds per square inch, about one-third normal atmospheric pressure. At that pressure things burn as they would in a normal oxygen-nitrogen atmosphere. But during the checkout the command module was pressurized to near normal sea level pressure with pure oxygen. Under these conditions materials burn explosively. A 2-1/2 month investigation resulted in a fireproof spacecraft. Other changes were implemented, delaying the program about a year and a half, but the goal set by President Kennedy was met. The United States made two lunar landings before the decade of the 60s was up.

Apollo 11 landed on the Moon July 20, 1969. Neil Armstrong's words "That's one small step for man. One giant leap for mankind." are part of history. A plaque was left behind, engraved with the words "Here men from the planet Earth first set foot upon the moon July 1969 AD. We came in peace for all mankind."

Apollo 13 nearly ended in disaster when on April 13, 1970, the third day out, an explosion in one of the oxygen bottles blew a hole in the side of the service module and started a leak in a second oxygen bottle. Without oxygen, the fuel cells could not generate electricity and the command module was disabled. The three-man crew squeezed into the two-man LM which became their lifeboat. There was no way to turn back; they had to continue on around the Moon, without landing, and back to Earth. The LM was designed to support two men for two days but it would take about six days to get back to Earth. The temperature in the LM dropped to 38°. Most of the food was dehydrated and required hot water to rehydrate; but no hot water was

Figure 1.8 An Apollo landing site. The lunar module is at the center and a lunar rover at the right. Because there is no air on the Moon, the flag staff was fitted with a horizontal bar to keep the flag "flying." *Courtesy of NASA.*



Figure 1.9 Three parachutes gently lower an Apollo spacecraft into the sea. *Courtesy of NASA.*

available. By careful minimal consumption of food, water, oxygen, and electricity, and by using the LM rockets for course adjustment, they managed to limp home. The three men lost a total of 31.5 pounds, but did not lose their lives. In that respect, the mission was a success. In spite of a serious problem the astronauts, with advice from the ground, used their limited equipment and supplies with great ingenuity and creativity to make it back.

Apollo was not only an exciting and spectacular adventure, it was also a scientific, technological, and political success. From 1969 to 1972 three manned flights were made around the Moon (Apollo 8, 10, and 13) and six landings were made (Apollo 11, 12, 14, 15, 16, and 17). The locations are shown in Figure 1.12. Ten landings were originally planned but three were deleted because of NASA budget cuts. Twelve American astronauts left footprints inthe lunar soil during 166 man-hours of surface exploration. About 850 pounds of soil and rocks were brought to Earth and nearly 100 experiments were carried out in orbit and on the surface.

As a result of the Apollo lunar exploration scientists have a pretty good understanding of the history of the Moon from its formation at the same time Earth formed, through a period of severe impacts by asteroids and meteoroids, to the

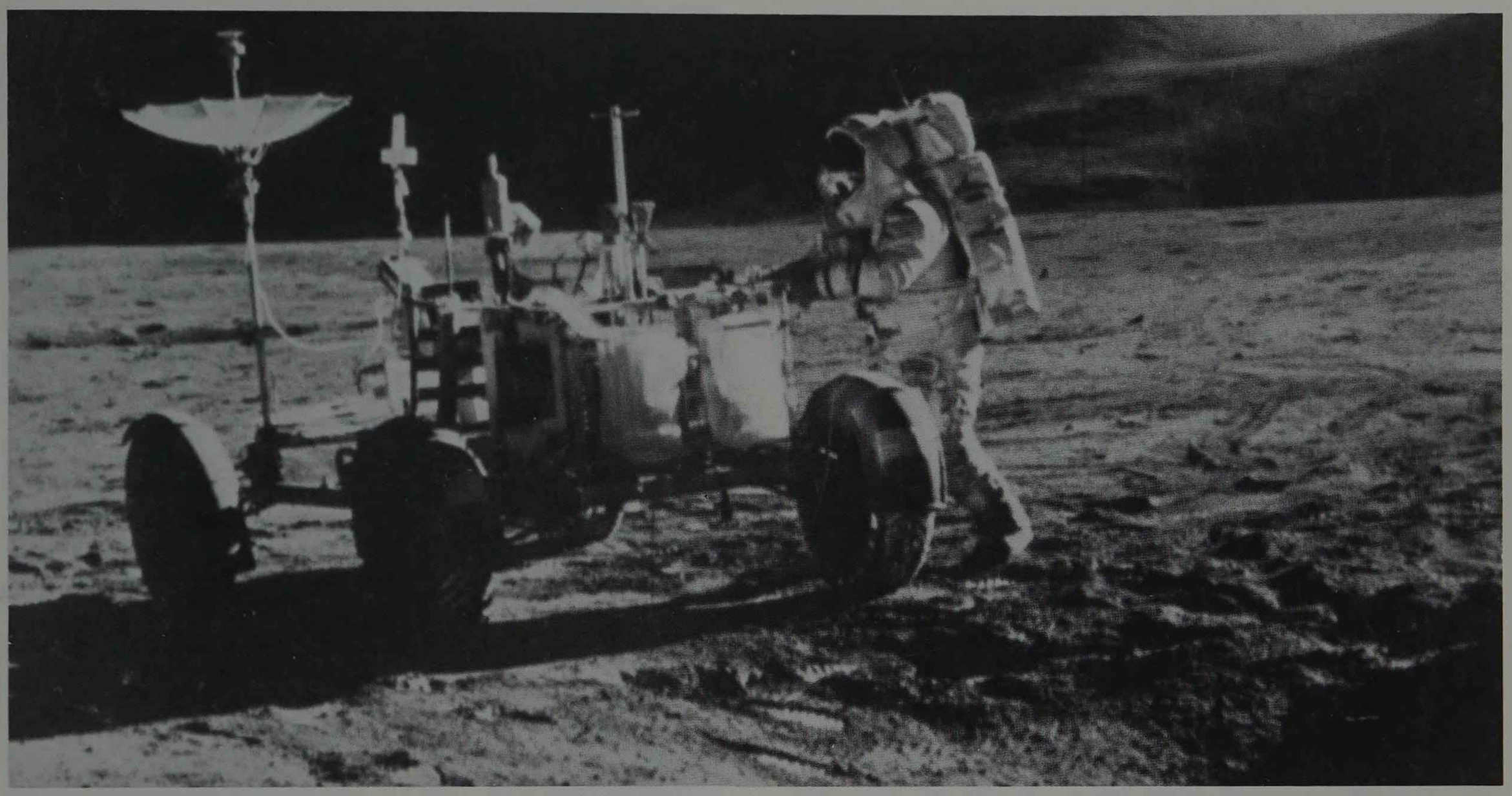


Figure 1.10 An astronaut and his rover on the Moon. *Courtesy of NASA.*

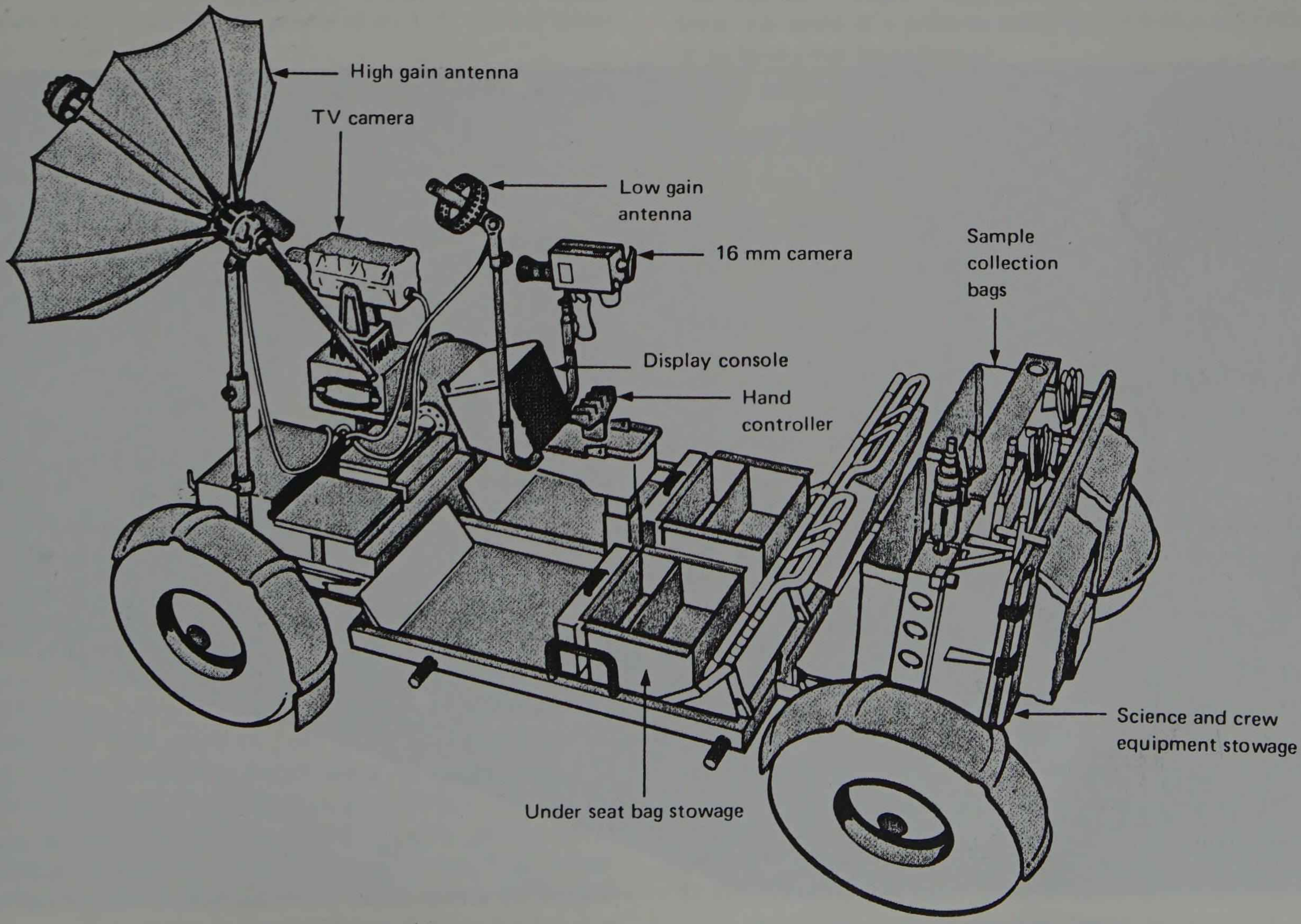


Figure 1.11 Diagram of the lunar rover. *Courtesy of NASA.*

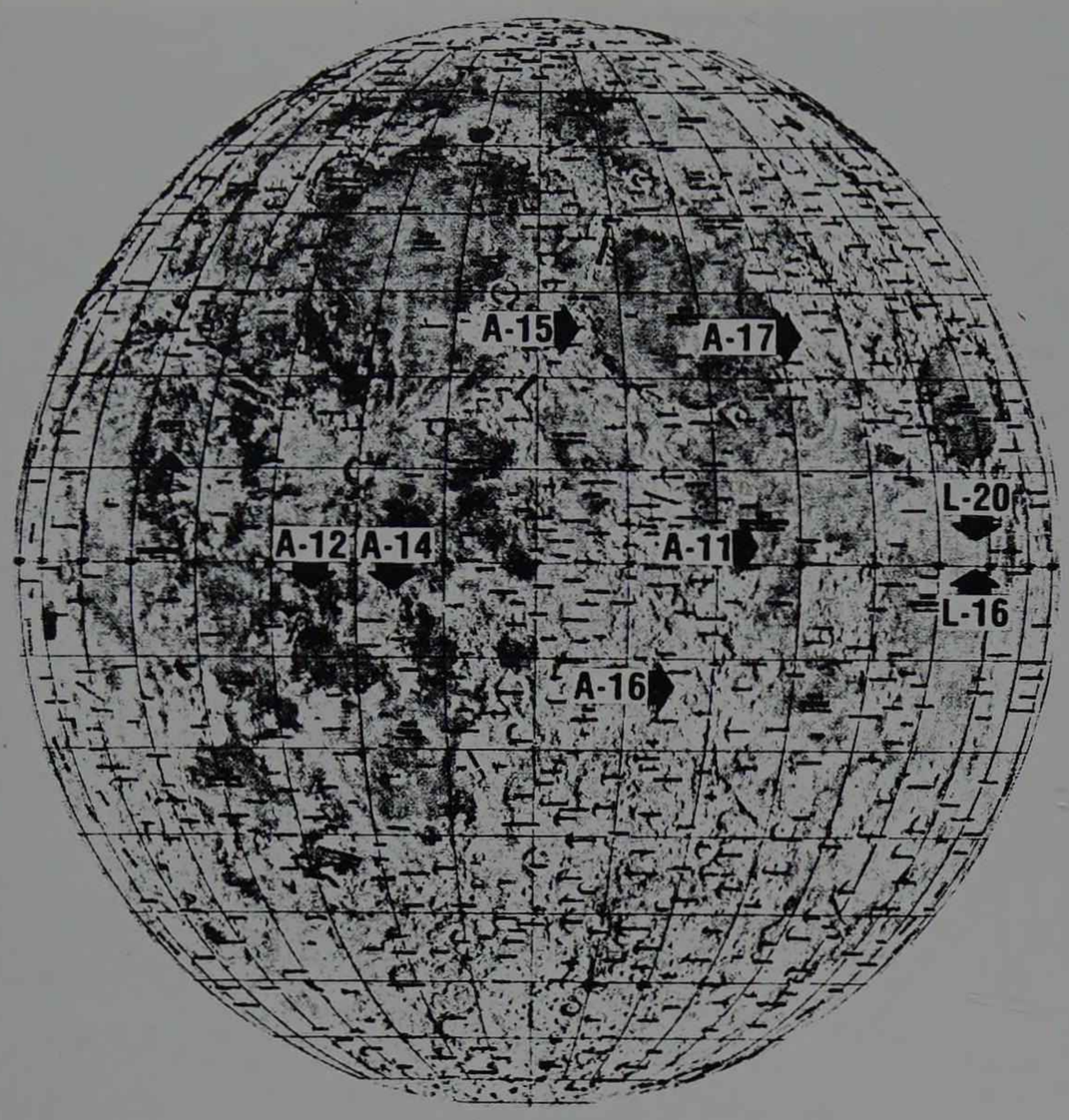


Figure 1.12 The six Apollo landing sites. The Soviet Union put two unmanned spacecraft on the moon, Luna 16 and 20, which picked up samples of lunar soil and returned to Earth. *Courtesy of NASA.*

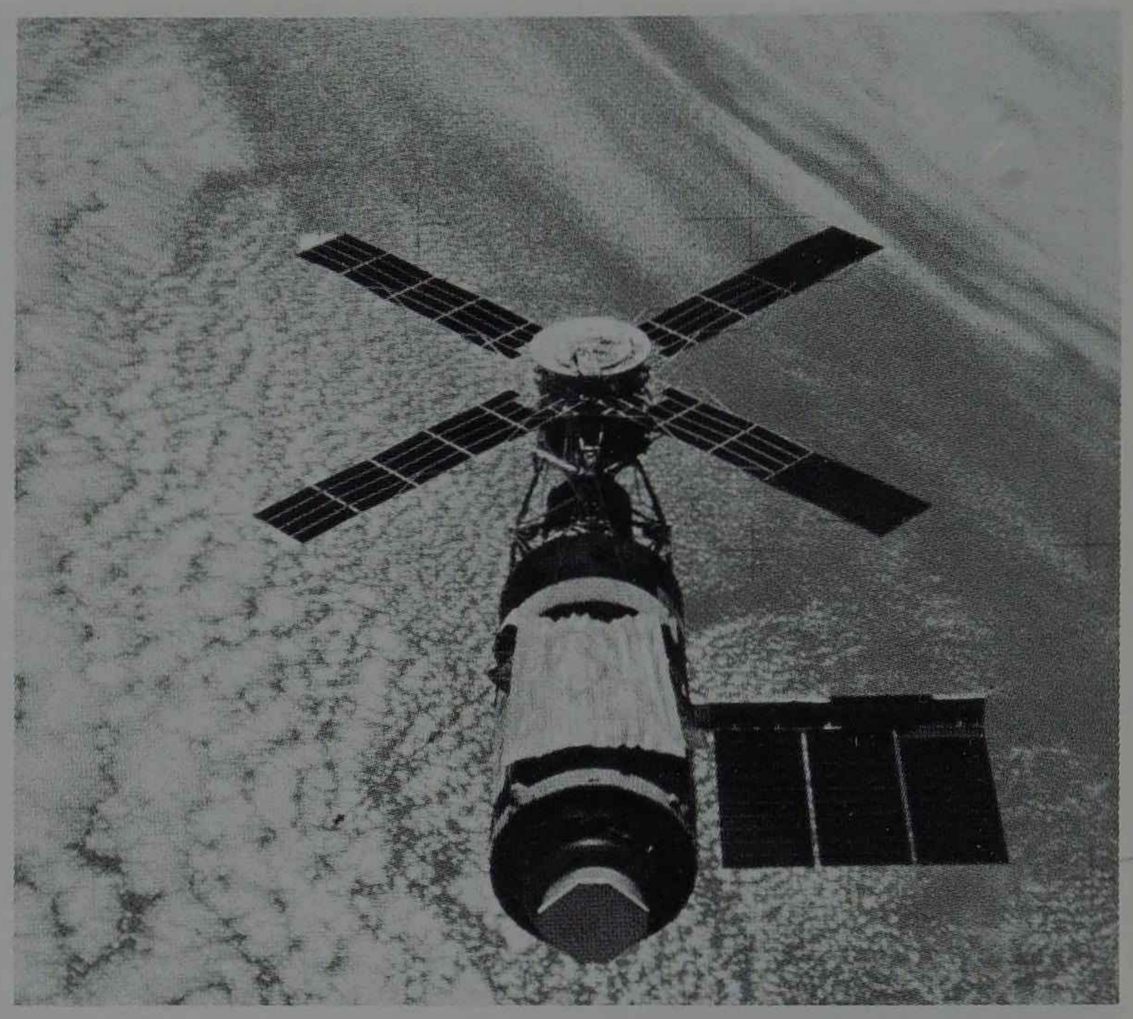


Figure 1.13 The Skylab space station, photographed by the crew as they departed for Earth in their Apollo capsule. Skylab was damaged during launch and had to be repaired on orbit by the astronauts. Solar cells cover the X-shaped structure and the panels to the lower right; the left solar cell array is missing. A sunshield was improvised over the top of the workshop where the micrometeoroid shield was torn off. *Courtesy of NASA.*

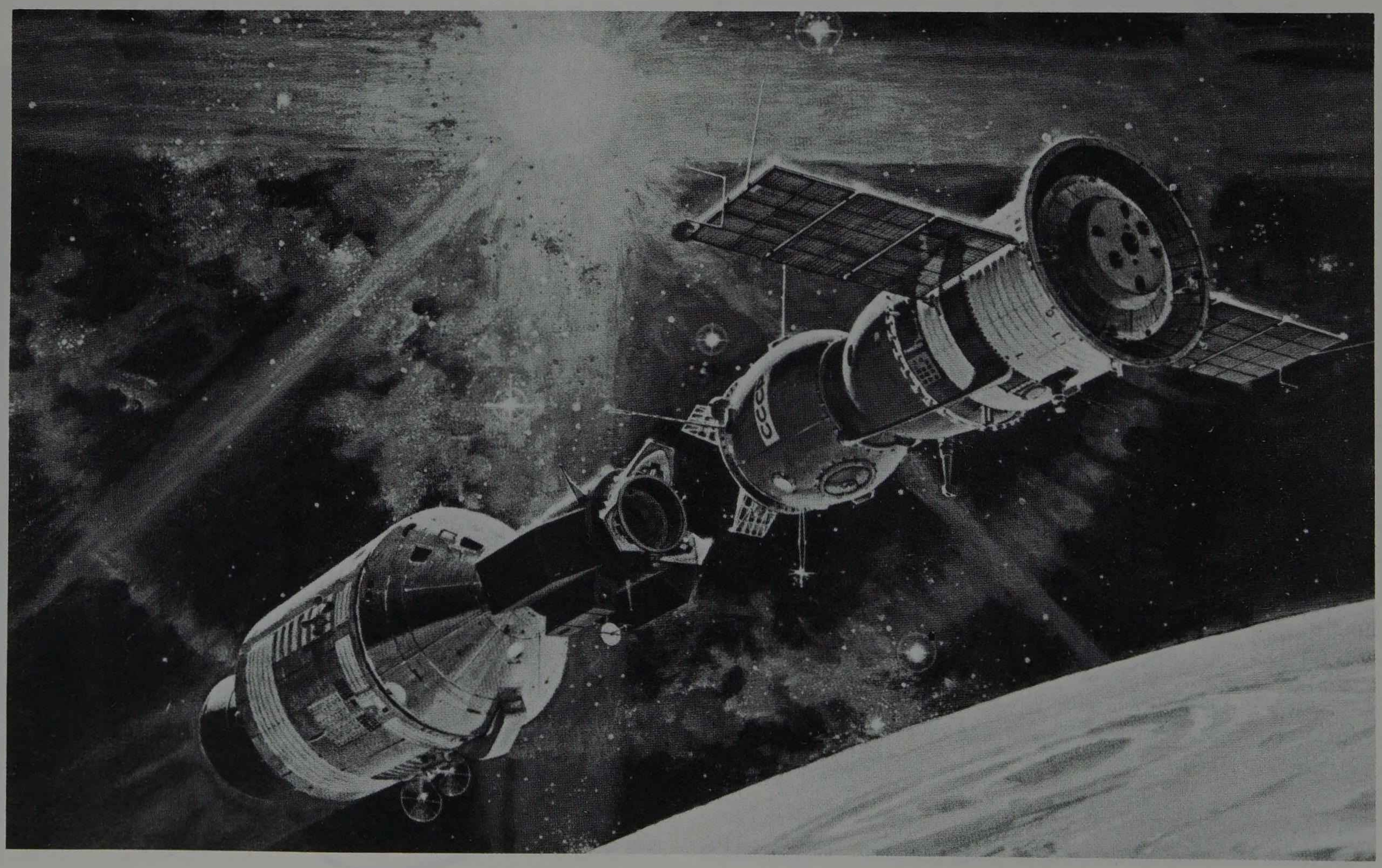


Figure 1.14 Artist's concept of the hookup of Apollo command and service modules (left) with Soviet Soyuz spacecraft on the right. *Courtesy of NASA.*

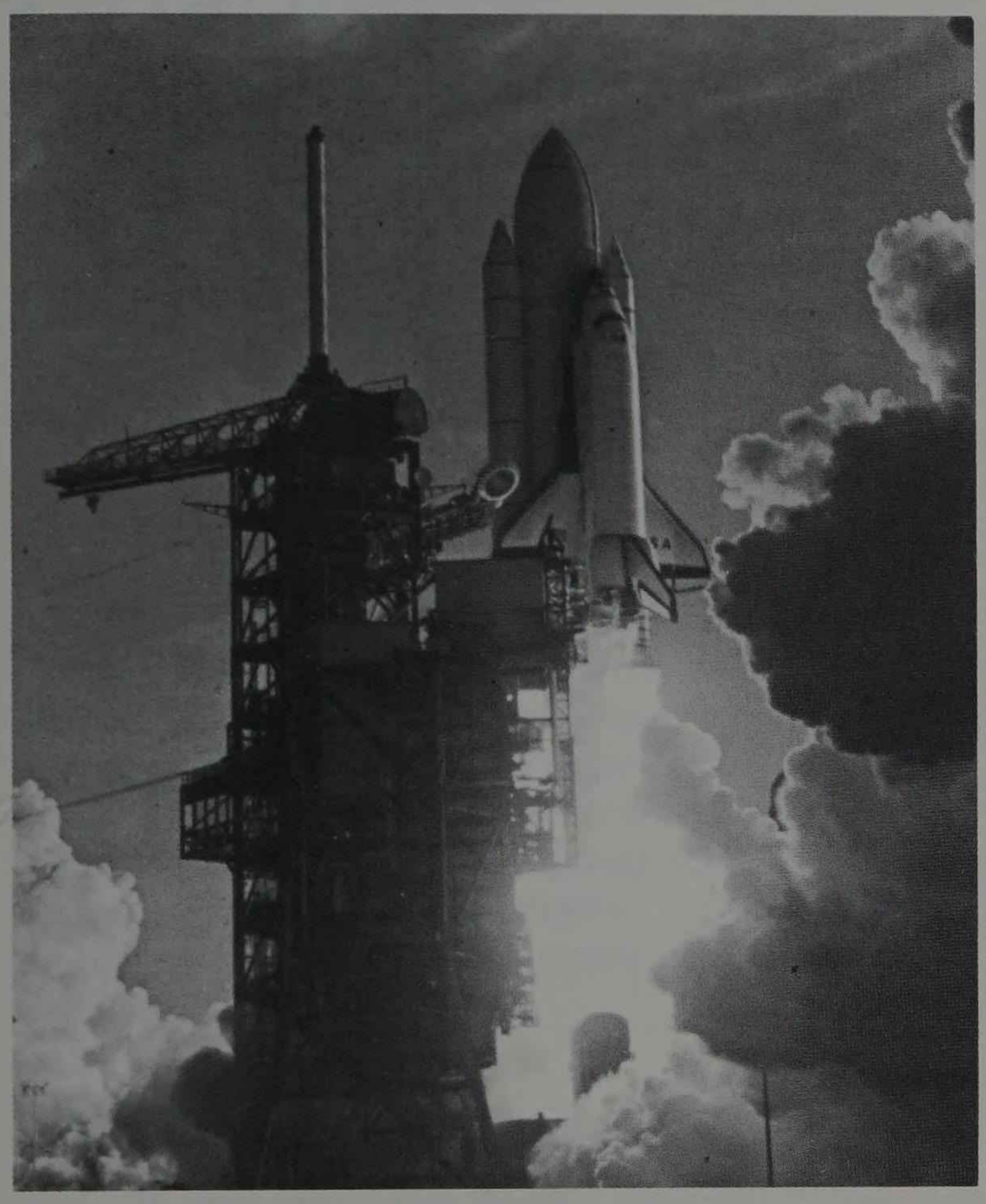


Figure 1.15 Space Shuttle, newest of the U.S. manned spacecraft. *Courtesy of NASA.*

present quiet. They also know the composition of lunar rock and soil so when a colony is established on Moon we know what kinds of raw materials are available for construction and mining. This is discussed in Chapter 12.

Equally important were the knowledge and technology gained from the research and development needed to make Apollo succeed: building huge reliable rockets, developing life support systems, refining orbital mechanics, miniaturizing electronic devices, and advancing computer technology. This kept America preeminent in space for the following decade.

Skylab: Our First Space Station

Built from the empty third stage of a Saturn V rocket, the 100 ton Skylab was about the size of a small three bedroom house. (See Figure 1.13.) It was launched on May 14, 1973, into a 270 mile orbit. In 1973 and 1974 Skylab was manned by three crews of three men. Crews and supplies were ferried to the space station using Apollo vehicles. The crew would rendezvous and dock with Skylab and enter the space station. The Apollo command module would remain attached to the service module until it was time to go home. The last Skylab mission still holds the record for the longest American spaceflight: 84 days. The crew included Edward Gibson, William Pogue, and Gerald Carr.

Much research in solar physics, space physics, earth science, and human biology was done. It gave the United States its best experience in long duration spaceflight, especially the effects of weightlessness on the human body. Medical research was given top priority. Many interesting problems arose: How do you weigh a weightless man? Answer: the period of oscillation of a seat attached to springs is proportional to the man's weight on Earth. How do you eat, sleep and take a shower? And the most asked question, ''How do you go to the bathroom in space?'' is the title of a fascinating book by William Pogue. These questions will be discussed in later chapters.

Apollo-Soyuz

The Apollo program ended in July 1975 with history's first international spaceflight when an Apollo spacecraft linked up with a Russian two-man Soyuz spacecraft. An artist's concept of the hookup is shown in Figure 1.14. For nearly two days the astronauts and cosmonauts moved between the two vehicles, did joint experiments, and displayed good fellowship. The Apollo capsule was equipped with a docking device which allowed it to connect to the Soyuz. Although 28 scientific experiments were conducted, this event was more of a political achievement than a scientific or technological breakthrough.

Space Shuttle

The Space Shuttle, Figure 1.15, is a reusable spacecraft that takes off like a rocket, flies in orbit like a spaceship, and returns to Earth like an airplane. The emphasis is on reuse in order to reduce the cost of transportation into orbit. The Shuttle is the mainstay of the U.S. manned space program through the 1980s and 1990s. We will discuss it in detail in following chapters.

DISCUSSION QUESTIONS

1. What, do you suppose, were some of the technical problems with the Apollo-Soyuz rendezvous in space?
2. Why couldn't an automobile gasoline engine have been used on the lunar rover?
3. What would have been some of the considerations in choosing the landing sites on the Moon?
4. Why did the returning manned spacecraft land in the oceans?
5. Do you think that exploration of space should continue, or should the government concentrate its resources on other more earthly problems?

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Cortright, Edgar M., ed. *Apollo Expeditions to the Moon.* NASA SP-350, Government Printing Office, 1975.

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Chapter 2

Propulsion

How does a rocket ship get off the ground? You have probably heard the terms *thrust, force,* and *acceleration.* These words have precise physical meaning but are often misunderstood and misused. To understand them, you need to understand a little physics. In this matter, we will follow Albert Einstein's advice, ''Everything should be made as simple as possible, but no simpler.'' That is, we will explain the laws of motion as clearly as possible without oversimplification.

Mass and Weight

First, we must distinguish between mass and weight. The *mass* of an object is related to the quantity of matter that goes to make up the object, the number of protons, electrons, and neutrons, plus the energy that binds them together. Its mass is the same wherever it is in the universe. You have seen pictures of astronauts floating around the cabin of their spacecraft. They are ''weightless''; they are not ''massless.'' They still have the same mass, the same number of particles of matter, that they had when they were on Earth.

The *weight* of an object, on the other hand, depends on gravity. Weight is the force that the object exerts downward as a result of the gravitational attraction between its mass and the Earth's mass. The farther you are from the center of the Earth, the less is the force of gravity. At the top of Pikes Peak you weigh less than you do at Houston. The change is very small, however: If you weigh 150 pounds at Houston, you would weigh 149.8 pounds on Pikes Peak. At 100 miles altitude, the decrease in weight is about 5 percent. MATH-BOX 2.1 shows how these calculations are made.

If gravity were zero, then weight would be zero. But gravitation is a natural and universal force of attraction between any two masses; it cannot be turned off. It does decrease with distance, but even in deep space, far from Earth, there is a force present due to the gravity of the planets, the Sun, and the stars.

A scale is a device which measures the force due to gravity. When you stand on a scale it tells your weight, that is, how much force you are exerting toward the center of the Earth. If it reads 150 pounds, then you are pushing on the Earth (through the scale) with a force of 150 pounds. You can feel that force on your posterior as you sit in your chair. If you and your chair were on the Moon your weight force would be only about one-sixth of what is on the earth, that is 25 pounds instead of 150 pounds. The gravitational force between you and the Moon is smaller because the Moon is so much smaller and less massive than the Earth. So weight, unlike mass, depends on where in the universe you are.

Incidentally, the type of scale you use can confuse the issue. Figure 2.1 shows that the ball weighs 4 ounces. On this type of scale, weights are put into the left pan until the scale balances. The two downward forces must then be the same; that is, the ball must weigh the same as the weights. Question: Where was the picture taken? It could have been taken on Earth, but when we take our experiment to the Moon, the picture would be the same. Both objects weigh only one-sixth of their Earth weight, but both still have the

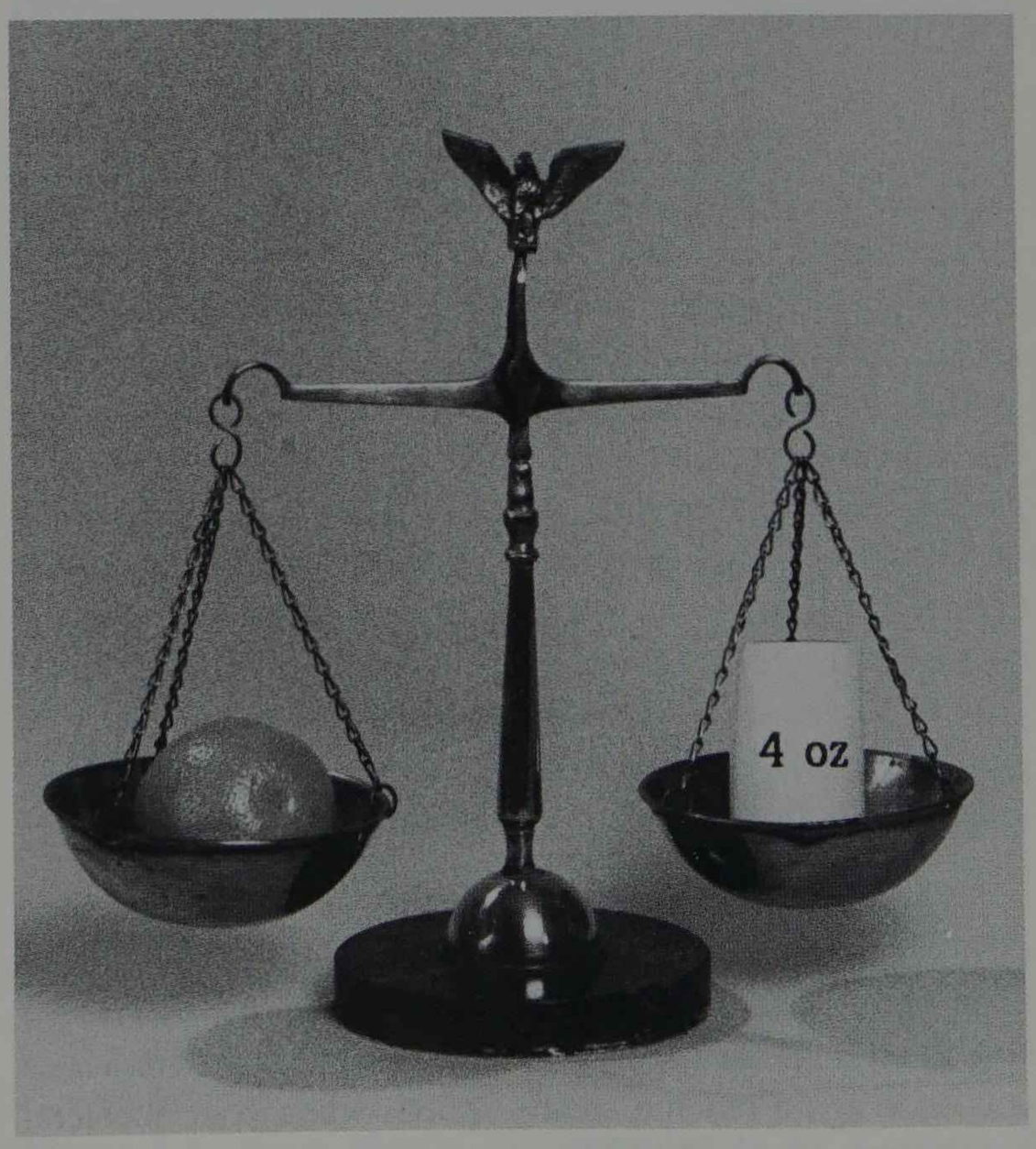


Figure 2.1 A pan balance compares masses.

MATHBOX 2.1

Change of Weight With Altitude

The weight of an object decreases as it moves farther from Earth. Because the force of gravity, which determines weight, decreases with the square of the distance from the center of Earth, the formula is

$$W = \frac{R^2}{(R + r)^2} w$$

where R is the radius of Earth (3,960 miles) r is the altitude of the object above the surface of Earth, w is the weight of the object at the surface, and W is the weight of the object at altitude r.

Example: If an astronaut has a weight of 120 pounds on Earth, how much does she weigh at an altitude of 100 miles?

$$W = \frac{(3960)^2}{(3960 + 100)^2} 120 = 114 \text{ pounds}$$

same mass. The scale actually compares the masses of the two objects. If they have the same mass, the scale is in balance.

Acceleration

Acceleration describes a change in motion. When accelerated, a motionless object will begin to move; an object already in motion will change its speed or its direction of motion.

Anytime you accelerate you get a sensation that your weight changes. For example, as an elevator accelerates downward, that is, as it starts moving from a stop, you feel momentarily lighter. Indeed, if you were standing on a scale, it would indicate that your weight is less. Similarly, as the elevator accelerates upward, you feel momentarily heavier, and a scale would register an increase in weight. Notice that your weight seems different to you only while the elevator is changing speed, that is, accelerating, either upward or downward. As long as the elevator's speed is constant, you feel nothing unusual. Of course, the force of gravity inside an elevator is no different than the force of gravity outside the elevator. It is the brief acceleration that gives the momentary sensation of a change in weight.

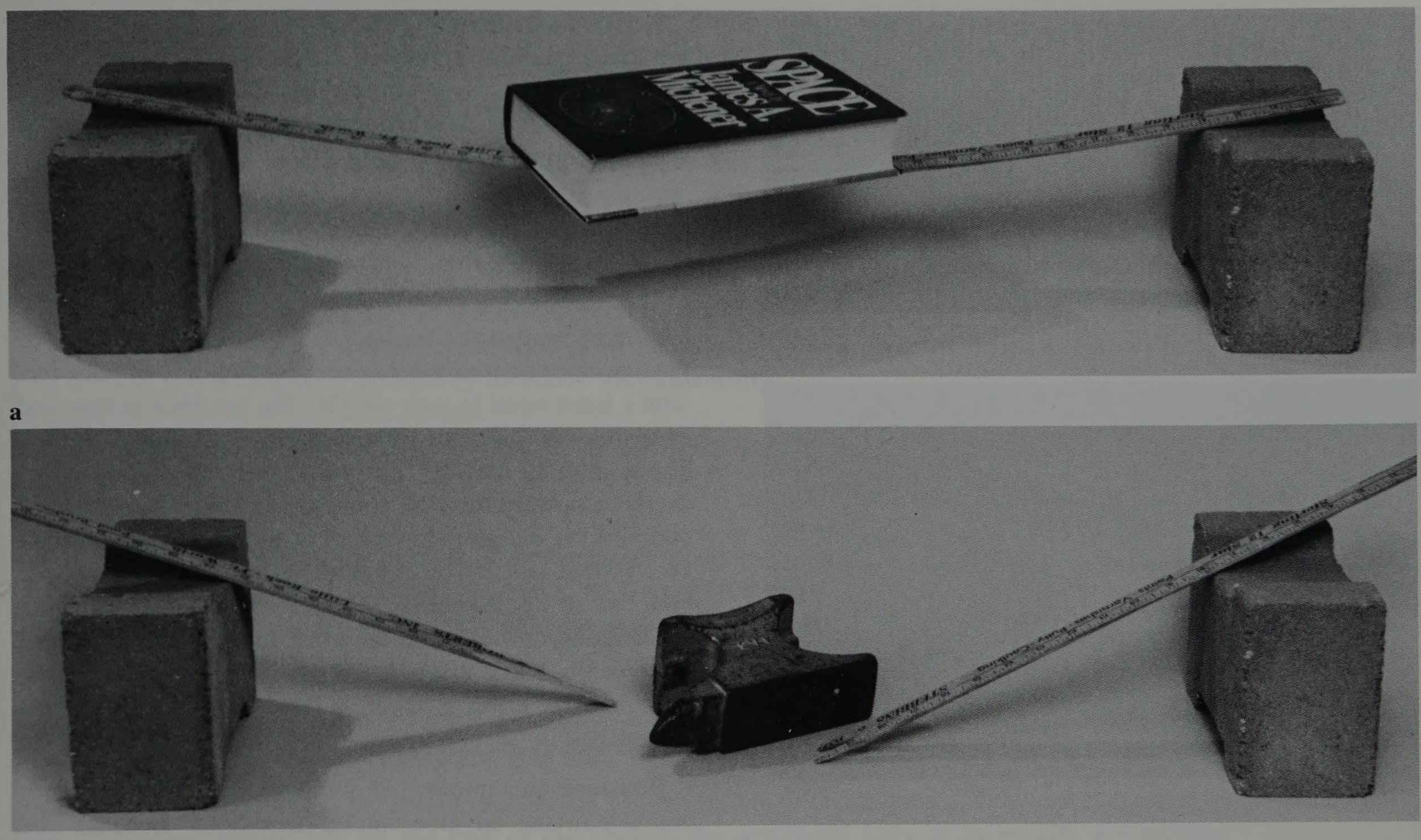
You feel a similar effect, horizontally instead of vertically, in a car when you press the accelerator to increase your speed. You are pushed back against the seat while your speed is changing, that is, while you are accelerating. When you once again reach a steady speed, when your acceleration is zero, you no longer feel the push against the back of the seat.

Forces

A *force* is simply defined as a push or a pull. When a force is applied to an object, the object will accelerate unless the force is cancelled out by other forces. If Jim gives you a shove on your right arm, you move to the left. If Mike shoves on your left arm you move to the right. If both push at the same time with equal but opposite forces you do not move. (You may wish they would quit, but in the interest of science you sit there and contemplate the laws of physics.) The sum of all forces acting on an object is called the *net force*. Two equal forces acting in opposite directions cancel each other out. They add to a net force of zero.

Sitting on your chair, you exert a force downward, your weight. Why do you not accelerate downward if you are exerting a force downward? There must be some balancing force such that the net force is zero. Fortunately, the interconnections between the molecules in a solid substance are a somewhat flexible lattice network. The lattice that makes up the chair "stretches," similar to the way a spring stretches, and it exerts a force upward on your bottom-side equal to the downward force the Earth's gravity exerts on you. The net force is zero and you remain still. Similarly, when you stand on the floor, the floor exerts an upward force to balance the downward force of gravity. If you push on a wall the wall pushes back, and so on.

But suppose you sat down on a shoe box. The molecular lattice of the shoe box probably could not exert an upward force equal to your weight without coming apart. The downward weight force exceeds the upward force from the box; the net force is not zero so you accelerate down to the



a

b

Figure 2.2 The molecules of wood in a yardstick apply an upward force to balance the downward weight force of the object. If the weight exceeds the force that holds the lattice structure together, then it comes apart.

floor. If the net force is not zero, then the forces are said to be unbalanced.

Figure 2.2 illustrates the principle. The molecular lattice of the yardstick stretches, applying an upward force to the weight, trying to hold together, until the downward weight exceeds what the molecules can hold and the yardstick breaks.

Isaac Newton

All of this was summarized by Isaac Newton (1642–1727) in a book titled *Philosophice Naturalis Principia Mathematica,* usually shortened to just *Principia,* published on July 5, 1687.

Newton's first law of motion says that an object at rest will remain at rest unless acted on by an unbalanced force. If the net force is zero, the object does not move. If the net force is not zero, the object will accelerate in the direction of the net force. A second part to this law states that an object in motion will continue in straight line motion at constant speed unless it is acted on by an unbalanced force. Newton's first law is sometimes called the law of inertia because it points out that a force must be applied to change the motion of a body, that is, to accelerate it.

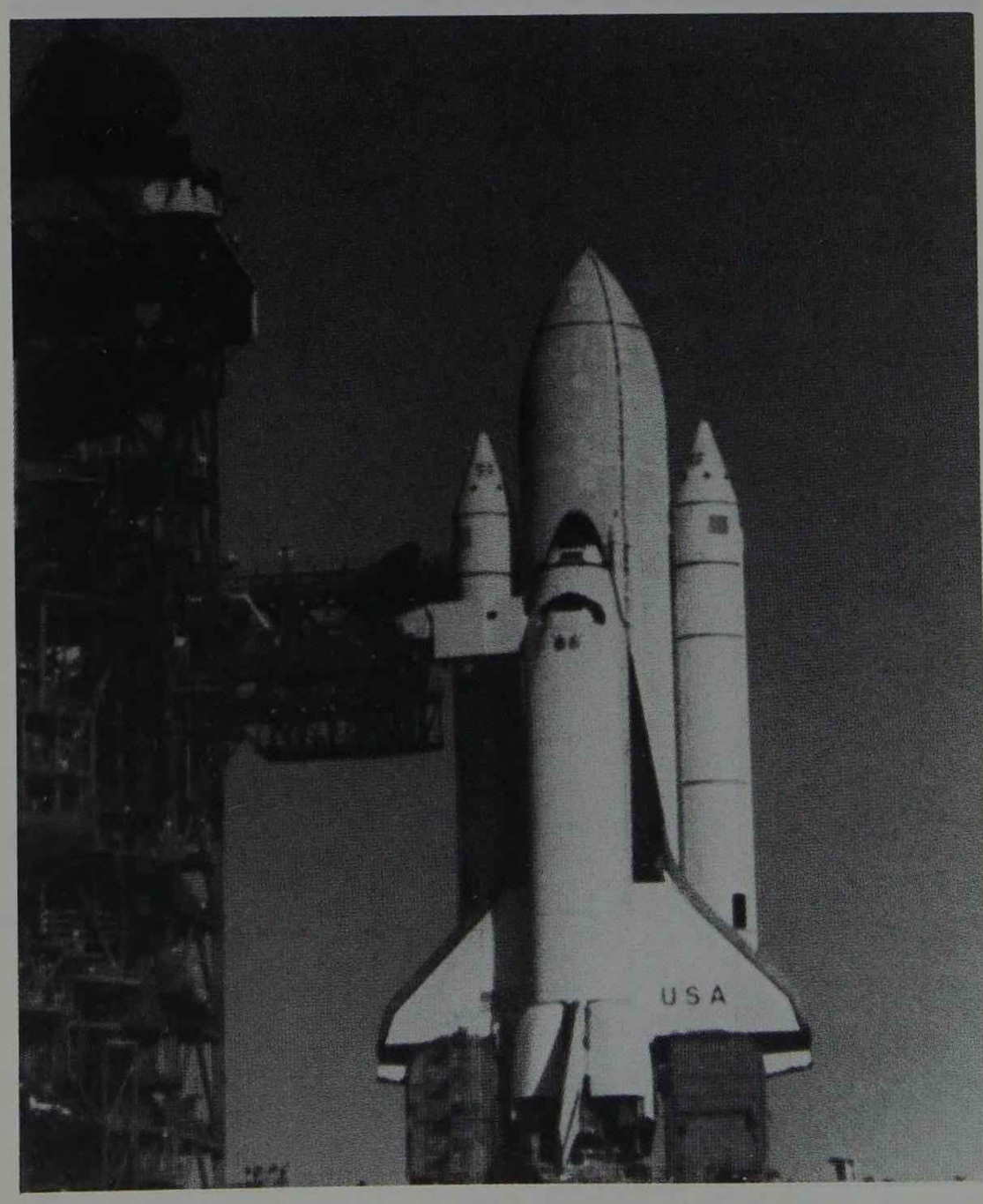
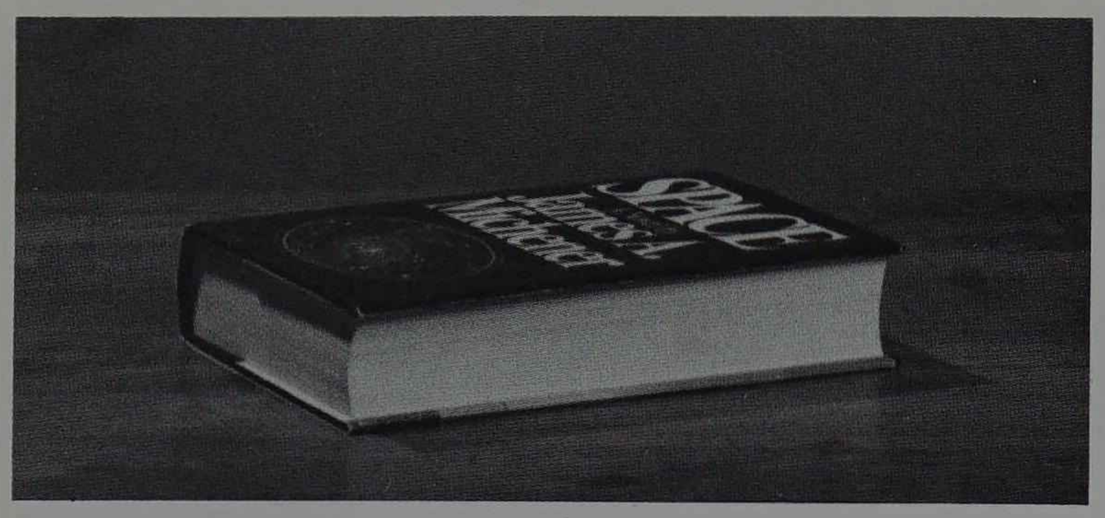
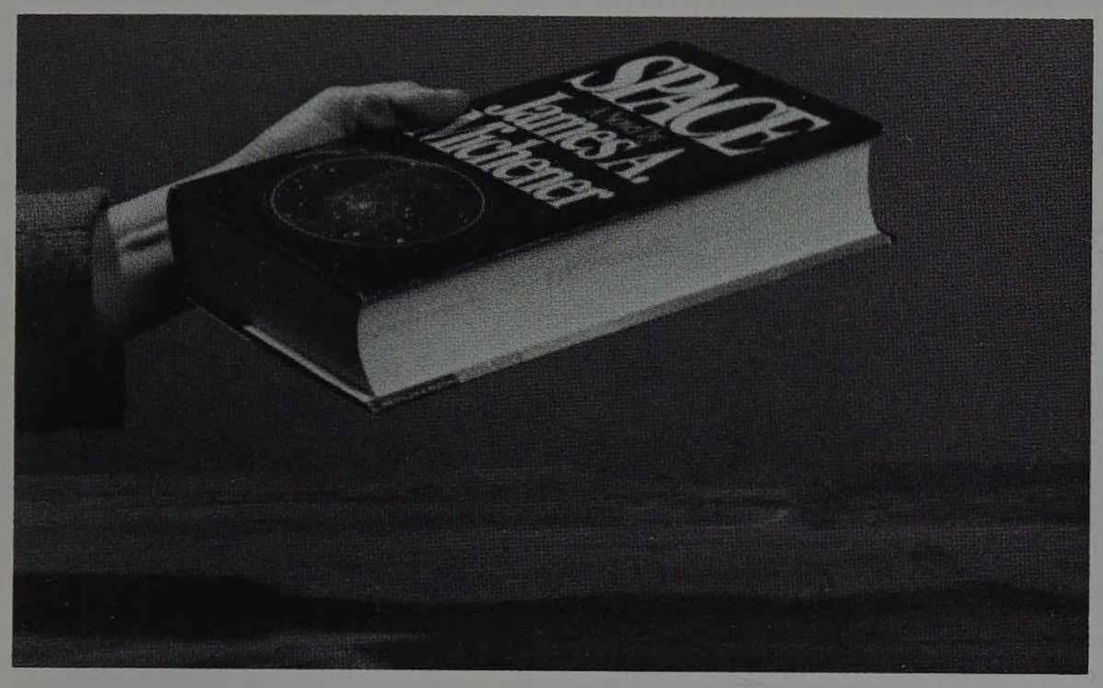


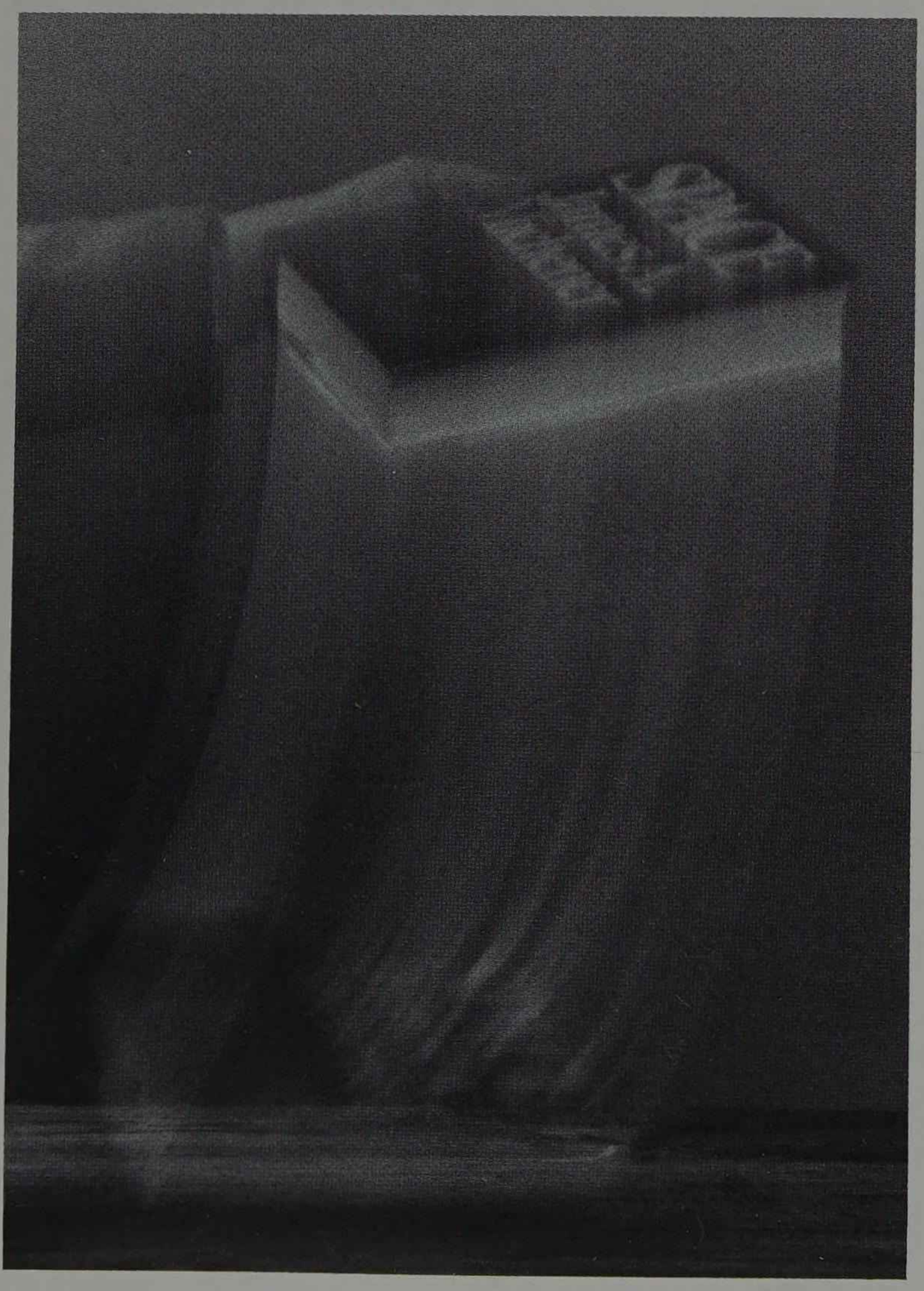
Figure 2.3 Space Shuttle . . . preparing to go. *Courtesy of NASA.*



a



b



c

Figure 2.4 Forces in balance (a and b) and unbalanced (c).

Newton's second law of motion tells us how to calculate the acceleration of an object: simply divide the net unbalanced force by the mass of the object. His *third law* explains the principle of rocket engines which we will encounter in a few paragraphs.

(And may the net force be with you!)

Freefall

Now suppose that you are back in the elevator. The floor of the elevator is pushing up against the bottoms of your feet with a force equal to your weight. The net force is zero and everything is OK. But what happens if the cable breaks? The floor of the elevator falls away under you and no longer exerts an upward force on your feet. Gravity is accelerating you and the elevator downward at the same rate; you are both in free fall. If you could manage to put a scale under your feet, it would register zero because it too is in free fall accelerating downward at the same rate. The gravitational force of the Earth still pulls on you, but because you, the scale, and the elevator are all in free fall together, you feel weightless.

Bouncing on a trampoline, jumping from a diving board, and sky diving all give similar sensations. Because you have no support, no upward force to balance your downward weight force, you are in free fall.

This is precisely the situation with the astonauts in their spaceship. The spacecraft, astronauts and all, are in free fall toward the Earth. Therefore they have the feeling of weightlessness. More about this in the next chapter when we discuss orbits.

Liftoff!

Consider the Space Shuttle in Figure 2.3 sitting on the launch pad attached to its external tank and booster rockets. Fully loaded and ready to go it weighs about 4.4 million pounds. That is, it is exerting a 4.4 million pound force downward on the launch pad. The launch pad, a structure of concrete and steel, is able to support the spacecraft; it can exert an upward force of 4.4 million pounds. The forces are in balance, the net force is zero, and the spacecraft just sits there. Now, how do you make it accelerate, preferably upward?

Think for a moment about a more manageable problem. The book in Figure 2.4a is lying on the table and you want to put it up on a shelf. The book weighs one pound; gravity is exerting a one pound force downward on the table. The table is exerting a one pound force upward on the book so the net force on the book is zero and it just sits there. Now pick it up in your hand (Figure 2.4b) and hold it stationary, Like the table, you are exerting a one pound upward force to balance the downward weight force. It does not move because the forces are balanced and the net force is zero.

MATHBOX 2.2

Newton's Second Law of Motion Applied

The Space Shuttle sitting fully loaded on the launch pad has a weight of 4.4 million pounds. It has three main engines and two solid rocket boosters. Rated at 375,000 pounds thrust each, the three main engines apply a total of 1,125,000 pounds force. The two boosters provide 2,650,000 pounds of thrust each. Total thrust from the five engines at takeoff, then, is 6,425,000 pounds!

Newton's second law states that the acceleration of an object is equal to the net force acting on it divided by its mass. Mathematically,

$$a = \frac{F}{m}$$

To solve this we must find the mass of the Space Shuttle on the launch pad. The mass of any object is found by dividing its weight by g, the acceleration of gravity, which is 32 feet per second per second at the surface of the Earth. For our present problem,

$$\text{mass} = \frac{\text{weight}}{g} = \frac{4{,}400{,}000 \text{ lb}}{32 \text{ ft/sec}^2} = 140{,}000 \text{ slugs}$$

The slug is the unit of mass in the English system of measurement. Now, apply Newton's second law. In the case of the Shuttle, the downward force is its weight, 4.4 million pounds and the upward force is the total thrust of the rockets, about 6.4 million pounds. The net force is, then, 2 million pounds in an upward direction. See Figure 2.2.1.

$$a = \frac{F}{m} = \frac{2{,}000{,}000 \text{ lb}}{140{,}000 \text{ slugs}} = 14 \text{ ft/sec}^2 = 10 \text{ mi/hr/sec}$$

This means that for each second that passes, the Shuttle accelerates, increases its speed by 10 miles per hour.

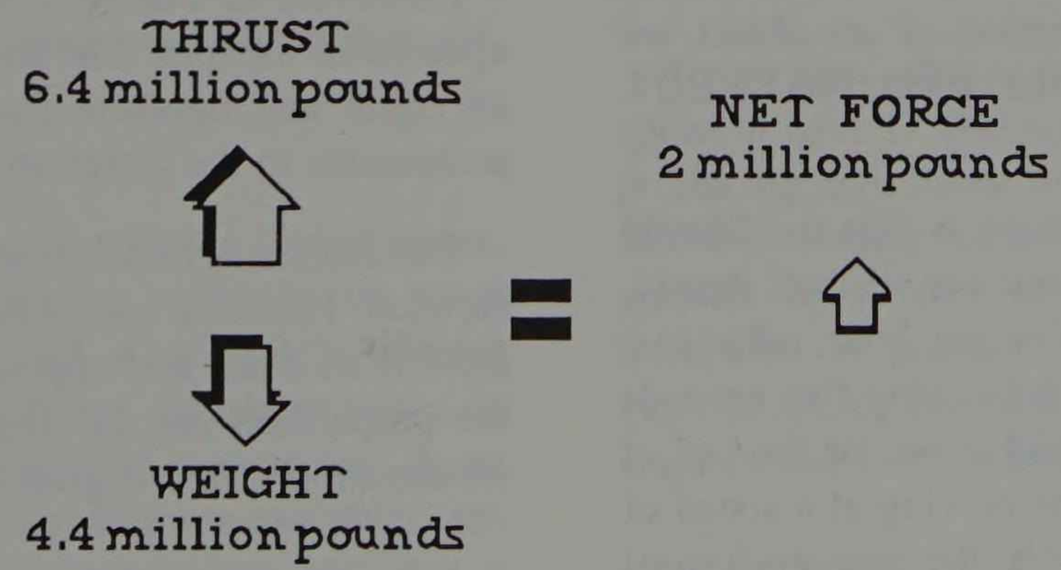


Figure 2.2.1 Net force on Space Shuttle at liftoff.

If you tighten your muscles and exert an upward force greater than the one pound downward weight force, the net force on the book is no longer zero. The net unbalanced upward force causes the book to accelerate upward (Figure 2.4c).

So it is with the Shuttle on the launch pad. All we need to start it accelerating upward is to apply an upward force greater than its weight. Where do you find a force greater than 4.4 million pounds? Rocket engines! As the rocket engines fire and the Shuttle lifts off, the launch pad no

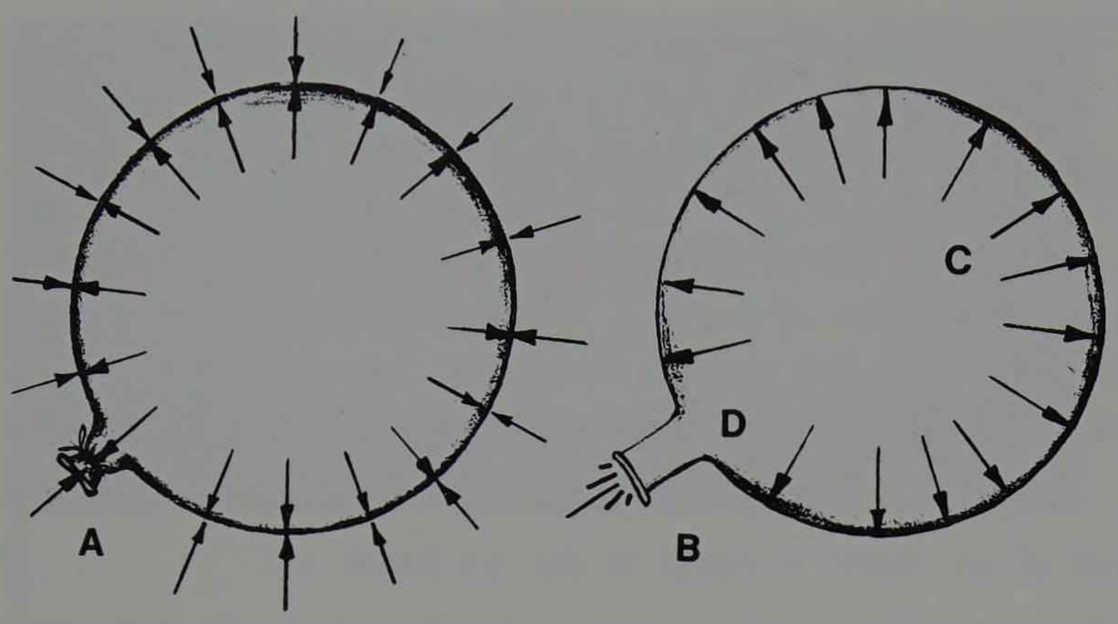


Figure 2.5 Forces in balance and out of balance in a balloon. *Courtesy of Estes Industries.*

longer provides support. The engines must provide the necessary 4.4 million pounds of upward force, and then some. To accelerate upward, there must be an unbalanced force, that is, a net upward force, greater than 4.4 million pounds.

When discussing the capabilities of rocket engines, we use the term ''thrust'' rather than ''force.'' A rocket engine rated at 100,000 pounds thrust, therefore, can lift 100,000 pounds off the ground. This does not mean, however, that the engine could put 100,000 pounds into orbit. In addition to lifting the spacecraft, the rocket engine must lift itself and its fuel. As fuel is burned and exhausted out the nozzle, the vehicle becomes lighter and requires less force to keep it accelerating.

The interaction of these and other variables becomes a complex mathematical problem. However, we can make a simple first estimate of the acceleration of the Space Shuttle as it lifts off the launch pad. *Newton's second law of motion* states that to calculate the acceleration of an object we divide the net force by the mass of the object. MATHBOX 2.2 shows the calculations.

The conclusion from this calculation is that the Shuttle accelerates at about 10 miles per hour per second; that is, after one second it is going 10 miles per hour, after two seconds its velocity is 20 miles per hour, after five seconds it will be going 50 miles per hour, and so on. At the end of five minutes, 300 seconds, it will be moving at a speed of 3,000 miles per hour. To go into orbit, the spacecraft must be travelling at more than 17,000 miles per hour.

In violation of Einstein's advice, we made this calculation too simple. During the flight, none of the numbers that we used remain constant. They all change as the Shuttle heads for orbit. The mass decreases as fuel is burned and thrown overboard. Parts of the vehicle detach and drop away, further decreasing the mass. The thrust of the rocket engines is made to vary during the flight, as we will see. As the vehicle pitches over to horizontal, its thrust no longer is directed directly against gravity. Also, we did not include atmospheric frictional drag. Air drag increases as the vehicle increases speed but then decreases as it reaches higher altitude where the air is less dense. In addition, the force of gravity decreases as the spacecraft moves away from the Earth. These factors are significant and must be taken into account in a ''real-world'' calculation.

Using computers, engineers make a step by step, second by second calculation, taking into account the changing mass, forces, and gravity. The result of their calculation is a predicted flight profile showing where the Shuttle should be, how fast it should be going, and in what direction it should be heading. During a flight, then, the actual position and speed is compared to the predicted values to see if everything is running OK.

Reaction Engines

A rocket is a *reaction engine*. It is basically a very simple device, consisting of a chamber in which a propellant (solid, liquid, or gas) is accelerated to high speed and expelled through the nozzle at the open end. In reaction to the motion of the propellant, the engine is accelerated in the opposite direction.

A toy balloon is a simple example of this principle. When you blow up the balloon, the air inside is contained under pressure. When you release it, the air is expelled from the nozzle and the balloon speeds off in the opposite direction. In Figure 2.5A the balloon is tied shut. The air inside pushes outward while the atmospheric pressure on the outside pushes in. The force in each direction is balanced by a force in the opposite direction; the net force is zero and the balloon does not accelerate.

However, in Figure 2.5B the nozzle of the balloon is open so air escapes. The force at C is no longer balanced by an equal and opposite force at D; therefore the balloon accelerates in the direction of the arrow at C.

The motion of balloons and rockets also was explained by Newton. His *third law of motion* states that for every action there is an equal and opposite reaction. The acceleration of the propellants out the engine in one direction causes an acceleration of the engine in the opposite direction.

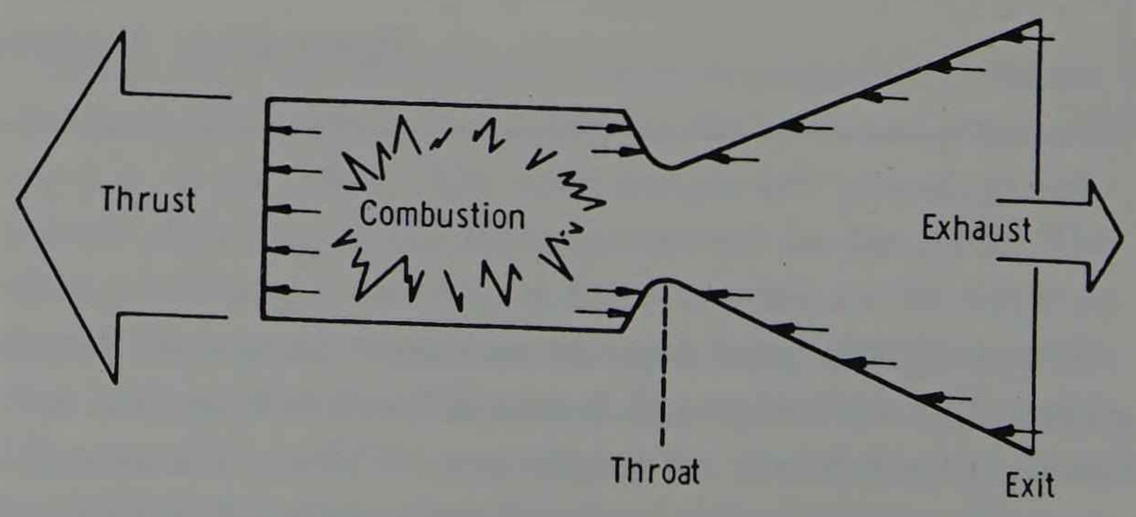


Figure 2.6 Rocket engine, a reaction engine. *Courtesy of NASA.*

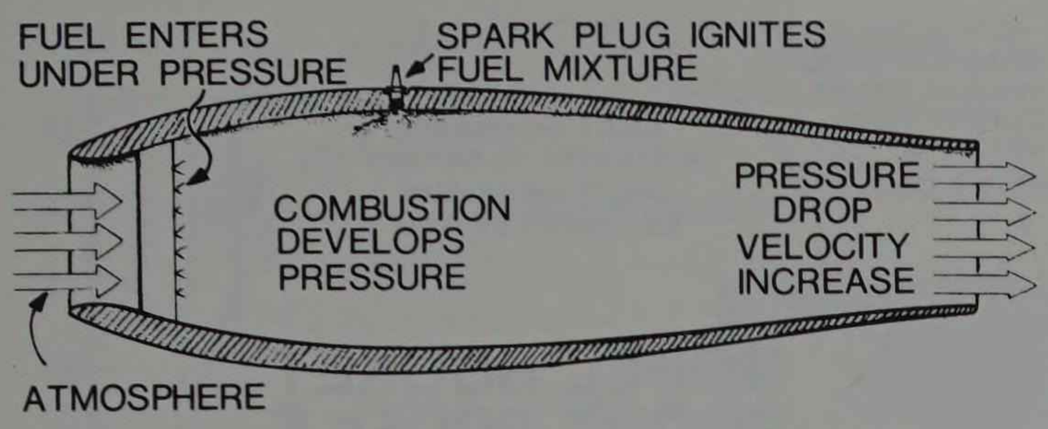


Figure 2.7 Ramjet engine. *Courtesy of Estes Industries.*

See Figure 2.6. Because there is an opening in the rear, the forces of the gases in the combustion chamber forward and rearward are unbalanced. Forces on the sides are balanced by forces on the opposite sides. But in the fore-aft direction there is a net force forward. The thrust of the rocket is, then, the unbalanced force on the forward wall of the combustion chamber which accelerates the vehicle forward. The thrust of any reaction engine is determined primarily by the amount of propellant expelled out the nozzle and how fast the propellent is moving. To increase thrust, simply throw more propellant out the nozzle at higher speed.

A ramjet engine is also a reaction engine. Air is taken into the front: fuel is burned and exhausted out the rear (Figure 2.7). The action of the jet of exhaust gas against the air being ''rammed'' in at the front produces a reaction which drives the engine forward (along with whatever is attached to it). A ramjet engine does not work at low speeds; it cannot start and take off from the ground. The craft must be moving to compress the air coming into the engine.

A rocket engine is a reaction engine also, but it does not intake air. It carries its own oxygen supply in addition to the fuel. Therefore, it can operate in space where there is no air.

Chemical Rockets

Combustion is a chemical process in which a fuel oxidizes, that is, combines with oxygen. An example is wood burning in air as in a campfire. An automobile's internal combustion engine burns (oxidizes) gasoline with air brought into the cylinders through the carburetor. A jet engine burns jet fuel mixed with air. In these examples, the oxygen supply comes from the surrounding air. But a chemical rocket engine carries both fuel and oxidizer. It does not depend on air to support the combustion.

In the combustion chamber of a rocket engine, Figure 2.6, the confined gases from the burning fuel build up tremendous *pressure,* exerting force against the walls of the chamber. Pressure is the force divided by the area over which the force is applied. The pressure is highest in the combustion chamber. On the way out, the exhaust gases pass through the throat, a constriction or reduced area which increases their speed. Once through the throat, the gases expand rapidly in the nozzle, accelerating further and reducing their internal pressure. Of course, pressure must be maintained in the combustion chamber in order to keep exhaust gases flowing out the nozzle. The burning of fuel heats the gas; pressure is maintained by the high temperature and the continuous flow of propellants into the chamber.

Ideally, when the exhaust reaches the end of the nozzle, its pressure should have dropped to equal the pressure of the outside air. At that point, the velocity of the gases would be maximum and the engine is most efficient. If the outside air pressure were greater, it would inhibit the flow of gases outward. If the exhaust pressure were greater, some of the energy of the exhaust would be wasted, producing no useful thrust.

It must be pointed out emphatically that a rocket does not obtain its forward motion by pushing against the outside air. If that were the case, it would not operate in the near vacuum of space. In fact, the outside air only hinders the motion of the rocket, reducing its efficiency in two ways. First, it causes a frictional drag which reduces its forward acceleration. Equally important, the gases expanding out the nozzle are retarded in their expansion by the surrounding atmosphere. Thus, pressure at the nozzle exit cannot drop as low as it could in a vacuum. Consequently, the pressure difference is not as great, the net force is not as great, and the thrust is lower. A rocket operating in a vacuum is significantly more efficient than one operating in the atmosphere. That is one of the major reasons for launching straight up, to get out of the dense lower atmosphere as quickly as possible.

To go into orbit a spacecraft must be accelerated to a speed of over 17,000 miles per hour, requiring a lot of fuel producing high thrust for a long time. In fact, the weight of fuel and oxidizer in the Shuttle at liftoff is nearly 3.8 million pounds, 86 percent of the total weight! It is all thrown overboard to produce the thrust. Only 5 percent is the payload which goes into orbit. The remaining 9 percent is engines and tanks which drop off along the way.

Specific impulse is a number which indicates the effectiveness of a rocket fuel. It may be thought of as the time that one pound of fuel will burn while it is producing one pound of thrust. The specific impulse of some typical fuel-oxidizer combinations is shown in Table 2.1. A typical solid fuel, gunpowder for example, has a specific impulse of 350 seconds; that means that one pound of gunpowder will produce one pound of thrust for 350 seconds. A higher number indicates a more effective thrust-producing fuel. Various fuel-oxidizer combinations will be discussed further in the following sections.

TABLE 2.1 Specific Impulse of Various Propellants

Propellants	Specific Impulse
Typical solid fuels, e.g., gunpowder	350 seconds
Kerosene-LOX	363 seconds
Liquid hydrogen-LOX	462 seconds
Liquid hydrogen-fluorine	483 seconds
Hydrogen heated by nuclear reactor	800 seconds
Hydrogen gas heated by electric arc	1,300–2,000 seconds

Solid Propellant Rockets

The first rockets, built by the Chinese, were propelled by a mixture of solids similar to black gunpowder: potassium nitrate, sulfur, and charcoal. These three ingredients burn together without the need for air. Oxygen for combustion is supplied by the oxidizer, potassium nitrate. (''ate'' at the end of a chemical name generally indicates that oxygen atoms are contained in the chemical molecule.) When combined in certain proportions these three ingredients will explode. The problem is to control the explosion, slow it down so the energy is released over a longer period of time rather than a quick bang. Varying the percentage of charcoal provides a control over the speed of the combustion; increasing the charcoal content slows the burning.

Products of the combustion in the confines of the rocket engine include carbon dioxide, nitrogen, sulfur dioxide, and oxides of nitrogen. These gases, heated by the combustion process, are expelled at high speed out the rocket nozzle to provide the forward thrust. Control of thrust can be achieved by varying the fuel-oxidizer ratio. As mentioned before, increasing the proportion of charcoal in black powder slows the burning.

Look for a moment at the flight of a model rocket shown in Figure 2.8. The components are shown in Figure 2.9. Some model rocket engines are constructed with low charcoal content at the start of the burn for maximum thrust (see Figure 2.10). Then the charcoal is increased to yield a slow burn of constant thrust. After a delay period while the rocket coasts to maximum altitude, an explosive charge at the top of the engine ignites to blow off the nose cone and eject the parachute for descent. This can be seen in the graph of thrust versus time in Figure 2.10.

Modern solid propellants include potassium perchlorate (oxidizer) with asphalt (fuel), ammonium perchlorate (oxidizer) with aluminum powder (fuel), and nitrocellulose with nitroglycerine (both oxiders and fuel). The ingredients are mixed with a binder to hold them in a desired shape, a stabilizer to keep them from decomposing, and sometimes a catalyst to speed up the reaction. The mixture is molded into a *grain* of the desired shape and size to fit into the outer casing or shell which provides structural intregrity.

A grain of solid propellant burns on its exposed surface and produces hot gases. Besides varying the fuel-oxidizer

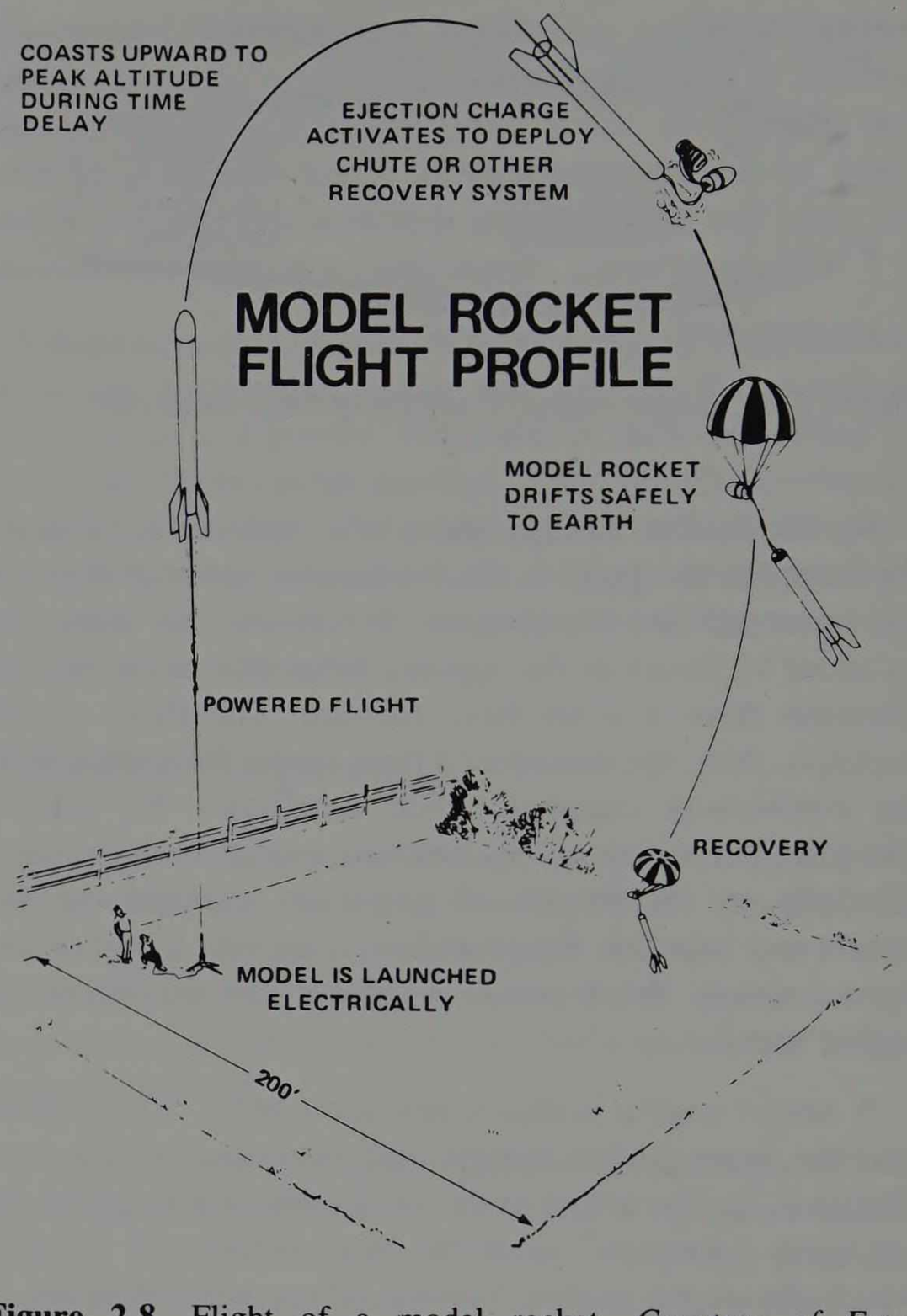


Figure 2.8 Flight of a model rocket. *Courtesy of Estes Industries.*

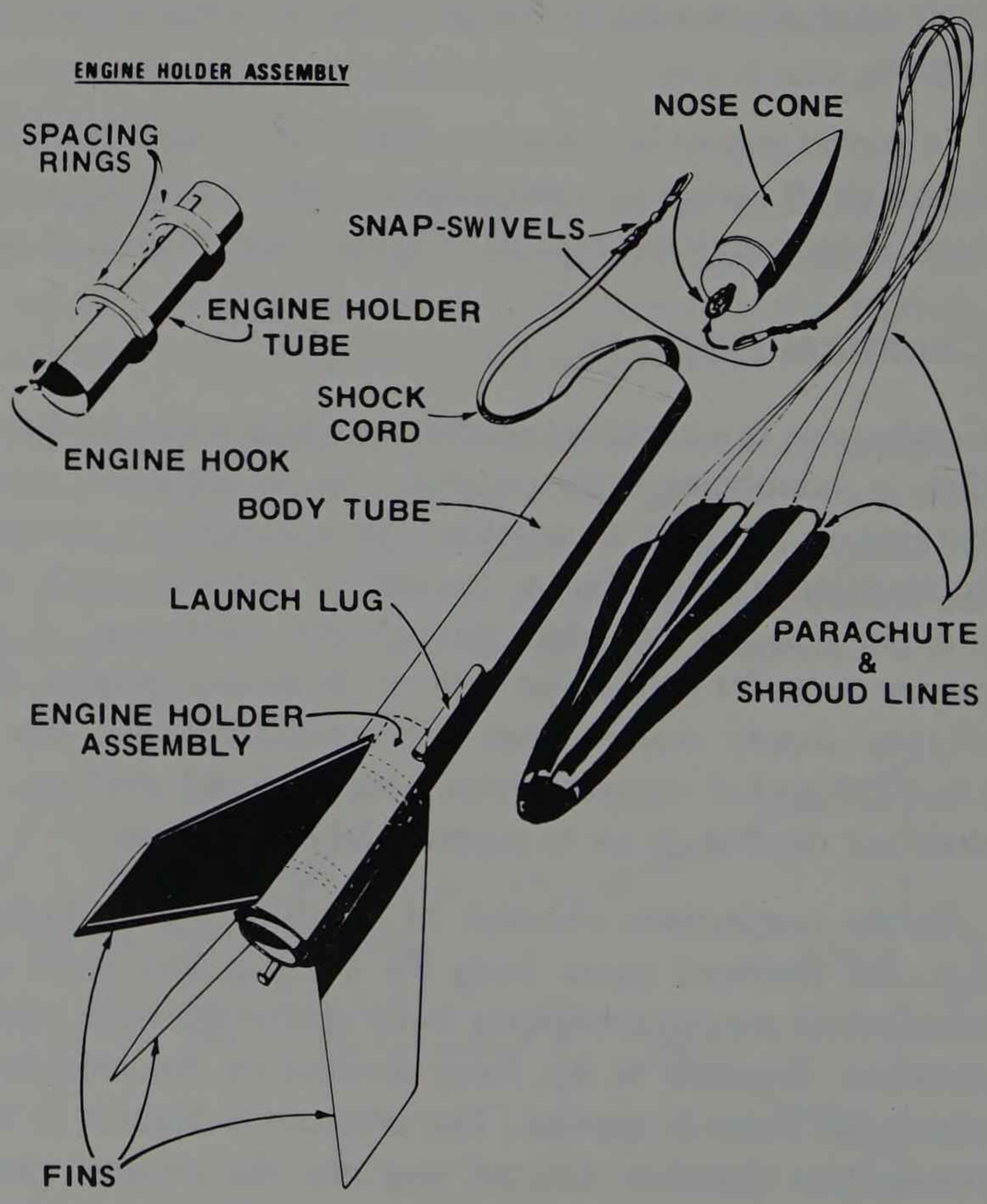


Figure 2.9 Parts of a model rocket. *Courtesy of Estes Industries.*

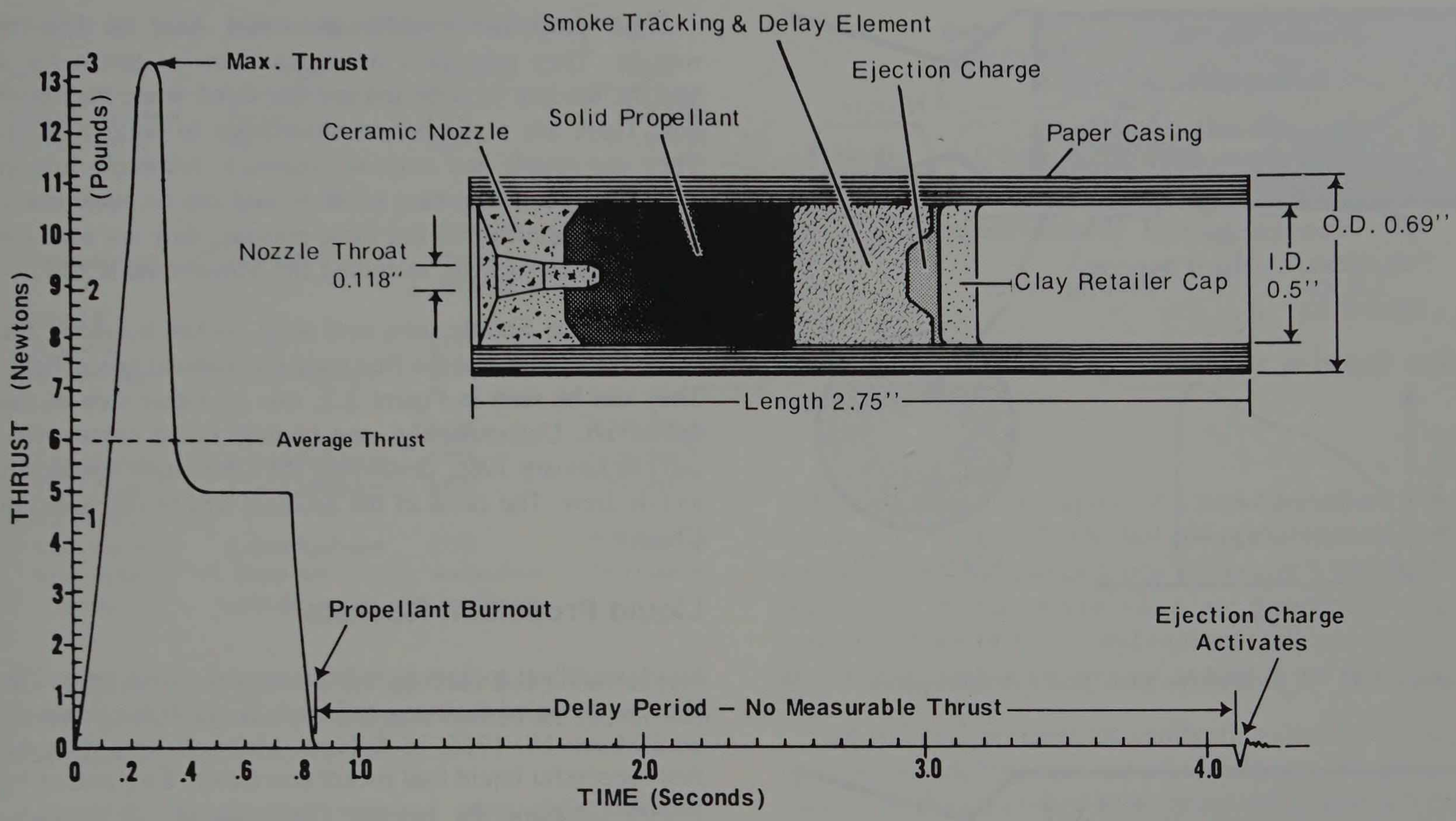


Figure 2.10 Cross section diagram of model rocket engine and its time-thrust curve. Thrust is given in both pounds and newtons (metric units of force). Note that the thrust rises quickly to maximum in about 0.3 second, and that the thrust is constant at about 1.1 pounds (5 newtons) from 0.4 to 0.8 second. The nose cone is blown off and the parachute is ejected about 4 seconds after ignition. *Courtesy of Estes Industries.*

mixture, thrust can also be controlled by the way the grain is shaped. Thrust depends on the rate of burning, that is, how fast the hot gas is being produced and exhausted through the nozzle. That, in turn, depends on the exposed surface area. Refer to Figure 2.11. A cylindrical shaped grain which completely fills the casing burns like a cigarette from one end to the other. Because the burning surface area remains constant throughout the burn, the thrust is constant, a *neutral burn* A problem that must be considered when designing a rocket with a cylindrical grain is that it becomes top-heavy as the bottom burns away.

Some grains are molded with holes of various shapes and sizes running down the center, called *perforations,* in which the burning takes place. See Figure 2.12. As the burn progresses, the surface area increases and so does the thrust, a *progressive burn.* Yet another type of grain is made smaller in diameter than the outer casing and held centered in the casing by metal spiders. See Figure 2.13. In this type, the outer surface of the grain is the burning surface. Because this surface area decreases as the burn progresses. the thrust decreases with time, a *regressive burn.*

Figure 2.14 shows several grain cross sections. The end-burning cylinder has a smaller burning area than those of the same size but with perforations; therefore, its thrust is lower and constant. A star-shaped perforation produces a

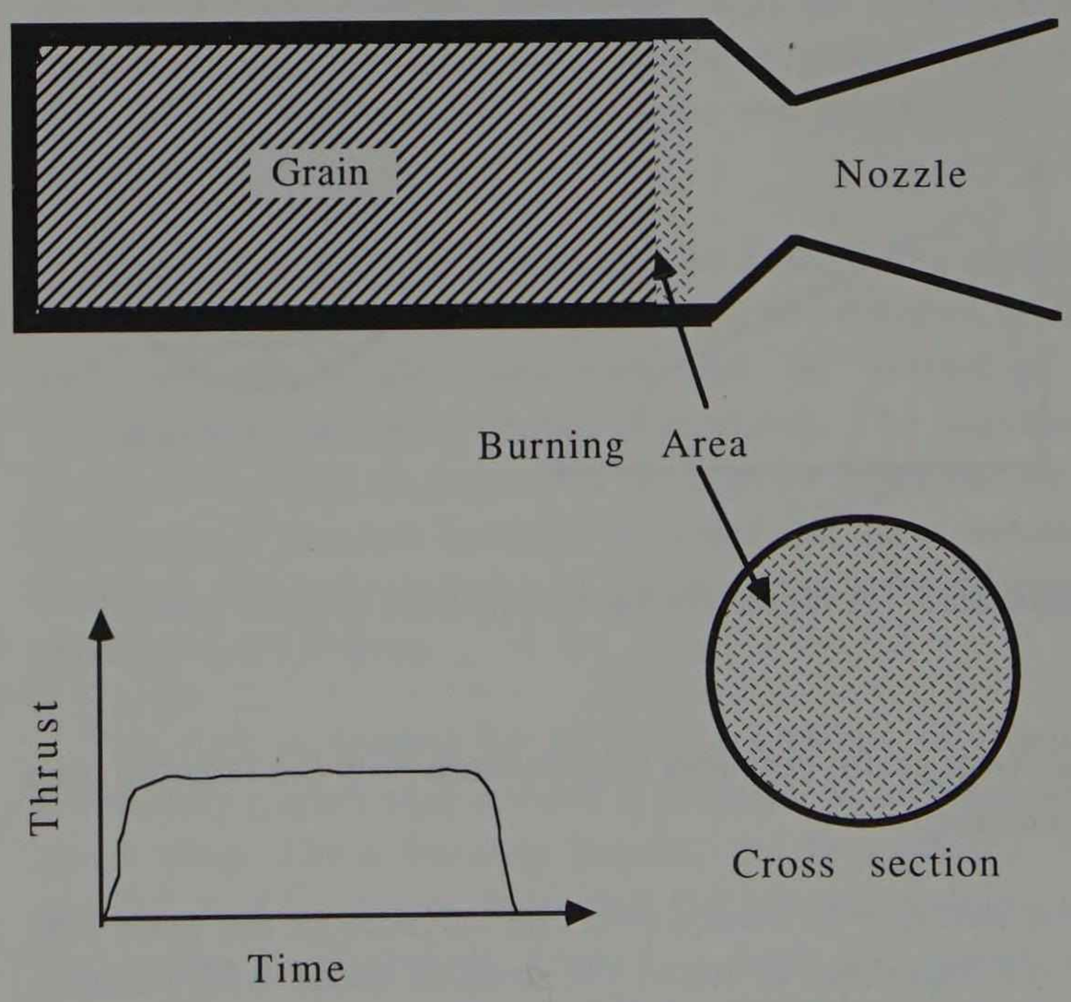


Figure 2.11 A neutral burn, cylindrical grain.

neutral burn. The multiperforated grain is progressive-regressive with a large increasing exposed area at first, then a decreasing as the tubes merge and the burn comes to an end. Try to figure out what kind of burn is produced by the

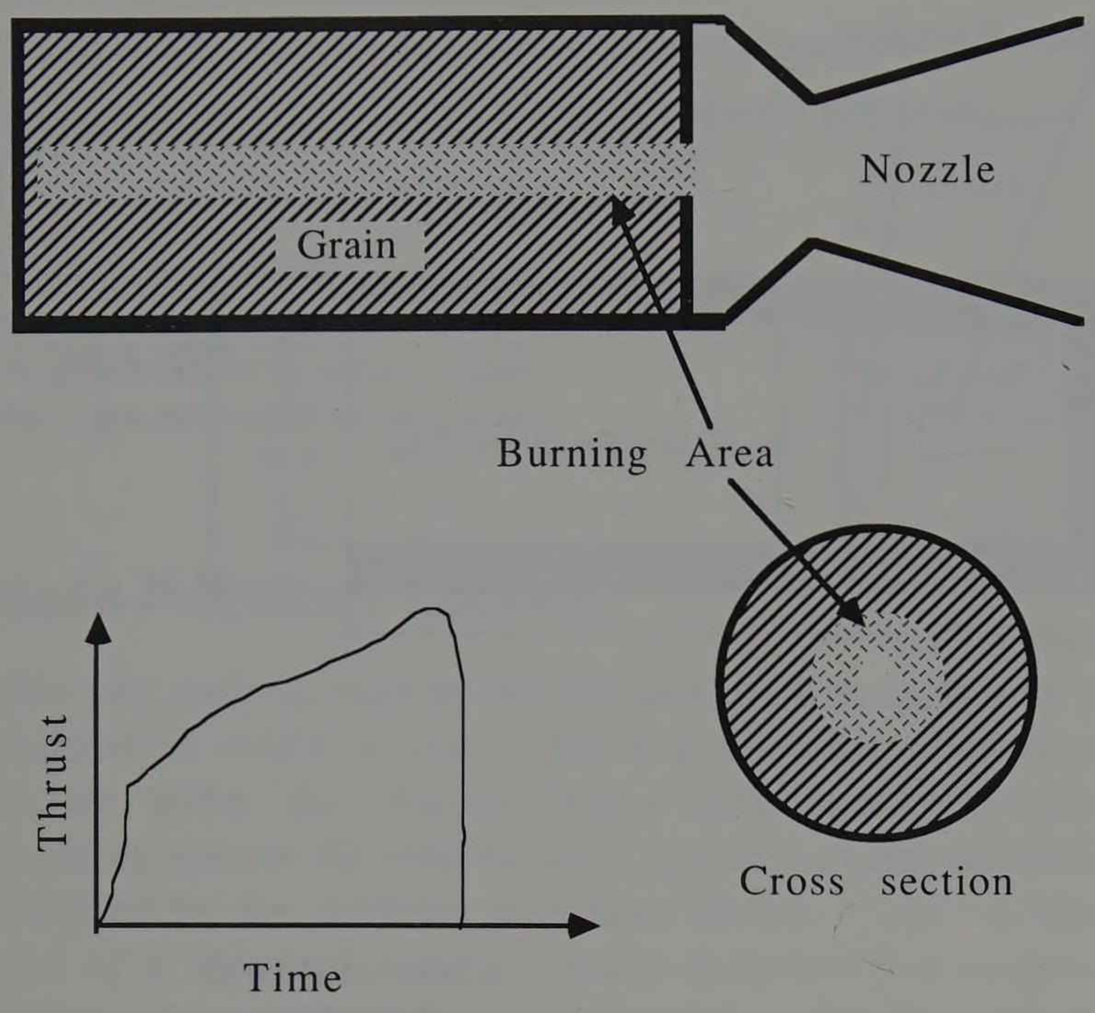


Figure 2.12 A progressive burn, bored cylinder grain.

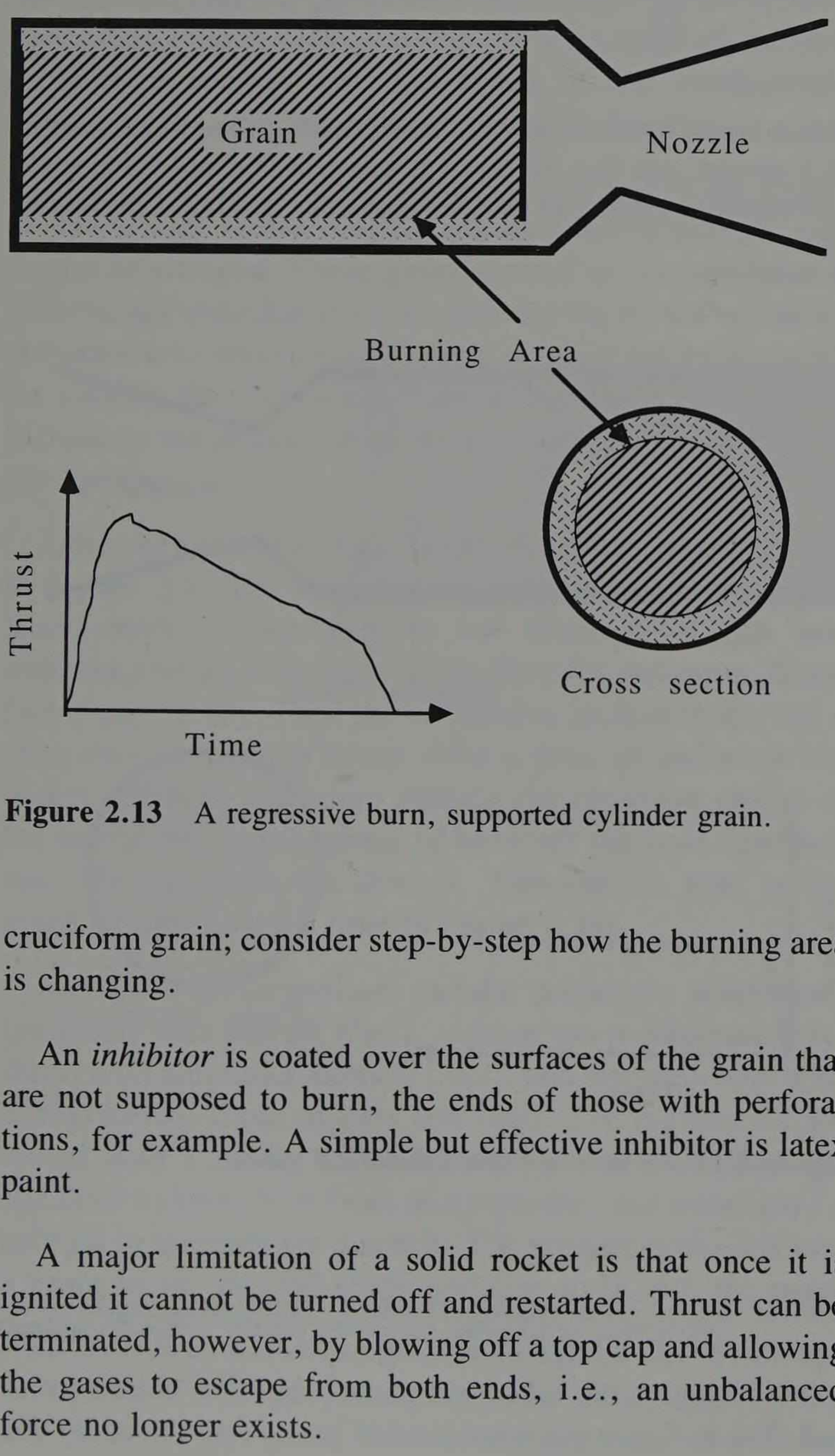


Figure 2.13 A regressive burn, supported cylinder grain.

cruciform grain; consider step-by-step how the burning area is changing.

An *inhibitor* is coated over the surfaces of the grain that are not supposed to burn, the ends of those with perforations, for example. A simple but effective inhibitor is latex paint.

A major limitation of a solid rocket is that once it is ignited it cannot be turned off and restarted. Thrust can be terminated, however, by blowing off a top cap and allowing the gases to escape from both ends, i.e., an unbalanced force no longer exists.

Solid propellant rockets are often used as booster rockets. They provide a desired amount of thrust for a specific amount of time and are discarded when they burn out. There are a number of advantages to solid rockets. They are simple and easy to construct, relatively low in cost, highly reliable, easy to store, and can be made ready to fire in a short time. For these reasons, they are used for most military rockets, including the Minuteman ICBM.

The Space Shuttle uses two solid rocket boosters, the largest ever built and the first used for manned spaceflight. They can be seen in Figure 2.3, one on either side of the spacecraft. Unfortunately, one booster failed catastrophically in January 1986, destroying the *Challenger* spacecraft and its crew. The cause of the accident will be discussed in Chapter 8.

Liquid Propellant Rockets

Solid propellant rockets have been around a long time. The Chinese recorded their use before A.D. 1200 but it wasn't until March 16, 1926, in Auburn, Massachusetts, that the first successful liquid fuel rocket was flown. Engineered by Robert Goddard the pioneer flight lasted 2.5 seconds, reached an altitude of 41 feet, a range of 184 feet, and a speed of 60 miles per hour. The rocket weighed less than 6 pounds and carried about 5 pounds of propellant. The development of liquid propellant rockets was not easy. Two formidable problems had to be overcome: the pumping of the propellants into the combustion chamber and the high temperature of the burning fuel. The propellants used first

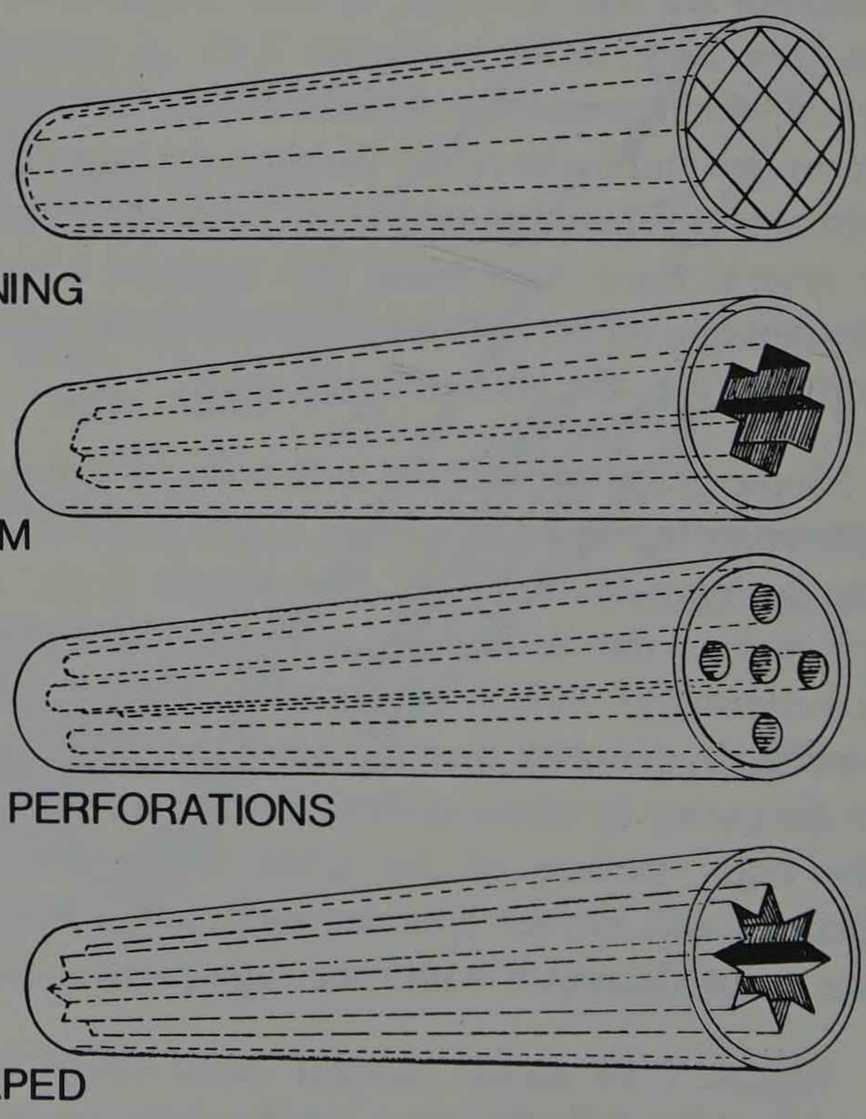


Figure 2.14 Cross sections of four types of solid propellant grains. *Courtesy of Estes Industries.*

TABLE 2.2 U.S. Manned Spaceflight Rocket Engines

Vehicle	Fuel	Oxidizer	Thrust
Mercury-Redstone	Alcohol	LOX	78,000 lb
Mercury-Atlas	RP-1	LOX	365,000 lb
Gemini-Titan			
First stage	Aerozine 50	Nitrogen tetroxide	430,000 lb
Second stage	Aerozine 50	Nitrogen tetroxide	100,000 lb
Saturn 1B			
First stage	RP-1	LOX	1,600,000 lb
Second stage	Liquid hydrogen	LOX	200,000 lb
Saturn V			
First stage	RP-1	LOX	7,760,000 lb
Second stage	Liquid hydrogen	LOX	1,150,000 lb
Third stage	Liquid hydrogen	LOX	230,000 lb
Space Shuttle			
Main engines	Liquid hydrogen	LOX	375,000 lb
Solid rocket boosters	Aluminum powder	Ammonium perchlorate	2,650,000 lb

by Goddard were gasoline for the fuel and liquid oxygen (LOX) as the oxidizer. An assistant ignited the rocket with a blowtorch.

Handling the gasoline was not particularly difficult. There had been considerable experience with automobile engines to draw on. It could be stored in steel tanks, easily pumped, and rubber gaskets could be used for seals. Liquid oxygen was another matter. It boils at −287 °F and must be kept colder than that or it boils away and returns to a gas. Metal valves and pipes contract and crack at that low temperature. Rubber freezes and shatters. Atmospheric water vapor freezes on and in everything. Lubricants solidify, oils congeal, and pumps freeze up. On the other hand, when LOX and gasoline burn, temperatures in the combustion chamber reach 5,560 °F. Steel melts at that temperature. The hot gases flowing out the combustion chamber at high speed can melt through the throat of the nozzle. All these engineering problems and many more took time, talent, and money to solve.

Liquid propellant rockets have been developed to a high degree of performance and reliability. Table 2.2 shows the propellant combinations used in American rockets for manned spaceflight. Note that liquid oxygen is most often used as the oxidizer. While there are more chemically energetic oxydizers (e.g., fluorine), LOX is the most widely used because it is generally easier and safer to handle and produces less hazardous exhaust products. RP-1 is a kerosene-like fuel.

Nitrogen tetroxide was used in Titan missiles because, unlike LOX, it is easily stored. Aerozine 50 and nitrogen tetroxide are *hypergolic*, that is, they react chemically on contact, like Alka Selzer in a glass of water: no igniter is needed. These features are most desirable for an ICBM which remains in "storage" for its entire life (we hope) yet must be ready to go instantly if necessary.

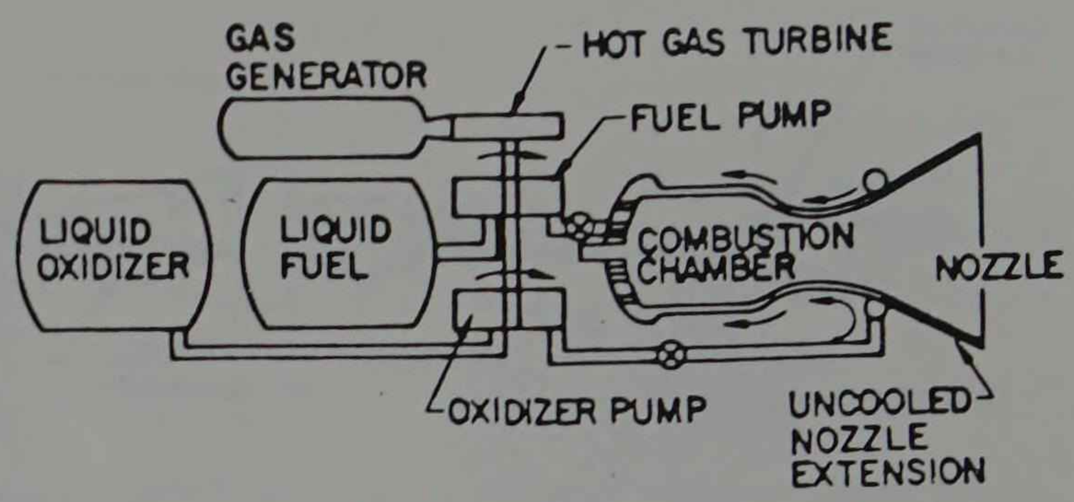


Figure 2.15 Simplified diagram of liquid propellant rocket engine. *Courtesy of NASA.*

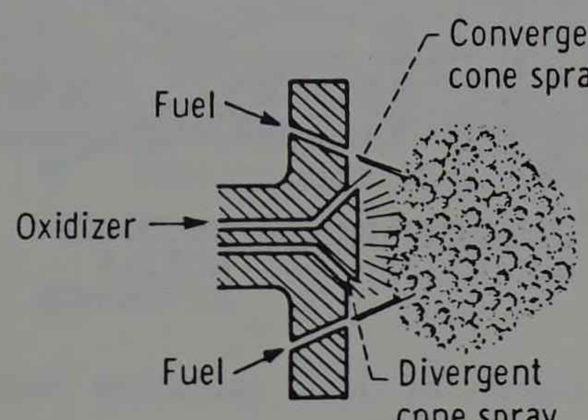
A much simplified diagram of a liquid propellant rocket is shown in Figure 2.15. The fuel and oxidizer are carried in separate tanks and pumped into the engine's combustion chamber by turbine pumps which are powered by a gas generator. Some of the fuel and oxidizer is burned in the gas generator to produce the pressure needed to run the pumps.

Fuel and oxidizer enter the combustion chamber through *injectors* where they are ignited and burn. The primary purpose of the injectors is to break up the propellants into fine streams or droplets and spray them into the combustion chamber. They perform a function similar to an automobile carburetor which sprays fuel from the gas tank into an incoming stream of air. Injectors come in a variety of designs, some of them quite complex. Early injectors were nothing more than metal plates punched with fine holes at the forward end of the combustion chamber. Later models looked something like shower heads or garden hose nozzles. Figure 2.16 shows some types and arrangements of injectors.

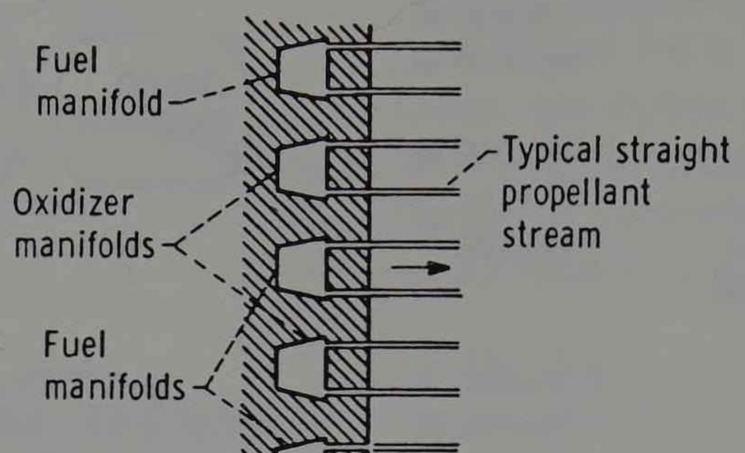
It is important that the burning take place in the center of the chamber so the side walls and injectors do not overheat and melt. It is also important that the propellant be thoroughly mixed in the proper proportions. The fineness of the spray depends on the size of the injector holes and on the difference in pressure between the pipes and the combustion chamber. Smaller holes and greater pressure difference produce a finer spray.

The fuel is ignited by any of a number of devices, commonly a spark plug similar in principle to an automobile spark plug. Once burning begins, the temperature rises rapidly, fuel ignites as it reaches the burning volume, and the igniter is no longer needed to keep the combustion going. As mentioned above, hypergolic propellants do not need igniters; they ignite on contact.

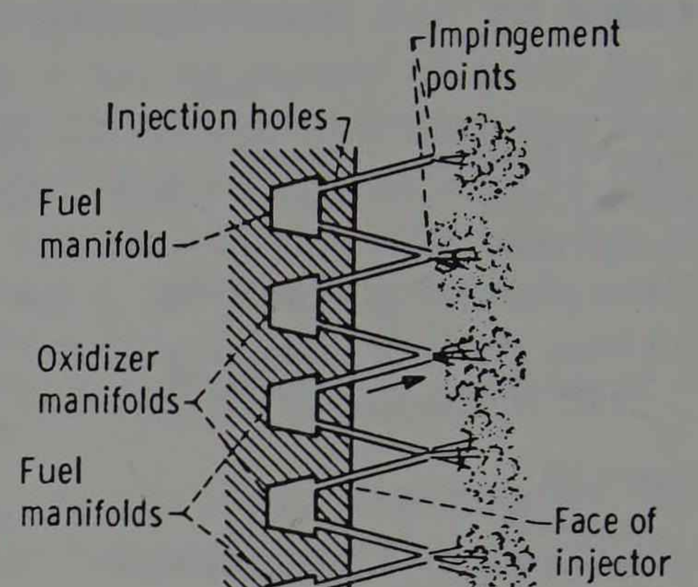
The high pressure produced by the burning fuel in the combustion chamber opposes the propellants spraying into the chamber through the injectors. Therefore, the propellant pumps must produce an even higher pressure than the combustion produces. Designing and building reliable high



Spray injection.



Shower-head stream.



Double impinging stream.

Figure 2.16 Liquid propellant rocket injector types. *Courtesy of NASA.*

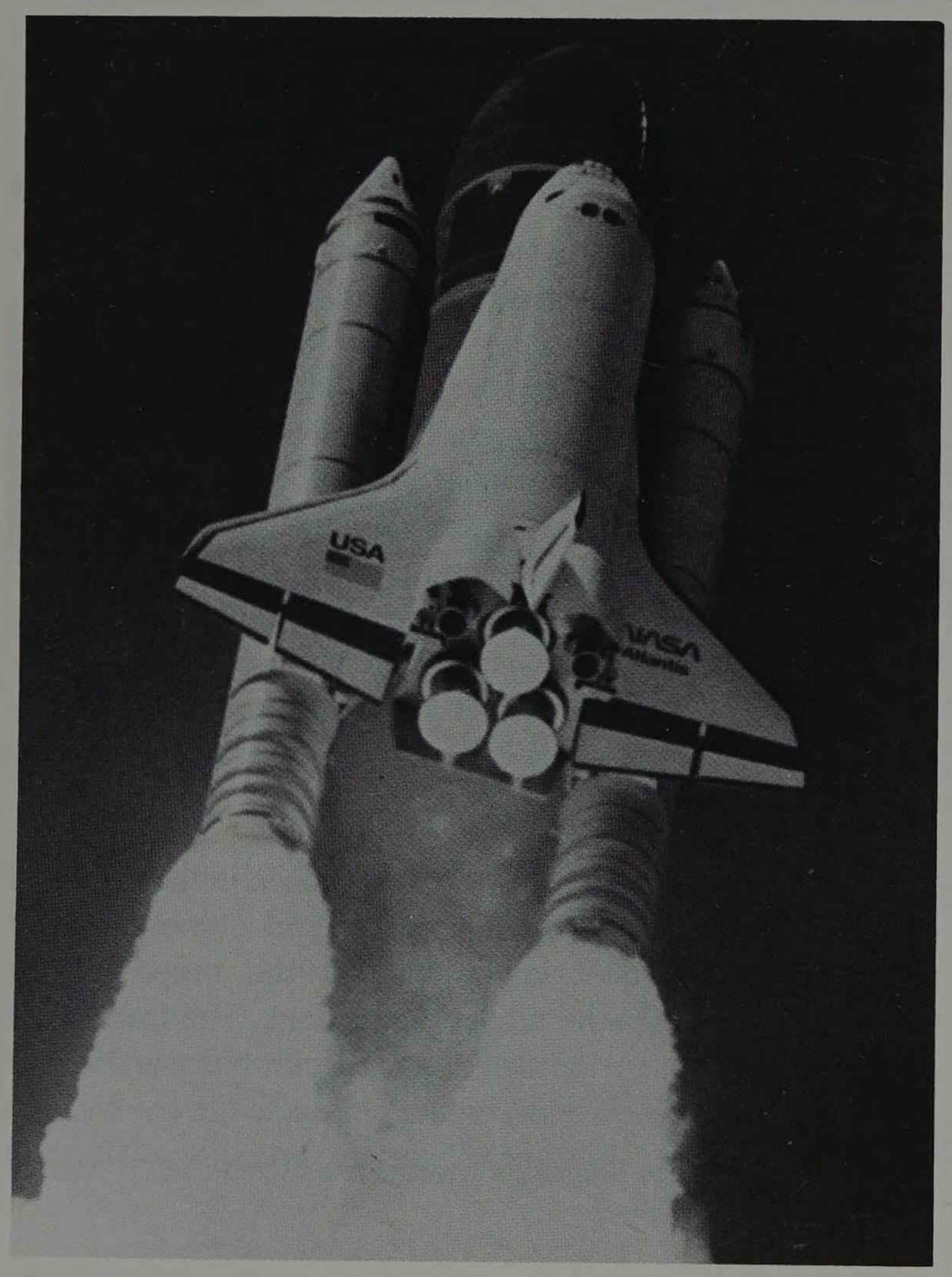
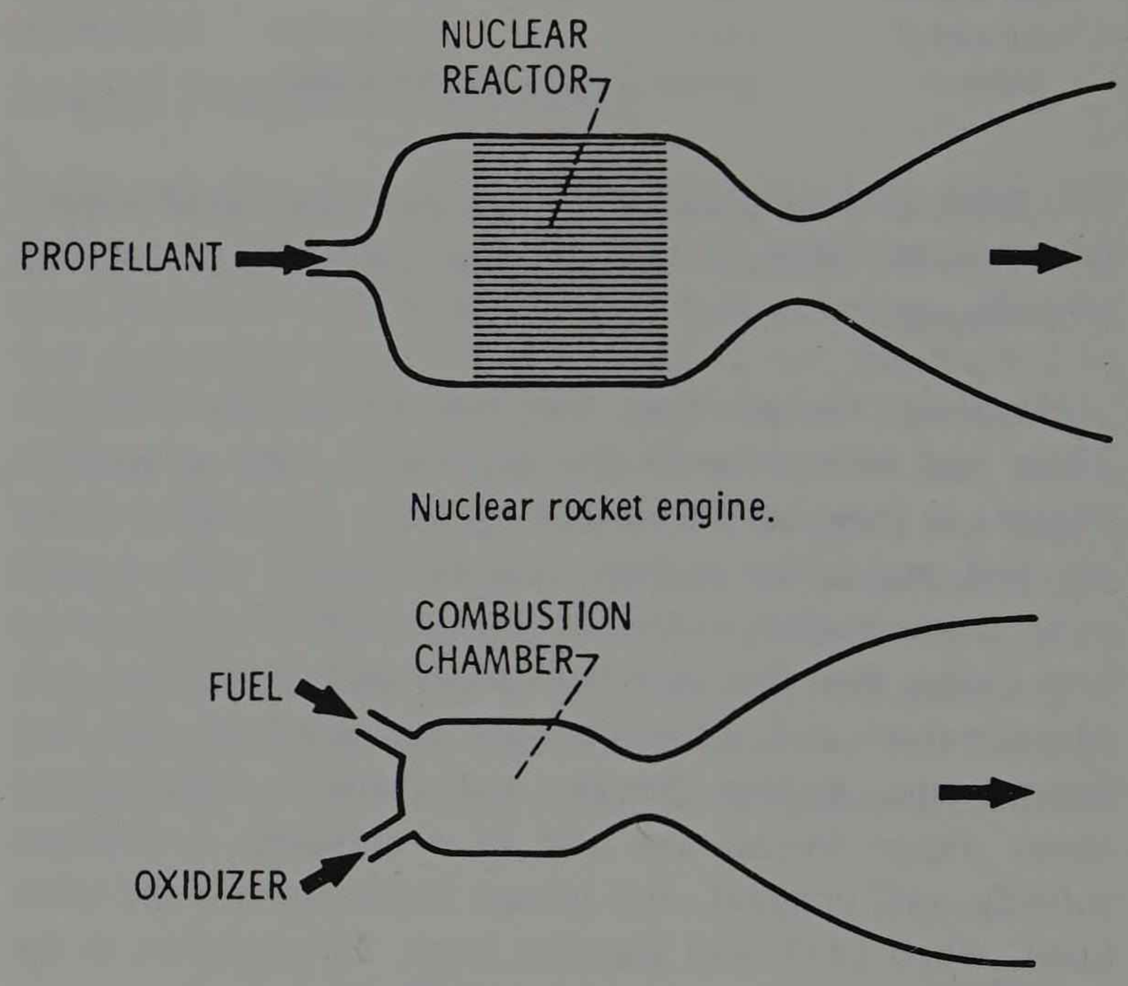


Figure 2.17 Space Shuttle on its way to orbit. Notice the exhaust from the three main engines is barely visible. They burn liquid hydrogen and liquid oxygen and the exhaust is pure water. By comparison, the solid rocket booster exhaust is a mixture of many different chemical compounds from the combustion of the aluminum fuel, ammonium perchlorate oxidizer, and other materials used in making the grain. *Courtesy of NASA.*



Nuclear rocket engine.

Chemical rocket engine.

Figure 2.18 Comparison of a nuclear rocket and a chemical rocket. They operate on the same principle, but the heat source in a nuclear rocket is a nuclear reactor while the heat in the chemical rocket comes from the combustion of the fuel and oxidizer. *Courtesy of NASA.*

velocity, high pressure pumps to pump liquid oxygen at near −300 °F was not an easy task.

To keep the combustion chamber from melting, one common solution is to run the cold LOX feed lines through pipes or a cooling jacket around the combustion chamber. This can be seen in Figure 2.15. An automobile engine has a similar arrangement. A water-antifreeze mixture circulates in a jacket around the cylinders to absorb the heat, then flows through the radiator where it loses the heat to the cool air passing through. In a rocket engine the cold propellant circulates around the combustion chamber and nozzle. This accomplishes two things: it cools the engine and preheats the propellant at the same time. It is important that the fuel and oxidizer be at nearly the same temperature. For example, if cold LOX and RP-1 are brought into contact, the RP-1 would freeze solid.

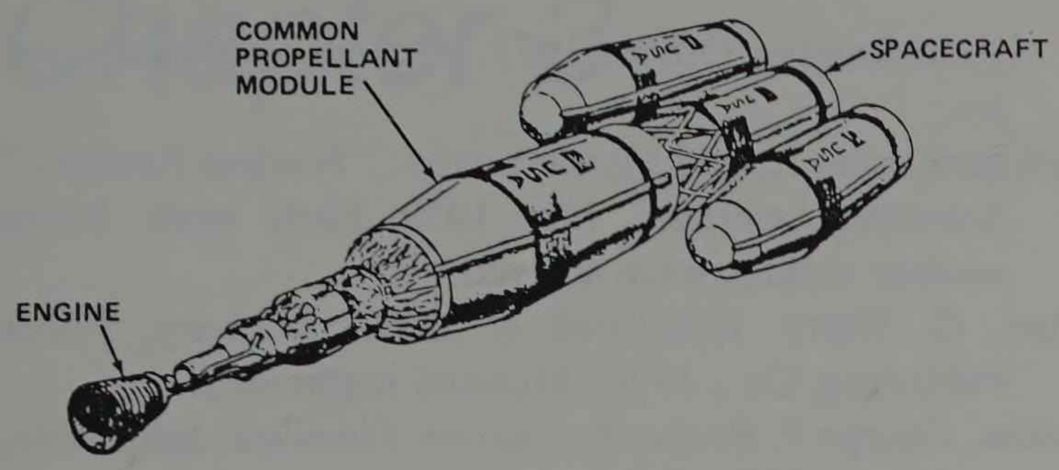


Figure 2.19 Sketch of vehicle using NERVA engine. *Courtesy of NASA.*

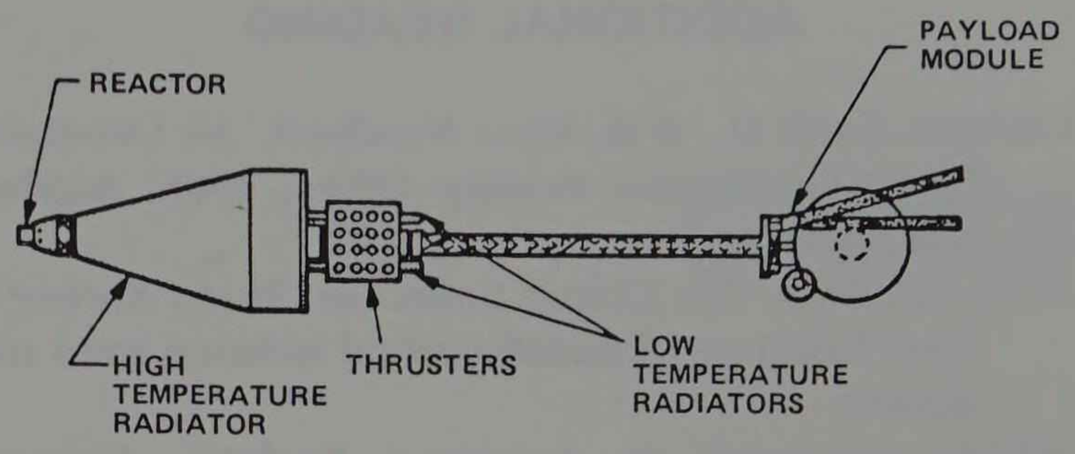


Figure 2.20 Simple concept sketch of a nuclear-electric propulsion vehicle. *Courtesy of NASA.*

Thrust of a liquid rocket engine can be controlled by varying the rate at which the propellants are pumped into the combustion chamber, thereby varying the rate at which exhaust gases are produced. A throttle works on the same principle as the accelerator pedal on a car. Also, some liquid rocket engines have been designed so they can be turned off and back on again as often as needed, using hypergolic fuels for reliable ignition.

The Space Shuttle has three liquid rocket engines at the rear of the Orbiter, visible in Figure 2.17. Propellants are fed to them from the large external tank between the solid rocket boosters. Pumps on the Space Shuttle carry 64,000 gallons of LOX and liquid hydrogen (at −420 °F) per minute to the engines through 17 inch pipes. An engineering problem of the highest order! They are probably the most complex rocket engines ever built.

When hydrogen burns in oxygen the result is water (H_2O). The cloud of exhaust coming from the three main engines in Figure 2.17 is a real cloud, nothing but pure water. The Shuttle has several other small liquid propellant rocket engines which will be discussed in Chapter 8.

Other Reaction Engines

Actually, any device which throws mass overboard in one direction in order to accelerate in the opposite direction qualifies as a reaction engine. Besides the solid and liquid propellant chemical rocket engines we have been discussing, several other ''exotic'' engines have been designed, some prototypes have been built, and some have even flown.

The use of nuclear reactors to heat matter and expel it from an exhaust nozzle was under serious study from 1955 to 1972 in Project Rover. Figure 2.18 compares a nuclear and a chemical rocket. In the NERVA engine (Nuclear Engine for Rocket Vehicle Applications) liquid hydrogen was pumped through the reactor where it absorbed heat to reach about 4,000 °F before being ejected through the nozzle at high speed. The hydrogen acted as a moderator to slow neutrons from the nuclear reactions. The pump was also driven by hydrogen gas warmed in the reactor. Figure 2.19 shows a concept of an interplanetary vehicle powered by a NERVA engine. Development of the flight test engine was just beginning when the project was cancelled as part of an overall national retrenchment on space which included a decision not to go to Mars in the early 1980s.

There is some interest in reviving nuclear propulsion systems for space vehicles. Now, however, the concept may be different. The nuclear reactor could generate electricity which ionizes and accelerates some fuel, such as vaporized cesium, to high speed and expels it out the rocket nozzle. Ionized particles are electrically charged and can be accelerated in an electric field to speeds unattainable in chemical combustion. Figure 2.20 is a simple sketch of such a vehicle. Note that in Figures 2.19 and 2.20 the payload is far removed from the nuclear reactor to avoid a radiation hazard. There would seem to be two options: a heavily shielded reactor on a physically smaller spacecraft or a lightly shielded reactor on a long spacecraft.

Both of these engines produce low thrust for long periods of time. Refer back to Table 2.1 and note their high specific impulse. Because acceleration is low they would not be used to take off from Earth. They eventually can achieve very high speed, however, making them suitable for interplanetary journeys.

DISCUSSION QUESTIONS

1. If an astronaut weighs 120 pounds at an altitude of 100 miles above the Earth, then why is she weightless in orbit?
2. Explain what is meant by miles per hour per second or feet per second per second as units of acceleration.
3. Why does a toy balloon fly an erratic path but a rocket ship flies straight?
4. How does the turbojet engine on an airliner work? Is it a reaction engine?
5. What precautions would have to be taken when using a nuclear-powered rocket?

ADDITIONAL READING

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Chapter 3

Orbits

Getting Into Orbit

Throw a ball straight up into the air (Figure 3.1). It slows down as it rises, stops at the top of its path, and comes back down to you, speeding up as it falls. Why? Once the ball leaves your hand, you have no more control over it. There must be some other force affecting its motion: gravity, of course. While it is moving away from Earth it slows down; as it falls back to Earth it speeds up.

Throw the ball harder and it goes higher before stopping and returning. If you could throw it hard enough, it would keep on going, slowing down but never stopping, never returning. It would escape the gravity of Earth. How hard is hard enough? From the surface of Earth, greater than 7 miles per second would do it. But in this experiment we have only succeeded in sending our ball out to escape Earth forever. How do we get it into an orbit around the Earth?

Let us try something else. Shoot a cannonball from a cannon. It follows a curved path as it falls to Earth (Figure 3.2). Eventually it hits the ground, perhaps at A. Fire it with a little more oomph and it travels farther before hitting the ground, perhaps at B.

Newton's first law of motion states that an object in motion will continue to move in a straight line unless some external force acts on it. Once the cannonball leaves the cannon, it is no longer affected by the cannon. The external force is gravity, which causes the normally straight line path to curve back to Earth.

In a larger perspective, consider that Earth is actually spherical. The cannonball travels part way around Earth before it strikes the ground (Figure 3.3). However, if it were possible to give the cannonball enough speed, it would never strike the ground. It would continue to fall in its curved path toward Earth, but would never quite get there. In other words, it would be in orbit. Isaac Newton knew this back in the 1600s; a diagram similar to Figure 3.3 appears in his notes.

There are two practical problems with this scheme for orbiting a cannonball. First, the speed necessary to follow a path which does not intersect Earth is over 17,000 miles per hour. No cannon has yet been built which can impart that

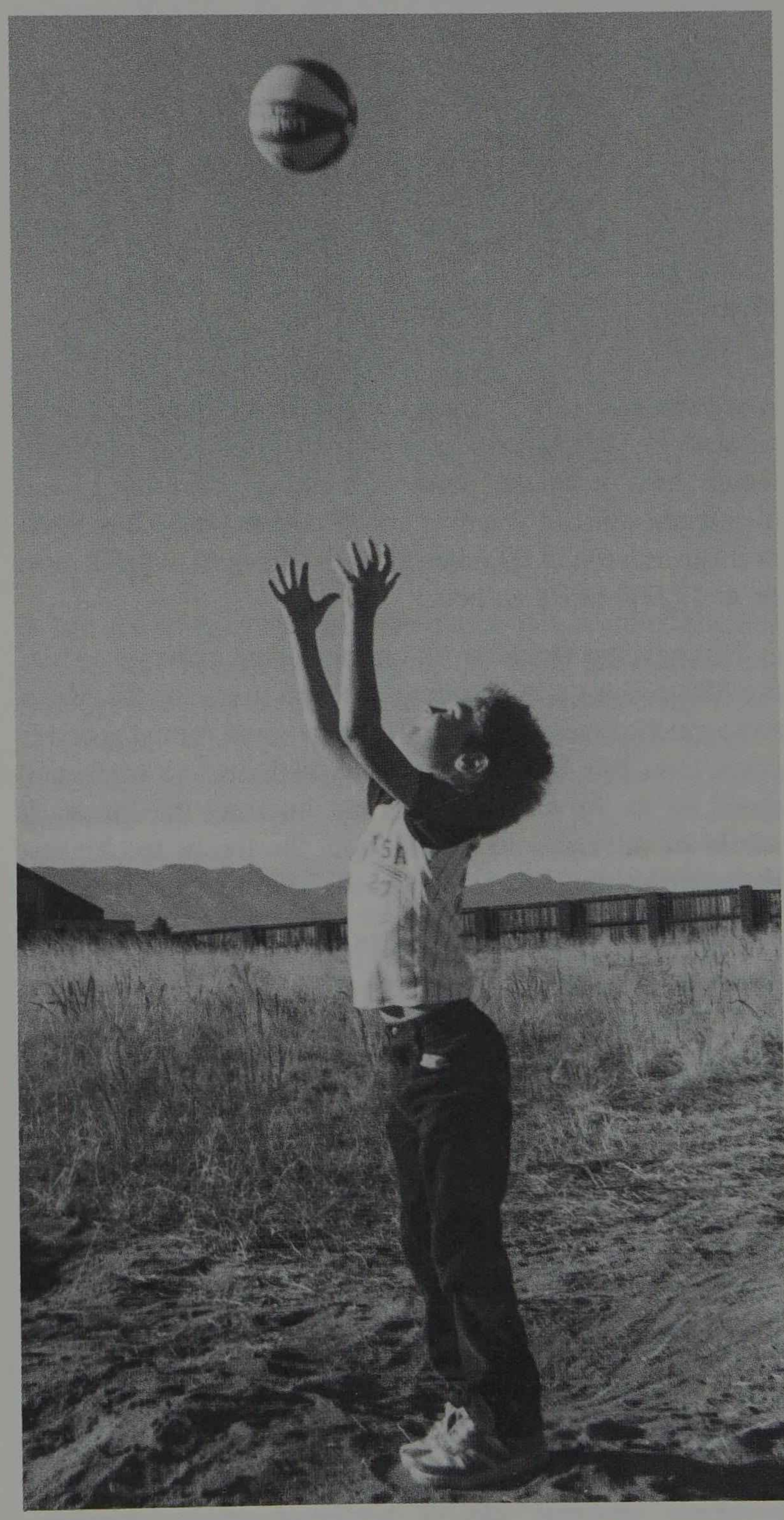


Figure 3.1 When Jimmie throws a ball up, it always returns.

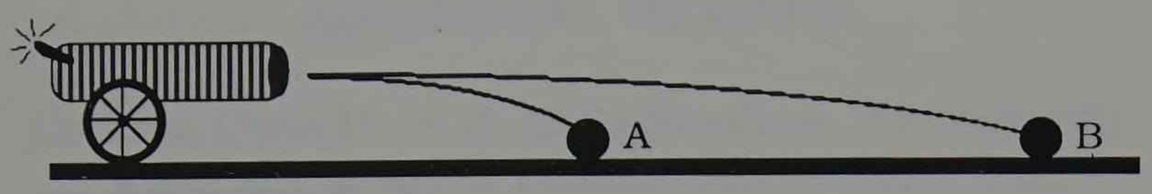


Figure 3.2 Can a cannon put an object into orbit?

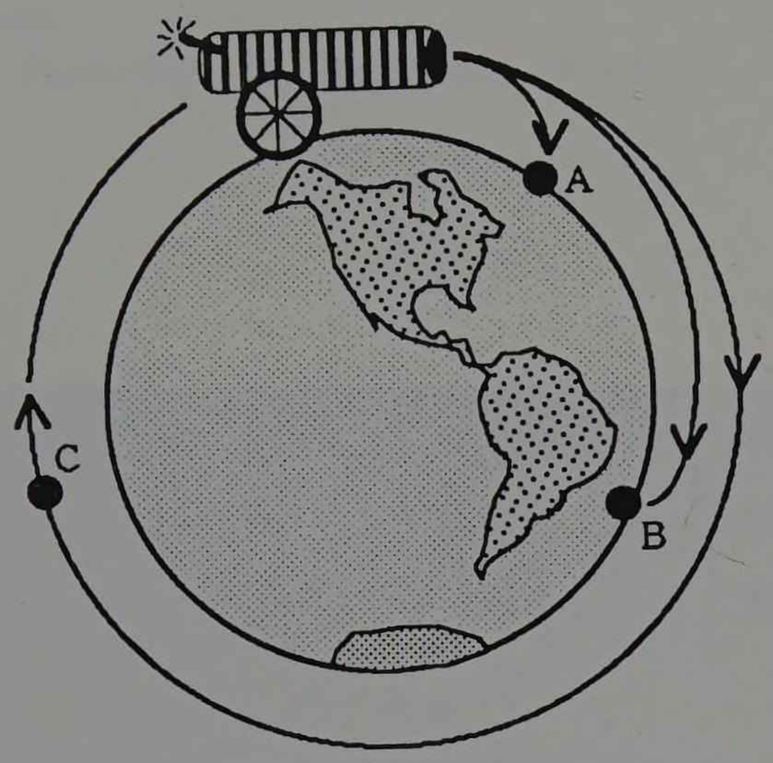


Figure 3.3 Putting a cannonball into orbit.

speed to a cannonball. Second, even if the cannonball could be shot at 17,000 miles an hour, the friction with the air would heat it to the point of melting, vaporizing, and disintegrating. Did you ever hold your hand out the window of a car moving at 60 miles an hour? Imagine what it must be at 17,000 miles an hour!

This scheme would work on the Moon, however. First, the Moon has no atmosphere. Second, because the Moon has a smaller mass than Earth, the required orbital speed is much less. Just fire the cannonball with enough horizontal speed so its curved path does not intersect the Moon. It would be advisable to launch from the top of the highest mountain so the orbit is high enough to clear all obstacles.

To launch a spacecraft into Earth orbit, it is first necessary to get it up out of the densest part of the atmosphere, then give it sufficient horizontal velocity so that its curved path toward Earth does not actually intersect the ground. It is a common misconception that satellites are launched straight up into orbit. The primary reason for launching vertically is to carry the spacecraft through the dense part of the atmosphere at a lower speed to keep it from burning up or breaking up. Then it is pitched over horizontally and accelerated to orbital speed (Figure 3.4). Without sufficient horizontal velocity it will simply fall back to Earth (Figure 3.5). It is that motion parallel to the surface of the Earth that keeps it in orbit.

Ellipses

Earth and the other planets are in orbit around the Sun in just the same way as satellites are in orbit around Earth. In the late 1500s, during a lifetime of study of the motion of the planets, Johannes Kepler discovered laws which describe their motion around the Sun. His initial assumption, like many other natural philosophers of the time, was that the orbits of the planets were circles. The circle was considered a perfect mathematical shape and if the universe were perfect, the orbits should be perfect. After years of studying the precise observations made in the observatory of the Danish nobleman, Tycho Brahe, Kepler finally came to the conclusion that planetary orbits were ellipses, not circles. Kepler was disappointed. He expected the universe to have been created with perfection. This important discovery applies as well to any object in orbit around another body, including spacecraft in orbit around Earth.

An *ellipse* is an oval shape as shown in Figure 3.6. You

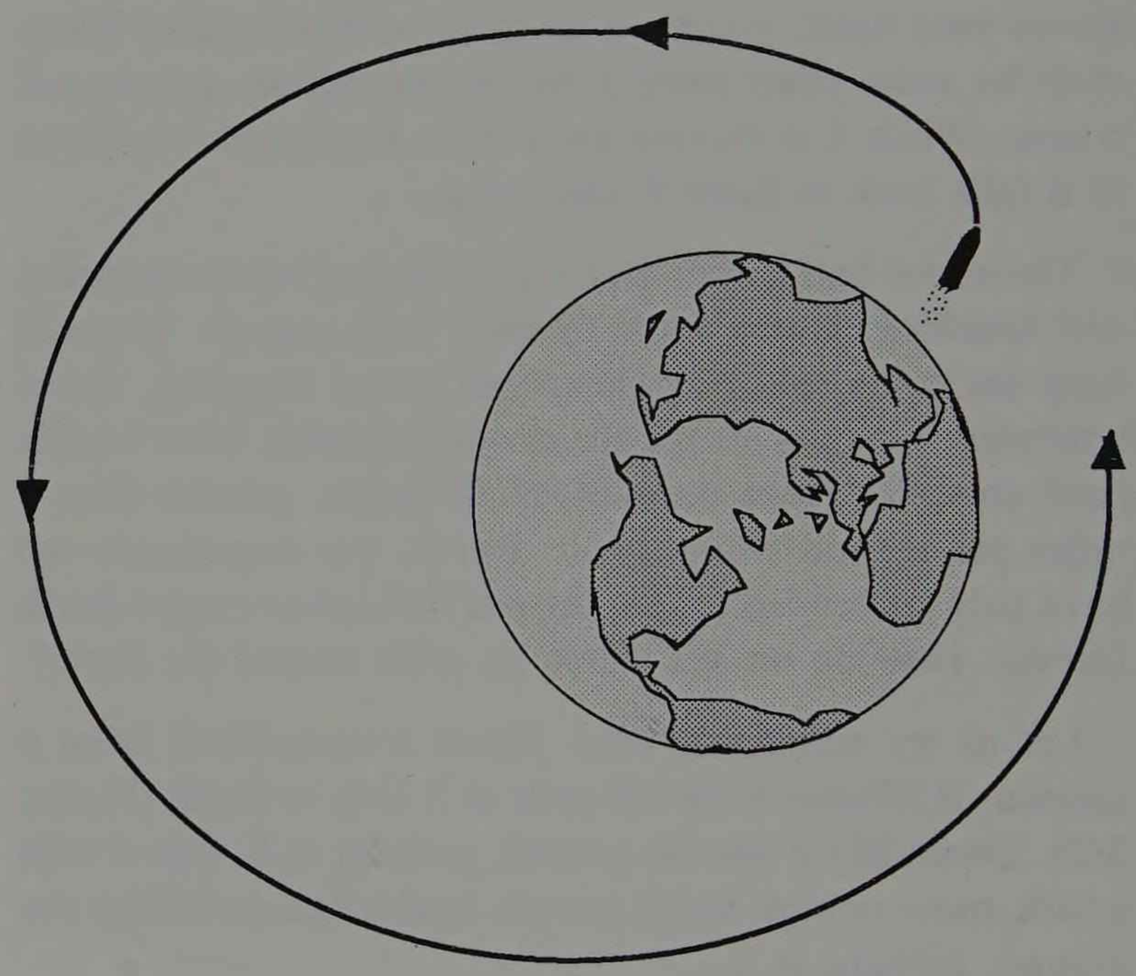


Figure 3.4 Launch up out of the densest atmosphere, then pitch over and accelerate to orbital speed.

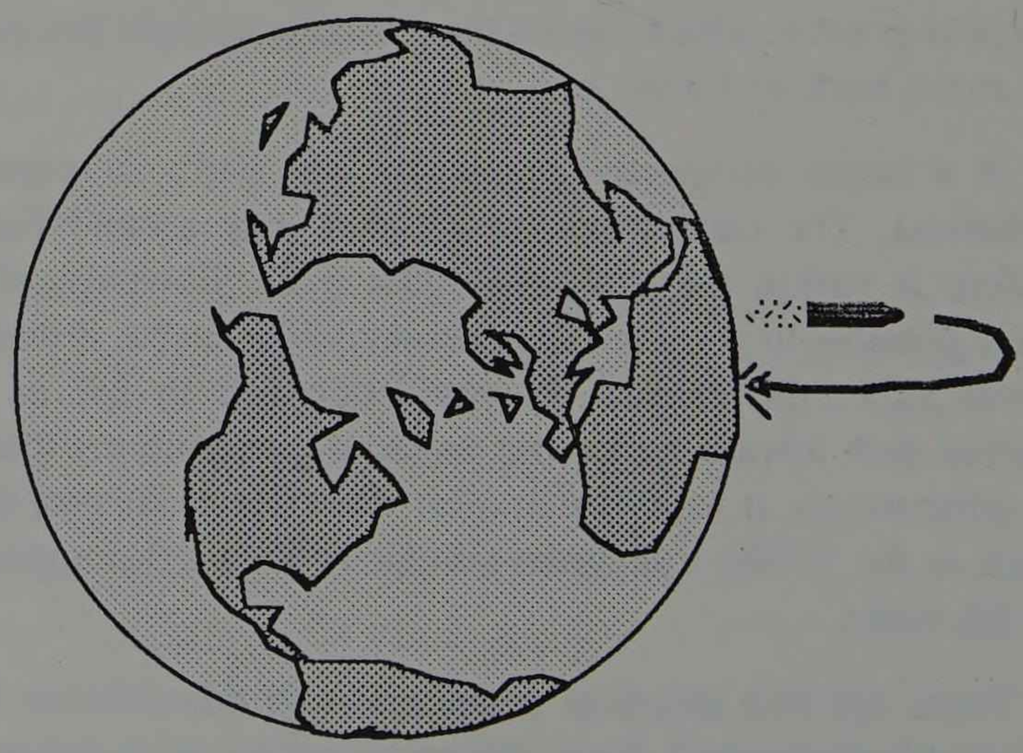


Figure 3.5 Launch something straight up and it comes straight down.

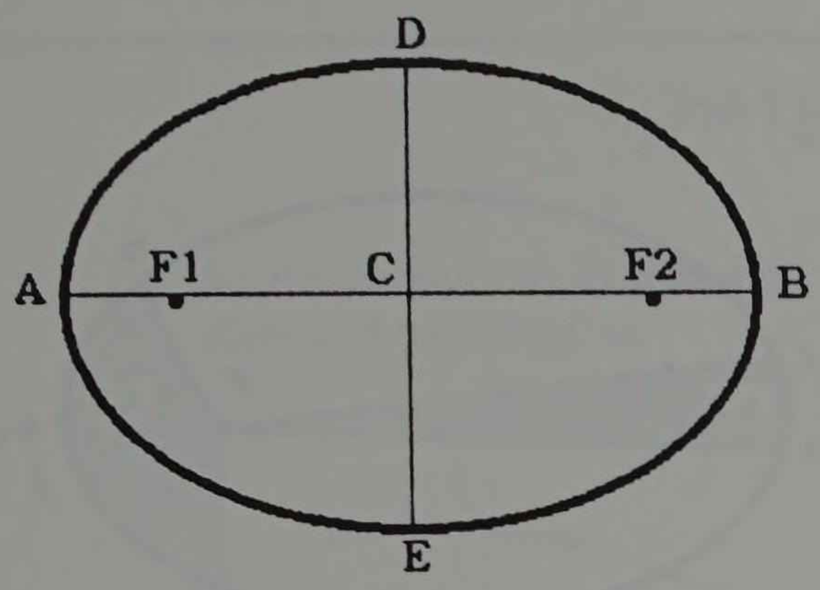


Figure 3.6 The ellipse. A to B is the major axis; D to E is the minor axis. The center is at C and the two focal points (foci) are at F1 and F2.

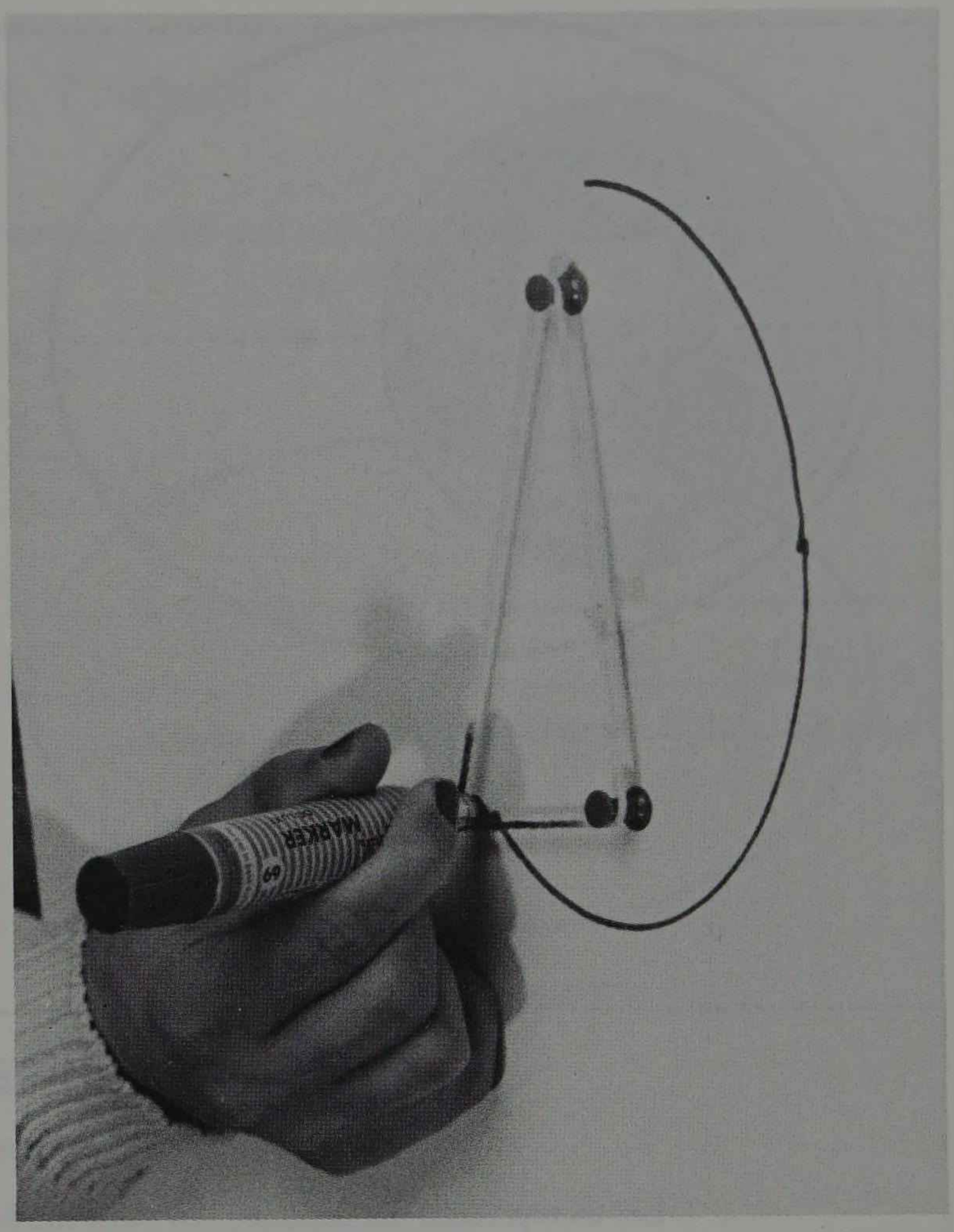


Figure 3.7 Drawing an ellipse.

can draw an ellipse by using two thumb tacks and a piece of string. See Figure 3.7. Stick the thumbtacks into a board; they will become the two *focal points* or *foci*. Tie the string into a loop and hang it loosely around the thumbtacks; then insert your pencil into the loop and draw it up tightly. As you move the pencil around the thumbtacks keeping the string taut, it will trace out an ellipse. Set the thumbtacks far apart for an elongated ellipse or set them close together for a near-circle. Set them on top of one another, i.e., use only one thumbtack at one focal point, and you will get a circle.

The *eccentricity* of an ellipse is a number between zero and one which tells just how elongated the oval is. It is calculated by dividing the distance between the foci by the length of the major axis as shown in MATHBOX 3.1. If the ellipse is a very elongated oval, then the eccentricity is close to one. At the other extreme, the eccentricity of a circle is zero.

Kepler's first law of planetary motion states that planets move in elliptical orbits with the Sun at one focus. The eccentricity of the Earth's orbit is very small, 0.017, indicating that the orbit is nearly circular. In fact, if you draw it to scale on a piece of paper, it looks like a perfect circle. Pluto's orbit has the greatest eccentricity of any of the planets, 0.248.

Satellite Orbits

Satellites in orbit around Earth also follow Kepler's first law, moving in elliptical paths with the center of Earth at one of the foci. The satellite's speed, direction, and distance from Earth at the instant the engines burn out determine the size and shape of the orbit. The only force acting is gravity, and left on its own, the satellite will follow its elliptical orbit and return to the point where the engines shut down.

The point of closest approach to Earth is called *perigee* and the point on the orbit farthest from Earth is *apogee*. (*Geos* is the Greek word for Earth.) In Figure 3.8, Earth is at F1, so perigee is at A and apogee is at B. Notice that perigee and apogee are on opposite ends of the major axis.

When referring to an orbit, the major axis is called the *line of apsides*. For an orbit around the Sun, the nearest and farthest points to the Sun are called *perihelion* and *aphelion* (The Greek word for Sun is *helios*.) The orbit is fixed in space with the spacecraft moving on it and Earth rotating under it.

The speed of a spacecraft varies from point to point in an elliptical orbit depending on how far it is from Earth. The farther out it is, the slower it travels. Thus, a spacecraft's speed must be greatest at perigee and slowest at apogee. As a consequence, its speed is increasing as it moves from apogee to perigee and it is slowing down as it moves from perigee back to apogee. This makes intuitive sense. A ball thrown upward, moving away from Earth, slows down; falling back, moving toward Earth, it speeds up. Of course, if the spacecraft's orbit is a circle then its distance from Earth does not change, perigee and apogee are undefined, and its speed is constant. MATHBOX 3.2 shows how to calculate the speed of a spacecraft in circular orbit.

Kepler recognized these facts in his studies of planetary motion around the Sun. His second law states that equal areas are swept out in equal times. At first glance, that statement seems unrelated to our previous discussion about speed, but look at Figure 3.9. In a certain time, say 10 minutes, the spacecraft moves from point a to point b

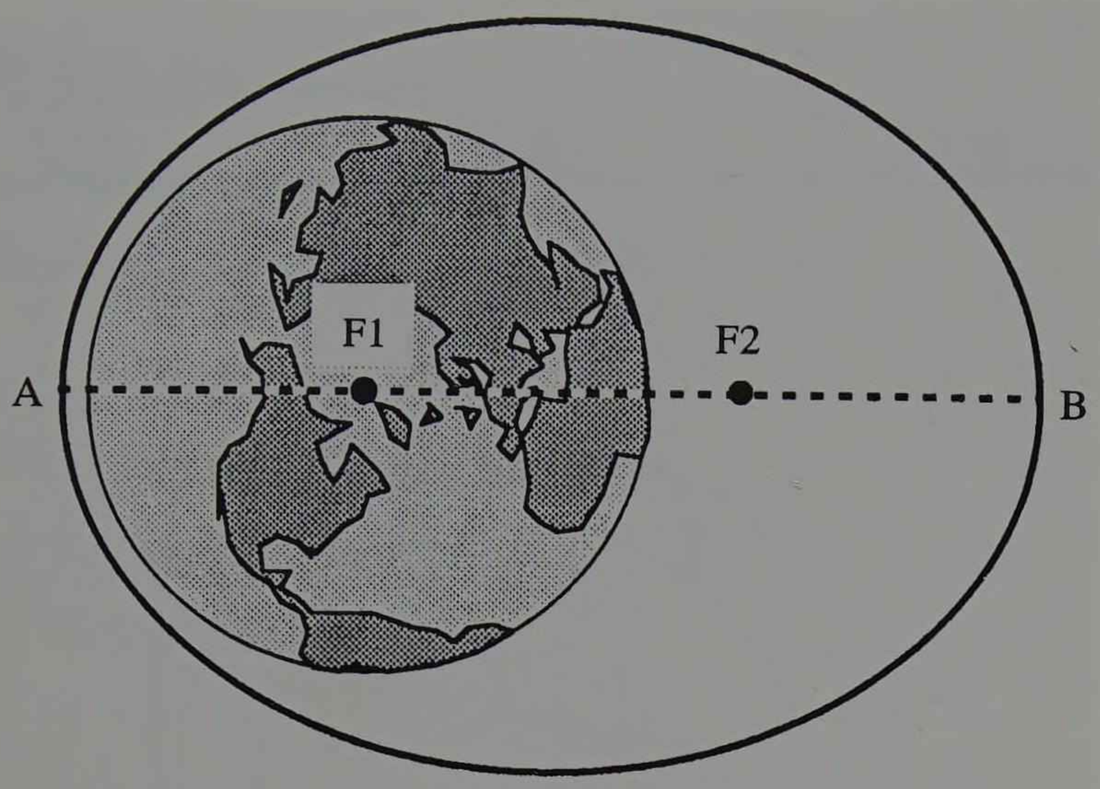


Figure 3.8 Elliptical orbit around Earth.

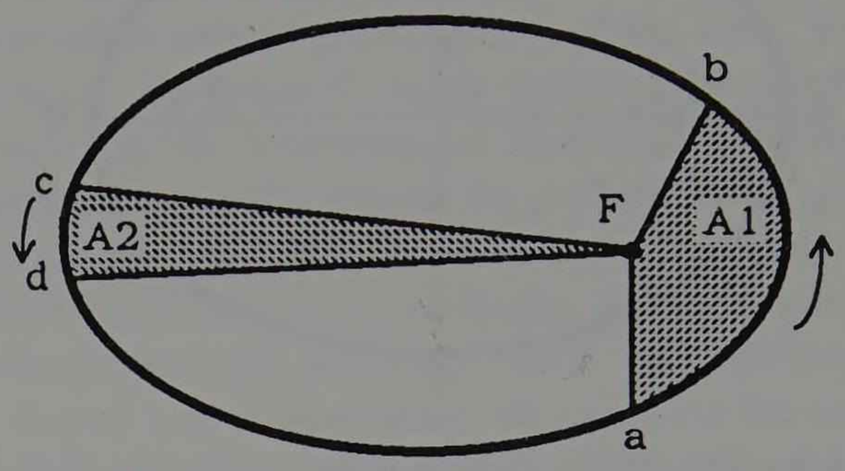


Figure 3.9 Kepler's second law of motion of orbiting bodies.

MATHBOX 3.1

Eccentricity

Let us represent the distance between the foci of an ellipse as f and the length of the major axis from A to B as d. The definition of eccentricity e is

$$e = \frac{f}{d}.$$

In the ellipse of Figure 3.1.1, f is 2 inches and d is 5 inches. Then its eccentricity is

$$e = \frac{2}{5} = 0.4.$$

In Figure 3.1.2, f = 4 inches and d = 5 inches. Its eccentricity is

$$e = \frac{4}{5} = 0.8.$$

Finally, the third ellipse in Figure 3.1.3 is really a circle with a diameter of 3 inches. The two foci are coincident so f = 0, and d is the diameter. The eccentricity of the circle is

$$e = \frac{0}{3} = 0.$$

Note that if the two foci are close together, the distance between them is very small, then the eccentricity is a very small number. In the extreme case where there is only one focus, the ellipse becomes a circle.

On the other hand, if the foci are far apart, the ellipse is elongated and the eccentricity is a larger number. In an extremely elongated ellipse, the distance between the foci is nearly the same as the length of the major axis of the ellipse and the eccentricity is nearly 1.

MATHBOX 3.1 continued

MATHBOX 3.1 Continued

So the eccentricity is a number with values between zero and one. It indicates how elongated the ellipse is.

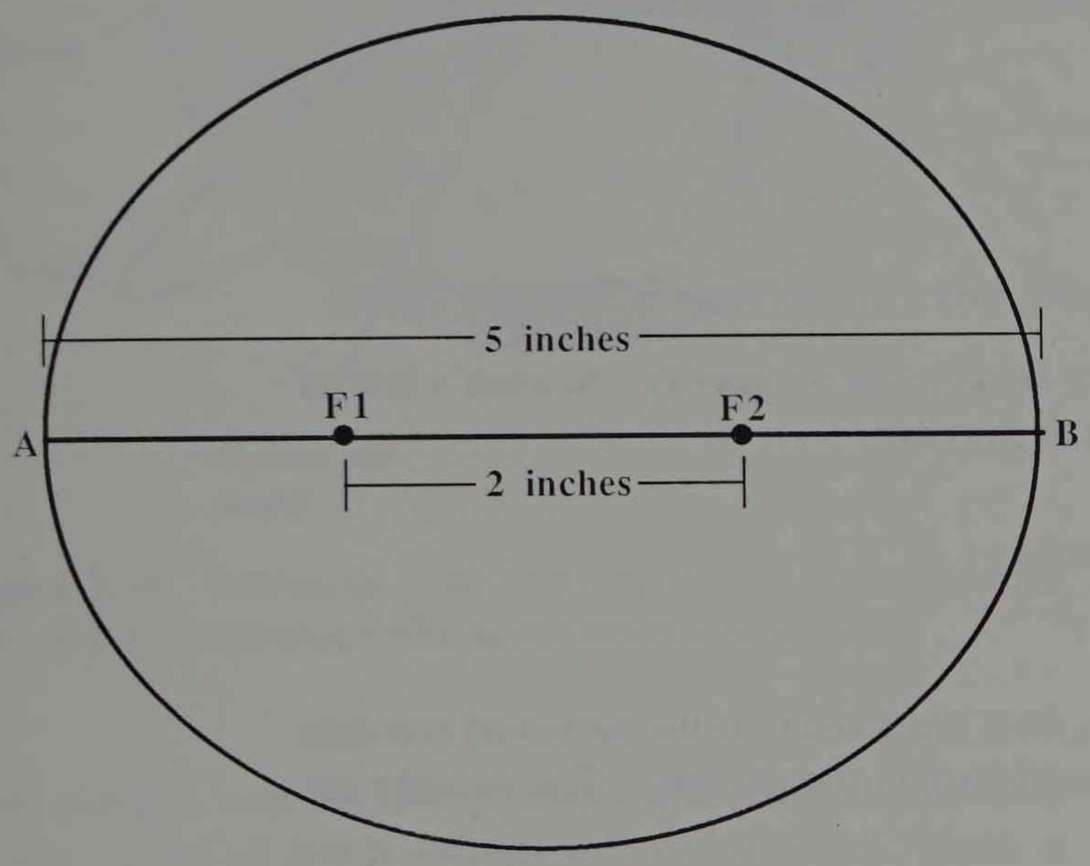


Figure 3.1.1 Ellipse, eccentricity of 0.4.

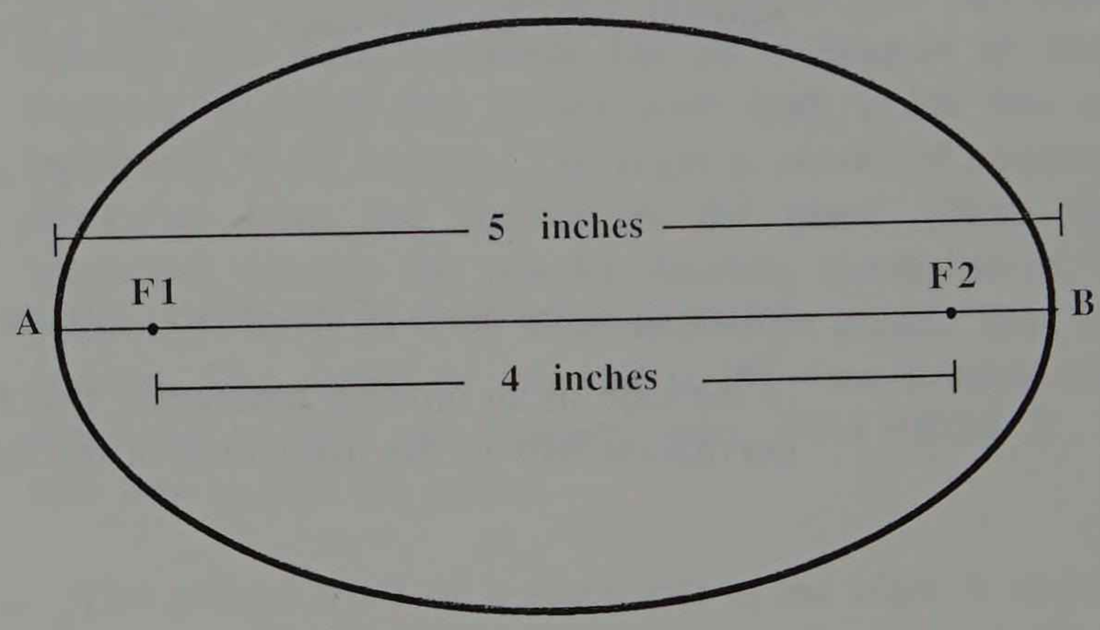


Figure 3.1.2 Ellipse, eccentricity of 0.8.

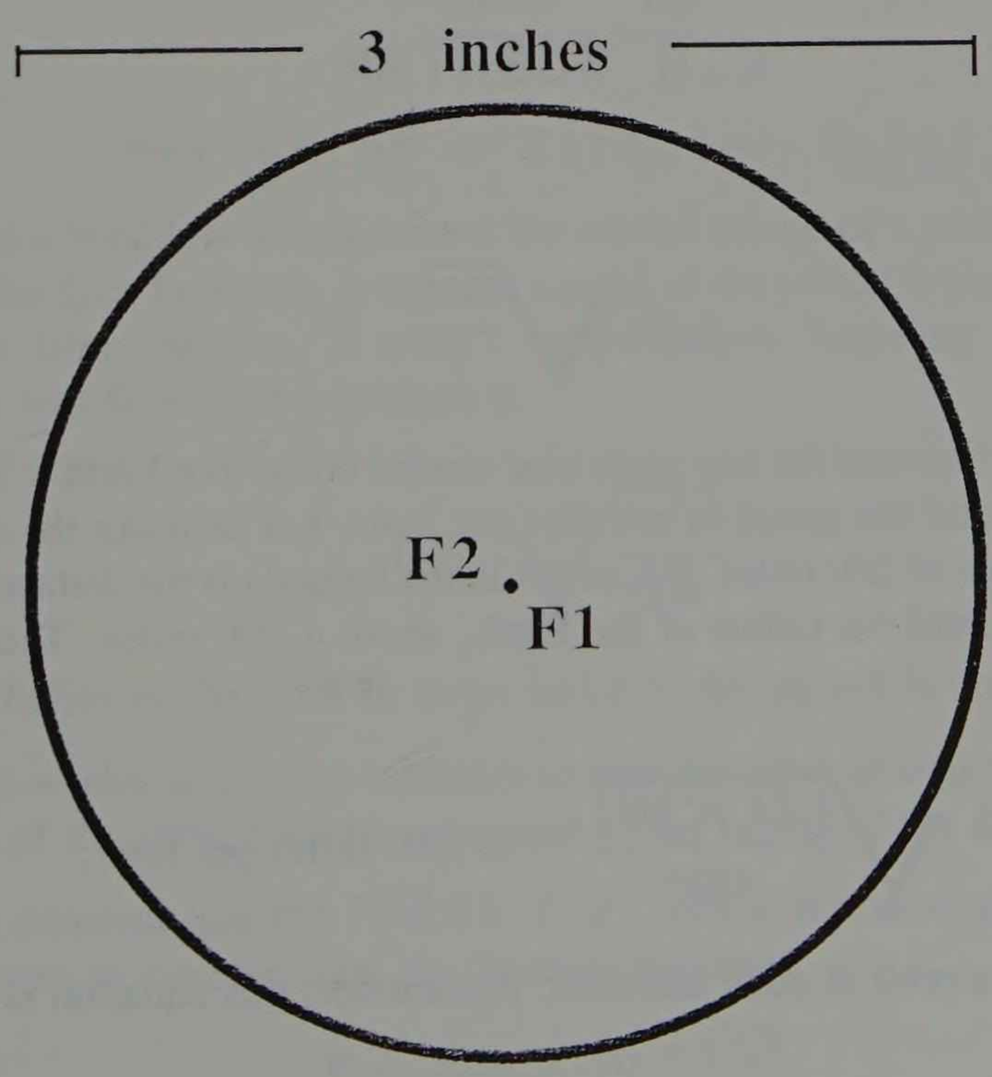


Figure 3.1.3 Circle, eccentricity of zero.

MATHBOX 3.2

Speed in Circular Orbit

According to Newton, an object will move in a straight line unless some force acts on it. Therefore, a force must be acting on a spacecraft to keep it moving in a circular orbit. That force, directed toward the center of the orbit, is gravity.

Any centrally directed force is called a *centripetal force*. Its magnitude is given by

$$F_c = \frac{mv^2}{r}$$

where m is the mass of the object, v is its speed, and r is its distance from the center.

In the case of an orbiting spacecraft, that force is supplied by gravity, Newton's law of gravitation tells us the magnitude of the force of gravity:

$$F_g = \frac{GmM}{r^2}$$

where M is the mass of the central body (Earth, Sun, etc.) and G is the universal constant of gravitation, a number which is the same everywhere in the universe. The m and r are the same as in the previous equation.

But the gravitational force is the centripetal force. therefore

$$\frac{mv^2}{r} = \frac{GmM}{r^2}.$$

If we solve this for v we get

$$v = \sqrt{\frac{GM}{r}}.$$

Now, G times M is a constant for any particular central body. For Earth it is 1.24×10^{12} if r is given in miles and the speed is in miles per hour. Let us make the calculation for an orbit with an altitude of 200 miles. Because r in the formula is the distance to the center of the orbit, we must add the radius of the Earth, about 4,000 miles. Then

$$v = \sqrt{\frac{1.24 \times 10^{12}}{4200}} = 17{,}180 \text{ miles per hour.}$$

Try this calculation for orbit at other altitudes. Remember, this equation is valid only for circular orbits.

G times M for the Sun is 4.13×10^{17}. How fast is the Earth moving, assuming the orbit to be circular?

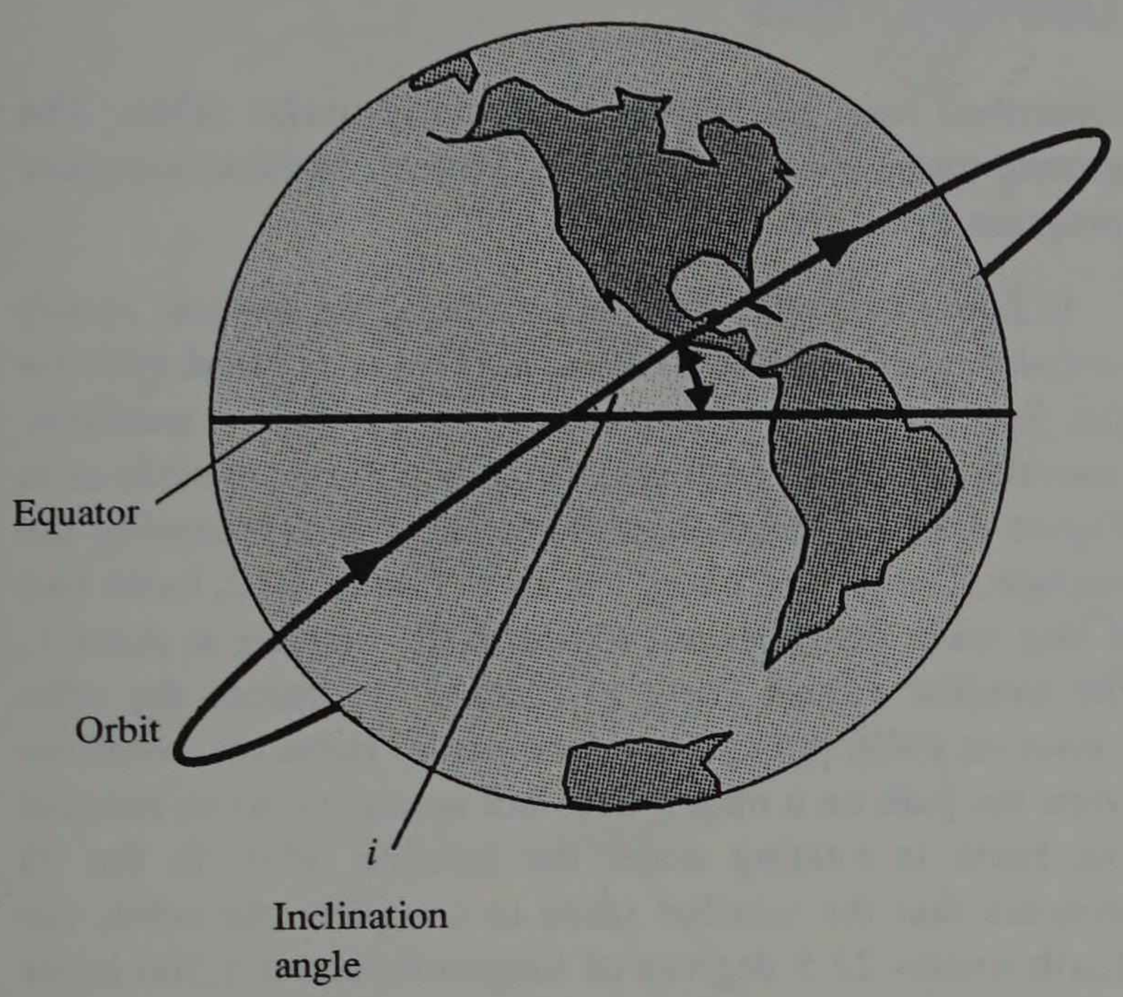


Figure 3.10 Inclination of an orbit, the angle, *i*, measured from the equator counterclockwise as the satellite heads north.

near perigee, and the line from the spacecraft to the focus at the center of Earth sweeps out the area A1. Since it moves slower at apogee, the distance covered in 10 minutes will be only from point c to point d, sweeping out area A2. Kepler's second law states that A1 must equal A2. The fact that the speed of an orbiting spacecraft depends on its distance from Earth is a most important consideration in orbital maneuvering and rendezvous.

The *inclination* of an orbit is the angle the orbit makes with the plane of the equator (Figure 3.10). An orbit directly over Earth's equator has an inclination of zero degrees; an orbit that passes over both poles has an inclination of 90 degrees. The angle is measured counter-clockwise from the equator at the place where the spacecraft crosses the equator heading north, so it is possible to have an orbit with inclination greater than 90 degrees. The *period* of an orbit is the time it takes the spacecraft to make one complete orbit. MATHBOX 3.3 tells how to find the period.

The *ground trace* of a spacecraft is the track it makes over the surface of the Earth. The inclination is the farthest north and south latitude that the spacecraft reaches on its ground trace. Ground traces, as we shall see, often make unexpected and unusual patterns when drawn on a flat map of Earth.

MATHBOX 3.3

Period of a Circular Orbit

Kepler also had a third law which related the orbital period of a planet, its ''year,'' to its distance from the Sun. In words, it says the square of the period is proportional to the cube of the distance from the Sun. It wasn't until Newton, however, that the constant of proportionality was found. The formula is

$$P = \sqrt{\frac{4\pi^2 r^3}{GM}}$$

where r is the radius of the orbit in miles and P is the period in hours.

Kepler's third law also applies to satellites in circular orbit around the Earth. Remember that the radius of the orbit must be measured to the center of the Earth.

Now, GM is a constant (see MATHBOX 3.2), and π is also a constant (3.14159). So for Earth satellites in circular orbit the formula becomes

$$P = 5.64 \times 10^{-6} \sqrt{r^3}.$$

For a satellite in a 200 mile orbit above the Earth, r is 4,200 miles. The period turns out to be 1.53 hours.

You can use the same formula to find the period of a planet given its distance from the Sun, or vice versa, but you must use the value of GM for the Sun. That number was given in MATHBOX 3.2. Try finding the period of the Earth.

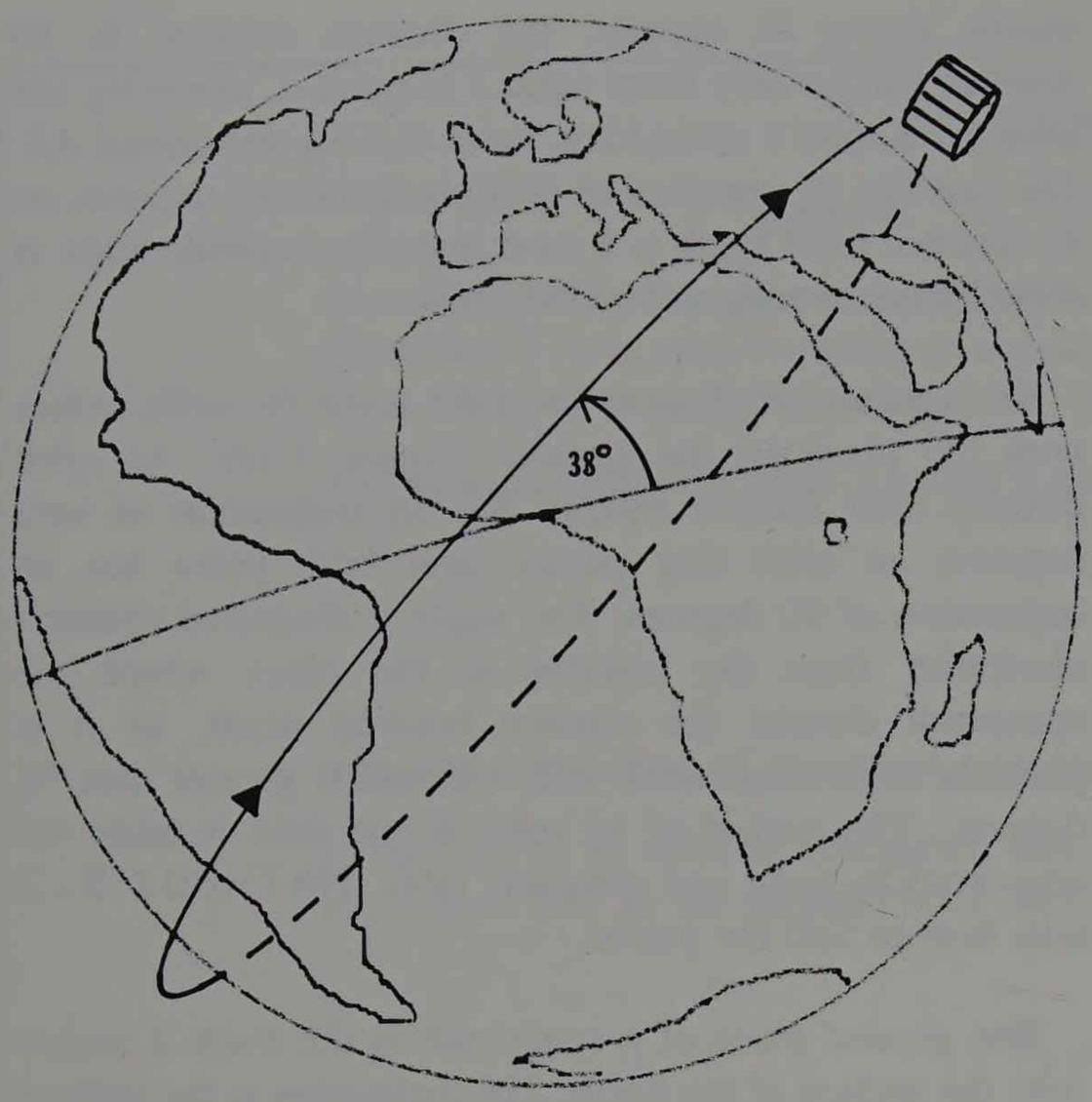


Figure 3.11 Circular low Earth orbit drawn to scale. Altitude is 150 miles, period is 90 minutes, inclination is 38 degrees. *Courtesy of Bob Damon.*

Useful Orbits

Described here are several particularly useful orbits. The ground traces were plotted using Project: Satellite computer program from Zero Page.

1. *Low Earth orbit, 150 miles above the surface, nearly circular, period about 90 minutes*. This is a typical orbit for the Space Shuttle, space stations, surveillance satellites, scientific research satellites, etc. When drawn to scale as in Figure 3.11 it appears remarkably low, just skimming the surface. The ground trace, shown in Figure 3.12, looks like a sine wave that does not repeat itself. Starting at point 1, the satellite circles Earth to point 5. In space, the orbit closes on itself; points 1 and 5 coincide. However, when we view the path on a map it does not appear to do so because the Earth is rotating under the satellite orbit. In the 90 minutes that the satellite takes to complete the orbit, the Earth rotates 22.5 degrees of longitude, about 1,500 miles at the equator. Therefore, during those 90 minutes the flat Earth map shifts to the east by that amount and the satellite does not pass over the point where it began, but 22.5 degrees of longitude further west. Each point on the ground trace is 22.5 degrees further west than the comparable point

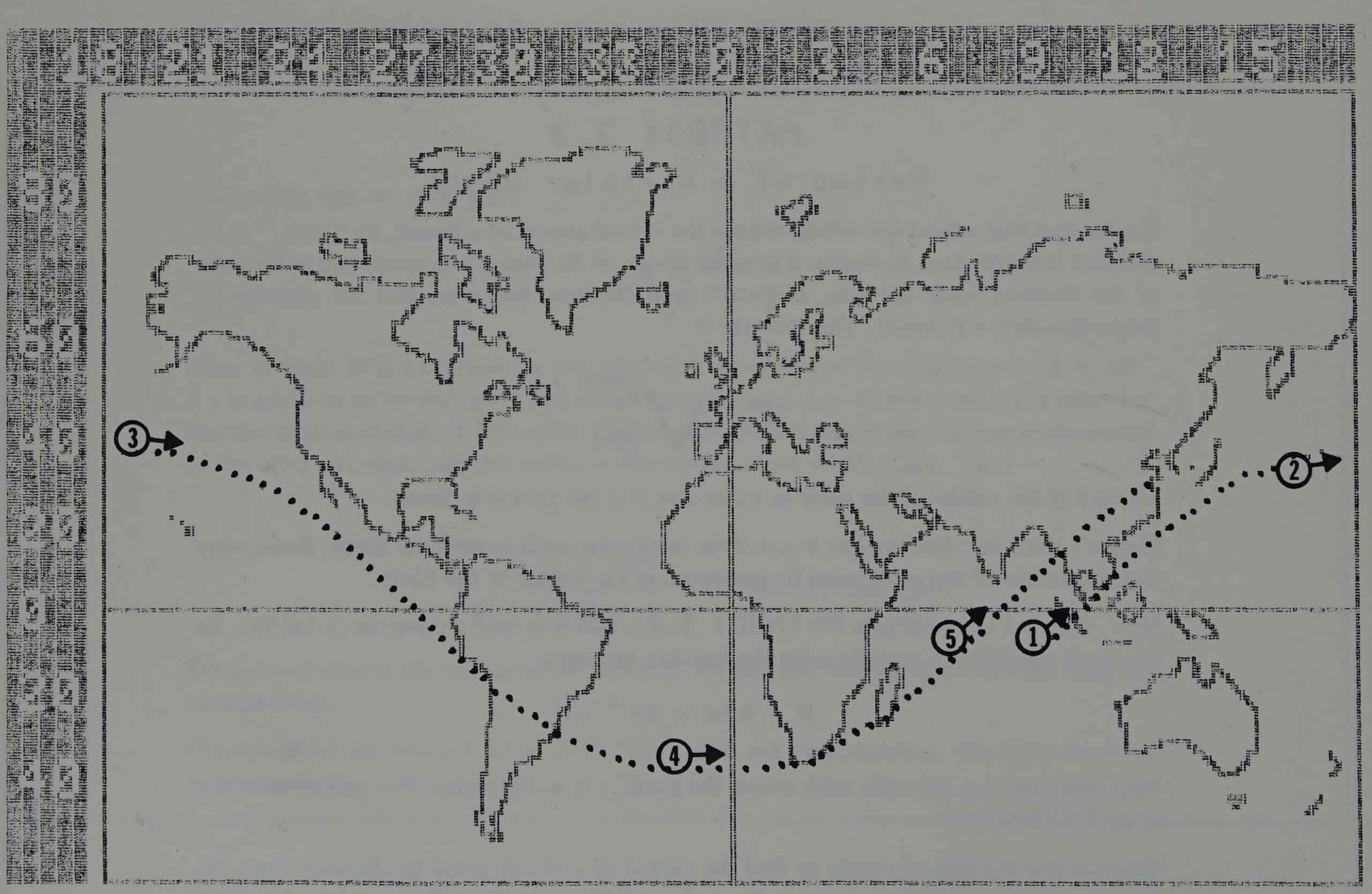


Figure 3.12 Ground trace of orbit shown in Figure 3.11. Dots show the location of the satellite at one minute intervals. Irregularities of the path are due to computer graphics limitations. Latitude is shown on the left in degrees north or south of the equator. Longitude, measured eastward from Greenwich, England, is shown at the top; add a zero to each number to read in degrees.



Figure 3.13 Polar orbit drawn to scale. Altitude is 500 miles, period is 100 minutes, inclination is 90 degrees. *Courtesy of Bob Damon.*

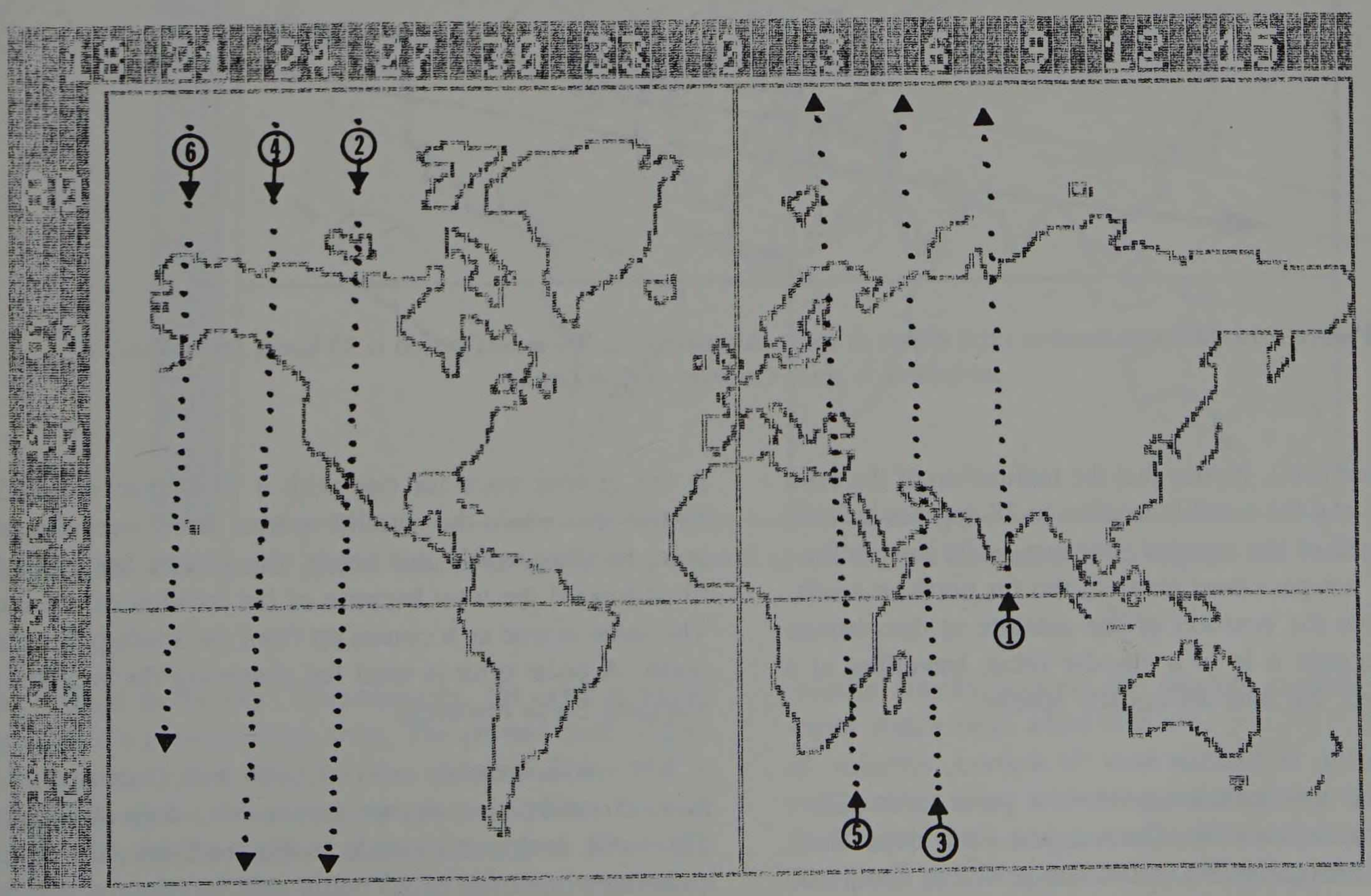


Figure 3.14 Ground trace of the 90 degree orbit shown in Figure 3.13. Two and a half orbits are shown. Dots show satellite positions at one minute intervals.

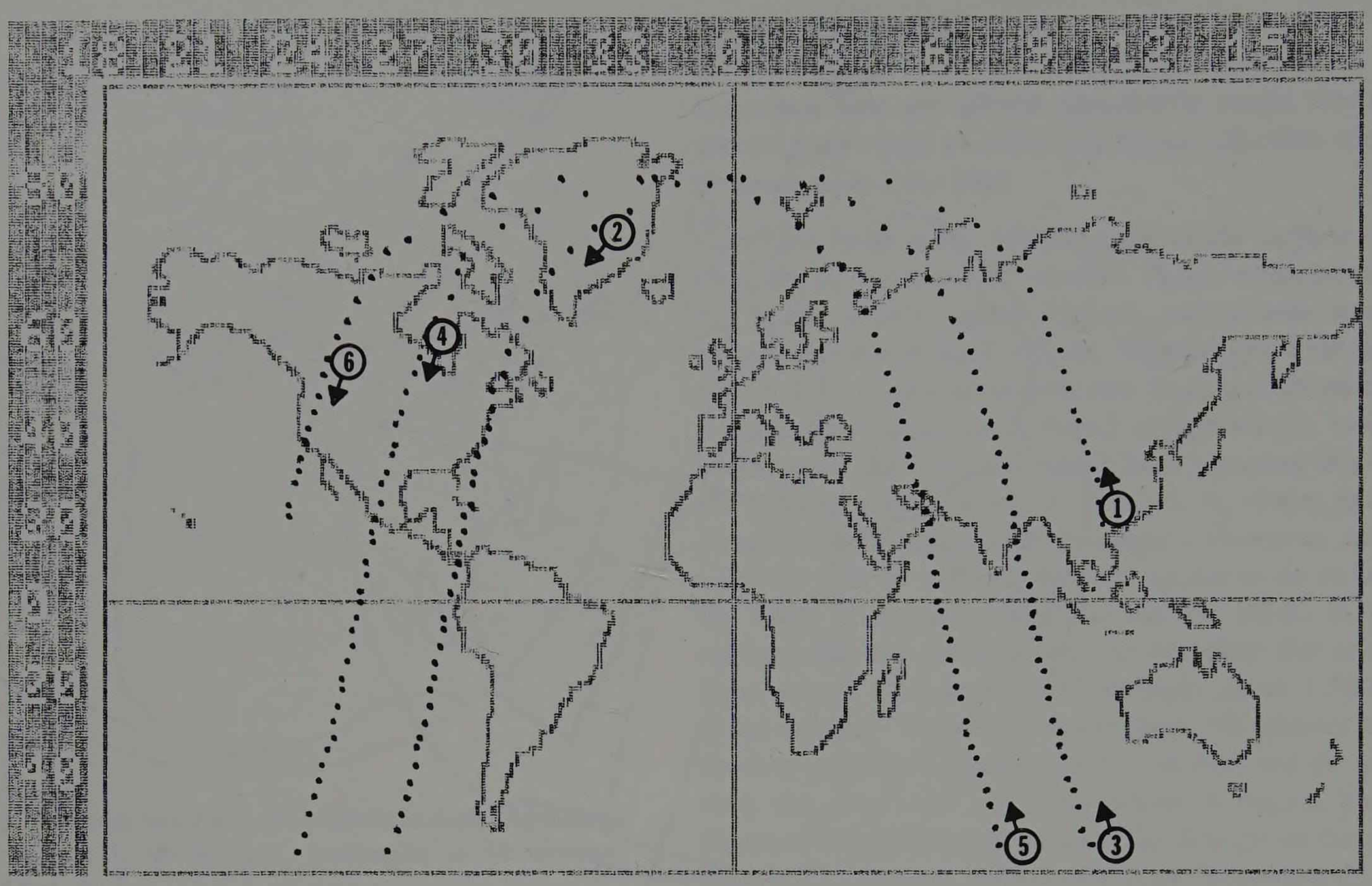


Figure 3.15 Ground trace of a 99 degree orbit. Notice that it reaches to 81 degrees latitude. Two and a half complete orbits are shown. Dots are one minute intervals.

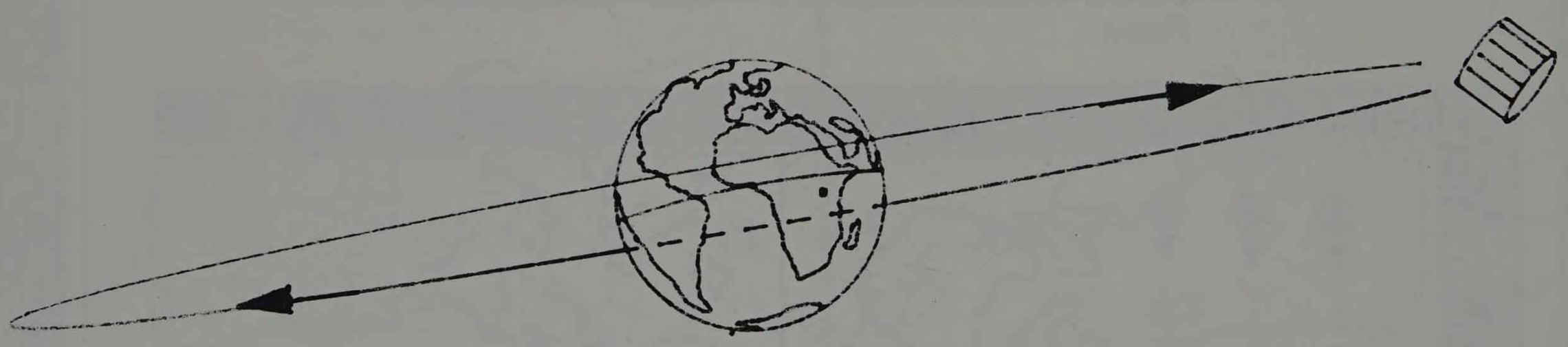


Figure 3.16 Geosynchronous orbit drawn to scale. Altitude is 22,300 miles, period is 23 hours 56 minutes, inclination is zero. *Courtesy of Bob Damon.*

on the previous orbit. Notice that the inclination of the orbit is 38 degrees and the satellite reaches to 38 degrees latitude north and south of the equator. Because of its low inclination, it does not pass over areas to the far north or south. The dots show the position of the satellite at one minute intervals. Because it is in a circular orbit, travelling at a constant speed, the dots are equally spaced.

2. *Polar orbit, inclination near 90 degrees, circular.* In contrast to the low inclination orbit, a polar orbit passes over the entire surface of the Earth in just a few days. Such an orbit at an altitude of 500 miles and period of about 100 minutes is drawn to scale in Figure 3.13. The ground trace for a 90 degree orbit is shown in Figure 3.14. Figure 3.15 is the ground trace for one with a 99 degree inclination. Notice that while the satellite comes down over the north pole, heading nearly due south, the ground trace is a line tilted toward the west because of the rotation of the Earth. The same is true as it comes up from the south pole headed north. A polar orbit is used for observing the weather and mapping Earth resources.

3. *Geosynchronous orbit, 22,400 miles above the surface, circular, zero degree inclination, over the equator.* This orbit is drawn to scale in Figure 3.16. The satellite completes one orbit in 23 hours and 56 minutes, the same time as it takes Earth to rotate once on its axis. Therefore, from a vantage point on Earth, the satellite appears to

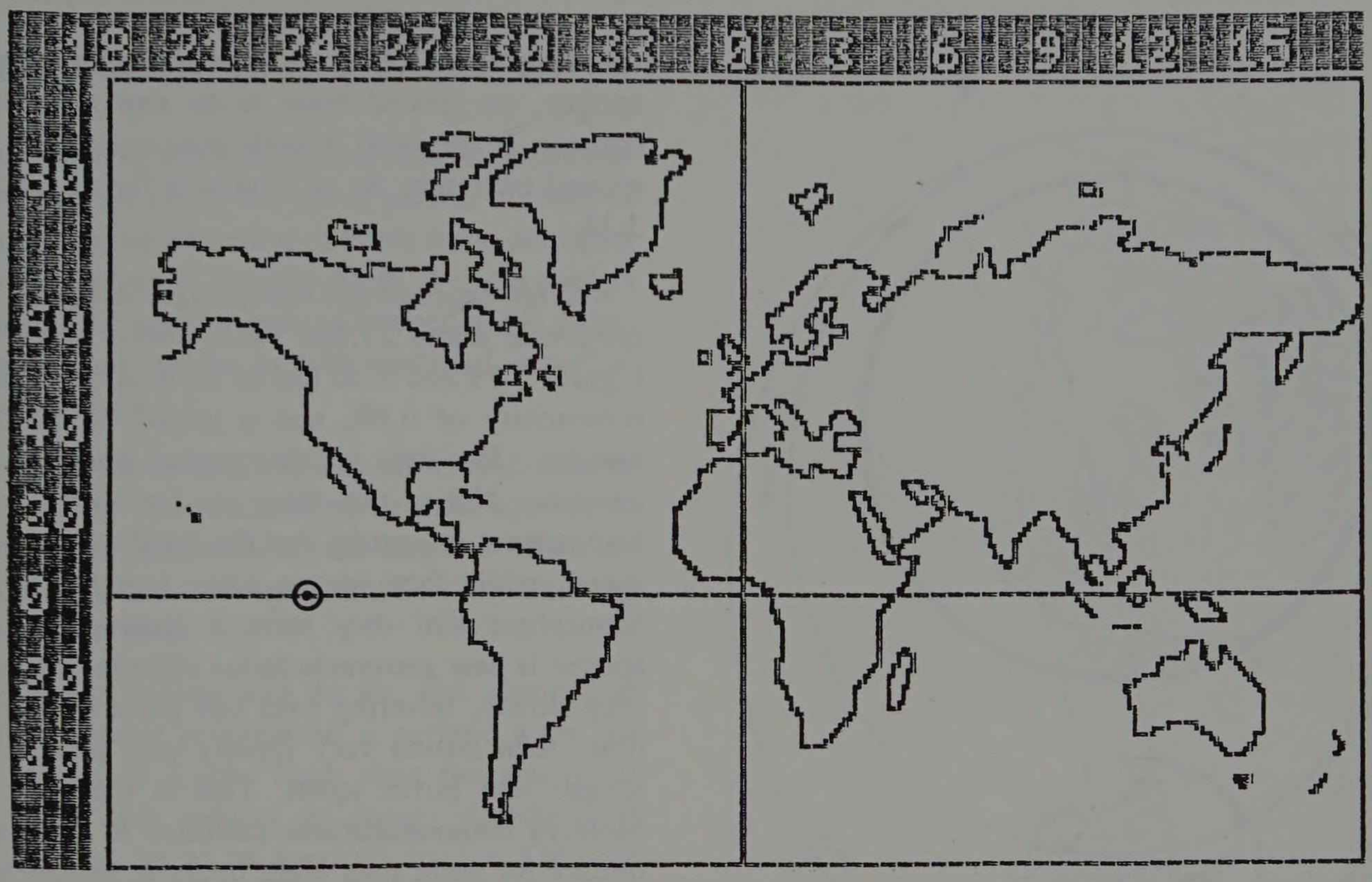


Figure 3.17 Ground trace of a geosynchronous satellite over a spot in the Pacific Ocean is simply a dot on the equator at that longitude.

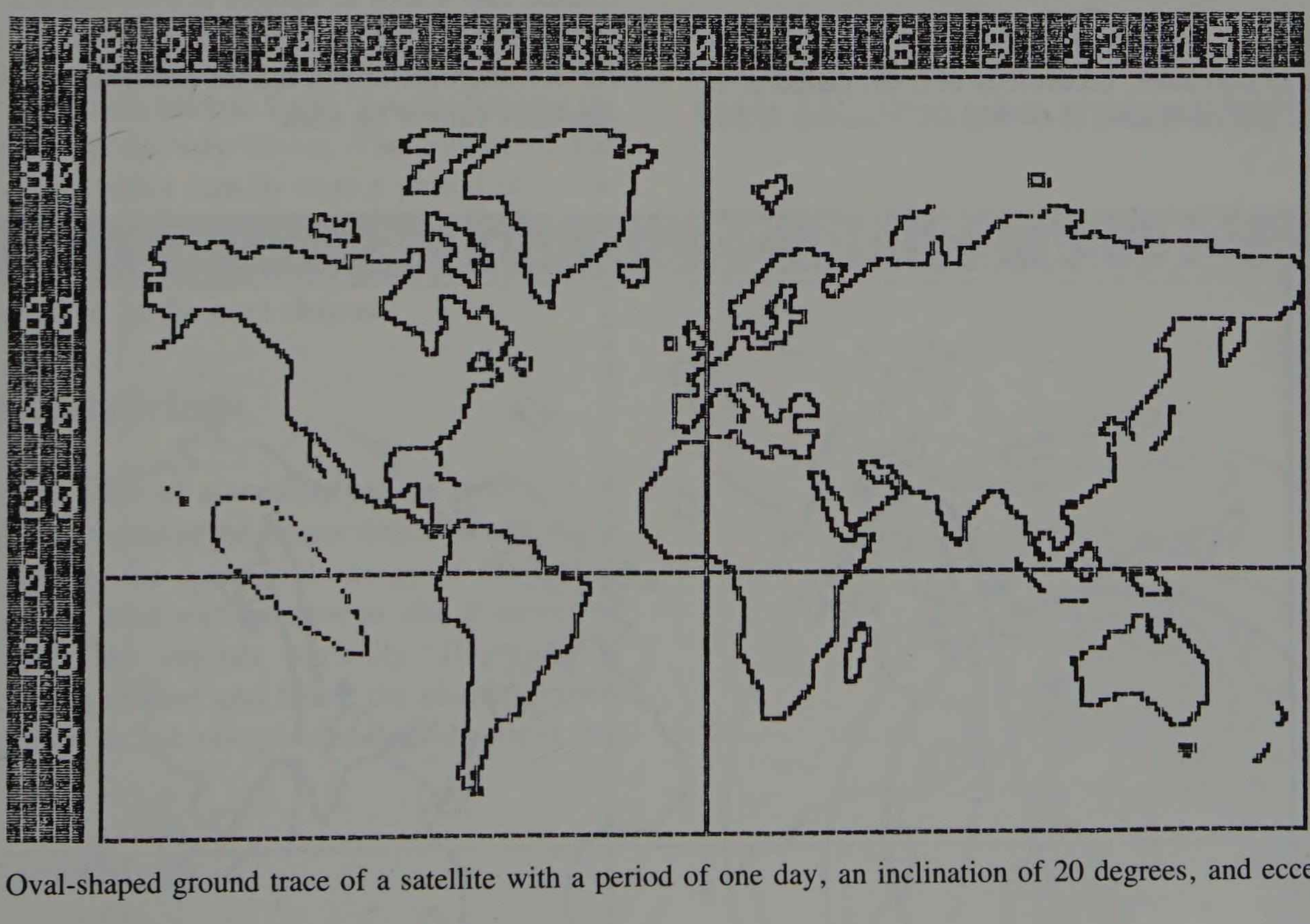


Figure 3.18 Oval-shaped ground trace of a satellite with a period of one day, an inclination of 20 degrees, and eccentricity of 0.2.

remain fixed in the sky. Consequently, the orbit is sometimes called a *geostationary orbit*. The ground trace, Figure 3.17, is simply one spot on the equator. This orbit is particularly useful for communications satellites because the antennas can be pointed at that fixed spot. From that altitude the satellite transmitter can cover nearly one-third of the Earth; it cannot reach far north countries, however. The geostationary orbit is also valuable for warning of missile attacks because the satellite sensors can continuously watch large areas of Earth.

There are some interesting variations on the geosynchronous orbit. If the orbit has an inclination other than zero, the satellite's ground trace is a line extending north and south of the equator to the latitude equal to the inclination of the orbit. If the orbit is not circular, then, because the satellite



Figure 3.19 Molniya orbit drawn to scale. Perigee is about 300 miles, apogee at 25,000 miles, eccentricity of 0.69, period of 11 hours 58 minutes, and inclination of 64 degrees. *Courtesy of Bob Damon.*

speeds up approaching perigee and slows down approaching apogee, its ground trace is an east-west line along the equator. If the orbit is both noncircular and inclined, the ground trace may be an oval or a figure eight. See Figure 3.18.

4. *High eccentricity, with perigee at about 300 miles and apogee at about 25,000 miles above Earth.* The orbit in Figures 3.19 and 3.20 has an inclination of 64 degrees, an eccentricity of 0.69, and a period of 11 hours and 58 minutes. The dots on the ground trace are at 5 minute intervals. Notice that they are far apart in the southern hemisphere, indicating that the satellite is travelling at high speed, while they are so close together in the northern hemisphere that they form a continuous line. Because apogee is near geosynchronous altitude, the satellite moves very slowly, hovering over one point on Earth for a long time, then moves very rapidly past perigee to return to apogee and hover again. This is the orbit of a Soviet Molniya communications satellite. It remains nearly stationary for more than eight hours at apogee over northern Siberia, and less than four hours as it drops down past perigee and returns to apogee. Meanwhile, Earth will have rotated half a turn so apogee is over Canada. Twelve hours later it is back over Siberia. This orbit is particularly useful for communications in the far north where geosynchronous satellites cannot be seen.

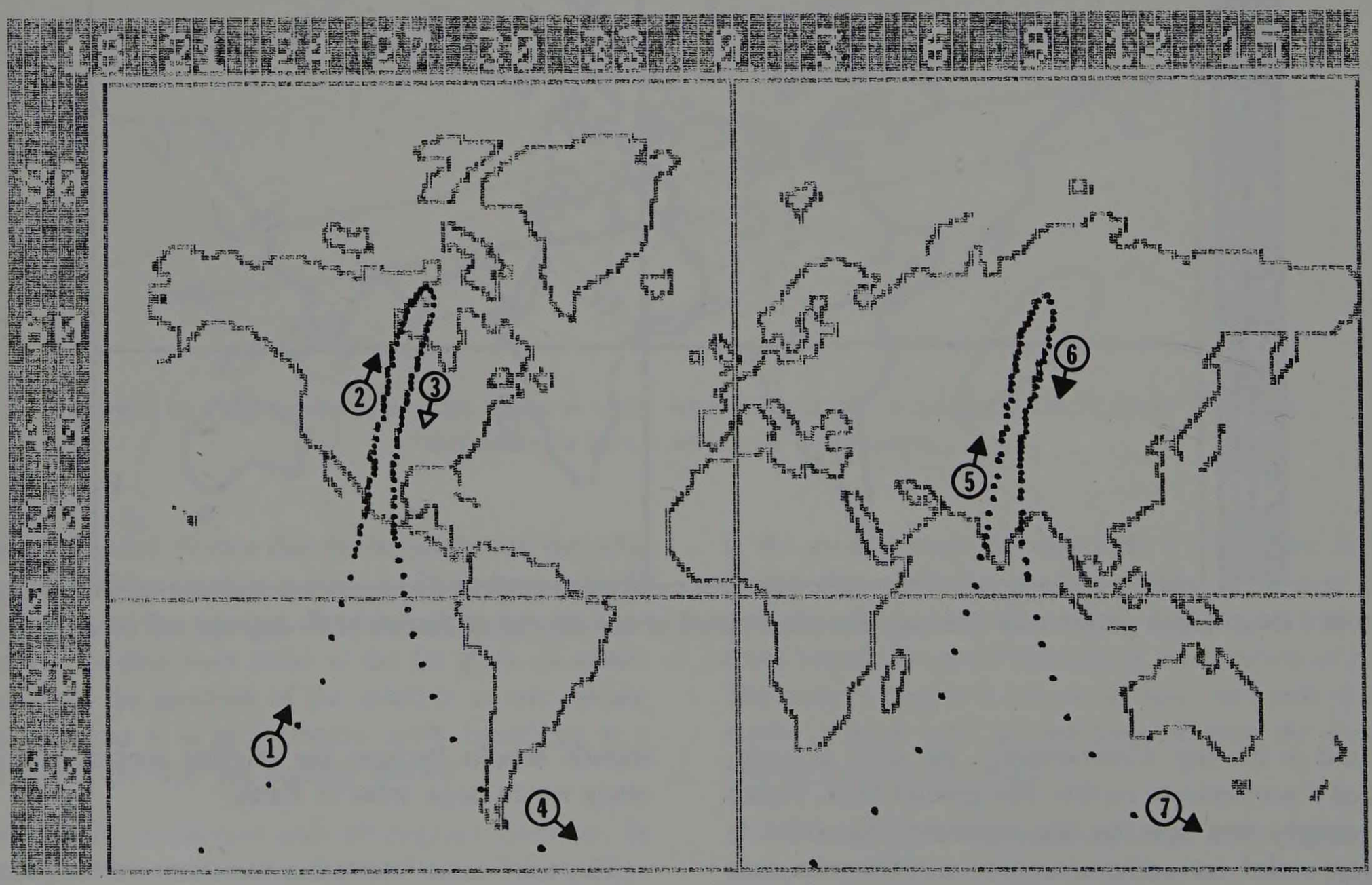


Figure 3.20 One day ground trace of Molniya orbit. Dots show satellite position at five minute intervals. Notice how the dots are close together in the northern hemisphere showing its slow speed near apogee; in the southern hemisphere the dots are far apart indicating the higher speed near perigee. Thus, the satellite ''hovers'' for 9 to 10 hours alternately over Siberia and over Canada and spends only about 2 hours in the southern hemisphere.

Orbital Perturbations

So far, our discussion of orbits has been somewhat theoretical. In the real world, orbits are never perfect ellipses or circles. The gravitational attraction of Earth is the dominant factor in shaping the orbit. But the Earth is not a perfect sphere; it bulges at the equator and is flattened at the poles. This causes the line of apsides to drift westward, a perturbation called *regression*.

The gravity of the Moon and Sun may affect high altitude satellites by changing their inclination or their altitude of perigee. The effect is small because the Sun and Moon are so far away, but may become significant as it accumulates over a long period of time.

Atmospheric drag, friction with the air, also changes an orbit. The effect is most pronounced at perigee when the spacecraft is closest to Earth. Each time the spacecraft passes perigee, the drag reduces its energy slightly so it cannot make it out as far as its previous apogee. On each orbit, then, apogee is lowered slightly while perigee remains at about the same altitude. The eccentricity decreases as the orbit becomes more circular. After a period of time apogee also lowers into the denser air so that the spacecraft experiences continuous frictional drag. Finally it cannot remain in orbit and it falls back to Earth, usually burning up in the atmosphere on its way down. The lowest of the satellite orbits decay rather rapidly over a period of a few weeks or months. Atmospheric drag varies seasonally, and with disturbances on the Sun and in the space environment, subjects to be covered in the next chapter.

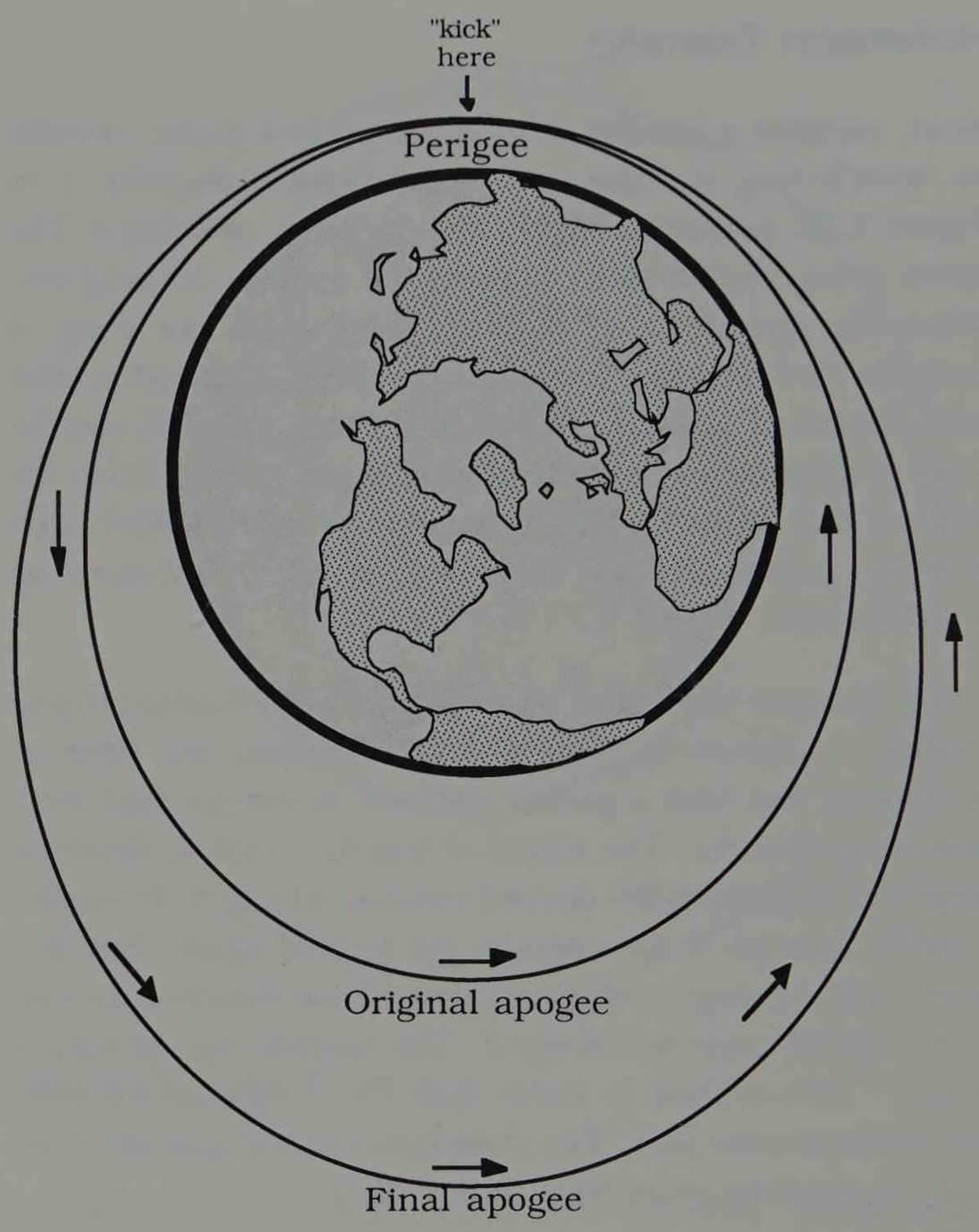


Figure 3.21 Firing rockets at perigee to increase eccentricity.

Orbital Maneuvering

Once in space, the orbit of a satellite can be modified or changed by applying thrust in the proper direction and at the proper time to change the speed and energy of the spacecraft. In general, the orbit will increase in size if energy is increased by firing the engines normally. If energy is decreased by turning around and firing the engines in the direction of motion, called *retrofiring*, then the orbit decreases in size.

Changing Eccentricity

Look at Figure 3.21. If the rockets are ignited at perigee the satellite's speed and energy increases. It will go into a larger orbit, farther out beyond its original apogee. The orbit has become more eccentric. Refer now to Figure 3.22. Suppose the satellite is at apogee when the rockets are fired. Once again, it transfers to a larger orbit because it has increased energy, but note that this time the orbit becomes less elliptical. If just the proper amount of energy is added the orbit becomes a circle. This technique, called "*apogee kick,*" is used to circularize the orbits.

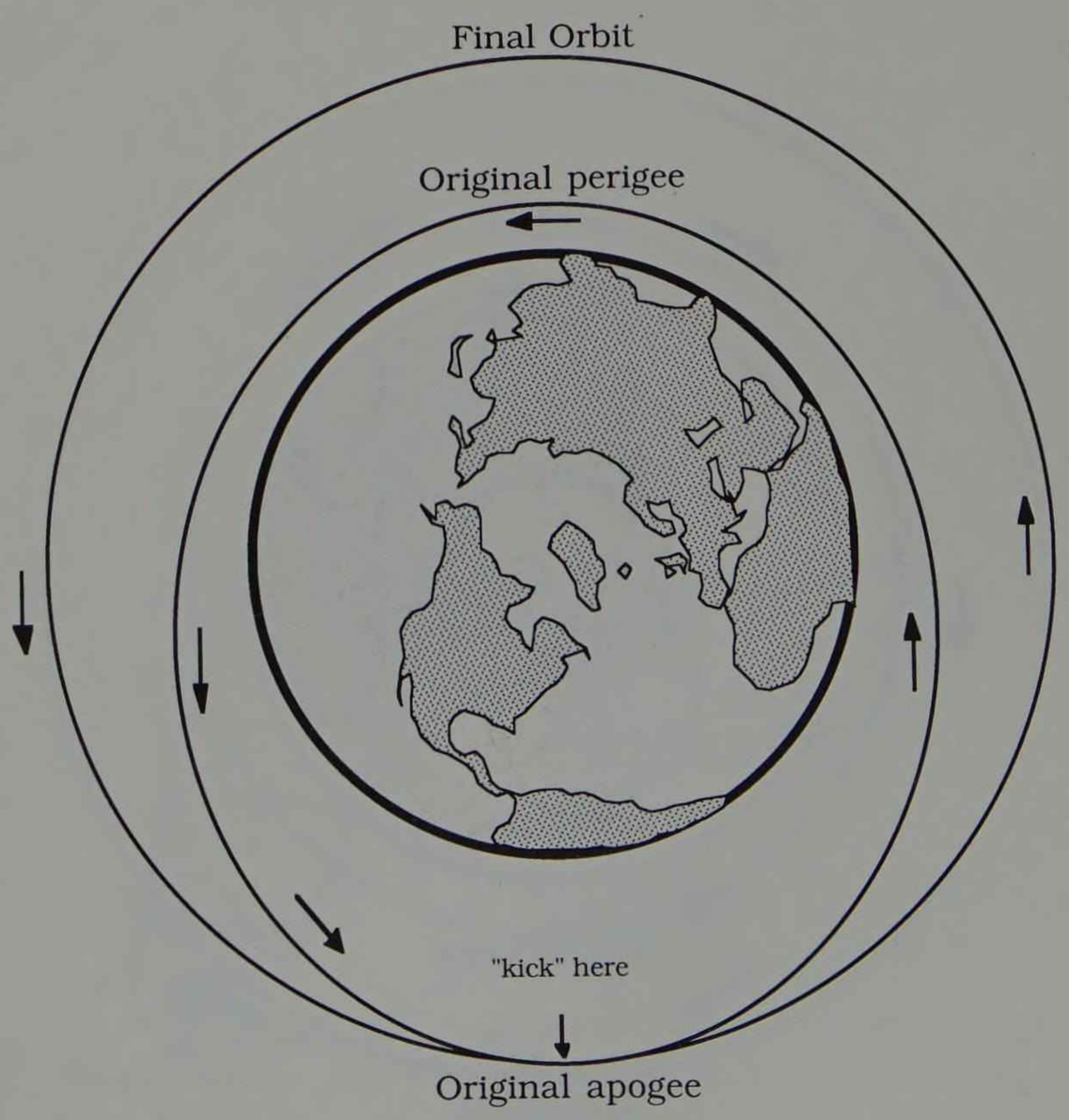


Figure 3.22 Apogee "kick" decreases eccentricity.

Hohmann Transfer

Next, suppose a satellite is to be raised to a higher altitude by transferring it from one circular orbit, position 1 in Figure 3.23, to another higher circular orbit, position 4. The move is accomplished by igniting the engines twice. First, when the satellite is at point 2, the rockets are fired to increase its speed and put it into an elliptical transfer orbit with apogee at 3, the desired final altitude. When it reaches point 3 the engines are ignited once more to circularize the orbit at that altitude. This maneuver is called a *Hohmann transfer,* named after the man who, in 1925, first came up with the idea.

An alternate method of moving from one circular orbit to another is shown in Figure 3.24. Engines are fired at position 2, but with a greater increase in energy than for a Hohmann transfer. The elliptical transfer orbit is therefore larger and intersects the desired circular orbit at 4. When the satellite reaches 4 the engines are ignited again, but this time greater energy is required because the direction as well as the speed must be changed. The satellite has to turn a corner. This method is faster than the Hohmann transfer, but requires more fuel. The Hohmann method uses the least fuel but requires more time to complete.

Moving from a larger, higher altitude orbit to a lower, smaller orbit may be accomplished by a Hohmann transfer, also. Retrofiring the rockets moves the satellite into an elliptical transfer orbit. Then a second retrofiring at the perigee of the transfer ellipse circularizes the orbit at the desired altitude. Again, there are faster ways of doing it, but the Hohmann technique requires the least fuel.

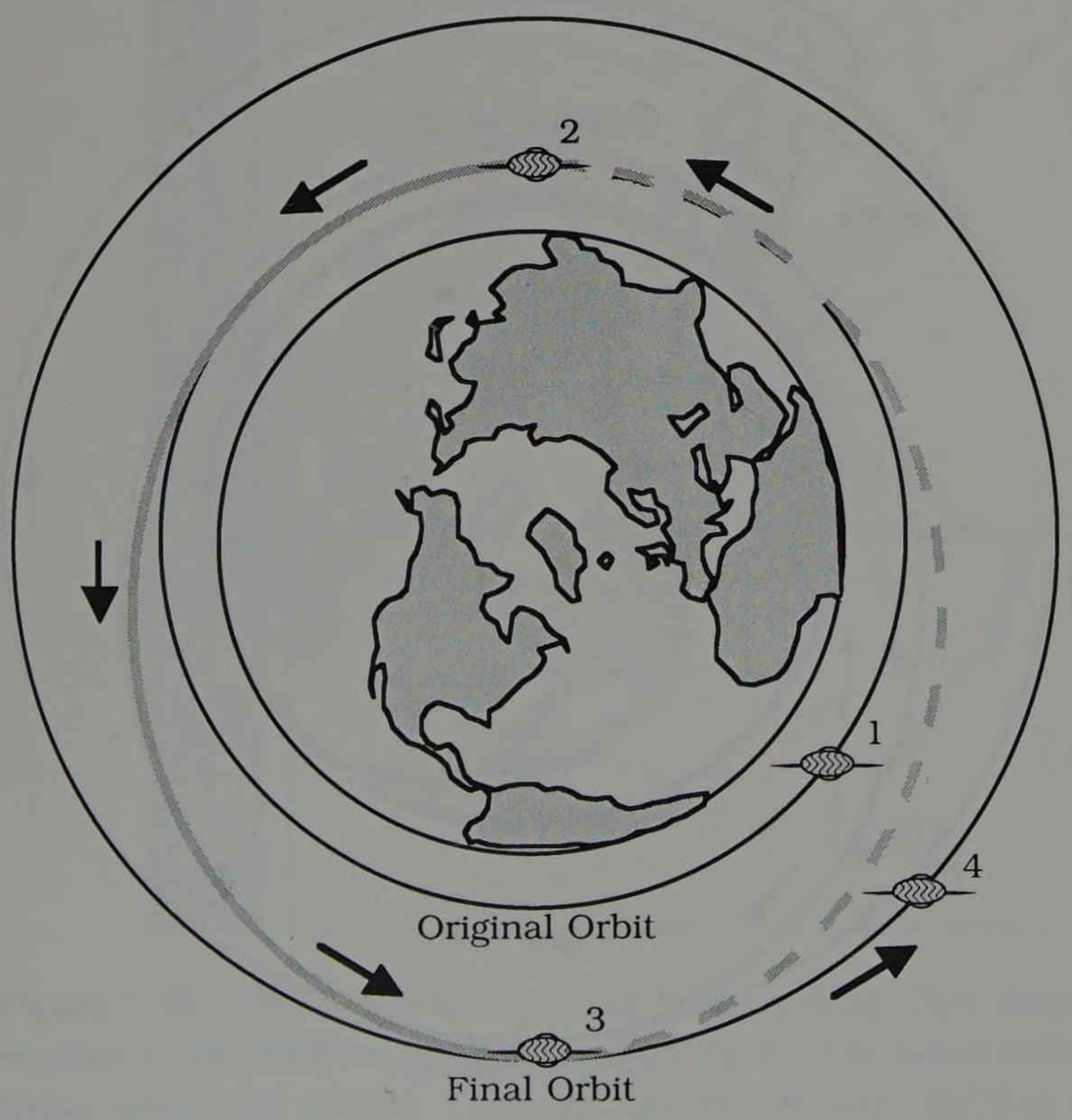


Figure 3.23 Hohmann transfer from a lower to a higher orbit.

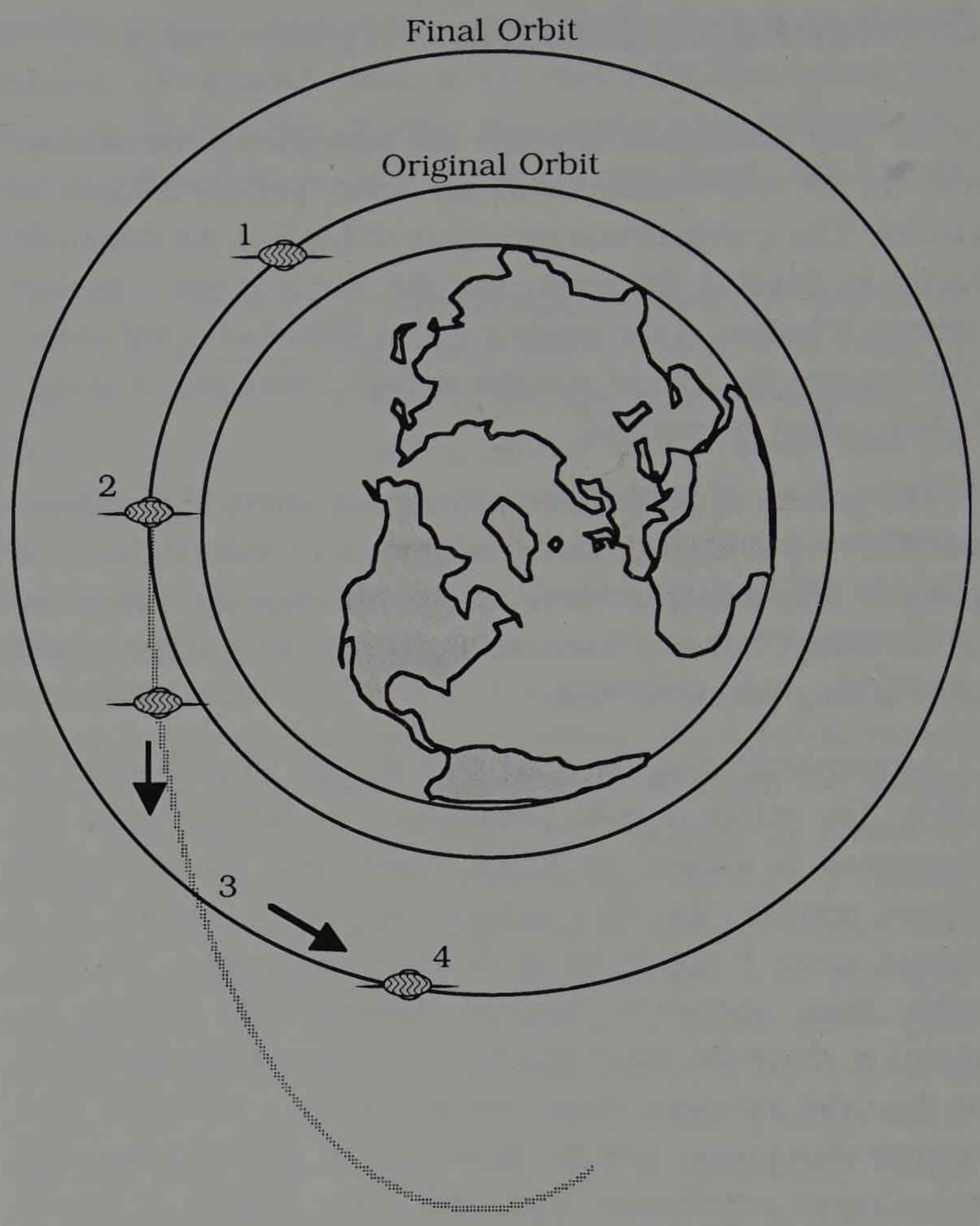


Figure 3.24 Fast transfer from a lower orbit to a higher one.

Rendezvous

How can one spacecraft catch up and rendezvous with another. It sounds like a simple problem. Luke Skywalker and Hans Solo had no problem in the Star Wars movies. Just point at the Empire tie fighter or cut inside his turn and "step on the gas." That is the way jet fighter pilots do it.

In the real world of space it is not so easy. A jet fighter is supported by its wings moving through the air and the air in turn produces a frictional drag on the aircraft. By increasing the drag more on one side than the other the plane turns in the direction of the greater drag. This is accomplished with ailerons, elevators, and rudders. But in space there is no air to "push against."

The first successful orbital rendezvous came in December 1965, when Wally Shirra and Tom Stafford in Gemini VI came within a foot of Gemini VII carrying Frank Borman and Jim Lovell and flew side by side for over five hours. Figure 1.5 is a photograph of their success.

Imagine you are in orbit in a spaceship and want to join up with a space station just ahead of you. You are both in the same orbit and therefore going at the same speed. You aim toward the space station, fire your engines to catch up, and discover that you fall further behind. Why?

Look again at Figure 3.24. Suppose your spaceship is in the inner orbit and you are at perigee. Fire your engines and you increase your speed and your energy. Therefore, you will not remain in that orbit, but will move to the larger, higher orbit. To further complicate the situation, because you have transferred to a higher orbit, you move farther from Earth and consequently you slow down, even though you just fired your engines to speed up.

Rendezvous with another spacecraft, then, is rather tricky. Increasing your energy to catch up will move you to a higher orbit and you will, instead, fall behind. Imagine you are at point Y1 in Figure 3.25 and want to rendezvous with the space station now located at point S1. Ignite your engines to move to the elliptical transfer orbit. The proper increase in energy will put you into an orbit which touches the space station's orbit at point 2, the apogee of your transfer orbit. When you reach 2 you again fire your engines, an apogee kick, to transfer to the space station's orbit. This is actually a Hohmann transfer.

The tricky part is to time your engine ignition in such a way that you and the space station both reach the rendezvous point, 2, at the same time. Because the space station is in a higher orbit, it is moving at a slower speed. Therefore, you must wait until it is closer to the rendezvous point than you are because you are travelling at a higher speed. Calculating the exact time is quite involved and we will not go into it here.

Other Maneuvers

It is also possible to change the inclination of an orbit, change the location of perigee, rendezvous with spacecraft

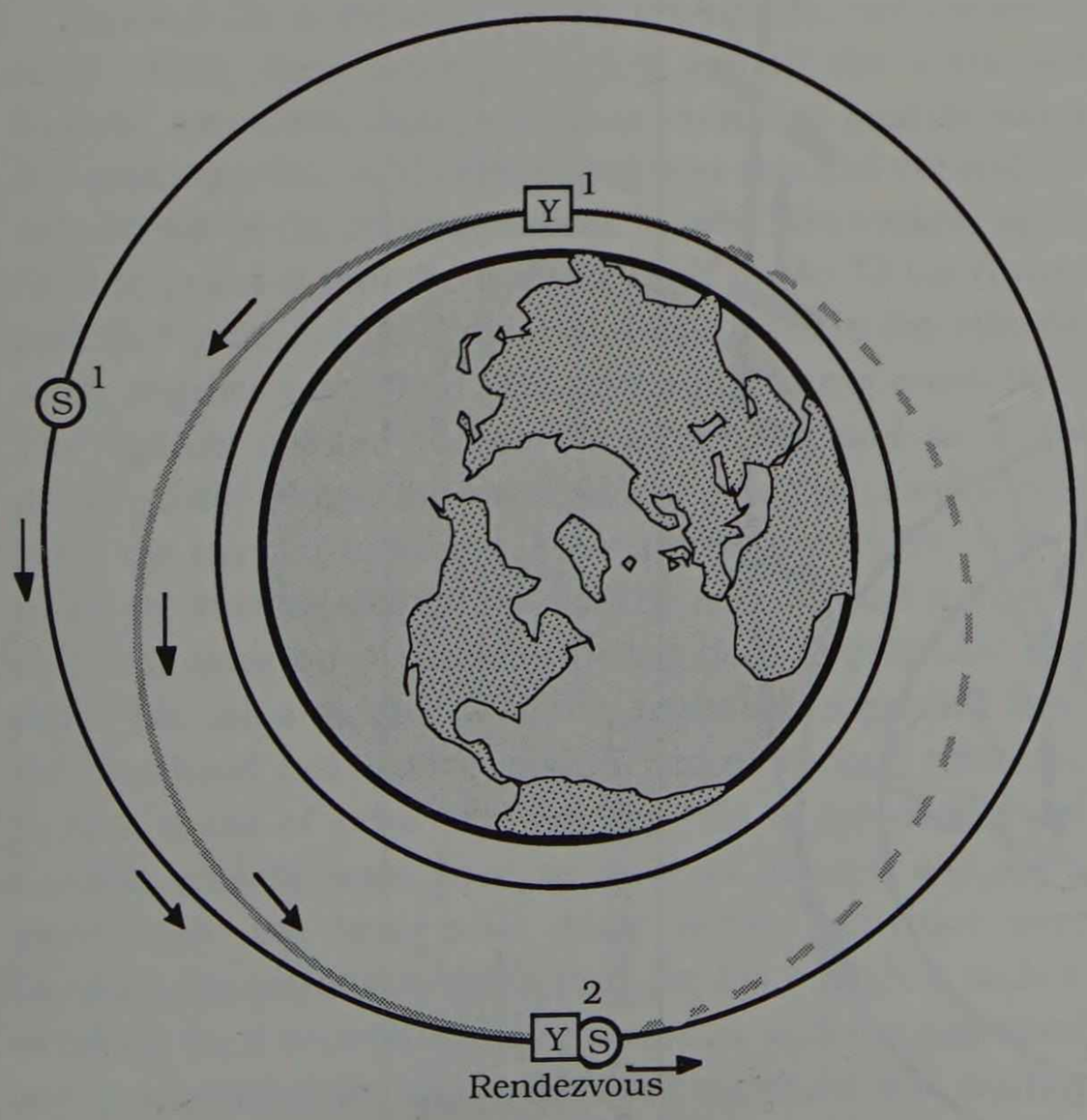


Figure 3.25 Rendezvous in space using a Hohmann transfer.

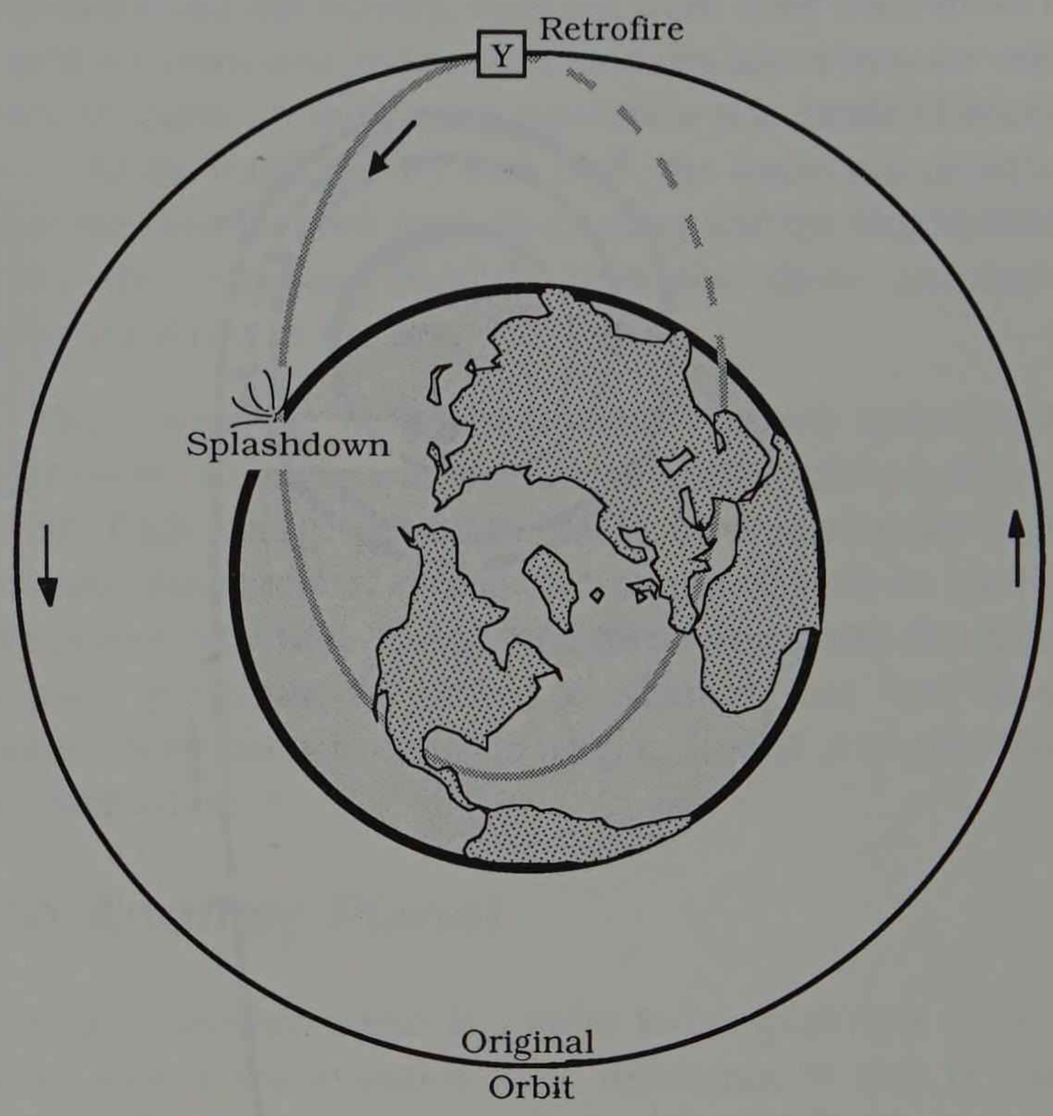


Figure 3.26 Deorbit maneuver.

in different orbital planes, and perform other maneuvers. Each requires the application of the proper amount of thrust in the proper direction and at the proper time.

Deorbit

Reentry and landing back on Earth is accomplished by turning the spacecraft around and firing the engines to apply thrust in the opposite direction. Retrofiring reduces the

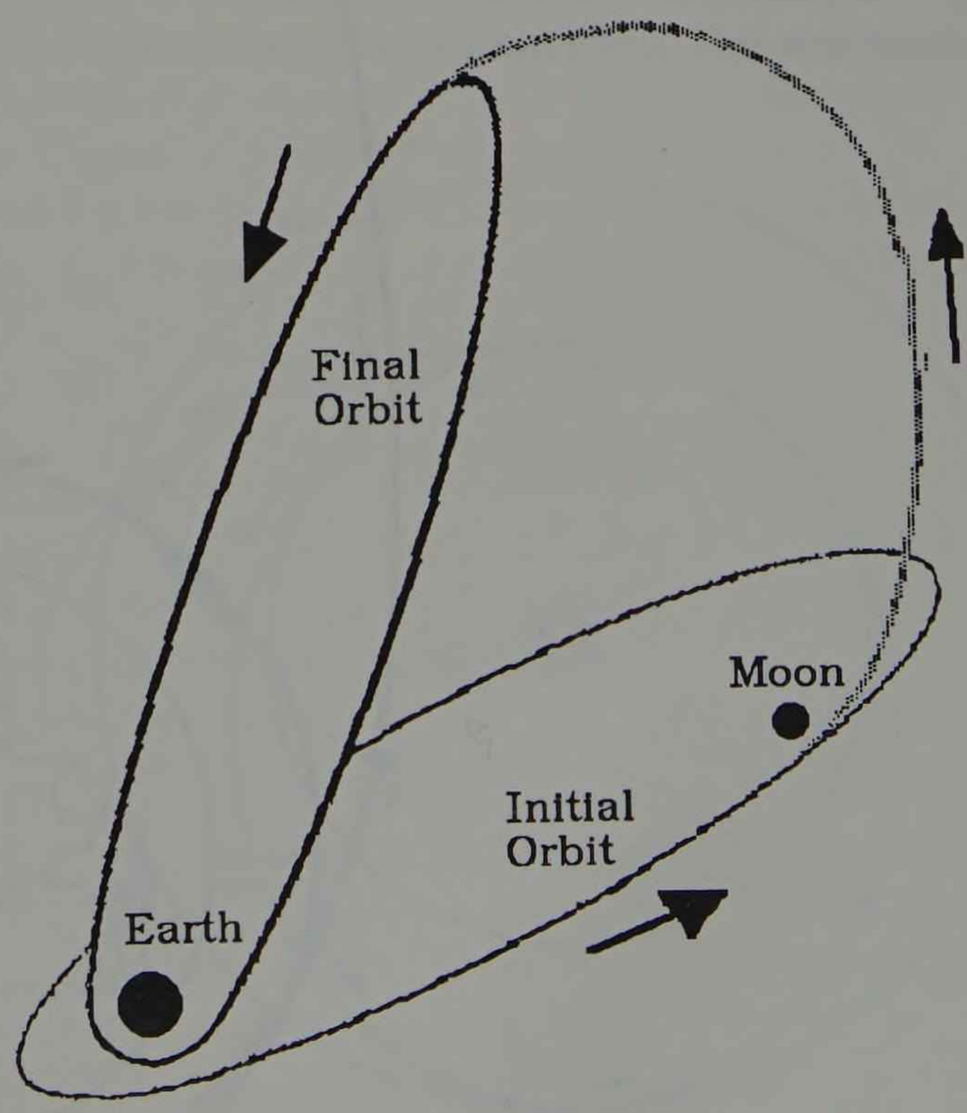


Figure 3.27 Trajectory past the Moon transfers the spacecraft to a new orbit around Earth.

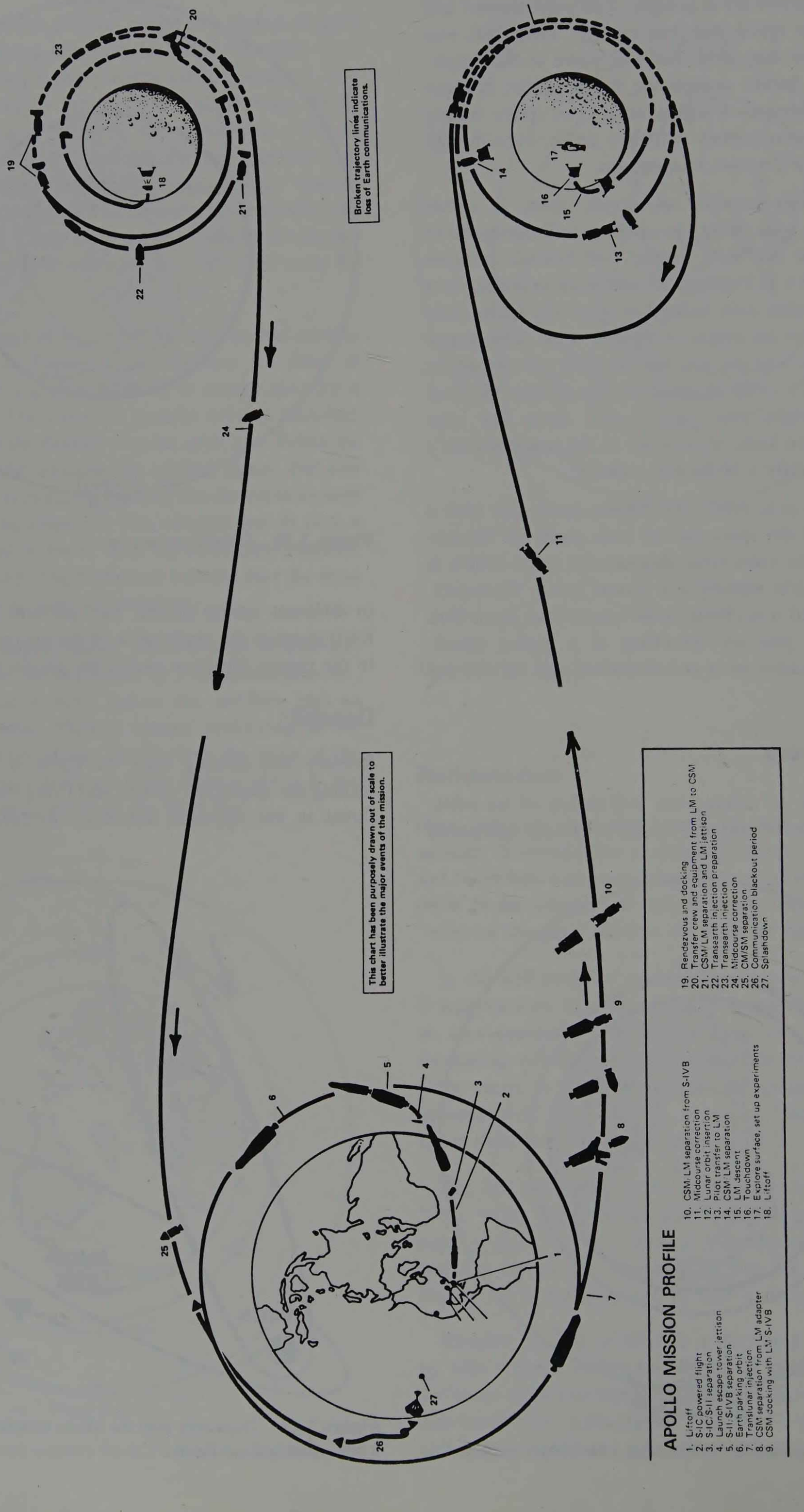


Figure 3.28 Apollo mission to the Moon. *Courtesy of NASA.*

spacecraft's energy, transferring to a lower orbit which intersects Earth, increasing speed as it falls. In Figure 3.26, retrofiring at the place shown transfers the spacecraft to the more elliptical orbit which intersects Earth at the place of splashdown. Timing and length of burn must be precise so the new orbit intersects Earth at the desired location for landing. The atmospheric drag during reentry distorts the orbit from a true ellipse which must be taken into account also.

Trajectory to the Moon

The Moon is in orbit around the Earth just like a spacecraft, so going to the Moon is similar to a rendezvous maneuver. There is one important difference, however; the Moon is so large that its gravitational attraction will control the orbit of the spacecraft as it draws near.

Consider first a Hohmann transfer. The rockets are ignited to inject the spacecraft from a low Earth orbit to an elliptical transfer orbit with apogee at the Moon. As the spacecraft heads for apogee it slows down, as usual. But as it approaches the Moon and comes under its gravitational influence, it deviates from its transfer ellipse and falls toward the Moon with increasing speed. One of two things may happen: 1) it hits the Moon or 2) it misses but, because of its speed, curves around the Moon and escapes. Continuing on, it is then in a different elliptical orbit around Earth. Figure 3.27 shows this situation. If our goal was to land on the Moon we did something wrong. We succeeded in our rendezvous, but our speed was too great. The solution is to slow down at the proper moment so the spacecraft is captured by the Moon and goes into a lunar orbit.

Figure 3.28 is the Apollo mission profile, not drawn to scale. First, the Saturn V rocket carried the command module, service module, and lunar excursion module into a low parking orbit. After everything was checked out and the vehicle was at the correct position in orbit, the rockets again fired to inject it into the transfer orbit to the Moon (lower path in Figure 3.28). If there was any error in the transfer orbit, engines were fired again for a midcourse correction. The vehicle coasted for nearly three days and as it approached the Moon, the gravitational attraction caused it to leave the transfer orbit and curve around the Moon. Retrofiring the rockets slowed the vehicle and injected it into an elliptical lunar orbit. Another rocket burn circularized that orbit. The lunar module with two astronauts separated from the command and service module and its rockets retrofired to take it out of orbit to a landing. As it approached the surface, rockets were fired to slow its descent and set it gently onto the lunar soil. After surface activities were finished, the astronauts again fired the lunar module rockets to take it back to orbit and a rendezvous with the command and service modules where the third astronaut was waiting (upper part of Figure 3.28). The lunar module was then separated and left behind. Engines were fired once more to inject the command and service modules into a transfer orbit back to Earth. A midcourse correction was made if necessary. As the Earth gravity took over, the spacecraft deviated from the transfer orbit for a direct entry into the atmosphere. Only the command module with the three astronauts splashed down in the sea.

These were the most complicated manned spaceflights ever made. Count how many times rocket engines had to be fired! Each firing had to be made at precisely the right moment for precisely the correct period of time in exactly the proper direction. Computing those times and directions applied principles of orbital mechanics that had never before been used in manned flight. It was a tremendous accomplishment.

To Another Planet

Flying to another planet is similar to completing a rendezvous with a space station. The difference is that in near Earth orbits, the gravitational attraction of Earth controls the orbit, while in interplanetary space the Sun is in control and toward the end of the flight the gravitational attraction of the target planet takes over. So we can examine the trajectory to a planet by separately considering these three segments.

Imagine a flight to Mars, depicted in Figure 3.29. The Sun is at the focal point of both the orbits of Mars and of Earth. From our point of view high above the north pole, Earth and Mars are both moving counterclockwise in their orbits. The spacecraft is first injected into a low Earth orbit. At just the proper time the engines are ignited and the spacecraft is transferred to the dashed trajectory at a speed greater than escape velocity from Earth. This new trajectory

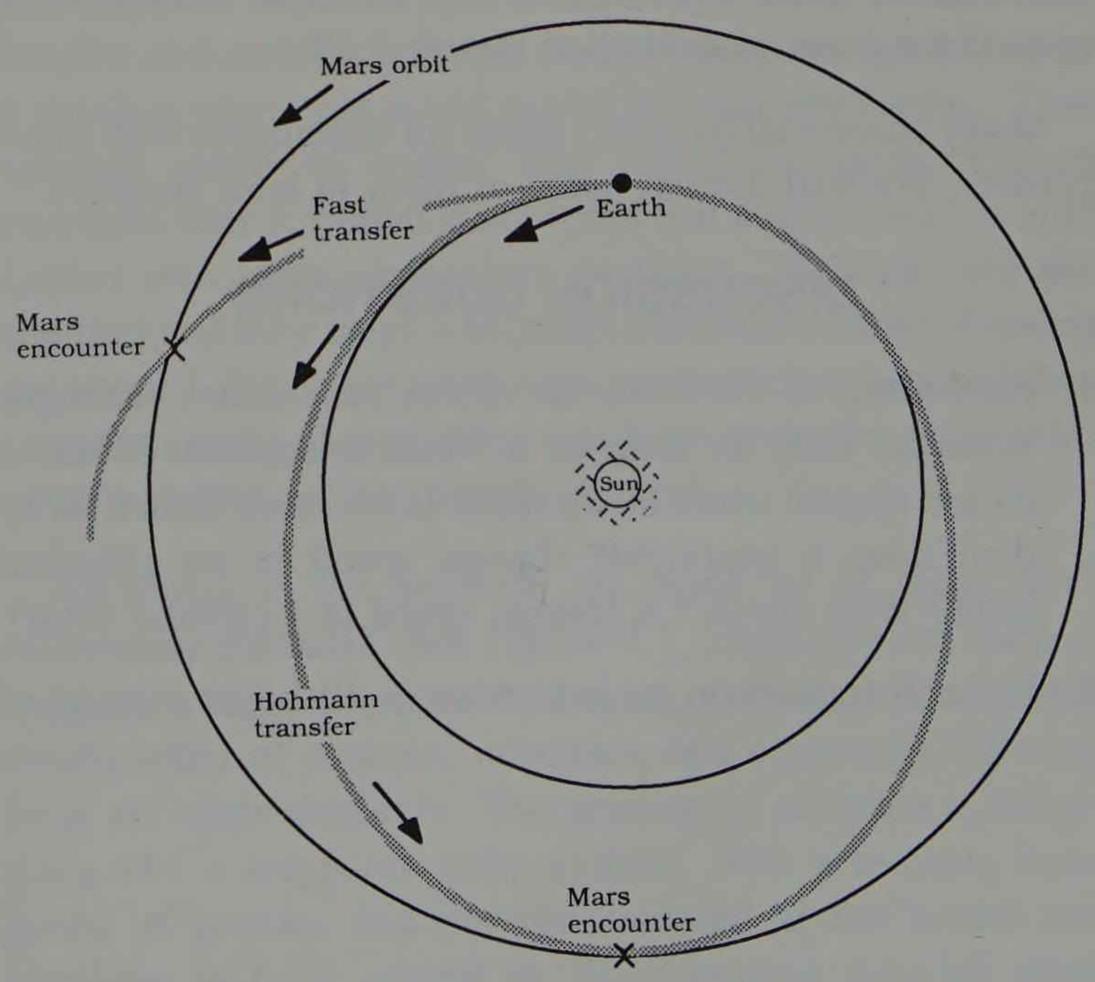


Figure 3.29 Transfer orbits to Mars.

is not a closed ellipse around Earth, but is an open curve called a *hyperbola*. It is curved at first but approaches a straight line as it gets farther from Earth. About a million miles out from Earth the gravity of the Sun becomes dominant and the vehicle is in an elliptical orbit around the Sun, just like a planet.

Now, we can look at the path of the spacecraft from two points of view: with respect to the Earth or with respect to the Sun. With respect to Earth it is on an escape trajectory, never to return. But with respect to the Sun it is in an elliptical orbit. Actually, the spacecraft was orbiting the Sun even when it was on the launch pad, since the Earth and everything on it is in orbit around the Sun.

When we fire the vehicle into the hyperbolic escape trajectory, we send it off in the same direction that the Earth is moving. It is then travelling faster than the Earth, which transfers it to an orbit larger than Earth's orbit toward the outer planets. This elliptical transfer orbit is like a Hohmann transfer except at the two ends where the gravity of the Earth and Mars control the motion.

If the spacecraft is to land on Mars, another maneuver is necessary. Just as in the flight to the Moon, as the spacecraft approaches Mars it falls in toward the planet and its speed increases. Retrofiring the engines reduces its speed so it enters an orbit around Mars. Without this "braking" maneuver the vehicle would be deflected somewhat by Mars gravity and continue on a modified orbit around the Sun. Actually, if the vehicle missed the planet completely, it would just continue to orbit the Sun.

Going to Venus is similar, except that Venus's orbit lies inside Earth's orbit. Therefore, the vehicle must be accelerated to escape velocity on a hyperbolic trajectory from Earth, but in the direction opposite to the direction of Earth's motion. Its speed with respect to the Sun is then less than Earth's speed and it moves into a smaller transfer orbit toward the inner planets. See Figure 3.30.

Many spacecraft have left Earth for encounters with other planets. We will discuss some of them in later chapters.

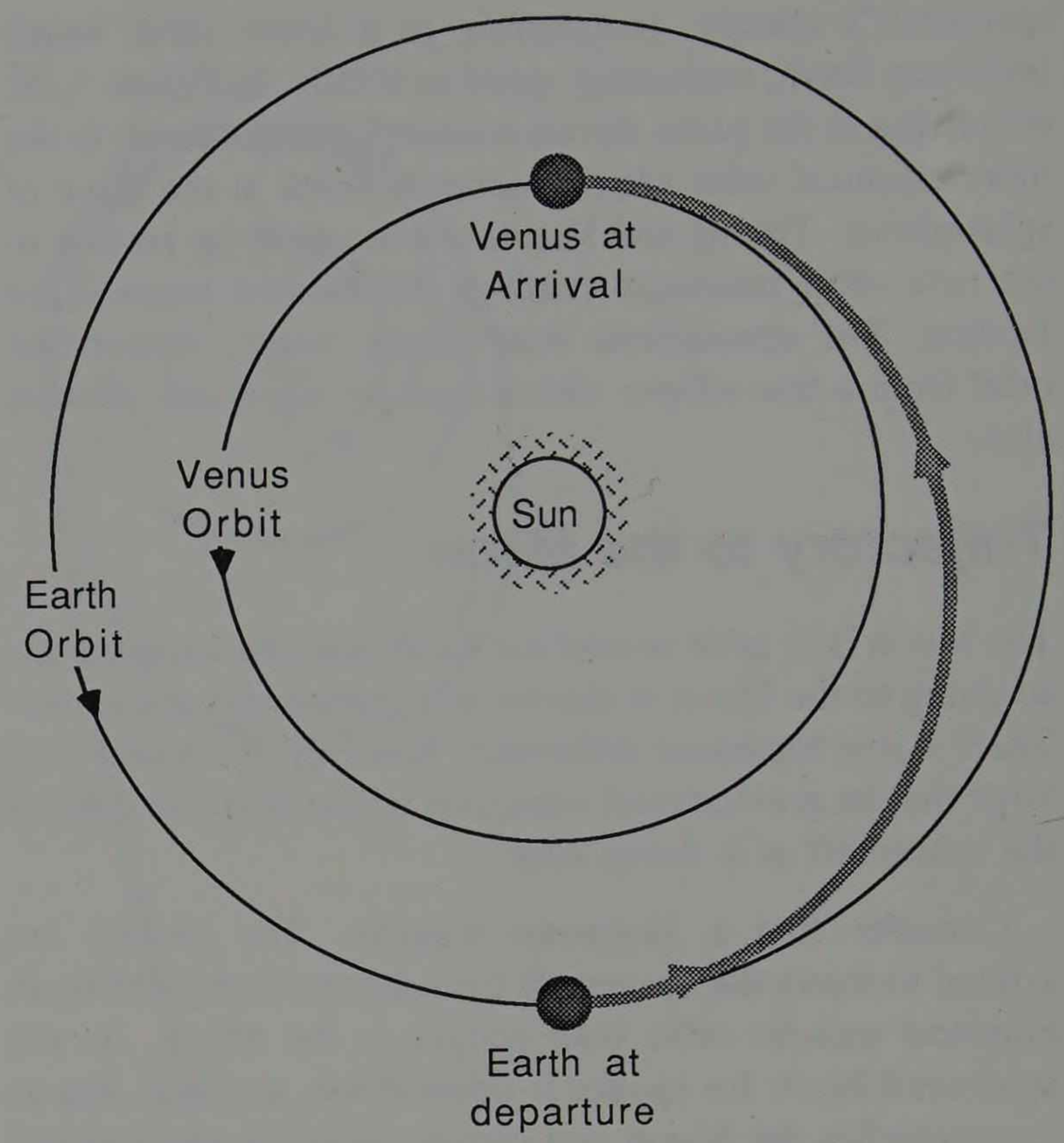


Figure 3.30 Hohmann transfer to Venus.

DISCUSSION QUESTIONS

1. According to Newton, an object accelerates (changes velocity) only as long as a force is applied. When a rocket engine shuts down there is no more thrust. Why then does a spacecraft change speed in an elliptical orbit? Why doesn't it change speed in a circular orbit?
2. If Earth rotated on its axis once in 12 hours instead of once in 24 hours, would a geosynchronous orbit be higher or lower?
3. What is the ground trace of a satellite in a circular orbit at an altitude of 40,000 miles?
4. If a spacecraft is 10 miles directly above a space station, how would you get it down for rendezvous and docking?
5. What are the advantages and disadvantages of a Hohmann transfer to carry a human crew to Mars? a cargo ship to Mars?

ADDITIONAL READING

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Chapter 4

The Space Environment

When a spacecraft leaves Earth it enters a rather unfriendly place. At the surface of Earth we live in a warm comfortable environment with air to breathe, water to drink, land to walk on. Space offers none of these. We often hear the term "empty space." True enough, the content of space is pretty sparse when compared to our earthly environment. The atmosphere surrounding us contains about 2 pounds of air in each cubic yard at a pressure of 14.7 pounds per square inch. At 150 miles up a cubic yard contains only a millionth of a pound at a pressure of 0.07 pound per square inch, a better vacuum than can be produced by laboratory equipment on Earth.

But space is far from being truly empty. In the space environment around Earth we find not only particles, many of them electrically charged, but also electromagnetic energy in the form of waves: x-rays, ultraviolet, gamma rays, visible light, infrared, radio waves, and microwaves. Also cosmic rays which are really particles, not rays, whiz past at high speed. In addition, meteoroids, which are small pieces of dust and debris, abound in space. Meteoroids are thought to be pieces of matter left over from the formation of the solar system. The electromagnetic radiant energy and the few pieces of matter that are present in space could damage a satellite and be lethal to an unprotected human. This chapter discusses these components of the space environment, their sources, and their potential hazard to spaceflight.

The Sun

The Sun is the source of all the particles and waves in the space environment except for cosmic rays and meteoroids. Some cosmic rays come from the Sun, but most come from outside the solar system. Indeed, some of them may come from outside our galaxy. To understand the contents of the environment in which our spacecraft and astronauts fly, we must first understand the structure and activity of the Sun. We also need to become familiar with the electromagnetic spectrum. An understanding of electromagnetic waves will be useful to us as we progress through this book.

The Sun is a star. We can see that it is round and through telescopes we can observe features on its surface. Other stars, even with the largest telescopes, appear as just points of light in the sky because they are so far away. The average distance from the Sun to Earth is about 93 million miles. Light from the Sun, travelling at 186,000 miles per second, takes 8.3 minutes to travel that distance. On the other hand, light from the next nearest star, Alpha Centauri, the brightest star in the constellation Centaur, takes 4.3 years to reach us.

The Sun is a sphere about 865,000 miles in diameter, 110 times the diameter of Earth and over a million times the volume of Earth. It is a medium sized star. Many stars are much larger; some giants are 400 times the diameter of our Sun. Like other stars, it is composed mostly of hydrogen with some helium and traces of other elements. Earth orbits the Sun with a period of one year; that is the definition of a year. The orbit is nearly circular with an eccentricity of 0.017, a perihelion of 91.3 million miles, and an aphelion of 94.4 million miles.

Atoms

Before going further, it is important to understand the structure of an atom. As long ago as 400 B.C. Greek philosophers believed that if an object were divided into smaller and smaller parts, it would eventually get down to a smallest piece that could not be divided any further. That smallest piece of matter was called an *atom*. Fifteen centuries later scientists discovered that atoms could be split further into three elementary particles. *Electrons* are the smallest and they carry a negative electrical charge. *Protons* are about 1,800 times more massive than electrons and they carry a positive charge. *Neutrons* have about the same mass as protons but are electrically neutral.

All atoms in the universe are made up of these three elementary particles. See Figure 4.1. Each *element* such as oxygen, iron, gold, lead, hydrogen, carbon, has a unique combination of protons, neutrons, and electrons, different from all other elements. The interior of an atom is something like a miniature solar system, with a nucleus composed of protons and neutrons located at the center and electrons in orbit around it. The simplest possible atom would be a one-proton nucleus and one electron in orbit;

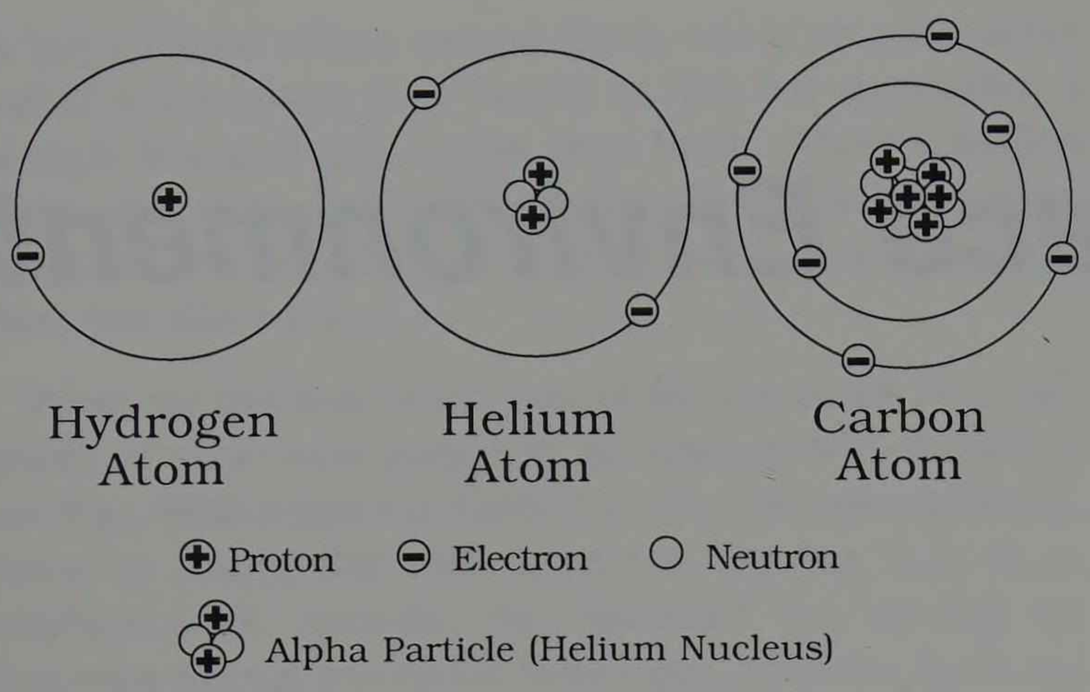


Figure 4.1 Structure of atoms.

that describes an atom of hydrogen. The next more complex atom, helium, has two protons and two neutrons in the nucleus with two electrons in orbit. Gold has 79 protons and 118 neutrons with 79 electrons in orbit. The number of neutrons may vary. For example, carbon has six protons and either six or seven neutrons in the nucleus. It is the number of protons that determines which element it is.

Notice that in a normal atom the number of protons and the number of electrons are equal. Thus, with an equal number of positive and negative charges, the atom is electrically neutral. Under some circumstances one or more electrons may be removed from an atom. We say that it is *ionized*. If all the electrons are stripped away, nothing is left but the nucleus. A hydrogen nucleus is simply a proton. A helium nucleus—two protons and two neutrons—is given a special name, an *alpha particle*.

A Nuclear Furnace

Now back to the Sun. The Sun shines by its own light; the Moon, planets, and comets shine by reflected sunlight. The source of the Sun's energy is a nuclear ''furnace'' in its center, powered by a process called *nuclear fusion*. Deep in its interior, hydrogen is being converted to helium with a release of energy. To be more specific, four protons, hydrogen nuclei, fuse together to form an alpha particle. In this fusion process two of the original protons have become neutrons; that is, they lost their positive charge. If you add together the mass of the four protons, you find that they total more than the mass of an alpha particle: about 0.7 percent of the mass has disappeared in the fusion. According to Albert Einstein's famous equation, $E = mc^2$, the lost mass is converted to energy. See MATHBOX 4.1 for an actual calculation. This mass-converted-to-energy is released in the form of a *gamma ray,* an electromagnetic wave.

Fusion requires temperatures in excess of 30 million degrees Fahrenheit and a pressure of a trillion tons per square inch. Such temperatures and pressures are common in the cores of stars. Once fusion begins, the heat produced keeps the process going until the hydrogen fuel runs out or the pressure drops. The necessary high pressure is maintained by the weight of the overlying mass of the star held together by gravity.

Nuclear fusion is the same process that takes place when a thermonuclear hydrogen bomb explodes. In a thermonuclear bomb, the fusion of a quantity of hydrogen into helium takes place in a fraction of a second and the energy is released as an enormous explosion causing a massive rearrangement of things in the immediate vicinity. It is a star on Earth for an instant. If it were possible to control the fusion, to slow it down so the energy would be released over a long period of time, it could be used beneficially, for example, to boil water to run steam electric generators.

Controlled fusion for fractions of a second has been experimentally successful in both the United States and the Soviet Union. It isn't easy to build a container that will hold something at 30 million degrees Fahrenheit! The trick is to use a magnetic field to keep the hydrogen nuclei suspended in a vacuum away from the container walls. High temperatures can be achieved by high powered lasers focused on small pellets of hydrogen fuel. Up to now, controlled fusion has not turned a profit; far more energy must be put into the machine than is produced by the machine. Some researchers expect eventual breakthroughs and predict that nuclear fusion will be the major energy source of the twenty-first century.

In the Sun, fusion started about 4.5 billion years ago. Hydrogen is fusing to helium in the central core of the Sun at a rate of nearly 5 million tons a second. And with the bountiful supply of hydrogen available, it will continue to do so for another 5.5 billion years. We do not have to worry that it will blink out on us, at least not this weekend. This calculation is also shown in MATHBOX 4.1. Our Sun, then, is a middle-aged star, about halfway through its lifetime. Temperatures and pressures are great enough to support the fusion in only about the central 10 percent of the Sun. After the hydrogen in that region is consumed, the nuclear furnace will go out and the Sun will go through various phases until it dies. The life cycles of stars is a fascinating study in nuclear physics and is the subject of investigation by astronomers. Here we are only concerned with our Sun at its present stage of evolution.

Solar Structure

Figure 4.2 shows a diagram of the surface and a cross section of the Sun. The *photosphere* is the visible surface of the Sun. Above the photosphere is the *chromosphere,* a region that can best be described as an atmosphere. Next is the *corona,* the upper atmosphere of the Sun, which extends out to the planets. It may truly be said that Earth lies in the solar atmosphere. The corona, for some unknown reason, is

MATHBOX 4.1

Nuclear Fusion

When four protons combine into one alpha particle some mass is "lost," converted to energy.

The mass of atomic particles is measured in atomic mass units (amu). A proton has a mass of 1.0078, so four protons have a mass of 4.0312 amu. An alpha particle has a mass of 4.0026.

$$4.0312 - 4.0026 = 0.0286 \text{ amu converted to energy}$$

$$\frac{0.0286}{4.0312} = .0071 = 0.71\% \text{ of the mass is converted to energy}$$

One atomic mass unit is 1.7×10^{-26} kilograms. So 0.0286 amu is 4.8×10^{-29} kilograms. The energy produced by this mass is found from Einstein's famous equation

$$E = mc^2$$

where c is the speed of light, 3×10^8 meters per second.

$$E = (4.8 \times 10^{-29} \text{ kg}) (3 \times 10^8 \text{m/s})^2 = 4.3 \times 10^{-12} \text{ joules}$$

Now, that is not very much energy per fusion. It must be going on at a tremendous rate in the core for the Sun to be radiating energy away at the rate of 3.8×10^{26} joules per second.

$$\frac{3.8 \times 10^{26} \text{ j/s}}{4.3 \times 10^{-12} \text{j/fusion}} = 8.9 \times 10^{37} \text{ fusions per second}$$

Let us go one step further. We found that 4.8×10^{-29} kg are converted to energy in each fusion. So the Sun must be losing

$$(4.8 \times 10^{-29} \text{ kg/fusion}) (8.9 \times 10^{37} \text{ fusions/s}) = 4.3 \times 10^9 \text{ kg/s}$$

In more familiar units, 4.3 billion kilograms per second is about 4.7 million tons per second of matter being converted to energy. At that rate, how long can the Sun last? The Sun has a mass of 2×10^{30} kg. About the inner 10%, 2×10^{29} kg, is involved in the fusion, and 0.71% of it will be converted to energy before the core goes out.

$$\frac{(2 \times 10^{29} \text{ kg}) (.0071)}{4.3 \times 10^9 \text{ kg/s}} = 3.3 \times 10^{17} \text{ seconds} = 10 \text{ billion years}$$

Since the Sun is about 4.5 billion years old, it still has enough fuel to run for another 5.5 billion years.

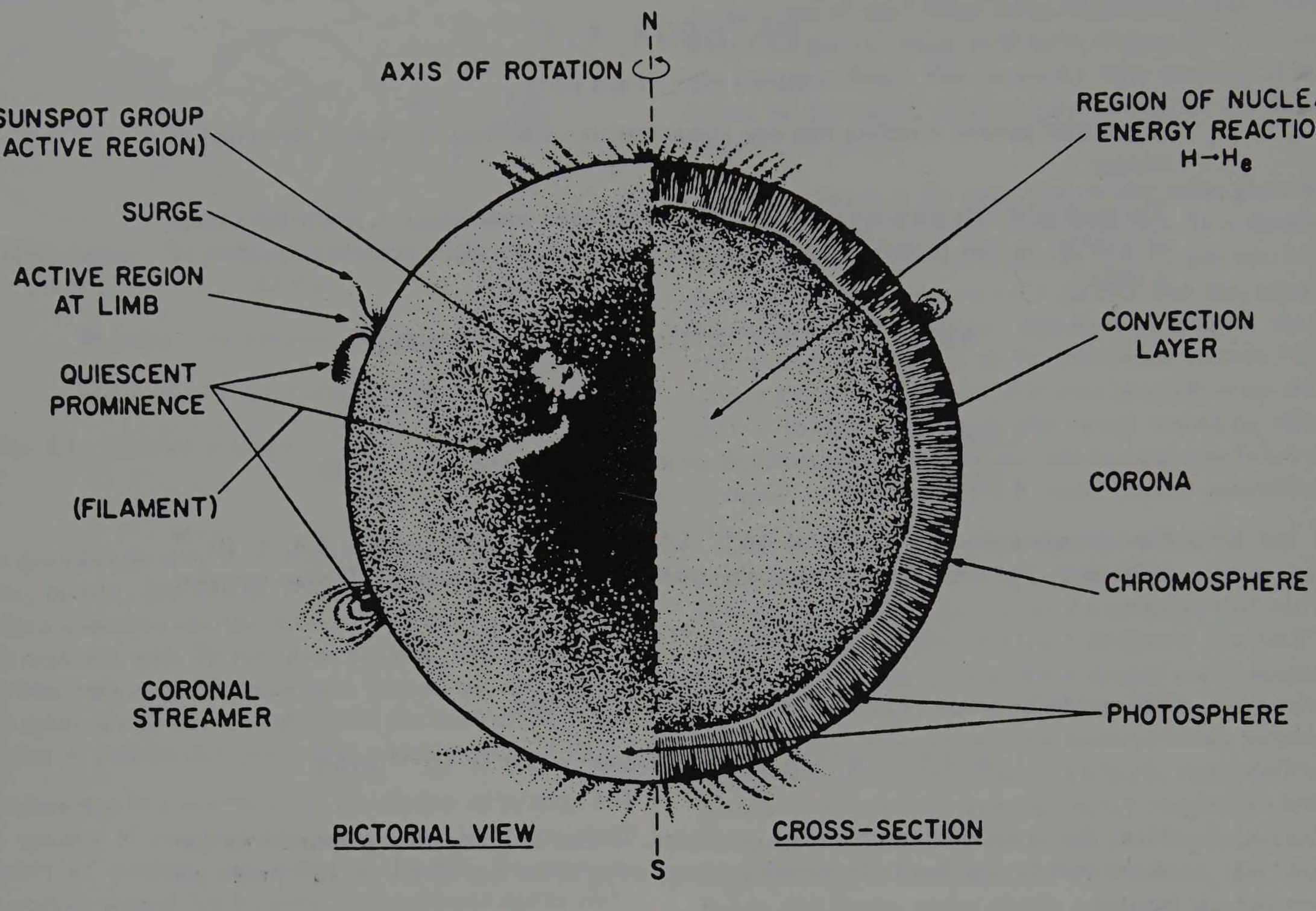


Figure 4.2 Diagram of the Sun. The left side of the diagram shows the surface features; the right half is a cross section of the interior. *Courtesy of the U.S. Air Force.*

the hottest part of the solar atmosphere. Its temperature reaches several million degrees Fahrenheit compared to about 90,000 °F in the chromosphere and 11,000 °F in the photosphere. Just why the corona is hotter than the lower regions of the Sun's atmosphere is one of the mysteries of solar physics.

The *core* is the nuclear furnace where the energy is produced. Temperature in the core is about 35 million degrees Fahrenheit and pressure is about a trillion tons per square inch. Gamma rays produced in the core radiate outward through the *radiation zone* as photons, bundles of electromagnetic energy. In free space all electromagnetic waves travel at the same speed, 186,000 miles per second. But in the dense interior of the Sun they travel much more slowly, so slowly that it takes more than 20,000 years for the gamma rays to reach the *convection zone*. Enroute, they lose energy to their surroundings. When they reach the convection zone, the electromagnetic energy is absorbed by the gases and converted to a form of heat energy. The hot gases rise upward while cooler gases from above sink into the deeper parts where they are heated and rise again.

These continuously circulating convection cells are very similar to the ones which produce cumulus clouds in Earth's atmosphere. Air in contact with the ground on a warm day is heated from below and rises, bubble-like, to higher altitudes, cooling as it goes. Meanwhile cooler air sinks toward the surface where it is warmed and rises. If sufficient water vapor is present then clouds form in the upward moving air. This continuous convective cell circulation can also be observed in a pot of water on the stove. Water heated by contact with the hot bottom of the pot can be seen to rise while cooler water sinks around the edges. If you look closely you can see the shimmering in the water. The heat is thus distributed by the circulating water.

Similarly, in the interior of the Sun, convective cells of circulating hydrogen carry the heat energy from the zone of radiation to the photosphere where it flows into space, mostly as light, infrared and ultraviolet. It is indeed fortunate for us that the lethal gamma rays do not reach the surface of the Sun and radiate into space. If they did, life would be impossible on Earth or anywhere else in the Solar System.

The Sun rotates on its axis just as Earth and other celestial bodies do. But because it is a fluid body, it rotates

differentially; that is, different parts of the Sun rotate at different speeds. The polar regions take about 32 days to make a complete rotation, while the equatorial regions rotate once in about 25 days. That leads to complicated flow patterns in the upper layers of the Sun and distortion of its magnetic field, leading to occasional explosions called flares. We will discuss flares in more detail later in this chapter.

Electromagnetic Waves

The Sun emits most of its energy in the form of light (41 percent of the total), infrared (52 percent), and ultraviolet (7 percent). Smaller quantities of x-rays, radio waves, and microwaves are also emitted. X-rays, gamma rays, ultraviolet, infrared, radio waves, television waves, and light are really all manifestations of the same thing: *electromagnetic waves*. The only difference among them is their wavelength. Certainly you have seen water waves or ripples in a pond. The wavelength of a wave is the distance from one crest to the next crest, or from one trough to the next.

Figure 4.3 lists various electromagnetic waves in order of wavelength from the longest to the shortest. Wavelengths are given in metric units. Remember that a meter and a yard are about the same, the meter being about 3 inches longer. A kilometer is about 0.6 mile. It takes about 25,000 micrometers to make an inch; a grain of sand is about 300 micrometers in diameter.

The length of a radio wave, measured from crest to crest or trough to trough, ranges from a tenth of a meter to many kilometers (a few inches to many miles). For example, channel 2 television waves are about 5 meters (15 feet) long. Microwave oven waves are about 1 centimeter (0.4 inch) long. Infrared waves range from a micrometer (millionth of a meter) to several hundred micrometers in length. (A micrometer is also called a micron and we will use the terms interchangeably.) Light waves, on the other hand, measure from 0.4 micron to 0.7 micron. Ultraviolet, x-rays, and gamma rays are even shorter. Gamma rays and x-rays come from the most violent, high energy events in the universe. The dividing line between the various types of waves is not as sharp as Figure 4.3 indicates. There is some overlap.

All electromagnetic waves are identical in character except for wavelength. As the name suggests, they have an electrical and a magnetic component. They are created when an electrically charged particle, such as an electron, oscillates or accelerates. For example, they are produced in atoms as the electrons change orbit around the nucleus, escape from the nucleus (ionization), or are captured by a nucleus (recombination).

Sound waves and water waves must have a medium in which to travel. Sound waves travel in air, through liquids, or through solids like walls and windows. But electromagnetic waves do not require a medium; therefore they can travel through empty space. All travel at the same speed, the speed of light.

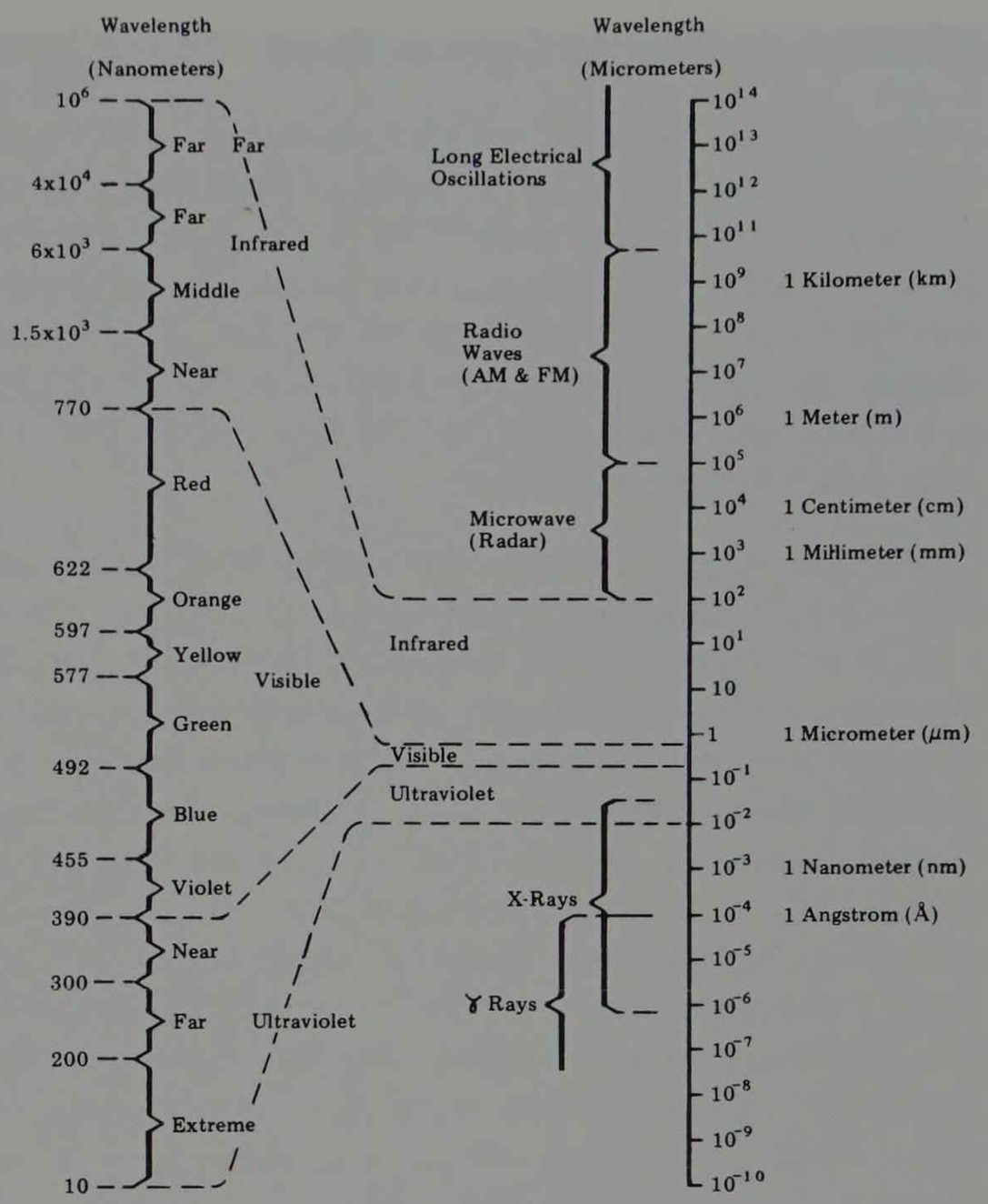


Figure 4.3 The electromagnetic spectrum. Wavelengths are given in metric units. In the right column they are millionths of a meter (micrometers); other perhaps more familiar units are indicated at some places, e.g., 10^6 micrometers is 1 meter. In the left column the wavelengths of infrared, visible light, and ultraviolet are given in billionths of a meter (nanometers). *Courtesy of NASA.*

Particles in Space: The Solar Wind

In addition to electromagnetic waves, charged particles also stream from the Sun, mostly electrons, protons, and alpha particles. These particles become so hot in the corona that some of them acquire energies greater than escape velocity from the Sun. A steady stream of these particles flows outward from the Sun in what has been named the *solar wind*. The solar wind, actually an extension of the solar corona, blows outward past the planets, filling the solar system with charged particles. Usually the speed past Earth is about 300 miles per second with a density of about 1,600 particles per cubic inch, but the solar wind increases in both speed and density during periods of high solar activity. Exposure to the solar wind is like being exposed to low level radioactive material. Dosage does not usually reach a dangerous level.

Particles in Space: Cosmic Rays

Cosmic rays are particles, not rays, travelling in all directions at extremely high speed, some of them approaching the speed of light. They come from two different sources. *Solar cosmic rays* are protons which are accelerated to high speed during explosive eruptions on the Sun. These solar cosmic ray events are relatively infrequent, but are deadly to humans when they do occur. We will discuss them in more detail later in this chapter.

A steady stream of cosmic rays comes from outside the solar system. These rays are referred to as *galactic cosmic rays*. When they were first discovered in the early part of this century they were thought to be electromagnetic radiation and were dubbed ''rays.'' We now know they are the nuclei of atoms stripped of their electrons and therefore bearing a positive charge. They are 85 to 90 percent protons, 10 to 12 percent alpha particles, about 1 percent electrons, and 1 percent nuclei of heavy atoms such as oxygen, nitrogen, iron, and neon. Some perhaps had their origin in events during or shortly after the ''big bang'' that started the universe. Others come from exploding dying stars, called supernovas. A few may come from other galaxies.

Many galactic cosmic rays travel at such high speed that they pass right through the spacecraft, people and all, at a rate of perhaps a dozen per square inch per hour.

Sunspots

Dark spots are often visible in the Sun's photosphere (Figure 4.4). Although they appear tiny from our viewpoint, smaller *sunspots* may be about the size of Earth and the largest are bigger than a hundred Earths. They vary in number from day to day and year to year. Sunspots were observed by Galileo in 1610 shortly after he first pointed a telescope at celestial bodies. Since then records have been kept of their number, although the records are quite erratic for the first two hundred years after Galileo discovered them. Actually observations of sunspots had been recorded centuries earlier in China on several occasions when the Sun was low on the horizon behind a veil of clouds and spots were large enough to be seen with the naked eye.

Sunspots may be observed with any telescope equipped with a device for reducing the light intensity by at least 98 percent. Looking through a telescope without some sort of light-reducing device will cause permanent eye damage. You have perhaps used a magnifying glass to focus the Sun onto a sheet of paper and watched the paper burst into flames. That is some indication of what happens to the retina of an eye focused on the Sun. Projection of the image of the Sun onto a white card held a couple of feet behind the telescope eyepiece also allows comfortable viewing.

Sunspots are ''cool'' regions in the photosphere. Photospheric temperature is nearly 11,000 °F; sunspot temperatures are about 7,600 °F. Although 7,600 °F is not very cool, the spots appear black against the hotter surroundings. Figure 4.5 is a closeup photo of a group of sunspots. If we could see a sunspot against the cold blackness of space, it would appear bright. The cause of the lower temperature is probably involved with the magnetic fields of the Sun. Whenever an electrically charged particle is in motion, it is accompanied by a magnetic field. The convection cells in the Sun are mass motions of charged particles, mostly negative electrons and positive protons. Therefore, magnetic fields are present. When complex flow patterns occur in the convection zone, the magnetic fields become entwined and tangled. This prevents the usual rather smooth flow of heat from the interior to the photosphere. Consequently, with the heat flow interrupted, the region becomes cooler. The differential rotation of the Sun also contributes to the complexity of heat flow. This simplified explanation may not be completely precise. However, complex magnetic field structures are observed in sunspot regions and there is undoubtedly some relationship between them.

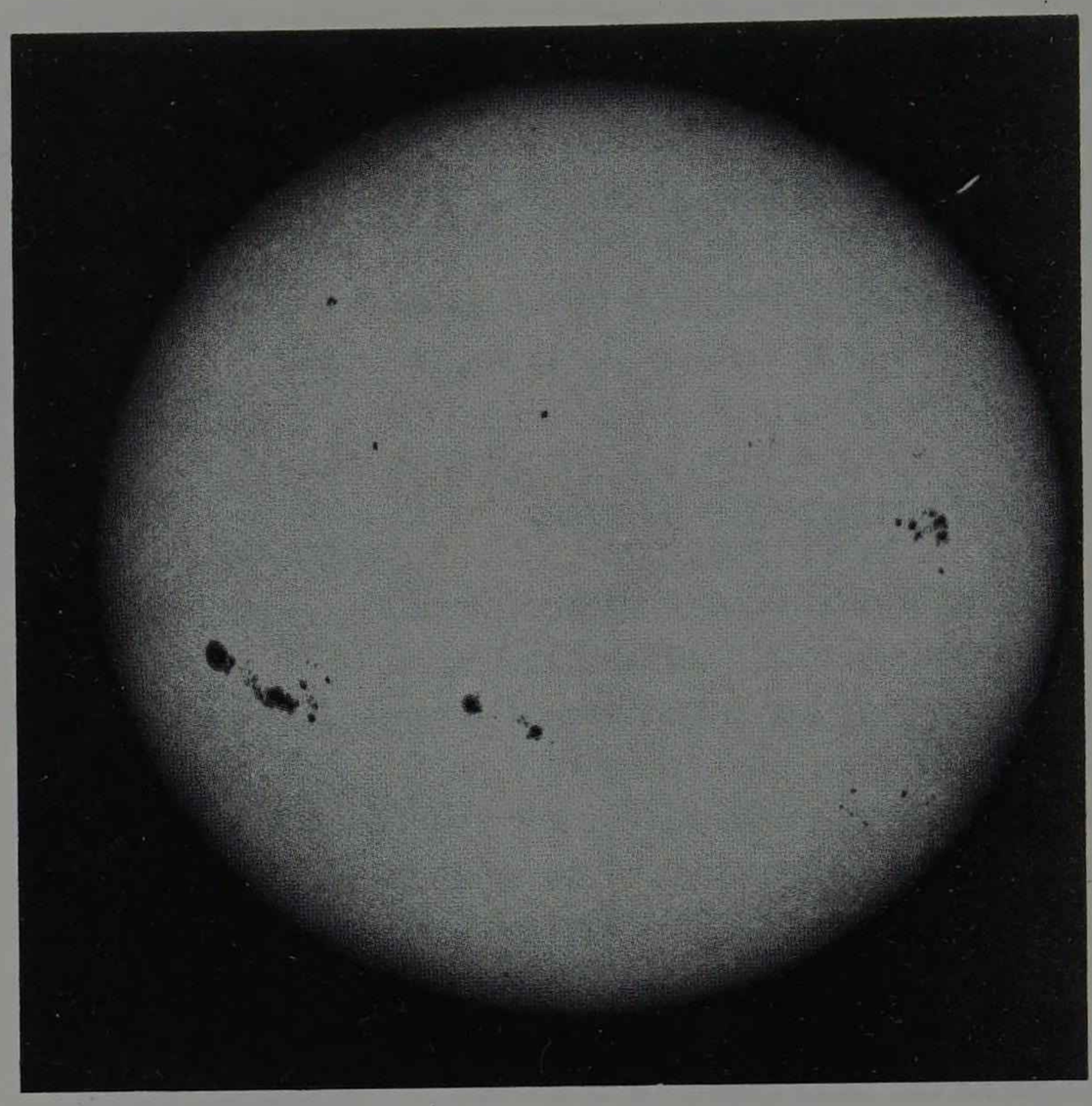


Figure 4.4 Sunspots. *Courtesy of NASA.*

For the past two centuries daily observations of sunspots have been tabulated and studied. Spots occur in groups with as many as 100 spots or as few as one to a group. A standard method of counting sunspots originated in the 1800s, when it was thought that the existence of a group might be significant. Therefore, the sunspot number for the day is equal to ten times the number of groups, plus the number of spots. An example is shown in Figure 4.6.

When sunspot numbers are averaged over 12 months and then plotted on a graph extending over many years, a

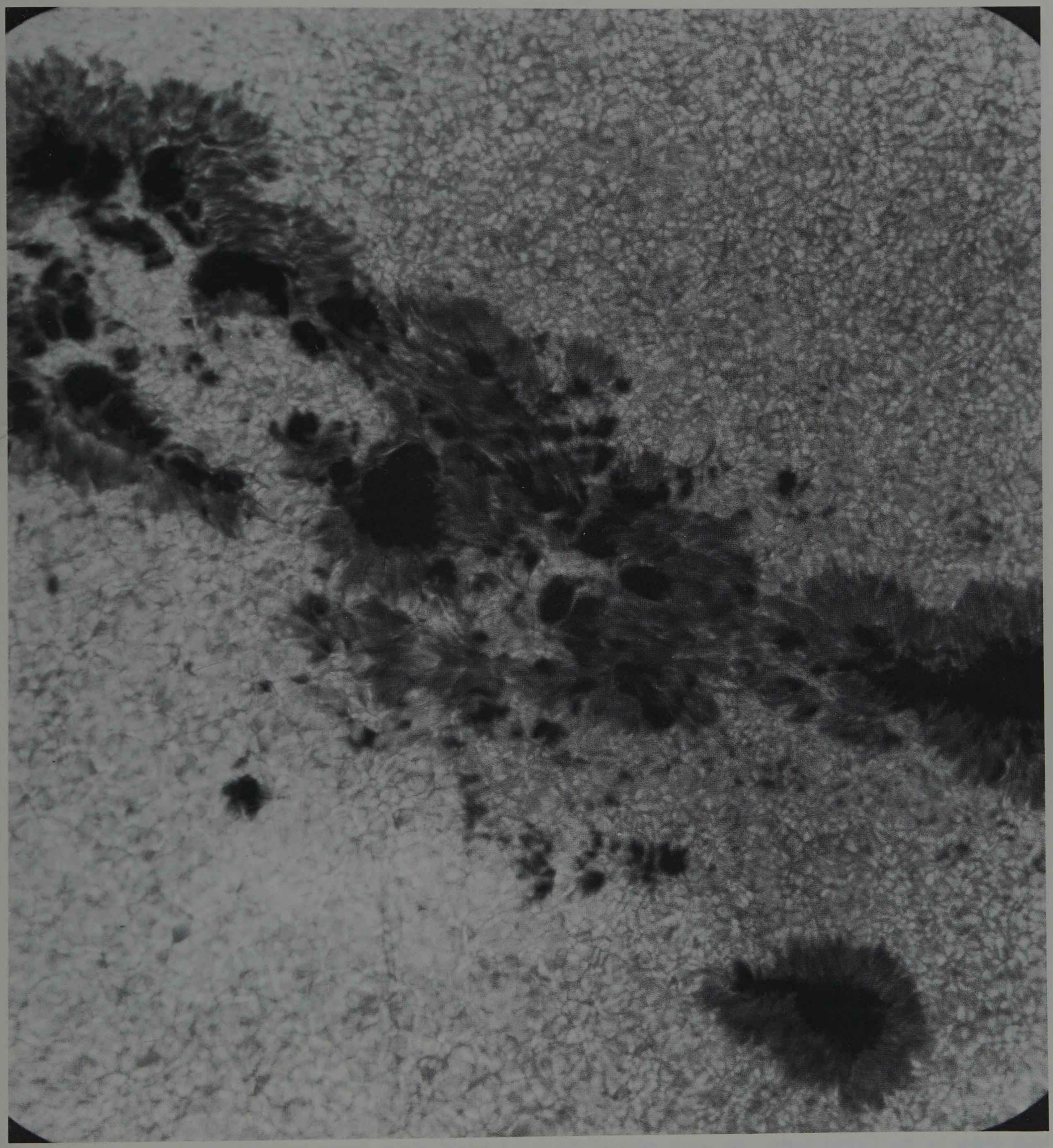


Figure 4.5 Closeup photo of a sunspot group. *Courtesy of National Solar Observatory, Association of Universities for Research in Astronomy, Inc.*

pattern shows up. Figure 4.7 shows such a graph from Galileo's time to the present. Most obvious is the irregular cyclic pattern beginning about 1700 with a period of about 11 years. Few spots were seen in the 60 years from 1645 to 1705. Indeed they were so rare that many people doubted their existence. The most recent maximum occurred in December 1979; the minimum prior to that was in mid-1976.

Sunspots by themselves do not do anything significant to

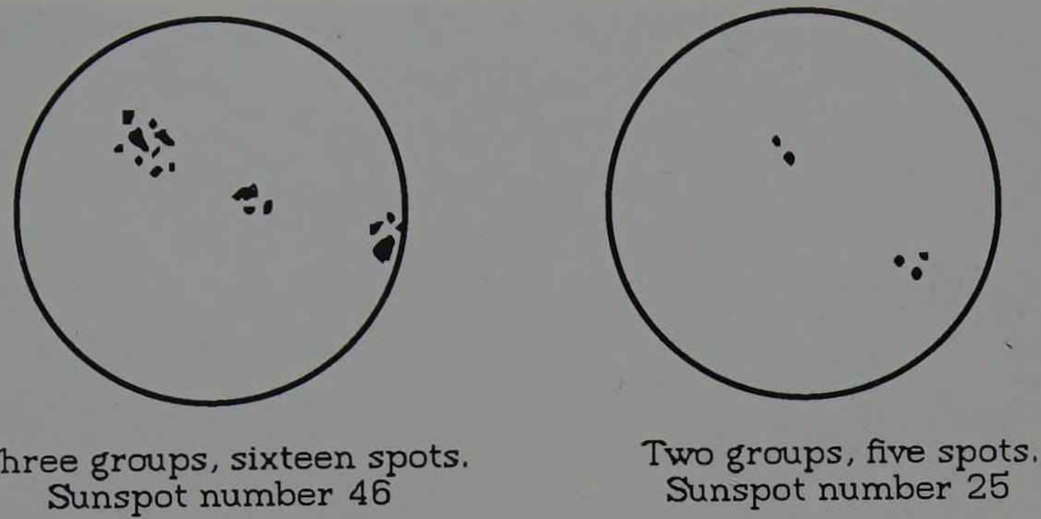


Figure 4.6 Counting sunspots.

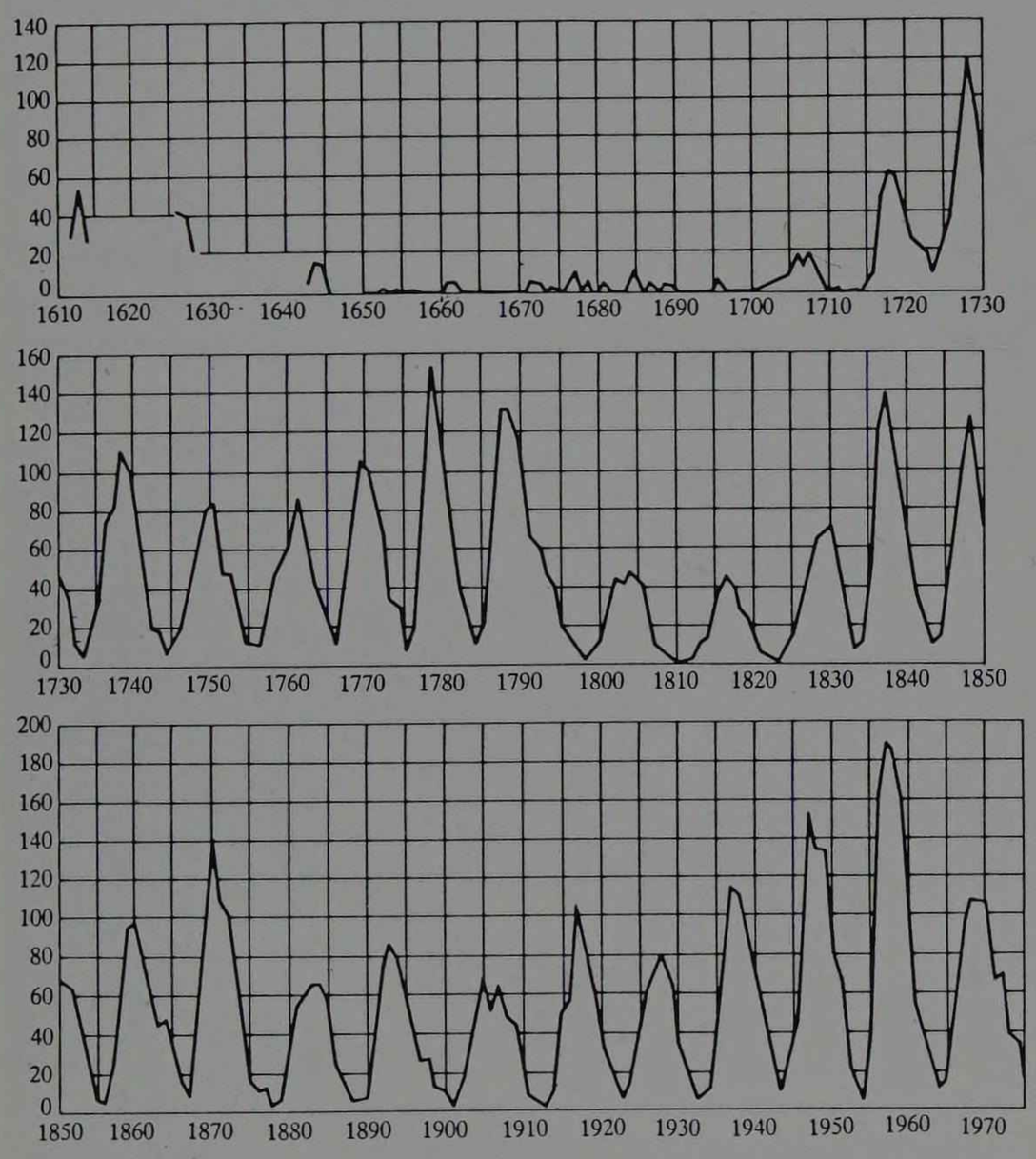


Figure 4.7 The 11 year sunspot cycle. *Courtesy of NASA.*

the space environment, but as we will see, they often accompany other activity on the Sun which may adversely affect spaceflight. There have been many attempts to relate sunspots to events on Earth, particularly weather and climate. Statistical correlations have been found between the sunspot cycle and many other things: droughts on the high plains of the United States, the stock market, the length of women's skirts. But no cause-effect relationships have been found. That is, given that the stock market varies with the sunspot cycle, what is the cause? ''Coincidence'' is the only logical response.

The Chromosphere

Some telescopes are equipped with a special filter which allows only one wavelength of light to pass through, the red light of hydrogen-alpha. The main source of hydrogen-alpha light is the chromosphere, the lower atmosphere of the Sun. Figure 4.8 is a photograph taken through a hydrogen-alpha filter which reveals interesting features. First, the bright areas that look like clouds are hot regions called *plages,* the French word for beach. They do have the appearance of a white sandy beach, although I wouldn't recommend them for a vacation spot.

The long black streaks are called *filaments*. They protrude upward into the corona and are cooler than the photosphere. Therefore they appear black, the same as sunspots do. If a filament is on the *limb,* the edge of the solar disk, it appears bright against the blackness of space and is called a *prominence* because of the way it sticks out from the limb (Figure 4.9). Prominences appear in many different shapes with fanciful names: loops, arches, hedgerows. In a time lapse movie they can be seen to grow, dissipate, change shape, oscillate, and sometimes explode into space. They are generally associated with *active regions,* near plages and sunspots.

Solar Flares

When the energy wrapped up in the magnetic fields of an active region can no longer contain itself, it is sometimes released suddenly in a gigantic explosion called a *flare*. Flares may last from a few minutes to a few hours. Even small ones may be larger than Earth and release as much energy as a billion hydrogen bombs. The frequency of occurrence of flares follows the sunspot cycle. As the sunspots increase, so does the number of flares. However, large flares often occur after the sunspot cycle reaches a maximum. The very large flare in Figure 4.10 occurred nearly four years after the 1968 peak in sunspot number.

The light from a flare can be seen in a telescope equipped with a hydrogen-alpha filter. Once or twice in an 11 year cycle a flare is so brilliant that it can be seen against the bright photosphere without a filter. Besides visible light, bursts of x-rays, ultraviolet, and radio noise are often observed. In addition, particles, mostly electrons and protons, may be accelerated to high speed, exceed escape velocity from the Sun, and spew out into space. See Figure 4.11.

Occasionally during very intense flares, protons reach speeds up to one-fourth the speed of light and fit into the classification of solar cosmic rays. At that speed they reach Earth in half an hour, compared to the usual three to four days for particles in the solar wind. A solar cosmic ray event, also referred to as a *proton event,* may last from several hours to a day. Solar cosmic rays would be lethal to an unprotected astronaut. The U.S. government has set a standard for the maximum amount of radiation that a worker may receive if he deals with radioactive material on a

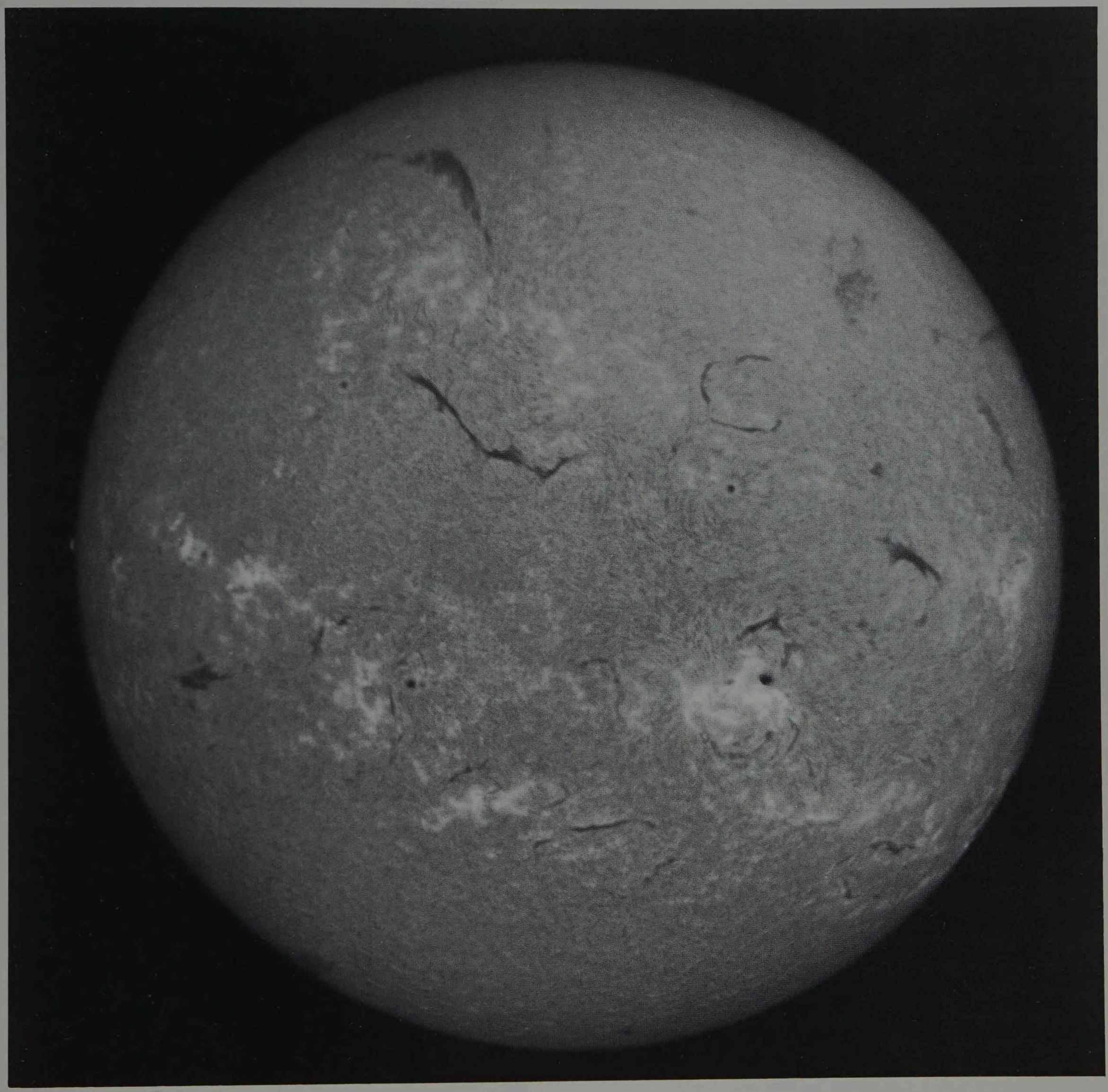


Figure 4.8 The Sun in hydrogen-alpha light. The north pole is at the top, south at the bottom, east on the left side, and west on the right. Many filaments and plages are scattered over the surface. Four large spots and some smaller ones are visible. A small prominence can be seen on the left (east) side. Little activity takes place at the equator. *Courtesy of National Solar Observatory, Association of Universities for Research in Astronomy, Inc.*

regular basis. During a proton event an astronaut could be exposed to more radiation in half an hour than is allowed a radiation worker in a year. For the most energetic of these events, even the cabin walls of the Space Shuttle would not be sufficient shielding. We will discuss this further in Chapter 9.

Sun-Earth Relationships

The Sun pours forth great quantities of particles and electromagnetic energy; Earth intercepts only a small percentage of it. Because of our distance from the Sun and the relatively small size of Earth in space, only about two-



Figure 4.9 Loop prominences on the edge of the Sun. To take this photo, a disk was placed in the telescope to block out the light from the surface of the Sun. Otherwise, the nebulous features on the edge would not be visible. *Courtesy of National Solar Observatory, Association of Universities for Research in Astronomy, Inc.*

billionths of the total solar output falls on Earth. Yet nearly all energy consumed on Earth can be traced to the Sun. For example, plants harvest sunlight to build their ''bodies'' by photosynthesis, humans and animals eat plants, and humans, in turn, eat the animals. The base of the entire food chain begins with photosynthesizing plants. Fossil fuels are really stored solar energy. Oil, coal, and natural gas come from ancient living organisms which died, were buried, and were transformed into those fossil fuels. Wind is caused by uneven heating of Earth's surface by the Sun. Windmills, therefore, derive their energy from the Sun. Rain is produced by solar energy evaporating water from lakes and soil. The vapor condenses into clouds and raindrops which fill the reservoirs. Falling water from the reservoirs drives electric generators. All of these examples, then, involve solar energy.

The only kinds of energy used on Earth that cannot be traced to the Sun are tidal energy, nuclear energy, and geothermal energy from the heat deep in Earth's crust. Even the tides are partially due to the Sun, though the Moon is the primary cause. The gravity of the Sun is enormous, but the

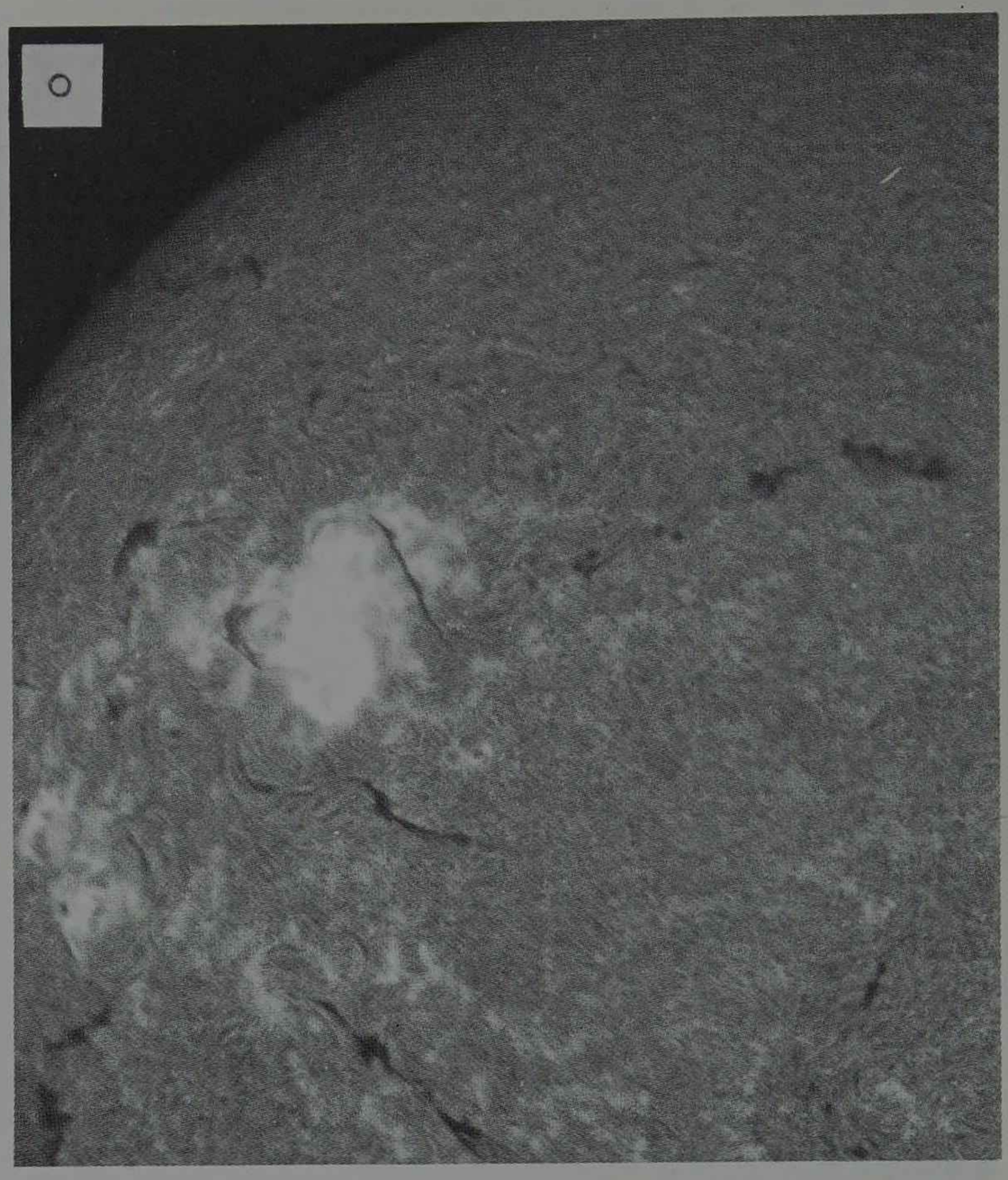


Figure 4.10 A large solar flare as seen through a hydrogen-alpha filter, August 7, 1972. For comparison, the circle at the upper left is approximately the size of the Earth. *Courtesy of National Solar Observatory, Association of Universities for Research in Astronomy, Inc.*

Moon's proximity makes its gravitational pull have more effect.

Life on Earth is well protected from lethal electromagnetic waves, charged particles, meteoroids, and cosmic rays. Earth's atmosphere and magnetic field act as a shield against these hazards.

X-rays and long wavelength ultraviolet are absorbed in the *ionosphere*, the ionized top part of the atmosphere above about 50 miles. The energy of these waves ionizes the oxygen and nitrogen atoms, removing an electron from them. Therefore, the ionosphere is called a *plasma*, a mixture of neutral and ionized atoms.

Ultraviolet is also absorbed by the ozone layer some 30 miles high. Ozone is made of three atoms of oxygen bonded together to form a single molecule. Normal oxygen in the air around us consists of only two atoms bonded together. Short wave ultraviolet can break the bond of an ordinary oxygen molecule, splitting it into two individual atoms. One of those atoms then attaches itself to normal oxygen to form ozone. The ozone layer, then, is effective in preventing the ultraviolet rays from reaching the ground.

Thus, hazardous x-rays and ultraviolet do not reach the surface of Earth to damage living organisms. On the other

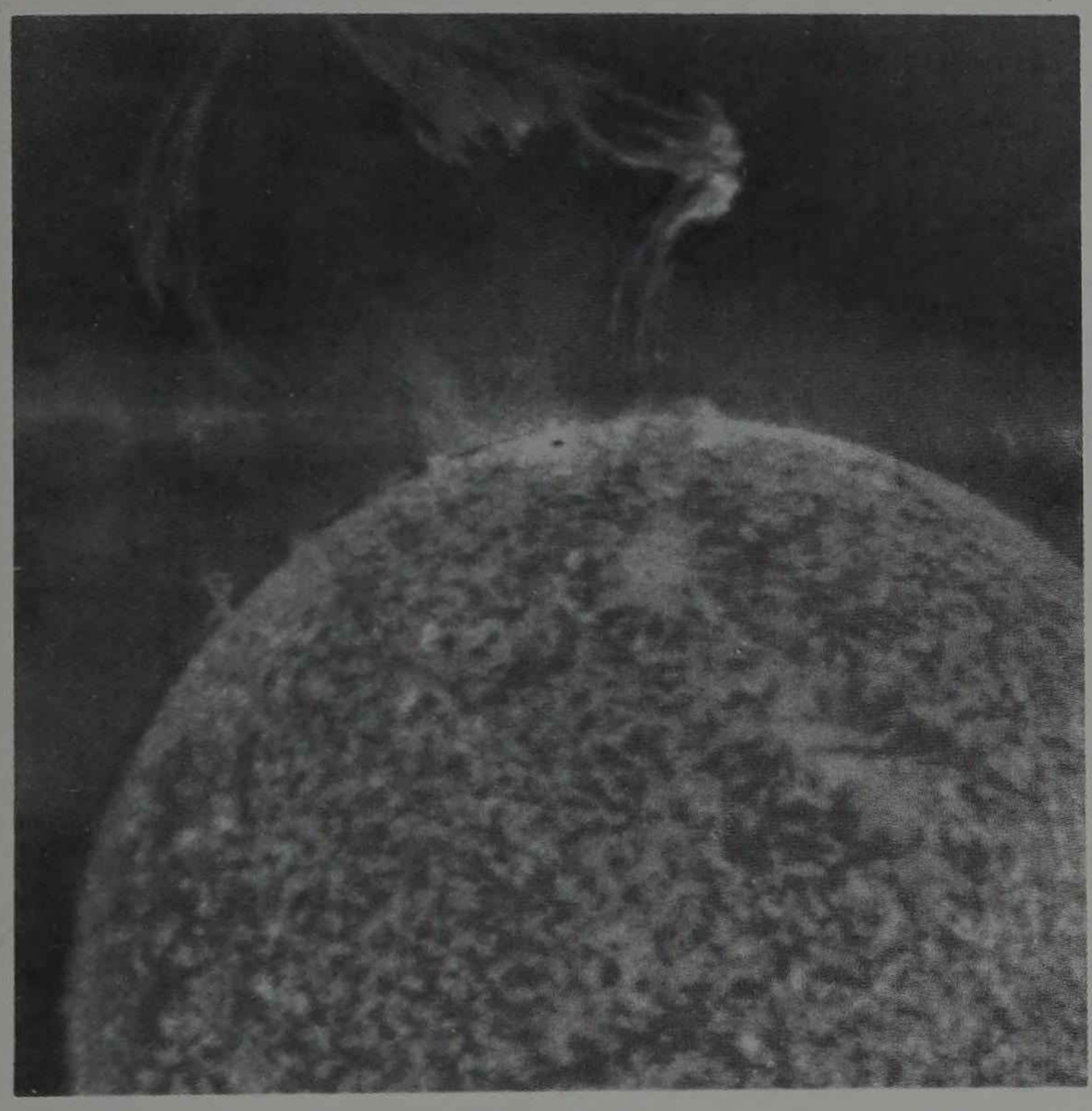


Figure 4.11 Photographed from the Skylab space station, a huge solar eruption throws high energy particles out into space. *Courtesy of NASA.*

hand, the atmosphere is transparent to visible light, the wavelengths that the Sun emits with greatest intensity and that our eyes respond to. A good arrangement!

The particles travelling from the Sun carry an electrical charge and electric charges in motion are always accompanied by a magnetic field. Earth has a permanent magnetic field, as if a giant bar magnet were buried deep in its interior. Figure 4.12 is a photograph of small bits of iron in close proximity to a bar magnet. Notice how they appear to follow curved lines which run from one end of the magnet to the other end. Compare this with Figure 4.13, a diagram of Earth's magnetic field. Remember that the solar wind blowing past Earth is composed of charged particles in motion and therefore bears a magnetic field. The interaction of the solar wind with Earth's magnetic field causes it to be distorted: compressed on the sunward side and stretched out downstream. It carves out a region of space called the *magnetosphere*. Solar wind particles follow the field lines and are deflected around the magnetosphere. Thus, the magnetosphere acts as a shield, protecting life on Earth from deadly particle radiation.

Some particles do make it into Earth's atmosphere, however, There are weaknesses in the magnetosphere in the polar regions where particles can enter. In Figure 4.13 these weak places are shown by the two arrows and broken line marked ''neutral line.'' Also, cosmic rays travel at such high speed that they can rip through the magnetic shield and collide with atoms of gas in the upper atmosphere, smashing them into bits. These bits are secondary radiation which

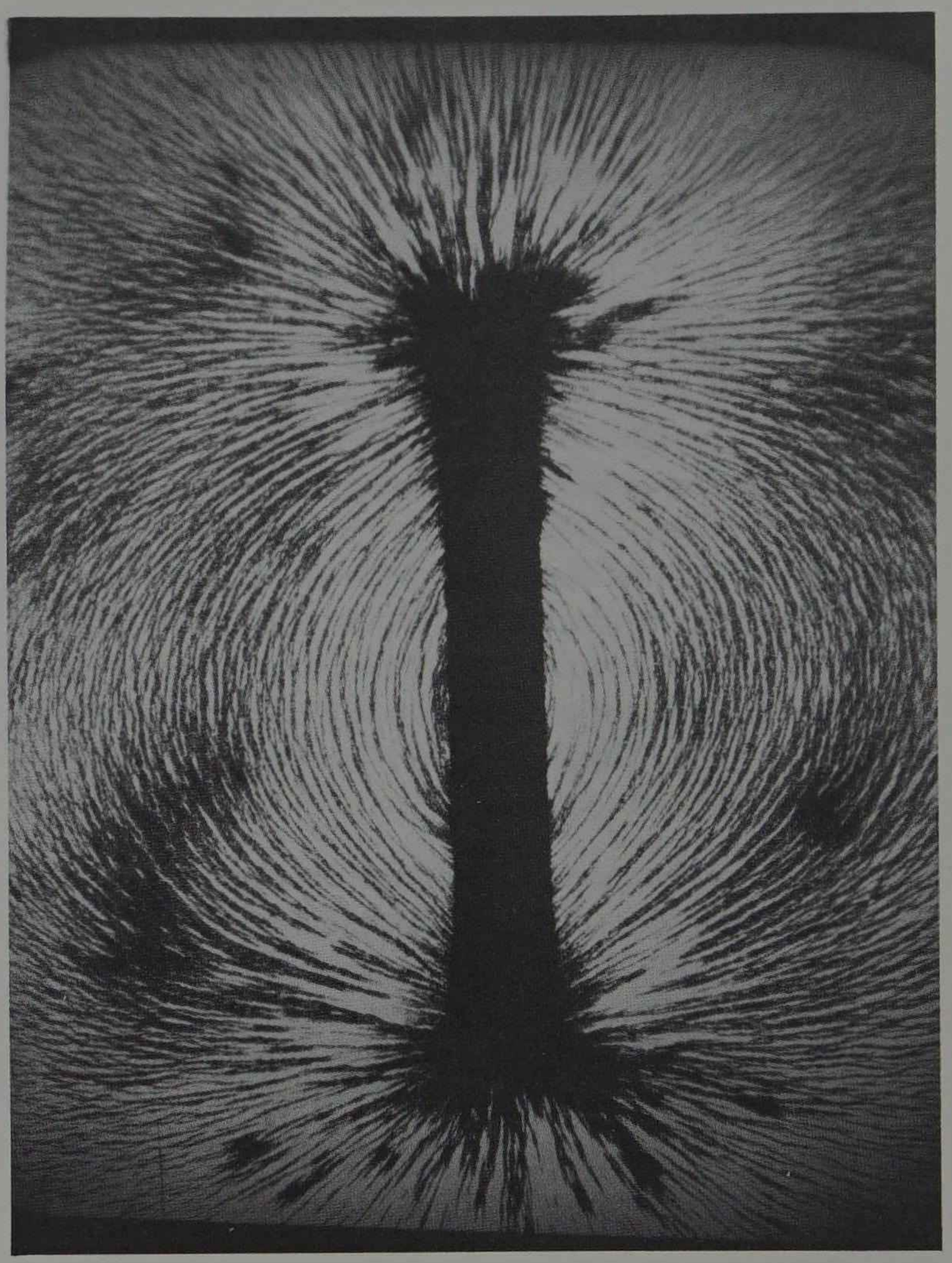


Figure 4.12 The magnetic field of a bar magnet made visible by sprinkling iron filings on a piece of glass over the magnet.

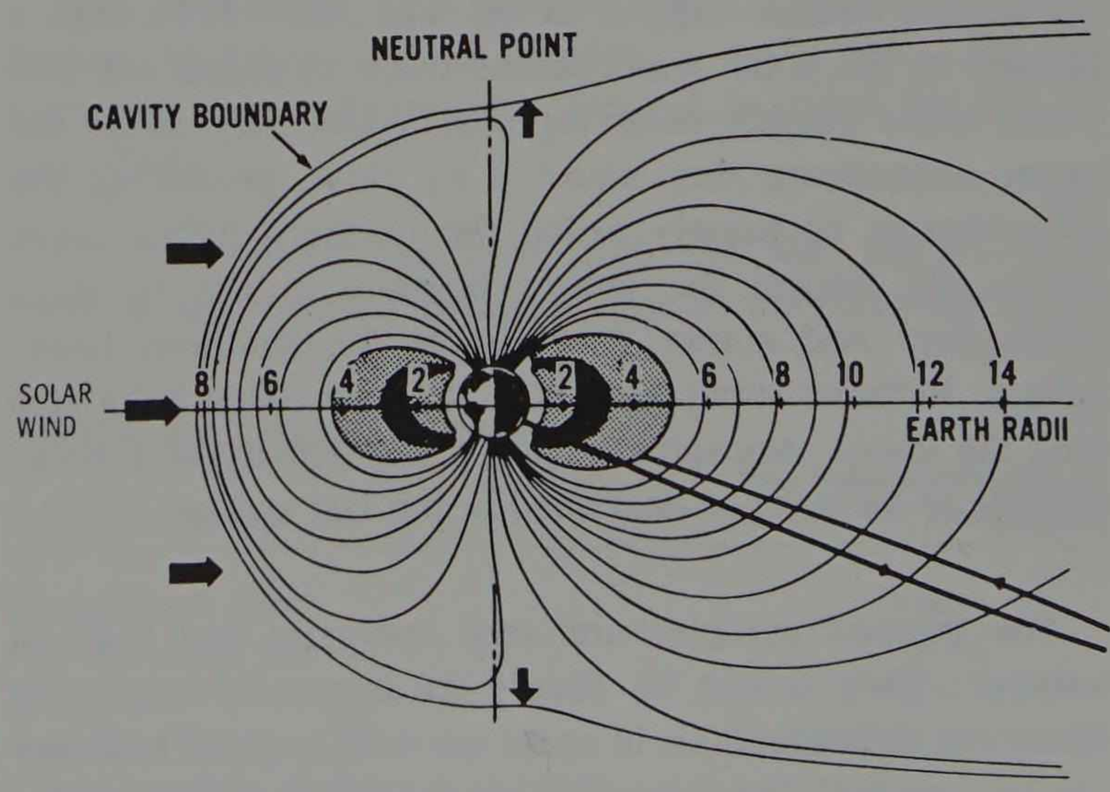


Figure 4.13 Earth's magnetic field. It is distorted by the solar wind, the flow of charged particles from the Sun; the cavity in space thus provided is called the magnetosphere. The distance scale on the diagram is marked in ''Earth radii''; the radius of the Earth is about 4,000 miles. The orbit of a spacecraft which investigated the magnetosphere extends to the lower right of the Earth. *Courtesy of NASA.*

does reach the ground. We are all constantly exposed to this low level radiation. It is more intense at higher altitudes than at sea level.

Solar Activity and Atmospheric Density

An important aspect of solar activity is its effect on the density of the air. The upper atmosphere is heated by the collisions with solar wind particles and by absorbing electromagnetic energy, particularly x-rays and ultraviolet. When solar activity increases, the temperature of the upper atmosphere increases. You usually hear that heating causes things to expand and therefore you would expect density of such substances to decrease. Not so in the upper atmosphere. When the temperature goes up the atmosphere does indeed expand, but at orbital altitude this expansion brings up more air molecules from below. Thus, at a given altitude the density increases.

The effect on a satellite orbit can be dramatic, particularly when there is a sudden increase in the solar wind. The result is a more rapid decay of the orbit and an early burn-in of the satellite. Also, the orbits of satellites at low altitude may change so rapidly that those who track and control the satellites may lose track of them.

Trapped Particles: The Van Allen Belts

Two donut-shaped regions circling Earth inside the magnetosphere trap charged particles and hold them. These regions are called the Van Allen radiation belts. See Figure 4.14. Their existence was unknown until James Van Allen of the University of Iowa discovered them from data recorded by the first U.S. satellite, Explorer I.

Particles remain trapped in the Van Allen belts until a change in the solar wind causes them to dump out and "rain" into Earth's polar regions. When they strike the upper atmosphere they cause it to glow, producing the phenomenon commonly called the northern lights, more technically named the aurora borealis in the northern hemisphere and aurora Australis in the southern hemisphere. Particles dumping out of the Van Allen belts also heat the upper atmosphere causing the density at a given altitude to increase as described in the last section.

The trapped particles are very energetic and high in number. They would be deadly to astronauts traversing them, but their locations in space are well mapped and they can be avoided. The inner belt begins at 250 to 750 miles, depending on latitude, and extends to about 6,200 miles. It is occupied mostly by protons which have a peak count over 60,000 per square inch per second at about 2,000 miles. The outer belt contains electrons and extends from the top of the inner belt, 6,200 miles up to 37,000 to 52,000 miles depending on solar activity. Peak electron count is at about 9,900 miles.

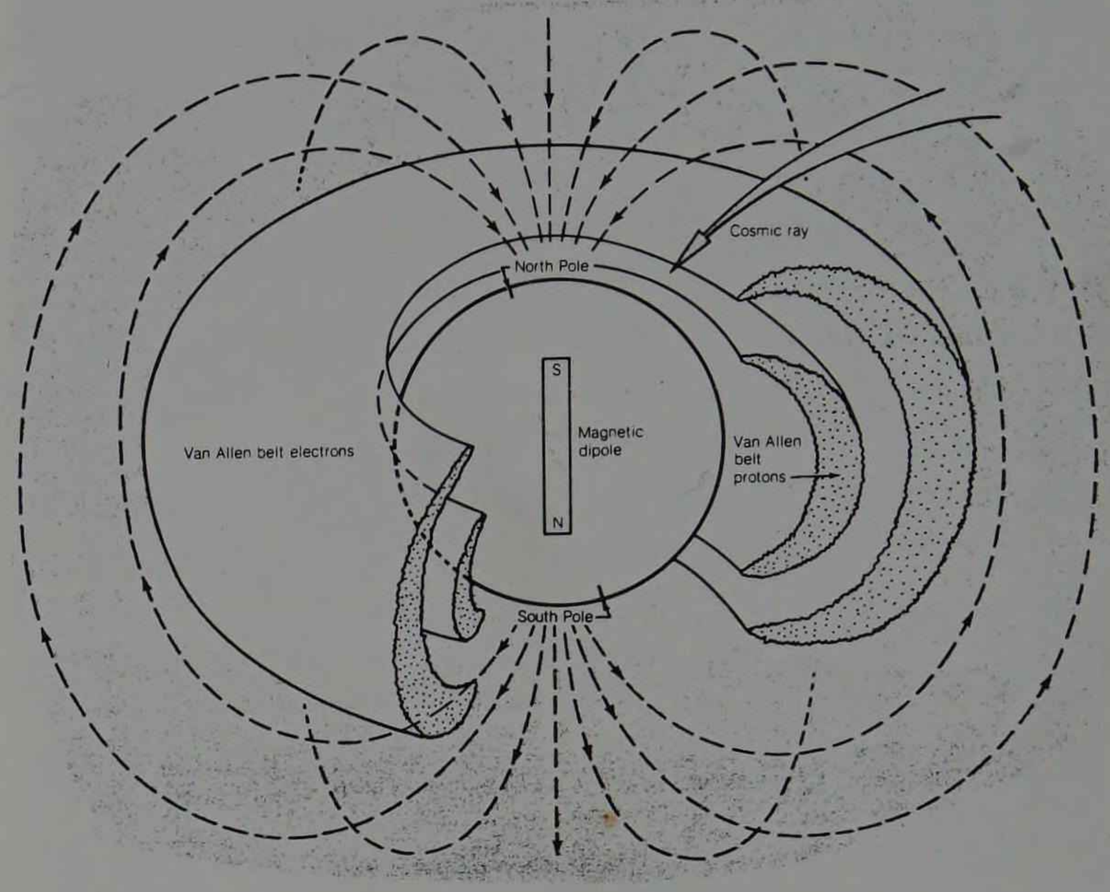


Figure 4.14 Van Allen radiation belts. Protons are trapped in the inner belt and electrons are found in the outer belt, while the dashed lines represent Earth's magnetic field. Cosmic rays can penetrate the magnetosphere especially in the polar regions. Note that Earth's north and south poles are tilted with respect to the magnetic field. *Courtesy of NASA.*

The Van Allen belts are far enough from Earth that they are no problem for vehicles in low Earth orbits except over the South Atlantic Ocean just east of Brazil. Because of an irregularity in Earth's magnetic field in that region, they dip to their lowest altitude. In a 275 mile orbit, a thousand fold increase in radiation is noted by spacecraft as they pass through; a hundred fold increase is seen at 140 miles.

Spacecraft at higher altitudes such as in geosynchronous orbits, highly elliptical orbits, and on trajectories to the Moon or other planets must either avoid the belts completely or be prepared to cope with the trapped particles.

Meteoroids, Meteors, Meteorites

From earliest recorded history people have watched streaks of light flash across the night sky—shooting stars or, more technically, *meteors*. At least a few appear every night, and on certain dates every year they occur in such profusion we call the event a meteor shower.

Occasionally we hear reports of a rock or chunk of iron falling from the heavens, sometimes a whole shower of them; on rare occasions someone is hit by one. In the early morning hours of March 4, 1960, near Edmonton in western Canada, a bright fireball crossed the sky and was followed a few minutes later by a thundering noise which rattled the windows. The next day farmers found more than 180 pounds of black stones scattered over the snow in a two by three mile area. Such stones are called *meteorites*.

A mile wide crater in northwestern Arizona was made by

the impact of a large chunk of iron-nickel which fell from the sky about 30,000 years ago. Because of Arizona's desert climate the crater has not eroded and we see Meteor Crater today much as it looked when it was created.

These happenings are related. They are all caused by pieces of space debris that fall to Earth. The only difference is the size of the piece. While they are still in space we call these objects *meteoroids*. They come in all sizes: some so small you need a microscope to see them (*micrometeoroids*), some the size of small planets (*asteroids*). By far the vast majority of them have a mass of less than a thousandth of a gram. (It takes nearly 30 grams to make an ounce.)

It is thought that meteoroids originated at the beginning of the Solar System, that they are pieces of debris left over when the Solar System formed. They are still being swept up from space by passing planets and moons. There is evidence of impacts on our Moon by all sizes of objects. Large craters where asteroid sized objects impacted are obvious in photographs of the Moon, and the Apollo astronauts brought back Moon rocks that bear microscopic sized impact craters.

We see few such craters on Earth because of our atmosphere and our weather. First, few meteoroids make it through the atmosphere to the ground. They burn up as meteors on the way down because of friction with the air. Those that do reach the ground, now called meteorites, must be quite large before their impact leaves a crater. Second, growing plants, running water, weathering, and erosion wear and tear the crater away so it is no longer recognizable after a few thousand years. Because our Moon has no atmosphere or weather, craters appear as they did when they formed, most of them three to four billion years ago.

Periodic meteor showers are probably associated with comets. Comets have been described as dirty snowballs, composed of water ice and dry ice with various kinds of dust and debris frozen in. Some comets are periodic, orbiting the Sun in elliptical orbits with periods of a few years to a few centuries. Each time they approach the Sun they heat up. The ices melt or sublimate and blow off some of the dust and debris into space. It is this material that forms the comet's tail. When the comet leaves the vicinity of the Sun, it once again freezes up until its next approach. The material of the tail eventually becomes distributed throughout the comet's orbit. If Earth's orbit intersects the comet's orbit, that material will fall to Earth as meteors. Cometary material is very small; little of it survives the atmospheric heating to reach the ground.

Asteroids are concentrated in the region of space between Mars and Jupiter. However, the orbits of some of them cross Earth's orbit and enter the inner Solar System. Non-cometary meteoroids are probably related to the asteroid belt.

Hazards to People

We have discussed the contents of space at some length. Let us now summarize the aspects of the space environment that need to be considered when planning either manned or unmanned spaceflights. At this point we are concerned mainly with the environment itself. The biological effects will be discussed further in Chapter 9.

An asteroid hitting a spaceship would of course be a catastrophe. Even a pea-sized meteoroid could be disastrous. But what is the probability of such a collision? Statistics on the number of meteoroids and micrometeoroids in space and their size distribution can be calculated from observing meteors in the night sky, from experience with satellites that carry impact counters, and from experiments carried on Gemini, Apollo, and Skylab and returned to Earth for examination.

To get an idea of the meteoroid content of near Earth space, consider a square surface one yard on a side. How frequently will meteoroids of various sizes impact that square? Table 4.1 shows a statistical estimate. However, this doesn't tell us whether or not the particle will penetrate the spacecraft. That depends on the thickness of the skin. Table 4.2 gives that information for a large aluminum space station. Credit for these calculations goes to P. M. Millman of the National Research Council of Canada.

Using a double layered hull for the spacecraft increases the protection markedly. When a meteoroid impacts and penetrates the outer skin, it shatters into many small pieces which have a much lower probability of penetrating the inner skin.

The probability of collision with a meteoroid large enough to cause serious damage is never zero, but the hazard is relatively small compared to other hazards of spaceflight.

Electromagnetic radiation from the Sun can severely harm an unprotected astronaut. For us on Earth the atmo-

TABLE 4.1 Meteoroid Impacts

Mass of Meteoroid	Time Between Impacts on One Square Yard Surface
One-millionth gram*	116 days
One-thousandth gram	63 years
One gram	3,200,000 years
Ten grams	320,000,000 years

*There are about 30 grams in an ounce.

TABLE 4.2 Meteoroid Penetrations

Thickness of Aluminum Skin	Frequency of Penetration
0.015 inch	10 per day
0.2 inch	1 per year
2.75 inches	1 per 10,000 years

sphere absorbs and filters out most of the harmful rays. Even so, you would avoid too much exposure to the Sun on the beach or in the mountains. Sunburns are not only uncomfortable, but excessive exposure to ultraviolet causes skin cancer. An astronaut does not have the protection of an atmosphere and must avoid exposure to the undiluted full blast of solar ultraviolet and x-rays. Protection is not difficult, however. The cabin of a spacecraft or the material of a spacesuit is sufficient.

Particle radiation is another matter. Normally the solar wind does not pose a threat to life. The electrons and protons are travelling slow enough that they are not harmful for short exposure times. Galactic cosmic rays are of concern on long duration flights. They travel at very high speed and are very penetrating, but are relatively few in number. It has been estimated that continuous exposure to galactic cosmic rays for a year would exceed a safe dosage by some 60 times, but for short trips into space the dosage is not excessive. Trapped radiation in the Van Allen belts would be a serious threat but these regions can be avoided in manned spaceflight.

Solar cosmic ray protons emitted during a large flare are a very serious problem. At least one solar proton event in recent years was of sufficient intensity that astronauts inside a Space Shuttle in polar orbit would have suffered from severe radiation sickness, perhaps death.

Effects on Equipment

Early in the space age, before much was known about the space environment, equipment aboard satellites sometimes failed from exposure to x-rays or cosmic rays. Particularly, transistors and other microcircuitry are susceptible to damage from x-ray bursts or high energy protons emitted during solar flares. Photographic film is fogged by x-rays and cosmic rays. Measuring instruments give false readings when high speed protons or cosmic rays pass through. We have learned to properly construct and shield equipment from most of these environmental hazards, but long exposure in space invariably degrades their operation.

Space Environment Forecasting

It would be nice to know if and when solar flares and cosmic ray proton events are going to occur so flights are not planned at that time. Unfortunately, forecasting flares is somewhat comparable to forecasting thunderstorms and predicting solar proton events is like forecasting tornadoes. Forecasts are made routinely at a joint civilian-military forecasting center and provided to NASA. They state the probability of occurrence of a large solar flare and a proton event. A definite ''yes or no'' forecast giving the exact time and intensity of a proton storm in space is beyond anyone's capability at present. If there are no active regions or sunspots visible on the Sun, the forecaster can issue a near-zero probability forecast. If there are several active regions with complicated sunspot configurations and large plage areas, then the probability of a flare is high.

Making flare forecasts involves evaluating the flare potential of each active region on the Sun. Some of the more important criteria used in this evaluation are:

a. high magnetic field strength around sunspots and plages
b. rapidly increasing magnetic fields
c. magnetic complexity
d. emergence of new magnetic fields in a stable or decaying region
e. shearing or twisting of the field
f. frequent small flares with increasing x-ray emissions
g. regions moving toward each other

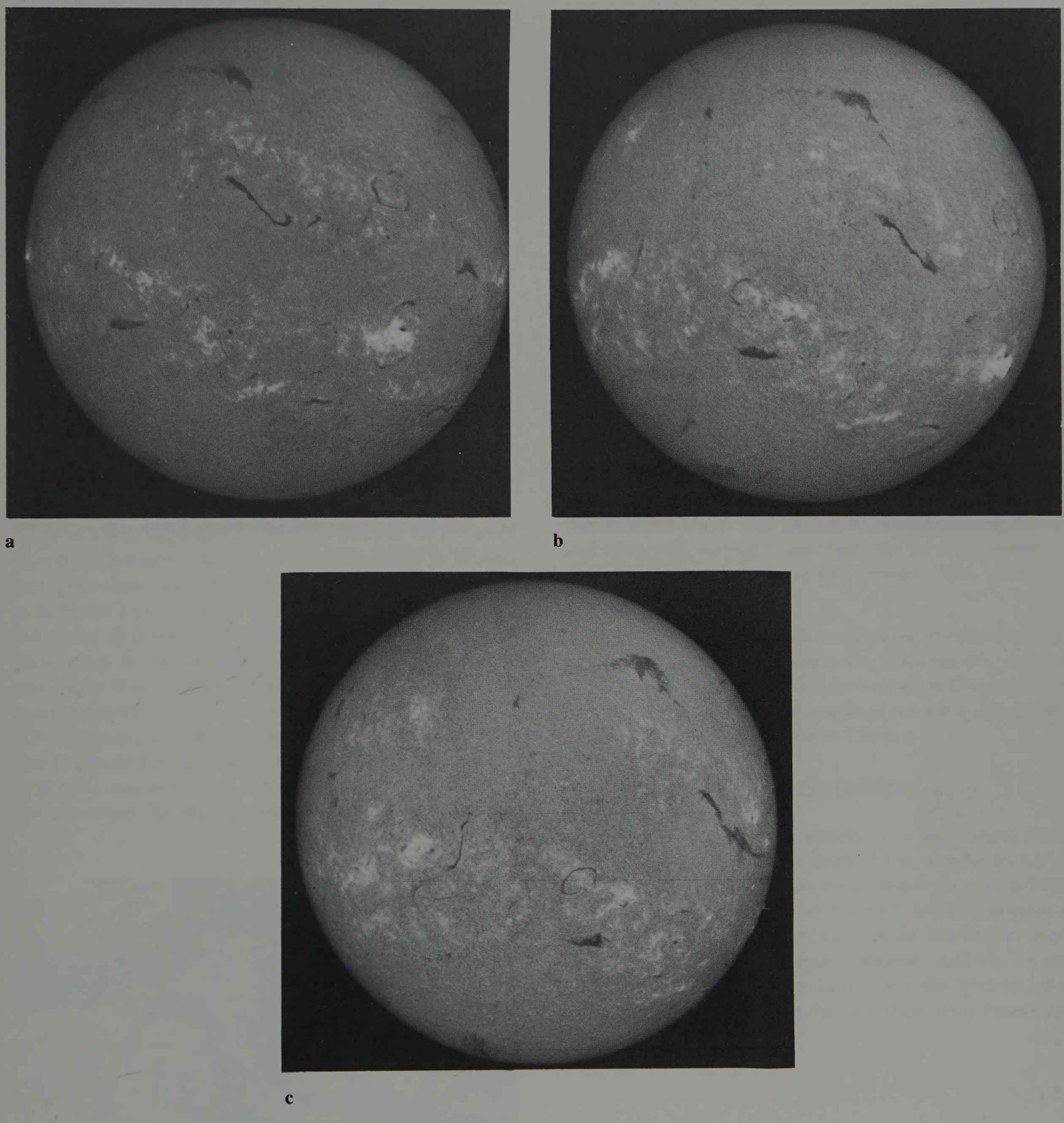
There are other factors as well, but note that the most important ones are concerned with the history of the active region, how it develops and changes, particularly the magnetic field configuration.

Figure 4.15 shows hydrogen-alpha pictures of the Sun taken two days apart. Notice how the plages and filaments appear to move from left to right (east to west since north is at the bottom) across the disk. Actually, this apparent motion is the rotation of the Sun on its axis. If the features seen on the disk persist, they eventually disappear off the right (west) side. About two weeks later those active regions that rotated off the west side will come back into view on the east side. Their return can be anticipated. During the two weeks when they are out of view, the regions may increase or decrease in complexity, or even fade away completely. Likewise, new regions are born and develop. All this must be taken into account by the space forecaster when the forecast is prepared.

The forecasts are quite reliable, especially the ''no flare'' forecast. Forecasters can generally tell whether a region will produce large flares, but predicting the time of occurrence varies from difficult to impossible.

Proton events are even more difficult to predict. However, given that a flare has occurred, the forecaster uses several parameters to state whether a proton event is likely in near Earth space. Some of the characteristics of a proton flare are:

a. a pair of parallel ribbons
b. coverage of the darkest portion of the sunspot
c. the location of the event on the Sun's disk
d. long bursts of radio waves and x-rays and



a b c

Figure 4.15 The Sun. (a) July 2, 1982; (b) July 4, 1982; (c) July 6, 1982. *Courtesy of the National Solar Observatory, Association of Universities for Research in Astronomy, Inc.*

e. high intensity radio noise at certain wavelengths and less intensity at certain others.

If the forecaster believes that a proton event is likely, a warning can be issued.

This is similar to the way in which severe weather warnings are issued. A probability forecast is issued first, then an advisory if conditions favorable to severe weather develop, and finally a warning when the severe weather is actually sighted.

To keep track of events on the Sun, a joint civilian-military network of solar observatories has been established around the world in such places as Hawaii, Australia, New

Mexico, and Italy. Sites were chosen for their good weather for observing the Sun. In addition, they are so spaced around the world that at least one is always able to see the Sun. Data is sent from the observatories to the forecasters in the United States who evaluate the information and pass it on to NASA and other interested parties. If a manned flight is in progress, the forecasters keep close contact with mission control, updating them on any solar activity that may prove hazardous.

DISCUSSION QUESTIONS

1. Why doesn't the solar wind blow satellites out of orbit?
2. The Sun is composed mostly of hydrogen. Why, then, is the solar wind mostly protons and electrons?
3. If the Earth's atmosphere suddenly became transparent to all electromagnetic radiation, what changes, if any, would you expect to take place on Earth?
4. If the Earth's atmosphere had always been transparent to all electromagnetic radiation, how might Earth be different?
5. If you had an important space mission to fly but there was a high probability of a solar proton storm, would you go anyway? What factors would determine your decision?

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Chapter 5

Satellites

Earth has one natural satellite: the Moon. Sputnik, the first artificial satellite of Earth, was launched by the Soviet Union on October 4, 1957. It carried a small transmitter that beeped a signal to ground stations following its trek across the sky. That is all it did.

At the end of 1987 there were over 7,000 man-made objects being tracked in their orbits around Earth, only 1,750 of which were useful satellites. The rest are pieces of burned out boosters, satellites whose transmitter or sensors have gone dead, and a few small objects such as bolts and an astronaut's glove. Since Sputnik, nearly 12,000 payloads and pieces of debris have fallen out of orbit, most of them burning up in the atmosphere during their fall. Orbiting man-made objects of sufficient size are catalogued by the North American Aerospace Defense Command (NORAD) at its command post inside Cheyenne Mountain, Colorado, near Colorado Springs, Figure 5.1. Tracking data is fed into NORAD computers from a worldwide network of radars and telescopes. Orbital parameters for the most important satellites are frequently updated so their locations are known at all times.



Figure 5.1 NORAD Space Surveillance Center. A space analyst studies the ground trace of a spacecraft on the computer display. The center operates 24 hours a day to maintain an up-to-the-minute catalog. *Courtesy of U.S. Space Command.*

What are they all doing up there? Some of the first practical uses for satellites included communications relay, weather observing, military surveillance, monitoring ocean wind and waves, geodetic mapping, and monitoring of Earth resources. Experiments have been conducted on satellites for search and rescue, locating fishing grounds, and observing icebergs. Satellites are used for scientific research in astronomy, space physics, and planetary science.

This chapter will deal with satellites for communications, navigation, and energy production. Satellites for viewing Earth and celestial objects will be covered in Chapter 6. By far the greatest number of satellites are for military purposes; they will be discussed in Chapter 7.

Communications Satellites

Radio waves propagate in straight lines and cannot travel around the curvature of the Earth. Thus, a radio or television receiver cannot pick up broadcasts from a transmitter that is beyond the horizon; see Figure 5.2. The *ionosphere,* a naturally occurring ionized layer of the atmosphere from about 60 miles to 200 miles altitude, reflects certain frequencies so they can be heard over the horizon, also shown in Figure 5.2. Long distance short wave broadcasts

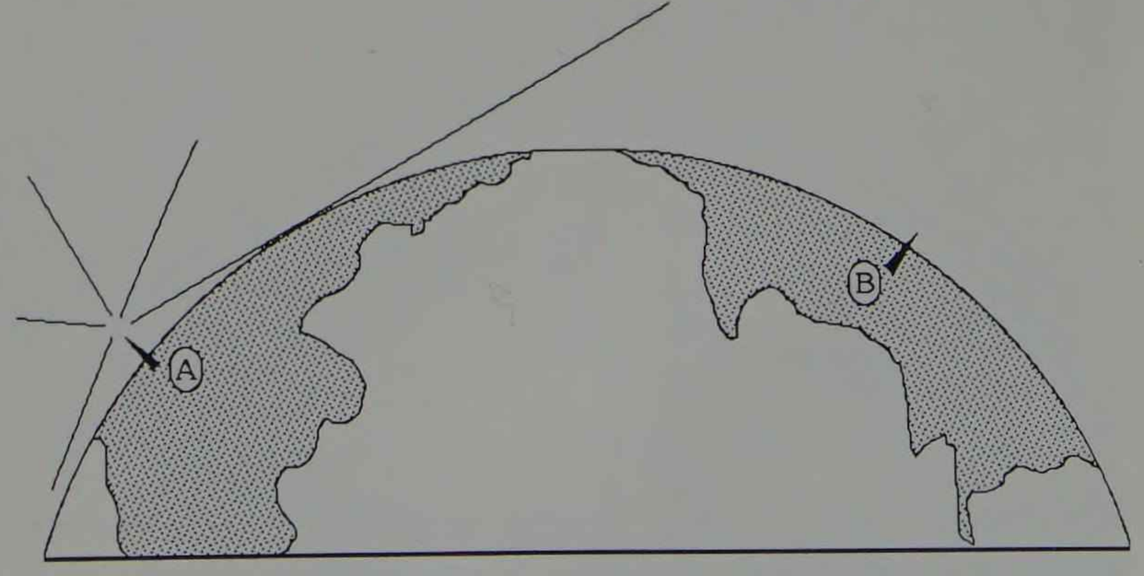


Figure 5.2 Radio signals do not curve around Earth. A radio receiver at B cannot receive the broadcast from the transmitter at A.

are received by ionospheric reflection, but the ionosphere is irregular and somewhat undependable. If an artificial ''mirror'' could be placed in orbit, communications could be reliably established between any two points on Earth.

The first U.S. experiment in communicating via satellite was Echo 1, a 100 foot aluminized mylar balloon launched into orbit folded in a small package which opened and inflated on arriving in orbit. Because it carried no receiver or transmitter it could be used only passively, as a reflecting surface to bounce radio signals beyond the transmitter's horizon (Figure 5.3). Its spherical shape scattered the radio waves in all directions and only a small amount reached the intended receiver. Echo 1 was launched August 12, 1960. Echo 2, 135 feet in diameter, was launched the following year.

Later, active relay satellites replaced the passive balloons. The active relay communications satellites carry receivers and transmitters. The signal is sent to the satellite, picked up by its receiver, and retransmitted on another frequency to a ground station.

Placing relay stations in space was a natural follow-on to the microwave relay stations on Earth. During the 1940s and 1950s, communications companies had set up a network of microwave stations across the country to replace the long wires and to extend telephone and television services to more remote areas. At each relay station the signal was received and retransmitted to the next station in line. Because radio waves travel in straight lines and do not follow the curvature of the Earth, the microwave towers had to be placed within line of sight of each other. On flat terrain the towers were built about 50 miles apart. This communications technology was well developed, and when satellites came along there was the opportunity to place the relay tower in space where broadcasts could be transmitted to vast areas from a single transmitter in orbit.

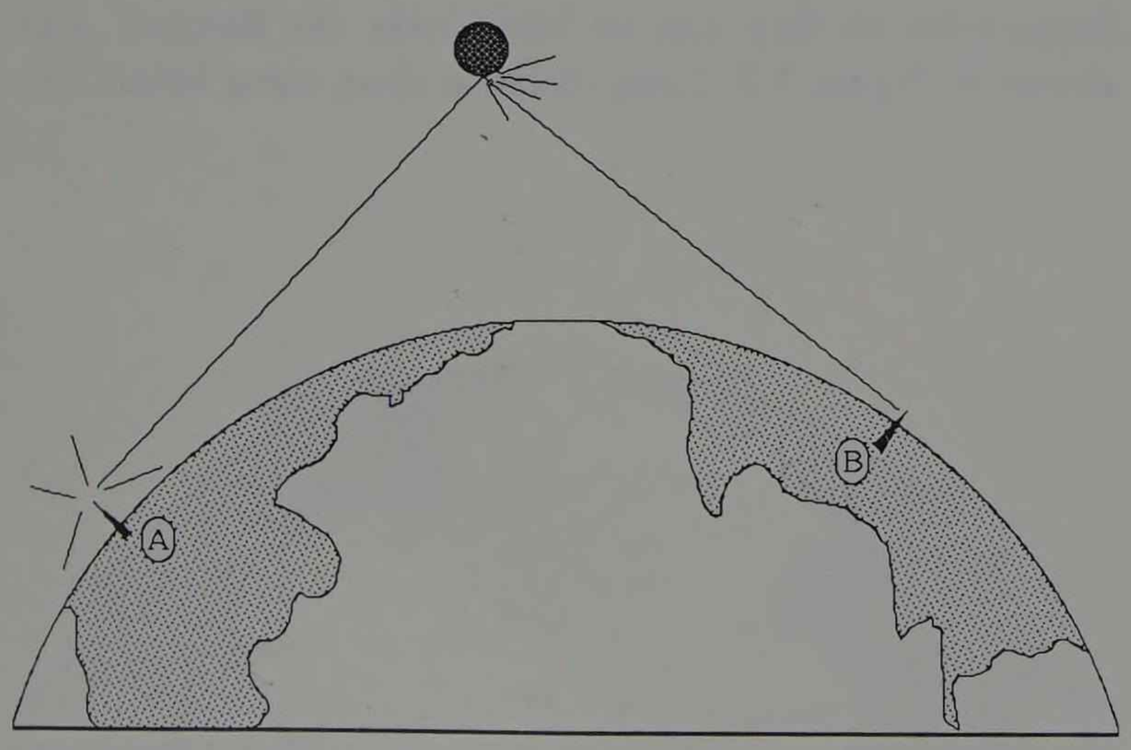


Figure 5.3 The Echo balloon in orbit acted as a reflector so signals from the transmitter at A bounced to the receiver at B. Later, relay satellites received the signal from the transmitter on the ground and re-transmitted it to receivers beyond the horizon.

The first American active repeater satellites were Bell Telephone's Telstar 1 and RCA's Relay 1, both launched in 1962. Relay 1 could handle 12 two-way telephone conversations simultaneously or one television channel. Now, each satellite in the Intelsat VI series handles more than 32,000 telephone calls at once.

The favored orbit for communications satellites is the geosynchronous orbit, a circular orbit with an inclination of zero degrees, 22,300 miles above the equator. (Refer back to Figure 3.16.) At that distance the orbital period is 23 hours and 56 minutes, the time it takes the Earth to make one rotation on its axis. Therefore, the satellite's angular speed is the same as the Earth's, 360 degrees per day. To a ground observer, the satellite appears to remain in the same spot in the sky. This has two advantages for communications satellites. First, the large dish antennas do not have to track a moving satellite. Construction is much simpler and cheaper. Second, from a distance of 22,300 miles, a satellite can ''see'' almost one-third of the Earth's surface. Theoretically, only three satellites are needed to cover the entire Earth except for the high latitude regions around the north and south poles.

These ideas originated with science and science fiction writer ''Arthur C. Clark, coauthor with Stanley Kubrick of *2001: A Space Odyssey.*'' In the 1940s and 1950s, Clarke was active with the British Interplanetary Society, a far-sighted group of scientists, engineers, and laymen who studied and developed many futuristic ideas about space travel. In the October 1945 issue of *Wireless World*, Clarke published a paper showing the technical feasibility of placing communications satellites in geosynchronous orbit. The geosynchronous orbit is sometimes called the Clarke orbit in his honor.

The first geosynchronous satellite was Syncom II, which achieved orbit on July 26, 1963. On August 19, 1964, Syncom III was locked into a stationary location near the international date line. It carried the first trans-Pacific television broadcast, the Tokyo Olympic Games. By 1988 there were more than 120 communications satellites in geosynchronous orbit.

Soviet Union Molniya communications satellites are in 63 degree, 12 hour orbits of high eccentricity as described in Chapter 3. They offer two advantages. First, the satellites dwell for many hours over high latitudes where geosynchronous satellites are difficult to use. Second, less energy is required to launch an object into a 63 degree orbit than into a geosynchronous orbit from the Soviet Union's northern launch sites. More than 100 Molniya satellites have been put into orbit, many of which have since burned up on reentry back into the atmosphere.

In the 1970s and early 1980s dish antennas were popping up in back yards all over town to receive television programs directly from the satellites. In the 1970s it was necessary to have a 30 foot dish antenna to receive signals

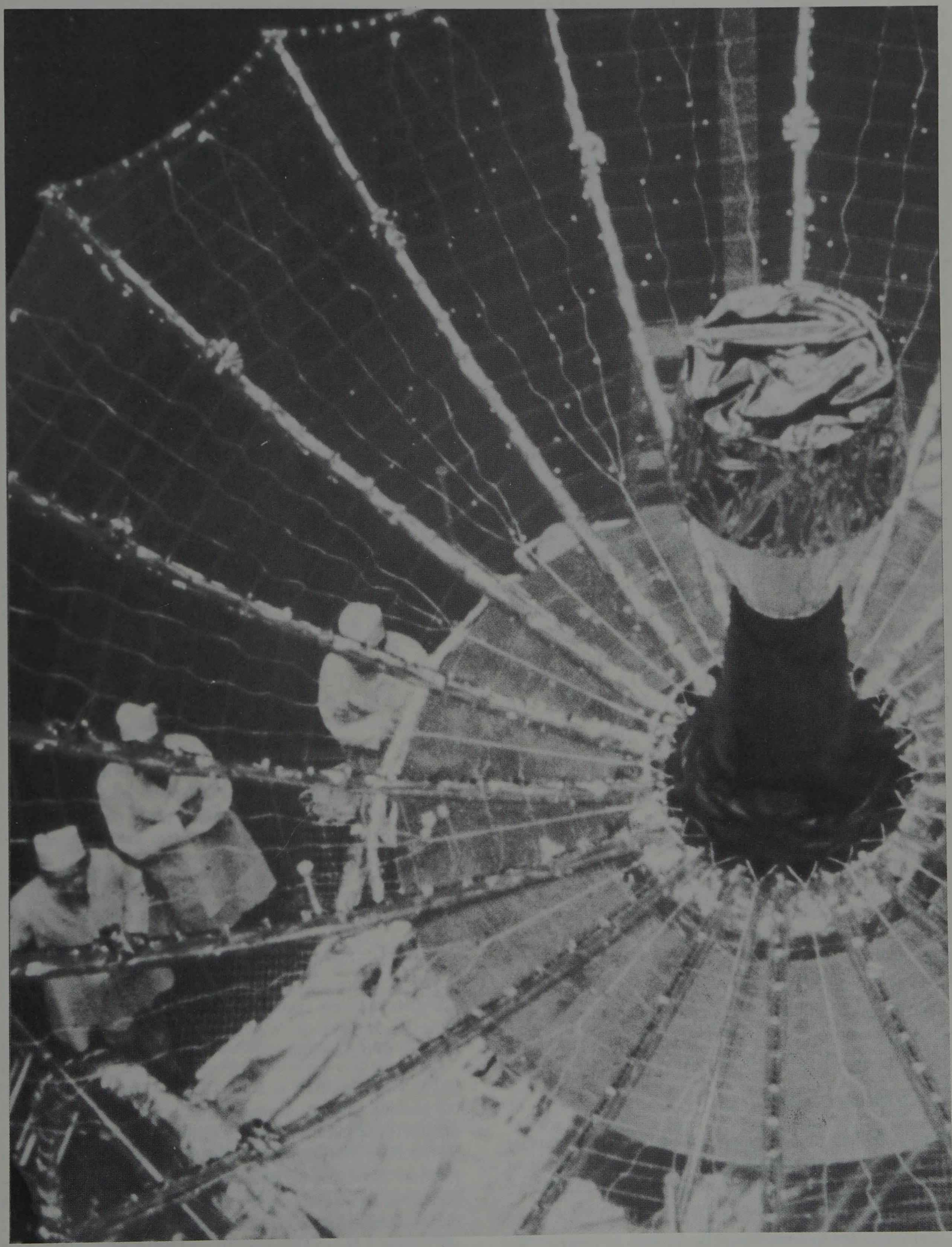


Figure 5.4 A NASA Tracking and Data Relay Satellite (TDRS) antenna open for ground testing. *Courtesy of NASA*.

reliably and clearly; now an 8 foot dish will do the job. Practically all television programming, except for local programs, is relayed around the world by satellite. A dozen or more satellites, each carrying half a dozen or more programs, can be seen from a single location. Even Soviet television broadcasts via Molniyas can be picked up from the Northern United States, although the color and sound are not compatible with a standard American television set.

To prevent interference between satellites, each is assigned specific operating frequencies and they are spaced at least 4 degrees or about 2,000 miles apart in orbit. This limits the number of satellites that can operate in geosynchronous orbit in the western hemisphere to about 20. An international organization of the United Nations is responsible for assigning frequencies and orbit positions so there is no mutual interference.

Most communications satellites operate in the C-band, 3,700 to 4,200 MHz (3.7 to 4.2 GHz). Recent satellites have been moving to higher frequencies in the Ku-band, 11.7 to 12.2 GHz. This allows the transmitter to carry more channels or conversations on a single carrier frequency. However, the higher frequencies are attenuated, absorbed, by clouds and rain. Because satellite transmitters have limited power output, any attenuation of the signal is a problem. Absorption by large size shower type raindrops is greater than by drizzle or small cloud droplets. A climatological study of the receiver site gives a clue as to the percent of time that the downlink may be wiped out due to heavy precipitation. The engineers' solution to the problem has been to increase the power of the satellite transmitters. However, as higher frequencies are called into use, the problem becomes more acute.

The antennas on the satellites may be designed for maximum area coverage, or they may be narrow beams, sending their signals to relatively small regions on the Earth. A NASA Tracking and Data Relay Satellite (TDRS) is shown with its antenna open for inspection in Figure 5.4. Next it is folded into a compact package for launch by the Space Shuttle (Figure 5.5). Figure 5.6 shows it deployed in space. As the state of the art advances, it may become possible to transmit to and receive from a communications satellite directly from a handheld walkie talkie radio. Pocket telephones may become a reality.

A dedicated military constellation of communications satellites called Milstar provides command and control of forces worldwide, on every continent.

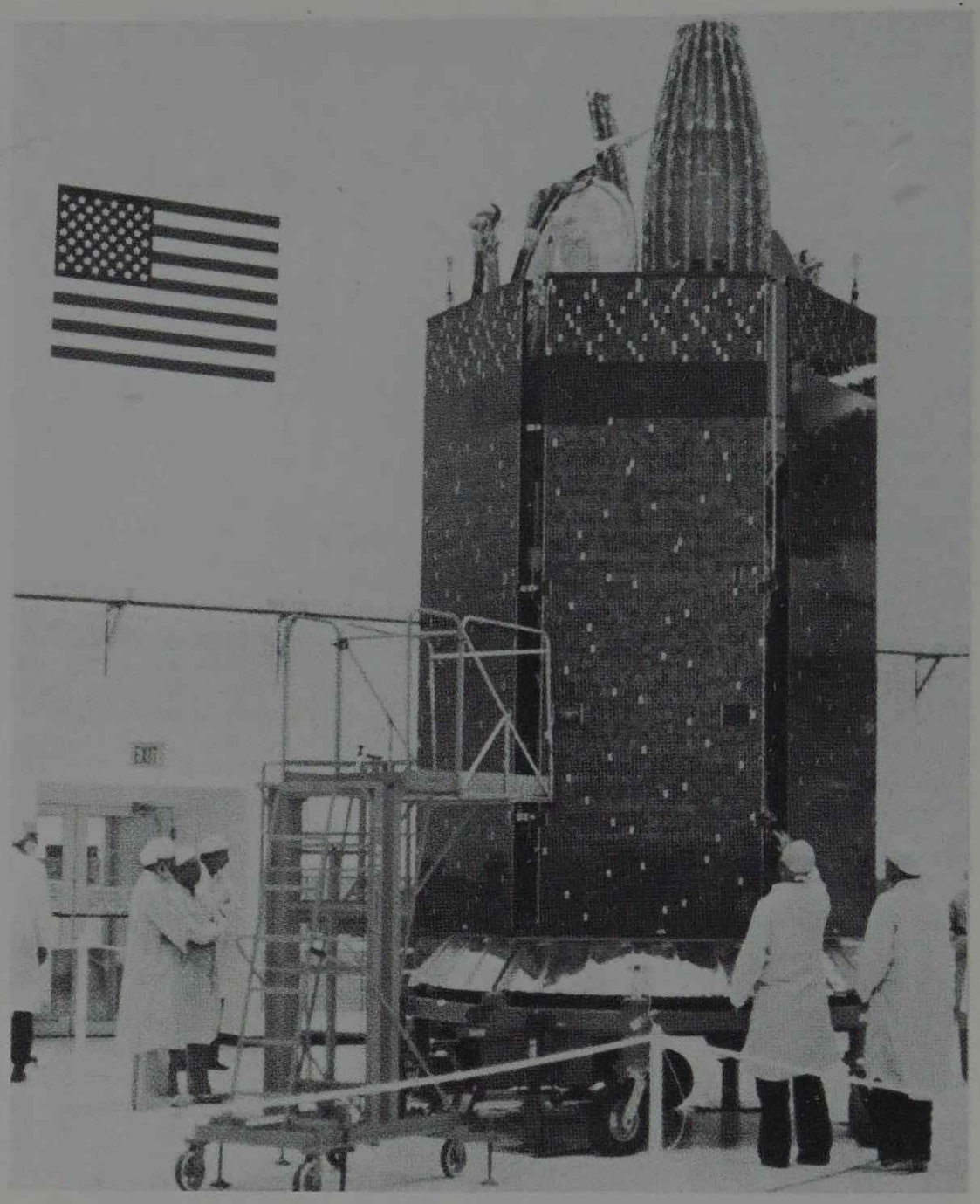


Figure 5.5 The TDRS folds into a compact package to fit into the Space Shuttle's cargo bay for lofting into space. A rocket is later attached at the bottom to boost it from the Shuttle's orbit to geosynchronous orbit. *Courtesy of NASA.*

Navigation Satellites

Using satellites it is now possible to find your precise location at any time and place on Earth with an accuracy of about 30 feet. How is it done? Look first at an example of how you determine distances travelled in your car.

Let's take a trip from Colorado Springs to Denver. We leave at 2:30 on the dot and arrive in Denver at exactly 3:45. Assume we traveled at a constant speed of 55 miles per hour. How far is it from Colorado Springs to Denver? Time elapsed from 2:30 to 3:45 is an hour and fifteen minutes, 1.25 hours. Multiply that times the speed and we get 68.75 miles. The accuracy of our answer depends on whether our watch gained or lost time during the trip and how precisely we held to a constant speed.

Using navigation satellites to locate our position on Earth is based on the same principles. A satellite transmits a radio pulse at a given time. The clock in our receiver tells us what time we receive the pulse. Assume that the radio pulse travels at a constant speed, the speed of light, and assume that the clocks are synchronized together so we can determine the elapsed time. We can then calculate the range, the distance to the satellite.

The range by itself is not sufficient information to find our position. It is also necessary to know the location of the satellite. The latest ephemeris (orbital data) is also transmitted from the satellite so we can calculate its precise location. Now that we have the satellite's location and its range, we know that we are somewhere on a sphere with a radius equal to the range and with the satellite at the center; see Figure 5.7.

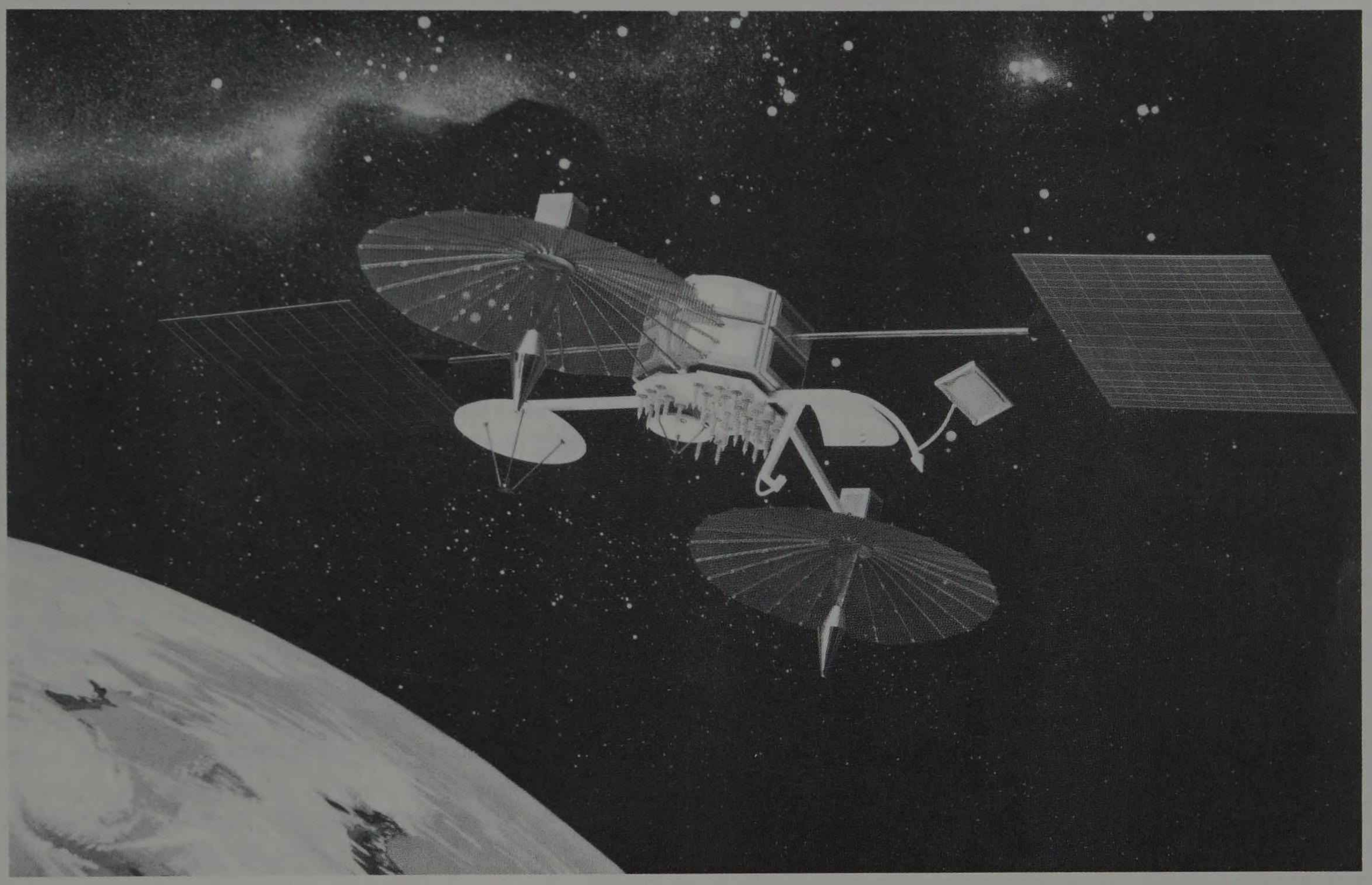


Figure 5.6 An artist's conception of TDRS in orbit. Seven antennas (can you find them all?) cover three frequency bands. The two largest ones, over 16 feet in diameter, are steerable. Receivers and transmitters are in the hexagonal box in the center. Arrays of solar cells on the two square paddles provide power. *Courtesy of NASA.*

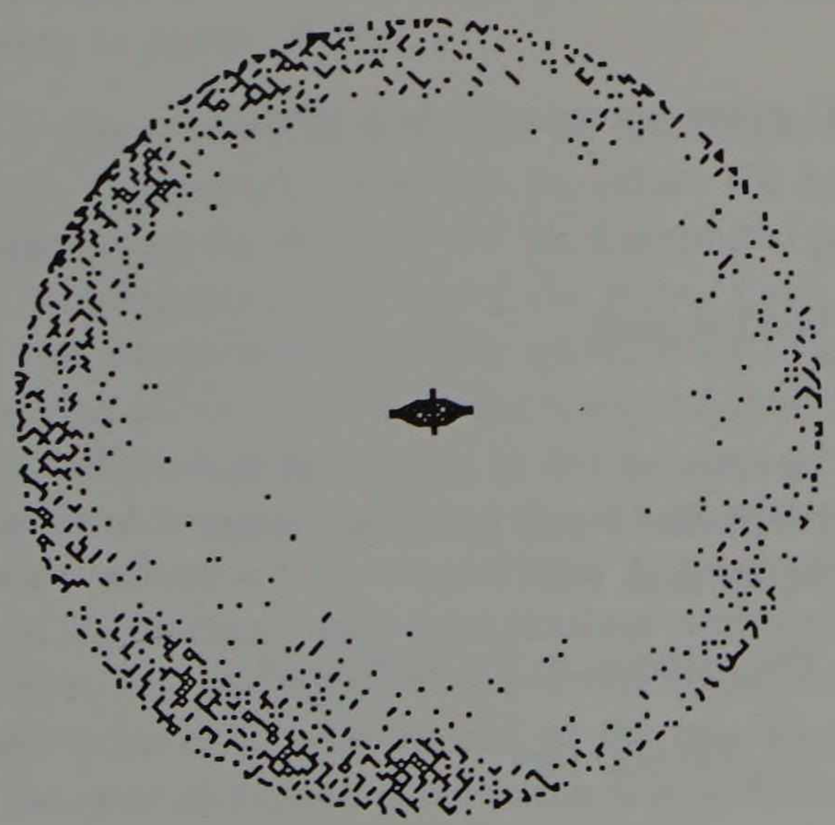


Figure 5.7 A sphere with a satellite at the center. The radius of the sphere is the distance (range) from the observer to the satellite.

This still does not tell us our precise location. Next we obtain the same information from a second satellite to locate ourselves on a second similar sphere. If we are on both spheres at the same time, we must be at the place where the two spheres intersect. See Figure 5.8 (it looks like a snowman). Notice that two spheres intersect in a circle (the

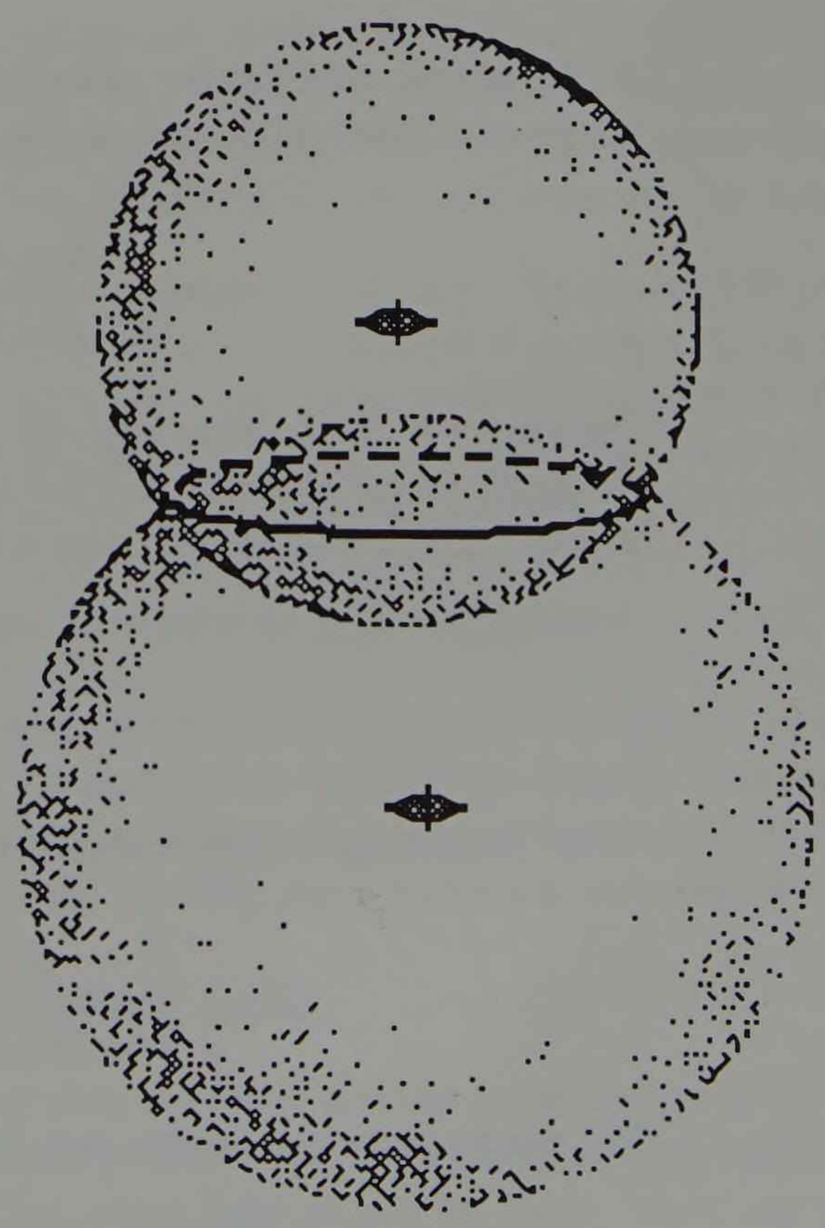


Figure 5.8 Two overlapping spheres, with radii equal to the ranges of the two satellites. They intersect in a circle.

waist of the snowman) so we know we must be somewhere on that circle. Getting warmer! Reading out a third satellite pins us down to our precise location (X on Figure 5.9), our latitude, longitude, and altitude with an accuracy of a few feet.

Working out our position is a mathematical problem of no small magnitude. It involves solving three equations in three unknowns: latitude, longitude, and altitude. Receivers specially designed for use with the navigation satellites incorporate a microcomputer chip preprogrammed to handle the calculations.

There are two difficulties with putting this relatively simple idea into practice.

First, in order for this to work, the clocks in the satellite's transmitter and the user's receiver would have to be exactly synchronized. The satellite clocks are updated and synchronized three times a day using atomic clocks which are accurate within one second in 300,000 years. However, atomic clocks are not mobile and the clock in a mobile receiver cannot be made accurate enough to precisely measure the travel time of the pulse. A small error in the travel time produces a large error in the range calculation. MATHBOX 5.1 shows some sample calculations. An

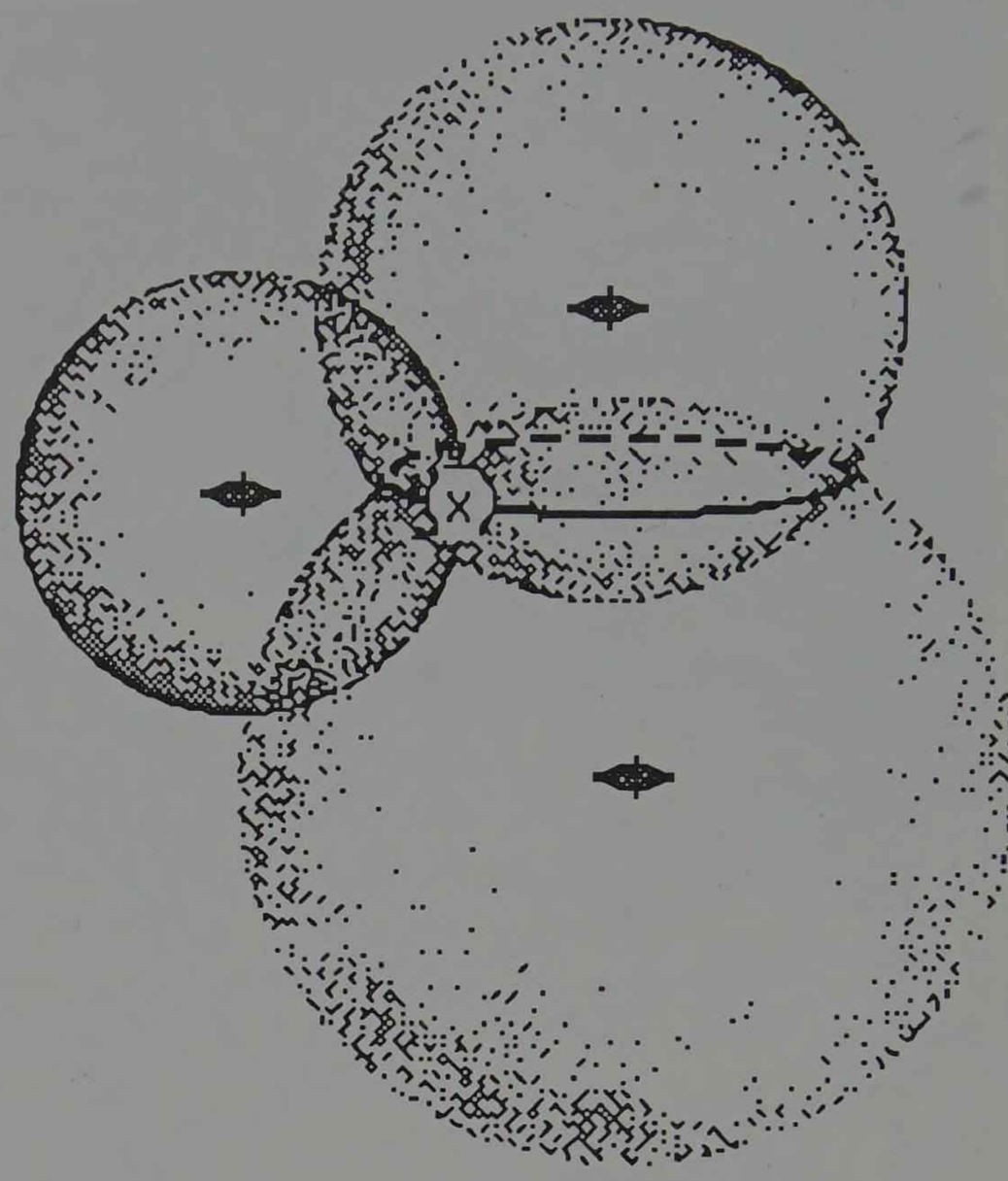


Figure 5.9 Three overlapping spheres with radii equal to the ranges of the three satellites. The position of the observer is marked "x".

MATHBOX 5.1

Range Error

Radio waves travel at the speed of light, about 186,000 miles per second. At a satellite range of 12,000 miles, travel time is

$$\text{time} = \frac{\text{distance}}{\text{velocity}} = \frac{12{,}000}{186{,}000} = 0.0645 \text{ second}$$

An error of 1% in measuring the time would produce an error of 1% in computing the distance. In our example, a 1% timing error is .0006 second; that would produce a range error of 120 miles! A navigator can guess his position better than that!

Suppose we want to reduce the range error to 50 feet. The distance to the satellite is

$$12{,}000 \text{ miles} \times 5{,}280 \text{ feet per mile} = 63{,}360{,}000 \text{ feet.}$$

What percentage of this distance is 50 feet?

$$\left(\frac{50}{63{,}360{,}000}\right) \times 100\% = 0.00008\%$$

We must reduce the timing error to

$$0.00008\% \text{ of } 0.0645 \text{ second} = 0.00000005 \text{ second!}$$

error of 50 billionths of a second in time produces a range error of 50 feet!

The way around this problem is to read out a fourth satellite and treat the receiver's clock error as a fourth unknown. In actual practice, the user receives transmissions from four satellites and the computer solves four equations in four unknowns: latitude, longitude, altitude, and clock error. MATHBOX 5.2 shows the algebra.

The second problem comes from the assumption that the radio pulse from the satellite travels at 186,282 miles per second, the speed of light in a vacuum. But here the pulse does not travel in a vacuum. It travels through the Earth's atmosphere during part of its trip to the ground, and its speed depends on atmospheric conditions, particularly conditions in the ionosphere. The ionosphere is the upper part of the atmosphere extending from about 50 miles to 250 miles. In this region the air is ionized by the intense solar x-ray and ultraviolet radiation, and the free electrons cause an apparent slowing of the radio pulse. The density of free electrons determines how much the actual speed of the pulse deviates from the speed of light in a vacuum. Electron density in the ionosphere varies in a somewhat predictable fashion through the day, the seasons of the year, and with the 11 year solar cycle. But minute by minute variations can be quite large and cause errors in the range calculations.

An additional error in the assumed speed is introduced by the lower atmosphere, the troposphere. However, the error is small and less variable. Uncorrected, these ionospheric and tropospheric effects on pulse speed cause range errors amounting to nearly 20 feet.

The problem of pulse speed can be handled in either of two ways, one more accurate than the other. The amount of error depends on the frequency of the transmitted pulse; the higher the frequency, the lower the error. Each satellite carries two transmitters operating on different frequencies. By receiving pulses on both frequencies and comparing the range calculations, it is possible to remove the error. A less accurate correction can be made using information about the ionosphere contained in the satellite transmission. It is based on the average daily and seasonal variations in the ionosphere. For this method of correction the user needs only one receiver to pick up one of the two frequencies. While the error correction is not exact, it is accurate enough for many purposes.

If the user is in a moving vehicle, its speed and direction can be calculated by getting two positions in a short time and finding the change in location during that time.

Navstar, the global positioning system (GPS), when completed will consist of 18 satellites in six circular 12 hour orbits at 12,000 miles altitude, 3 satellites in each orbit. A ground station in Colorado Springs sends messages regularly to the satellites to update the clocks and orbital parameters. The system will give an unlimited number of users the capability to determine their position within 30 feet, their velocity within 0.07 mile per hour, and the time within a millionth of a second. While the system was originally developed for military purposes, many civilian activities can benefit from its use. Merchant ships could follow the most favorable routes, taking advantage of ocean currents. The Maritime Administration estimates that a large tanker could save $17,000 in time and fuel in crossing the Atlantic. Airlines could similarly benefit by taking advantage of favorable winds. Sea and air collisions could be reduced by each craft knowing its exact position. Search and rescue operations would be more efficient. Receivers have been miniaturized down to the size of a pack of cigarettes. Carry a GPS receiver with you and you will never be lost!

Energy Satellites

Proposals have been made to use satellites to collect solar energy and beam it to our energy-hungry Earth. The prime source of energy consumed by humans now comes from the fossil fuels: coal, oil, and natural gas. But they are not inexhaustible; they will eventually run out. In addition, most of Earth's air pollution problems are traceable to combustion of fossil fuels. Even nuclear energy is not an unlimited source of power. Nuclear electric generators run on uranium fuel, and uranium is not inexhaustible either. An additional factor is the strong public concern over how to dispose of the radioactive waste from nuclear power plants.

One practically endless source of nonpolluting energy exists: the Sun, which will continue in its present state of energy production for another 5.5 billion years. The problem is how to efficiently and economically tap into it.

There has been much popular interest in solar energy in recent years. We see solar collectors popping up on roofs around town. In larger scale installations they are designed to heat the building interior; smaller collectors heat water for household use. In principle, a solar collector is simply a glass covered box which gets hot when the Sun shines into it. Water is pumped through pipes in the box or air is blown through ducts. The heated water or air is then sent to the building or the water storage tank to do its job. In the early 1980s, interest was so high in solar energy that the federal government and some state governments gave tax breaks to people who installed them in homes or businesses.

Photovoltaic Cells

Another way to collect and use solar energy involves *solar cells*. More properly called *photovoltaic cells*, they generate electricity when light shines on them. They are semiconductor devices made of thin wafers of pure silicon, like transistors and computer chips but much larger in diameter.

MATHBOX 5.2

Navstar Equations

Before we examine the equations used by the Navstar system in three dimensional space, let us consider a more manageable problem, the position of an object, P, on a two dimensional surface with respect to another object, A.

Look at Figure 5.2.1. The point A is at position $A_x = 5$, $A_y = 2$. This is written (5, 2). Similarly, P is at $P_x = 1$, $P_y = 1.5$, written (1, 1.5). Notice the right triangle formed by a horizontal line from P, a vertical line from A, and the line r connecting A to P. Our question is, how far apart are A and P? Because r is the hypotenuse of a right triangle,

$$(A_x - P_x)^2 + (A_y - P_y)^2 = r^2.$$

In this case, $r^2 = (4 - 2)^2 + (1.5 - 1)^2 = 4 + .25 = 4.25$. And $r = \sqrt{4.25} = 2.1$.

When we deal in three dimensional space, we must include a third factor.

$$(A_x - P_x)^2 + (A_y - P_y)^2 + (A_z - P_z)^2 = r^2$$

Let us apply this to Navstar. The distance to satellite A is r_A; the distance to the satellite is also the speed of light times the time of travel: $r_A = vt_A$. But we cannot count on our clock to be correct, so we must add a correction factor, e, to the time; $r_A = v(t_A + e) = vt_A + ve$.

Now we are ready to read out four satellites (A, B, C, and D) and write four equations, one for each of them.

$$\begin{aligned}
(A_x - P_x)^2 + (A_y - P_y)^2 + (A_z - P_z)^2 &= (vt_A + ve)^2 \\
(B_x - P_x)^2 + (B_y - P_y)^2 + (B_z - P_z)^2 &= (vt_B + ve)^2 \\
(C_x - P_x)^2 + (C_y - P_y)^2 + (C_z - P_z)^2 &= (vt_C + ve)^2 \\
(D_x - P_x)^2 + (D_y - P_y)^2 + (D_z - P_z)^2 &= (vt_D + ve)^2
\end{aligned}$$

The unknowns in these equations are our position (P_x, P_y, P_z) and the clock error, e. The positions of the four satellites are given in their transmissions, the travel time of the wave is measured by our receiver, and the speed of light is a constant. These are knowns. Because we have four equations we can solve for the four unknowns. (That is, we can let the computer do it).

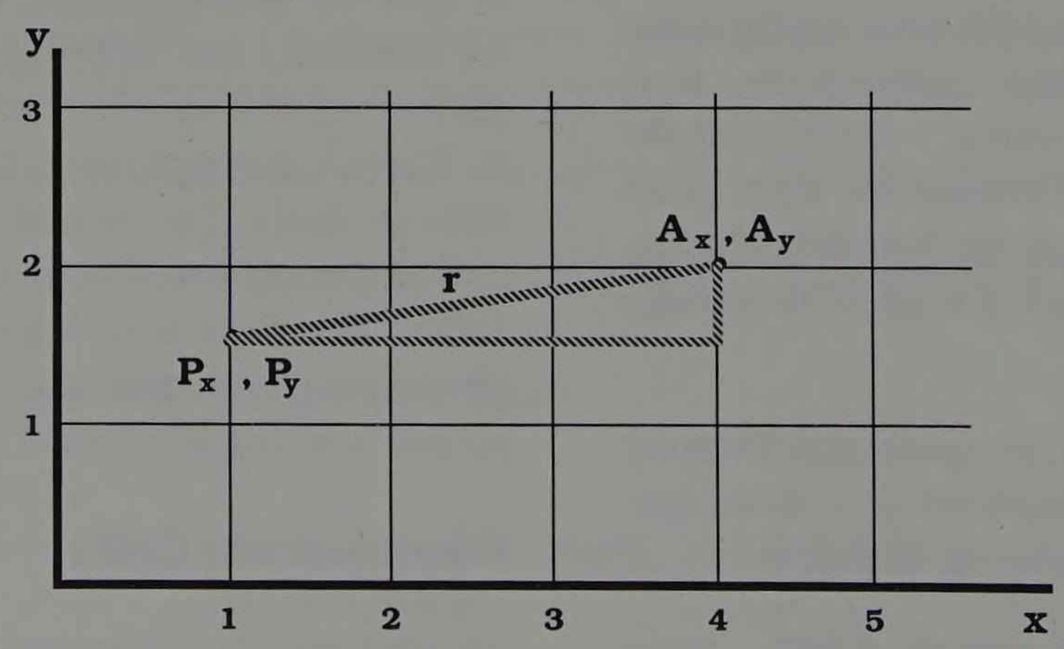


Figure 5.2.1

Figure 5.10 shows a typical cell. There are no moving parts and no fuel is needed to provide clean, quiet, nonpolluting, free electricity. As a bonus, another country cannot cut off the source of supply.

Photovoltaic cells are commonly used as power sources for spacecraft. In fact, the first practical application of solar cells was for powering satellites. You can see them covering the sides of spacecraft or sometimes installed on large wing-like panels attached to the vehicle (Figures 5.11 and 5.12). Skylab, the first U.S. space station, shown in Figure 1.13, was powered by an array that produced 10 kilowatts. They have been used for low power requirements in rural areas (Figure 5.13) and in isolated locations on Earth where it may be too expensive to run an electric power line (Figure 5.14). They are also used to power pocket calculators and exposure meters in cameras.

In theory, you could install an array of solar cells on the roof of your house or in your yard and generate electricity to run your house. A 20 by 30 foot panel would yield a peak of 5,000 watts at midday and an average of more than 1,000 watts over the year. There are a few problems, however. Most obvious, what do you do after sunset and on rainy days? One solution is to charge up storage batteries during the daytime and run the house from them at night. Car batteries are common and have the lowest cost of appropriate storage batteries, but even they would be quite expensive. A car battery costs perhaps $50.00 with a 4 year warranty. To assure that you have enough electricity for overnight plus periods of heavy cloudiness when little electricity is generated by the cells you would need perhaps

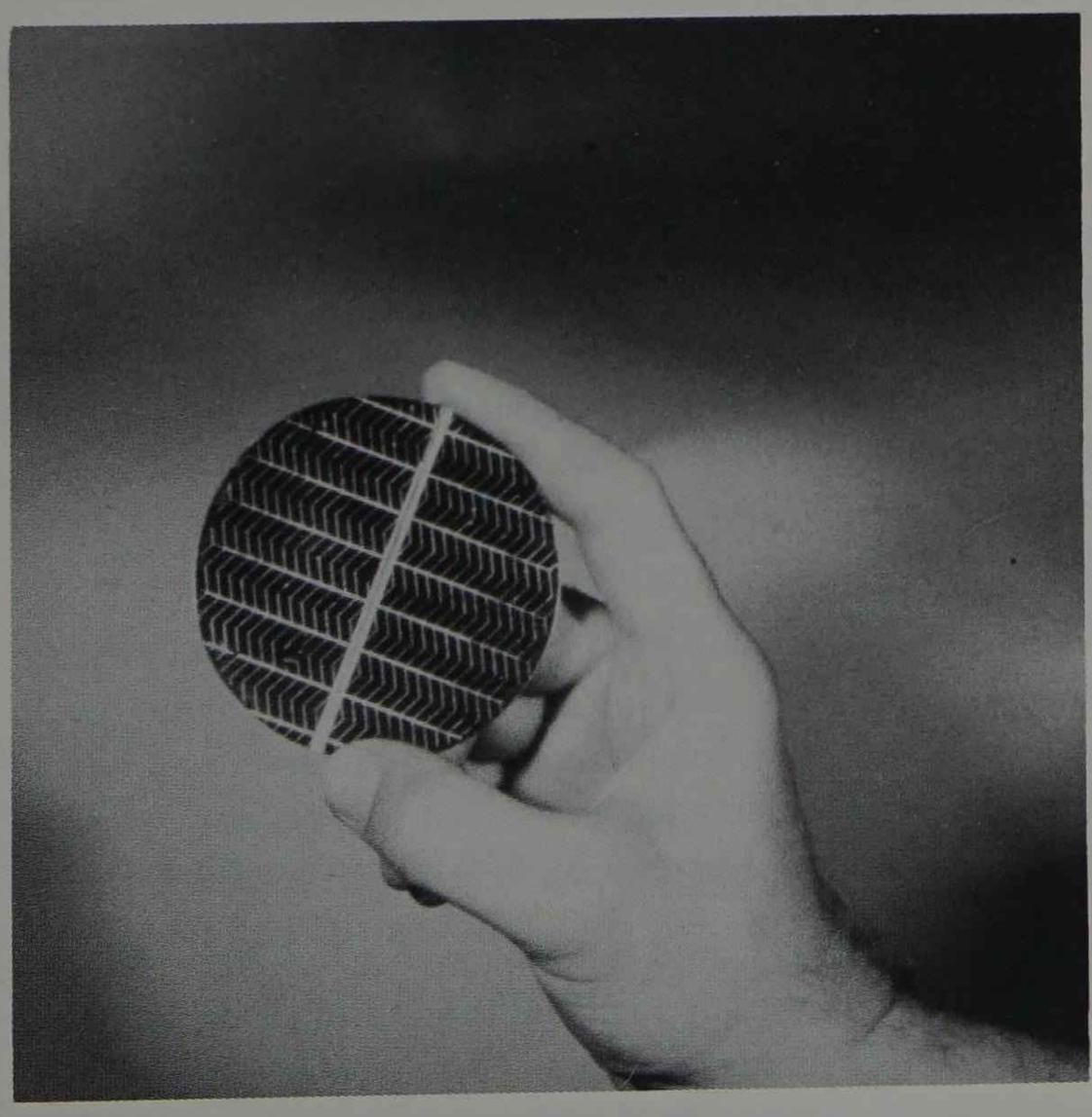


Figure 5.10 Typical photovoltaic cell. *Courtesy of Solar Energy Research Institute*.

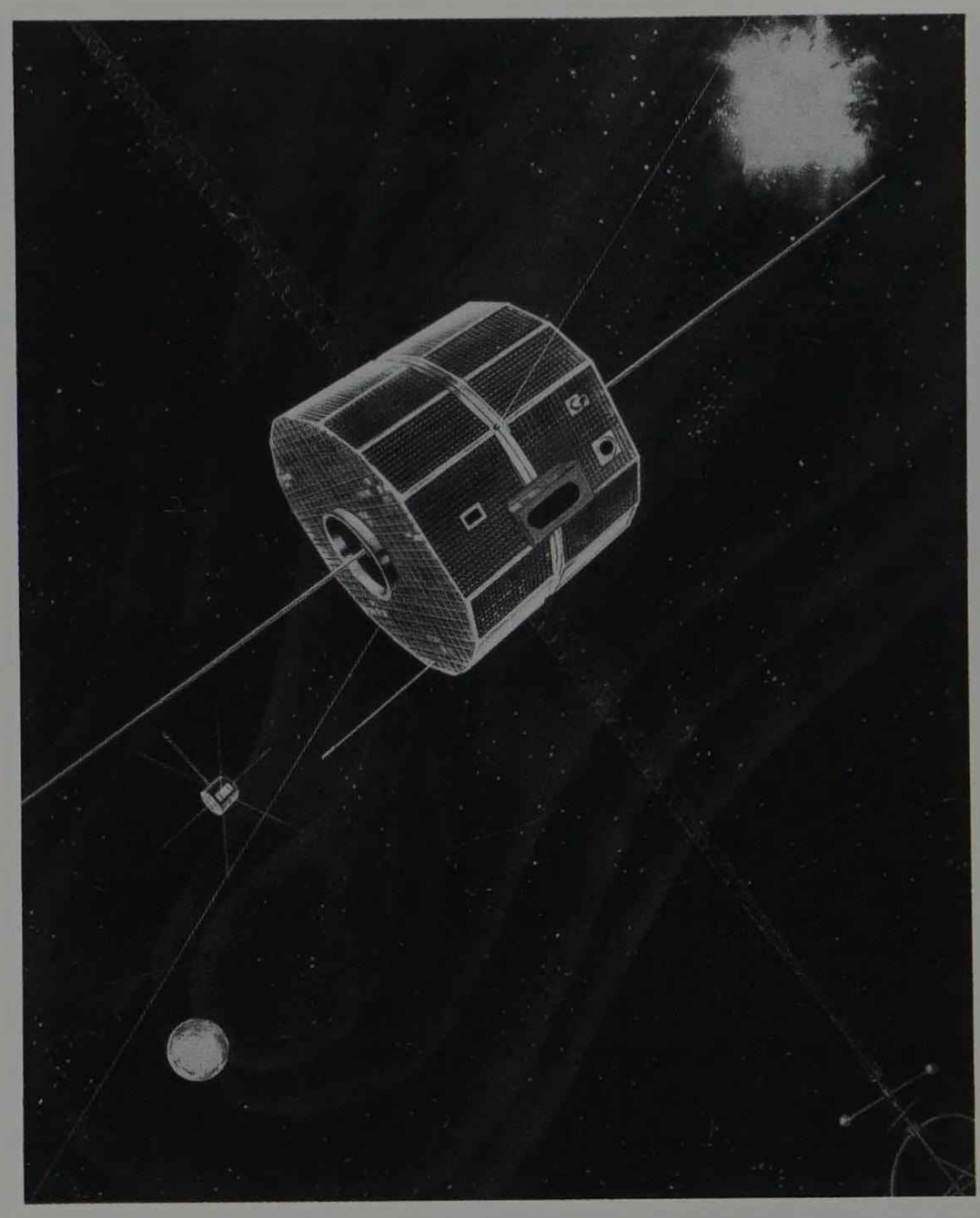


Figure 5.11 Power for the Dynamics Explorer is provided by solar cells covering the main body of the satellite. *Courtesy of NASA*.

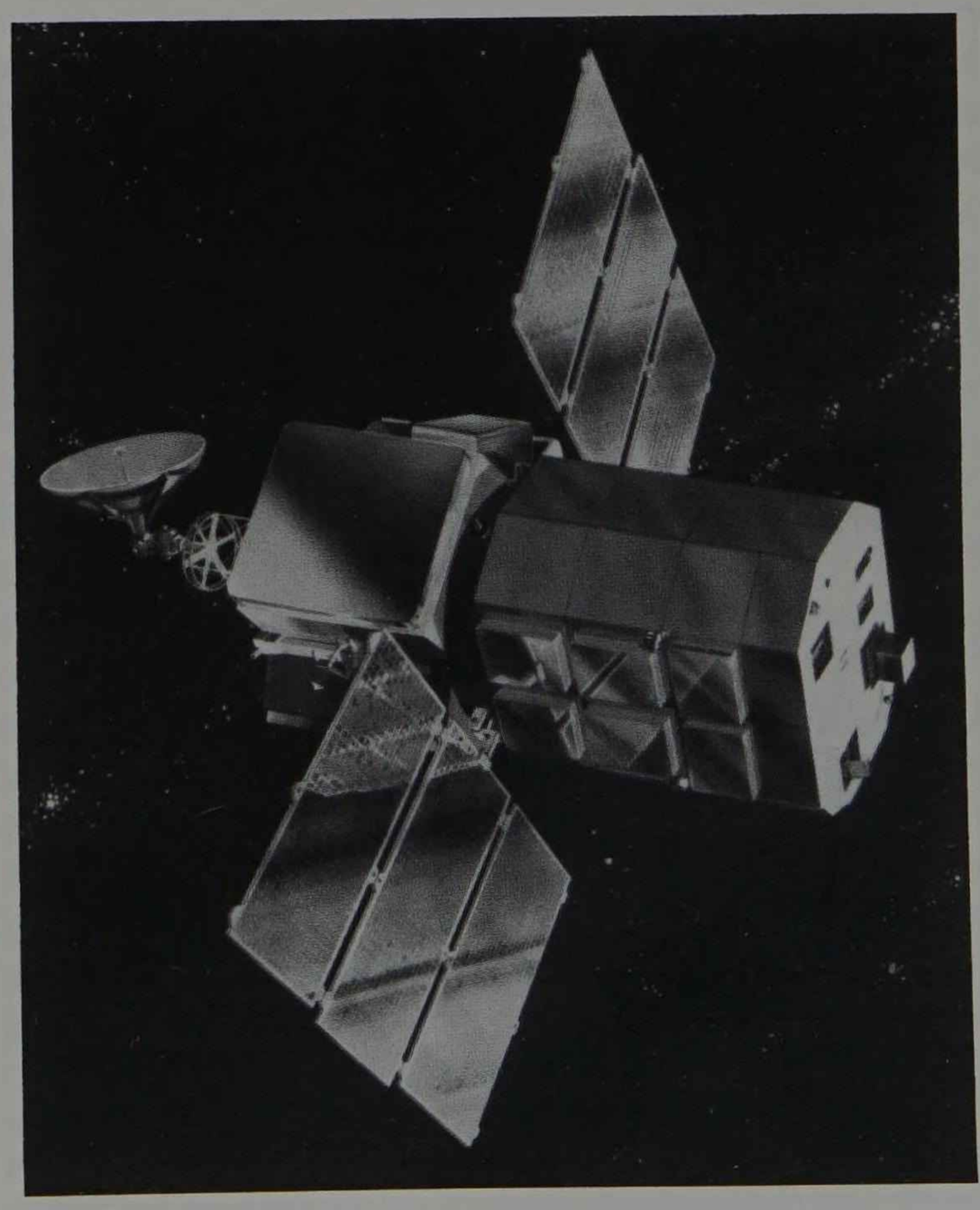


Figure 5.12 Solar cells on six paddles produce electricity for the Solar Maximum Mission satellite. *Courtesy of NASA*.

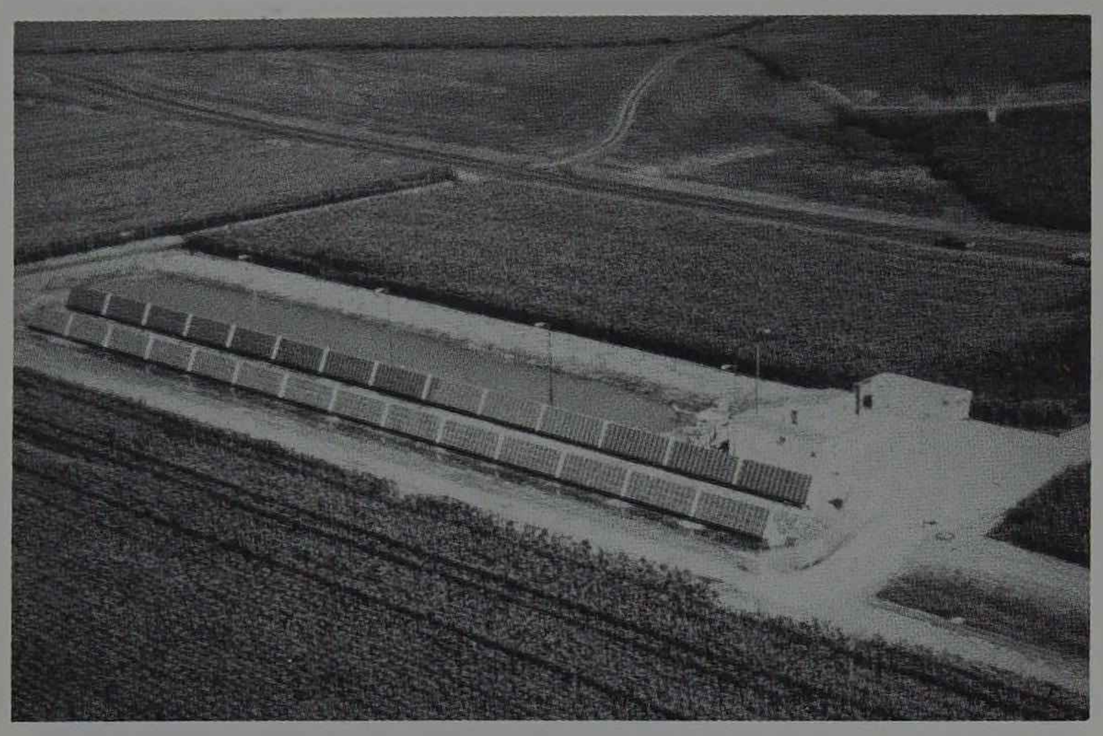


Figure 5.13 A photovoltaic array on a farm near Mead, Nebraska. Eighty acres are irrigated by a 10 horsepower pump for 12 hours a day using only solar energy. *Courtesy of Solar Energy Research Institute.*

40 batteries. If they needed to be replaced every four years, the cost of your ''free'' electricity is $500.00 per year.

Photovoltaic cells are expensive at present, of the order of $15 per peak watt. The 20 by 30 foot array mentioned above costs about $75,000. The cost has been high because much hand work has been required to manufacture the cells, similar to the processes involved in making semiconductors a few years ago. If techniques for mass production can be perfected, then prices will come down dramatically just as they have for other semiconductor devices. Research sponsored by the federal government may bring the cost of a house-sized array down to $5,000 within a few years.

Photo cells are quite inefficient. The best they can accomplish is to convert 14 percent of the light falling on them into electricity, although experimental cells have been built which are 27.5 percent efficient. Also, sunlight is lost on the way down through the atmosphere by scattering, clouds, and pollution. The solution to such inefficiency is simply to build a larger array.

Solar Cells in Space

An experiment in deploying a large photovoltaic array was carried on the Space Shuttle *Discovery*. See Figures 5.15 to 5.17. The accordion-pleated array 13.5 feet wide and 105 feet tall was extended and retracted 17 times successfully. When folded into its box in *Discovery's* cargo bay, it was only 4 inches thick! For the experiment, only one of the panels had active solar cells. If completely covered with photovoltaics, it would have produced 12.5 kilowatts.

From favorable experiences with photovoltaic power supplies came the idea to produce power in space for use on Earth. The concept is to erect very large arrays of solar cells in geosynchronous orbit to produce electricity to generate

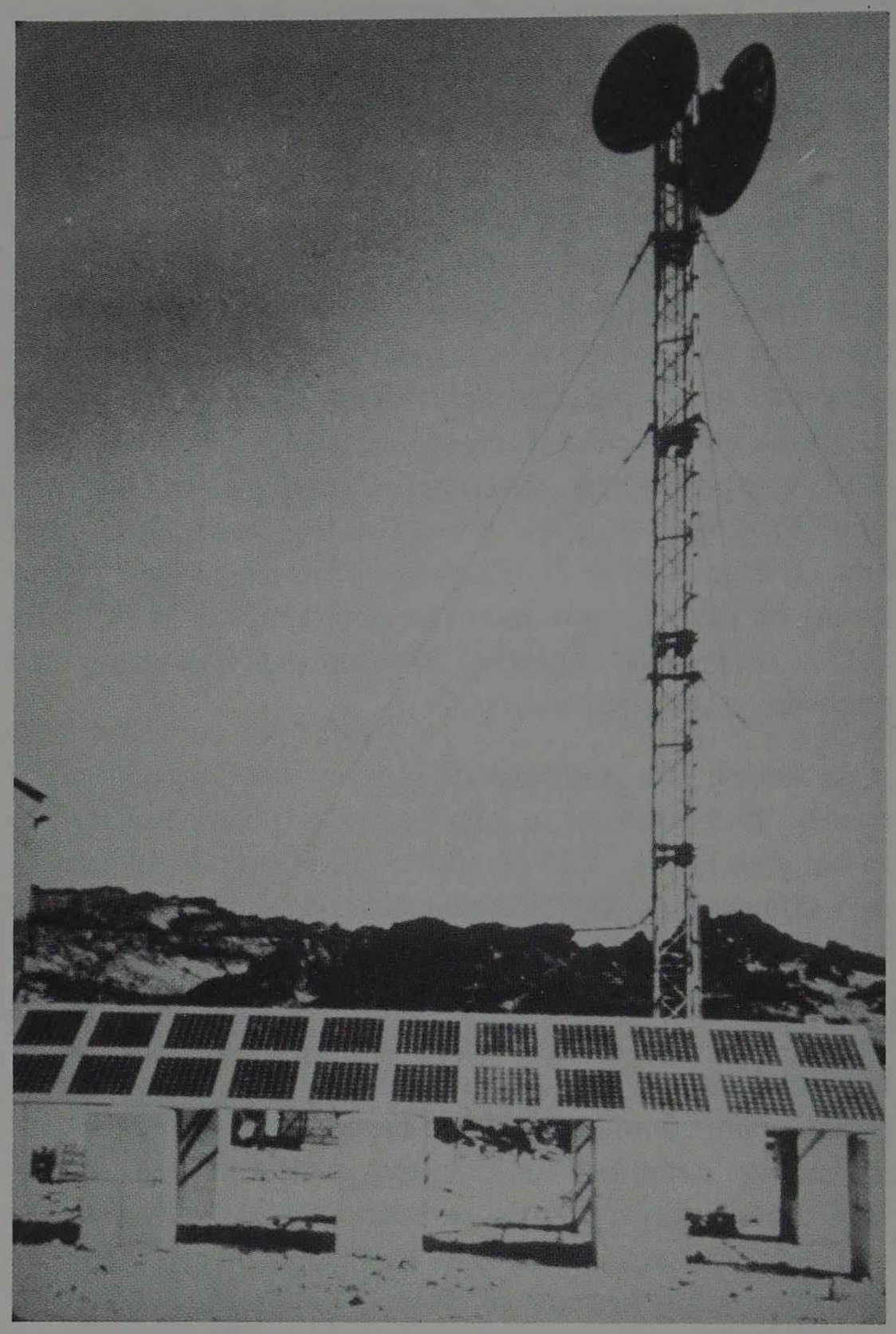


Figure 5.14 Radio relay repeater station on remote island powered by a photovoltaic array. *Courtesy of Solar Energy Research Institute.*

microwaves and beam them to Earth where they are reconverted to electricity and fed into the commercial power grid to customers. The night and atmospheric loss problems are absent in space. A satellite in geosynchronous orbit is in almost continuous sunlight and can harvest solar energy continuously, 24 hours a day.

The array would be very large, 15 to 20 square miles in area, covered with millions of solar cells! On Earth it would weigh 50 million pounds. One such satellite would produce several million kilowatts of electricity. Two of them would meet the maximum requirements of Manhattan or Chicago or Houston. Projections show that 10 percent of U.S. energy needs could be met by 300 power satellites.

The electricity would be converted to microwaves and transmitted to Earth in a narrow beam using a dish antenna half a mile in diameter (Figure 5.18). The Earth stations receiving the beams would be located in remote areas where there would be no hazard from the microwaves (Figure 5.19). The receiving antenna would cover perhaps a square

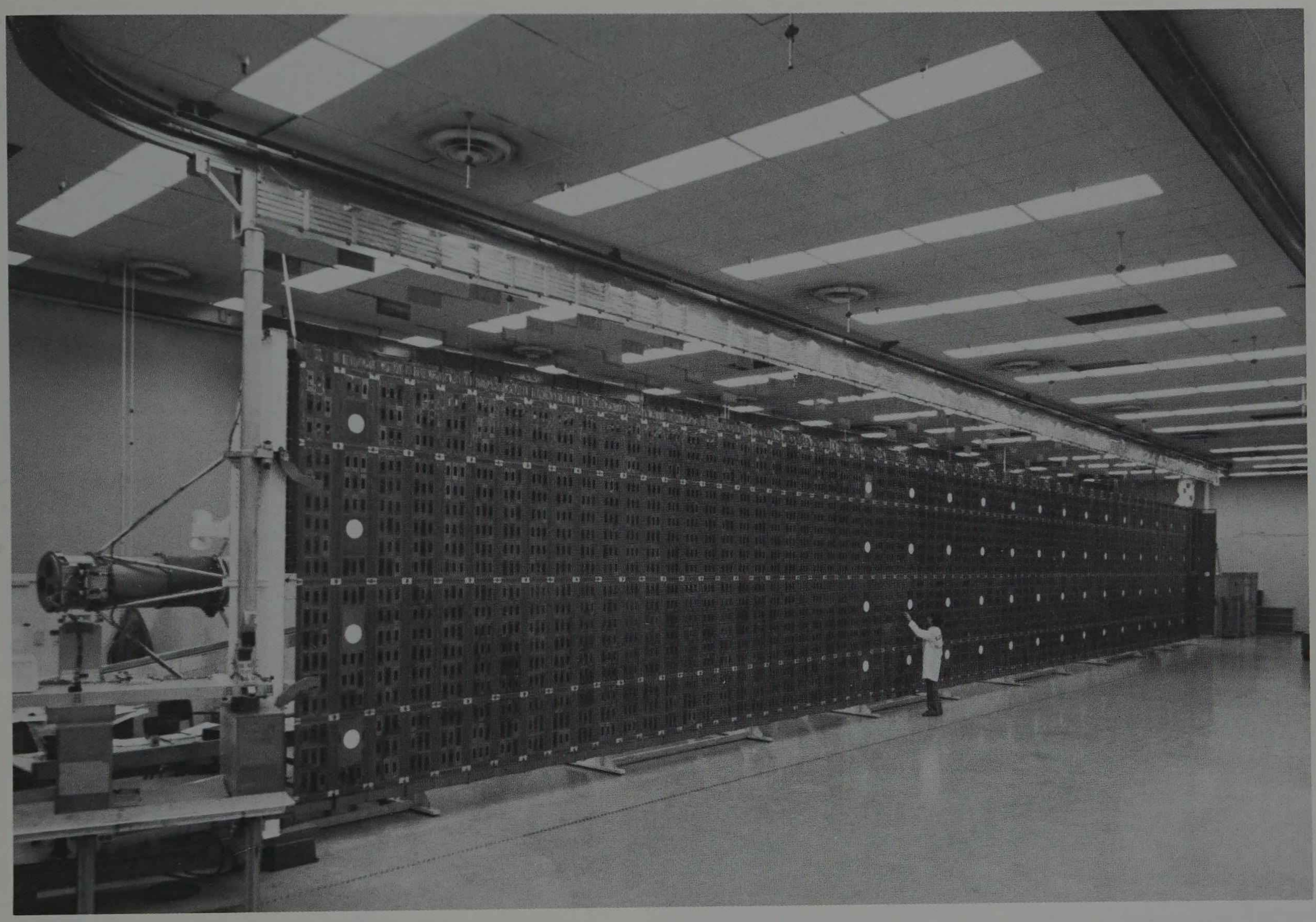


Figure 5.15 The solar cell array during preflight tests prior to installation in *Discovery*. *Courtesy of Lockheed.*

mile. Because the satellite power station is in geosynchronous orbit, it is fixed in the sky and the antennas on both ends would point in fixed directions.

Although the power density in the center of the beam would be more than double the safe limit, the edge would be at very low power. A restricted area would have to be designated to keep airplanes from flying into the beam. (There are many such restricted areas in the world where aircraft are prohibited). An automatic system on the satellite would shut the beam off if it strayed from its designated path. One concern is the effect of the microwave beam on the ionosphere as it passes through. Microwave beams affect the ionosphere, but the extent and consequences are not well known.

At the ground station the microwaves would be converted back to electricity and fed into the established national electric power grid just like power from a coal powered generator or hydroelectric dam generator.

There are, of course, problems. Building such a power station in space would be extremely expensive in time and money. There would be three possible approaches. One, carry the pieces into low Earth orbit, assemble it there, and boost the completed structure to geosynchronous altitude. Serious problems are inherent in this approach. First, large booster rockets would require enormous amounts of fuel which would have to be carried up to the construction site. Second, the structure would have to have additional bracing to withstand the stresses of acceleration when the boosters fire. That means additional weight. Another alternative is to build the power station in geosynchronous orbit. The problem here is that the Space Shuttle cannot reach geosynchronous altitude. New heavy lift launch vehicles would have to be designed to carry workers and materials to that altitude. Also, the radiation exposure of the workers would be greater. A third alternative may be mentioned. Manufacturing the parts on the Moon and transporting them to geosynchronous orbit would require less total energy than either of the other two alternatives. A colony on the Moon is a prerequisite which we will discuss in Chapter 12.

Meteoroid impacts, even micrometeoroids, will slowly degrade an array of solar photovoltaic cells and their electrical output would gradually decrease. Even so, it

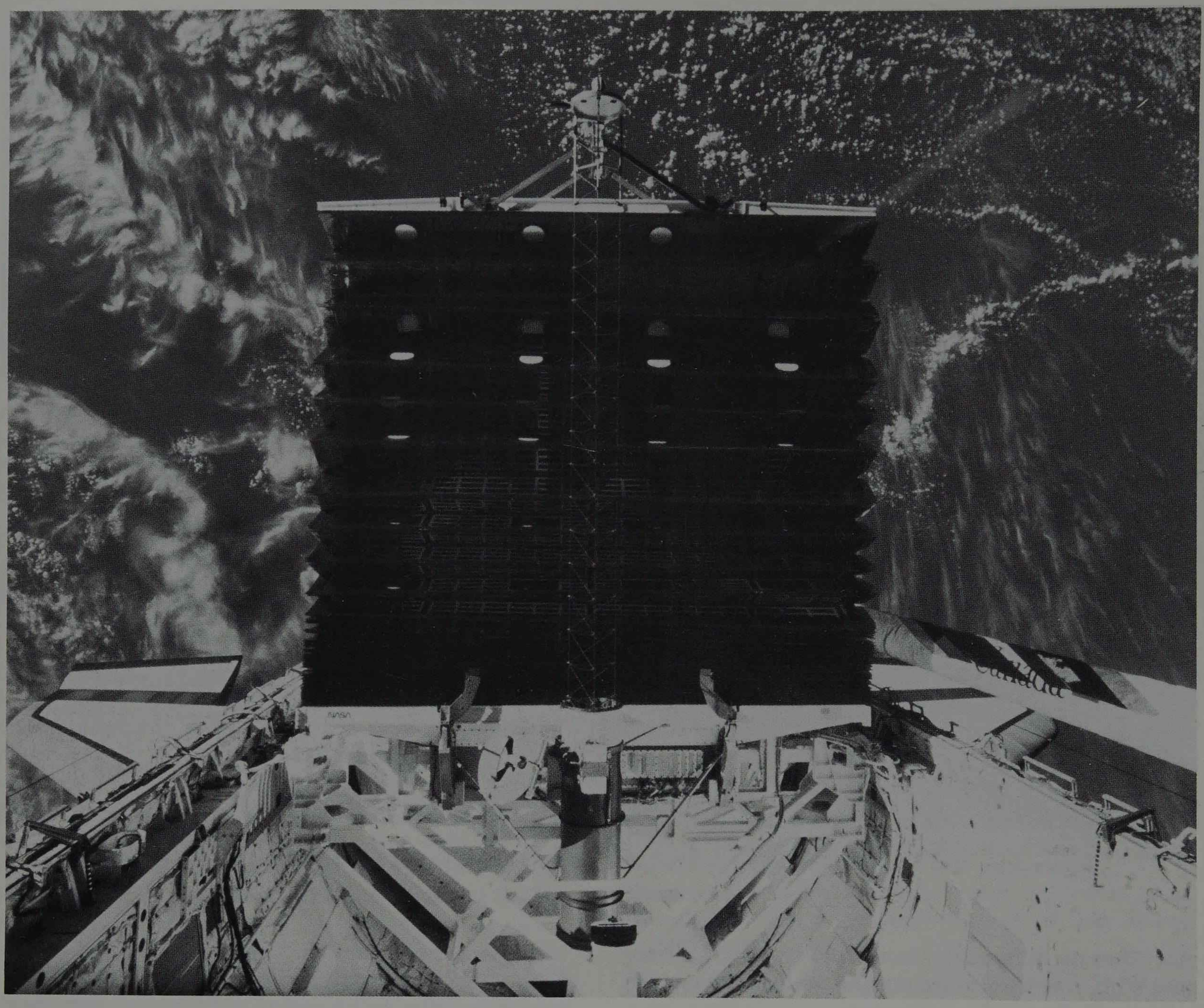


Figure 5.16 Photovoltaic array beginning to extend from the cargo bay of the Space Shuttle *Discovery*. Photo was taken from the flight deck looking toward the rear of the Shuttle. *Courtesy of Lockheed and Threshold Corp.*

should be possible to build a power station that would last 40 years. They are expensive to build but cheap to operate.

Space Debris

Objects remain in orbit unless some force returns them to Earth. Some satellites and pieces of rocket have been up there for 30 years. By 1988 there were over four million pounds of material orbiting the Earth. Almost half of that is debris. One-fourth is pieces of rockets that went into orbit with the payload. Another one-fourth consists of satellites, 80 percent of which do not work. The number of spacecraft approaches 2,000 and large pieces of debris number about 5,000. In addition, there are at least 30,000 marble-sized to baseball-sized pieces of debris and perhaps a hundred million paint chips and smaller sized particles.

With new satellites being launched every week, something will soon have to be done about artificial space debris. The smaller pieces are already a hazard, probably a greater hazard than meteoroids. During an early flight of the Orbiter *Challenger* a flake of paint hit a window causing enough damage to necessitate replacing it.

One of the tasks of NORAD is to check out the planned trajectories of satellites and Shuttles and to compare them with the orbits of the trackable objects in space to assure there will be no collision. Occasional ''holds'' have been necessary during Shuttle launch preparations because of passing objects. It is not possible to track all the small

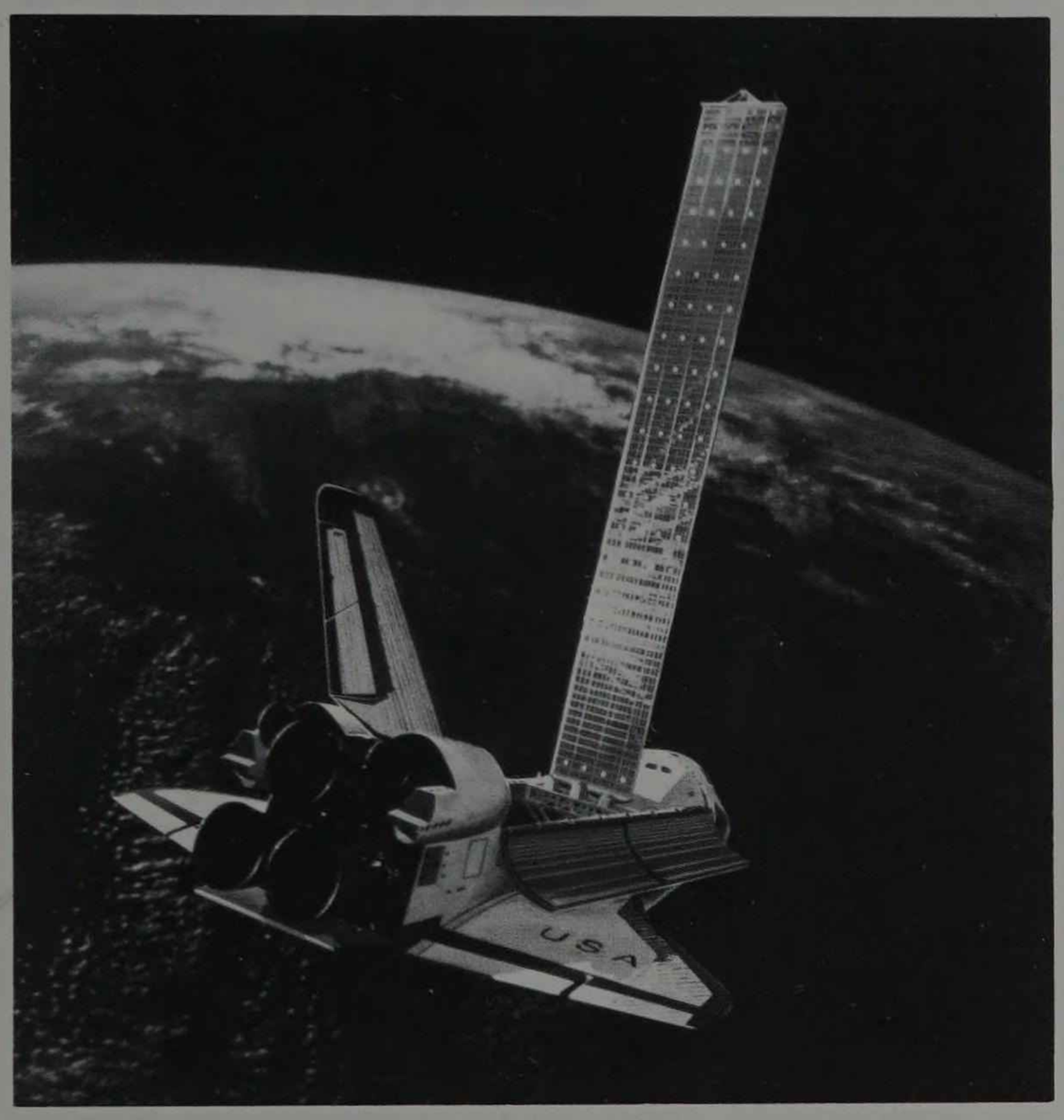


Figure 5.17 Artist's concept of the collapsible solar array carried to orbit on the maiden voyage of the Space Shuttle *Discovery*. *Courtesy of Lockheed; artist Joe Boyer.*

pieces of junk, however, and they pose the greatest hazard. A pea-sized fragment moving at high speed relative to a satellite could easily put it out of commission. During a Shuttle mission, NORAD warns the crew of any object on a collision course, giving time for an orbital maneuver to avoid the object. When the U.S. space station is operational in the 1990s, bumper shields may be attached to the habitats and laboratories, because maneuvering to avoid a collision

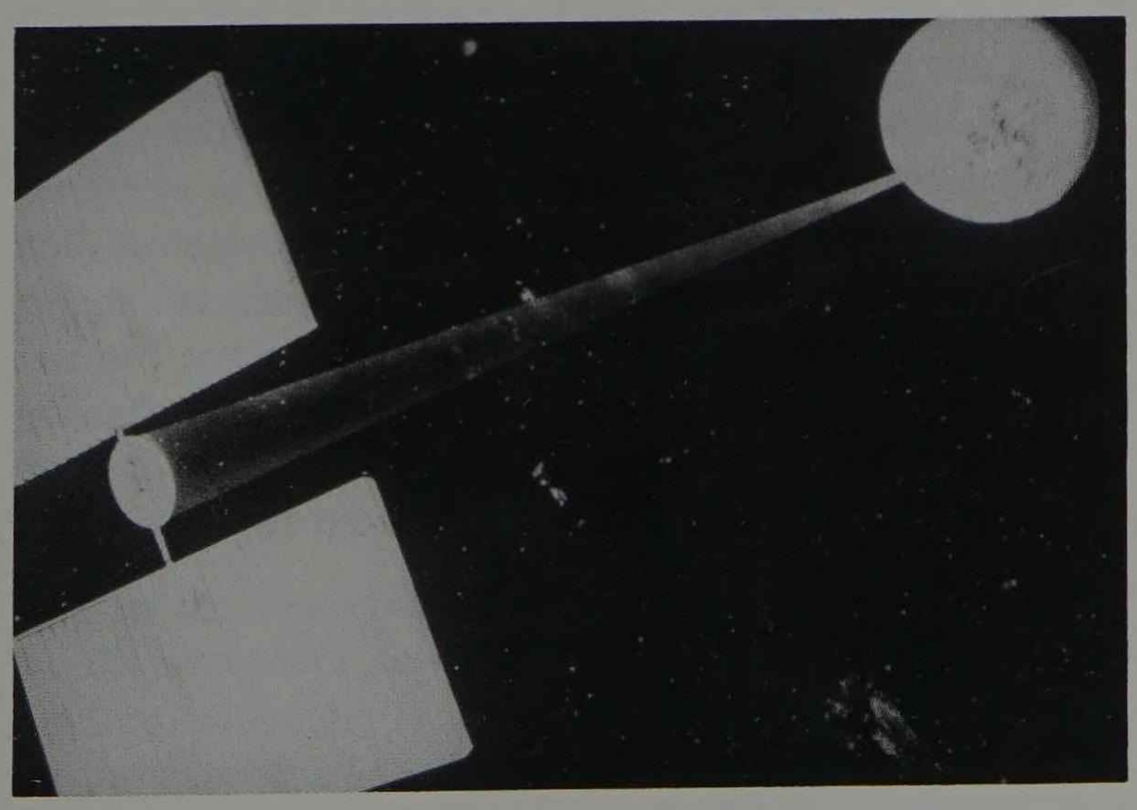


Figure 5.18 Artist's concept of a solar power satellite, transmitting microwave energy to a receiving station on the ground. The photovoltaic array may have an area of 20 square miles. *Courtesy of Solar Energy Research Institute.*



Figure 5.19 Antenna "farm" for receiving microwaves transmitted from a solar power satellite. The antenna elements are arranged in a circle because the beam coming from the satellite has a circular cross section. *Courtesy of Solar Energy Research Institute.*

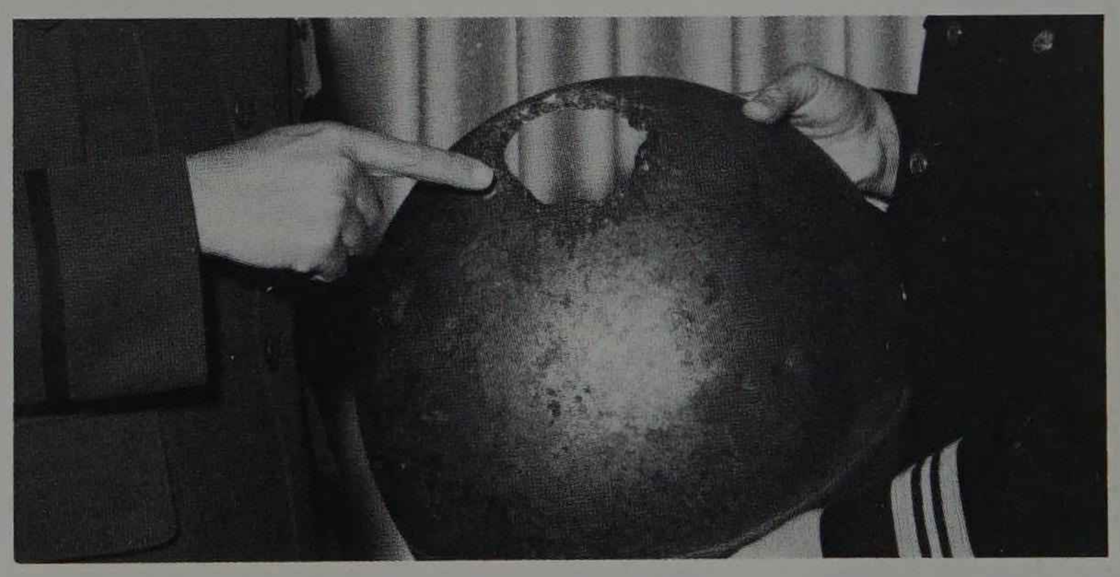


Figure 5.20 A piece of the Soviet satellite Cosmos 954 which fell to Earth. It is probably part of a propellant tank for attitude control. *Courtesy of U.S. Space Command.*

would be difficult. Firing rockets would disrupt station operations, particularly zero-g experiments.

Many objects return to Earth naturally as atmospheric drag decays the orbit and they burn up on reentry into the atmosphere. The largest object to burn in was the Skylab space station, which broke up on reentry in 1979. The pieces fell into the Indian Ocean and the Australian desert. Many Russian spacecraft use nuclear generators for electric power. One of them reentered and fell in Canada, spreading radioactive material over a wide area. Another fell into the Indian Ocean in 1983. A piece of the Soviet satellite Cosmos 954 is shown in Figure 5.20. Because most of the Earth is covered with water and only a small part of the land area is populated, the probability of a falling satellite doing any serious damage is remote.

So how do you cope with the problem? You cannot get rid of a satellite by blowing it up. Instead of one object, you would then have hundreds, each in a different orbit. One

solution is to boost the satellite to a high "parking orbit" well above any remnant atmosphere where it will remain essentially forever. The Soviets now do this to satellites carrying nuclear generators. Still, such action only moves the problem to a higher altitude. The Space Shuttle has picked up several disabled satellites and returned them to Earth. However, these maneuvers involve just a few of the large debris pieces and the real problem of the millions of smaller pieces remains.

DISCUSSION QUESTIONS

1. What has been the social impact of international television broadcasts in less developed countries and countries with closed borders?

2. Name possible users of a precision positioning system other than those mentioned in this chapter.

3. Give some suggestions as to how to reduce the amount of space debris in orbit around Earth.

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Johnson, Nicholas, and Darren McKnight. *Artificial Space Debris*. Krieger Publishing Company, 1987.

Kaplan, Marshall H. *Modern Spacecraft Dynamics and Control*. John Wiley and Sons, 1976. Calculus level math.

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PERIODICALS

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Countdown, Main Stage Publications, 64 E Stimson Ave., Athens, OH 45701. Monthly magazine covering current events.

Chapter 6

Remote Sensing

When you look across the room at an object you are "sensing remotely." Your eyes are sensors, sensitive to light waves, and your brain interprets their message. When you use a camera to make a photograph you are also sensing remotely, using a machine to sense the object and make a permanent record on the light sensitive film. The camera becomes an extension of your eyes.

Hearing is also remote sensing. Ears and their associated anatomy are sensitive to sound waves. Microphones, amplifiers, and speakers are machines which extend the capabilities of the human ear.

Even human touch sensors can operate remotely. Consider that you can feel a hot stove without actually touching it. The touch sensors are sensitive to the infrared heat waves emitted by the hot object.

Remote sensing then, is learning something about an object at a distance, without coming into physical contact with it.

Remote Sensing From Space

Many spacecraft are remote sensors, acting as extensions of human senses. They look up into the universe and down to Earth. One of the earliest and most practical applications of remote sensing has been for weather observing using both visible and infrared waves. Mapping and cataloging the resources of Earth is another application of remote sensing with widespread benefits. Military early warning satellites detect launches of missiles and spacecraft by means of infrared sensors which respond to the heat of the rocket exhaust. Spy-in-the-sky satellites looking and listening from their orbits keep each side informed in remarkable detail what the other side is up to.

Even the news media are becoming interested in using satellites to cover news events from space. In the 1990s a satellite will carry a sensor designed expressly for the media, capable of seeing things as small as a truck, in full color, available within hours, with global coverage.

The science of astronomy is based on remote sensing, first using Earthbound telescopes, now using spacecraft carrying sensors above the atmosphere for a better view. They observe the skies not only with sensors of visible light but also radio waves, infrared, ultraviolet, x-rays, and gamma rays. Many of these emanations from stars and galaxies are not visible at Earthbound observatories because they are absorbed in the atmosphere before they reach the ground.

Electromagnetic Waves

Radio, infrared, visible light, ultraviolet, x-rays, and gamma rays are all electromagnetic waves, differing only in their wavelengths. The electromagnetic spectrum was described in Chapter 4. Refer back to Figure 4.3. The length of a light wave, measured from crest to crest or from trough to trough, is 0.4 to 0.7 micrometer. A micrometer, also called a micron, is one-millionth of a meter. Therefore, visible light waves are very short electromagnetic waves. Shorter still are the ultraviolet, x-rays, and gamma rays, ranging down to a trillionth of a micrometer. On the other hand, infrared, microwaves, television, and radio waves are all longer than visible light, ranging up to many miles for AM radio.

Anything which has a temperature above absolute zero emits electromagnetic radiation. An object of high temperature radiates shorter waves; an object at a lower temperature emits radiation of longer wavelengths. The photosphere of the Sun at 11,000 °F emits most of its radiant energy in the visible light portion of the spectrum. On the other hand, a human body at 98.6 °F emits longer infrared waves. When you turn on the burner of an electric stove you can feel the heat, that is, the infrared waves, before you see the glow. When the temperature goes higher, the burner becomes red hot and emits visible light as well as infrared. In fact, almost everything emits some amount of infrared, making it a favored region for remote sensing. The infrared portion of the electromagnetic spectrum is sandwiched between visible light and radio waves, with wavelengths from 0.8 micron to about 1 millimeter (1/25 inch). `MATHBOX 6.1` shows how to calculate the wavelength at which an object radiates the maximum amount of energy when you know its temperature.

Objects also reflect electromagnetic waves which fall on

MATHBOX 6.1

Wavelength of Maximum Emission

In the late 1800s Wilhelm Wien found a simple relationship between the temperature of a body and the wavelength at which it emits the maximum amount of electromagnetic radiation:

$$L = \frac{2900}{T}$$

where T is the temperature in Kelvins (degrees above absolute zero) and L is the wavelength in microns. (To find the temperature in Kelvins, just add 273 to the Celsius temperature.)

Wien's law says that the higher the temperature of an object, the shorter the wavelength of maximum emission. Very hot objects emit ultraviolet; cold objects emit radio waves.

For example, the Sun's surface temperature is about 5,700 K. So

$$L = \frac{2900}{5700} = 0.51$$

micron, in the middle of the visible light part of the spectrum.

A human body is at 98.6 °F which is 37 °C or 310 K. It emits radiation at

$$L = \frac{2900}{310} = 9.4$$

microns in the near infrared. People glow at that wavelength.

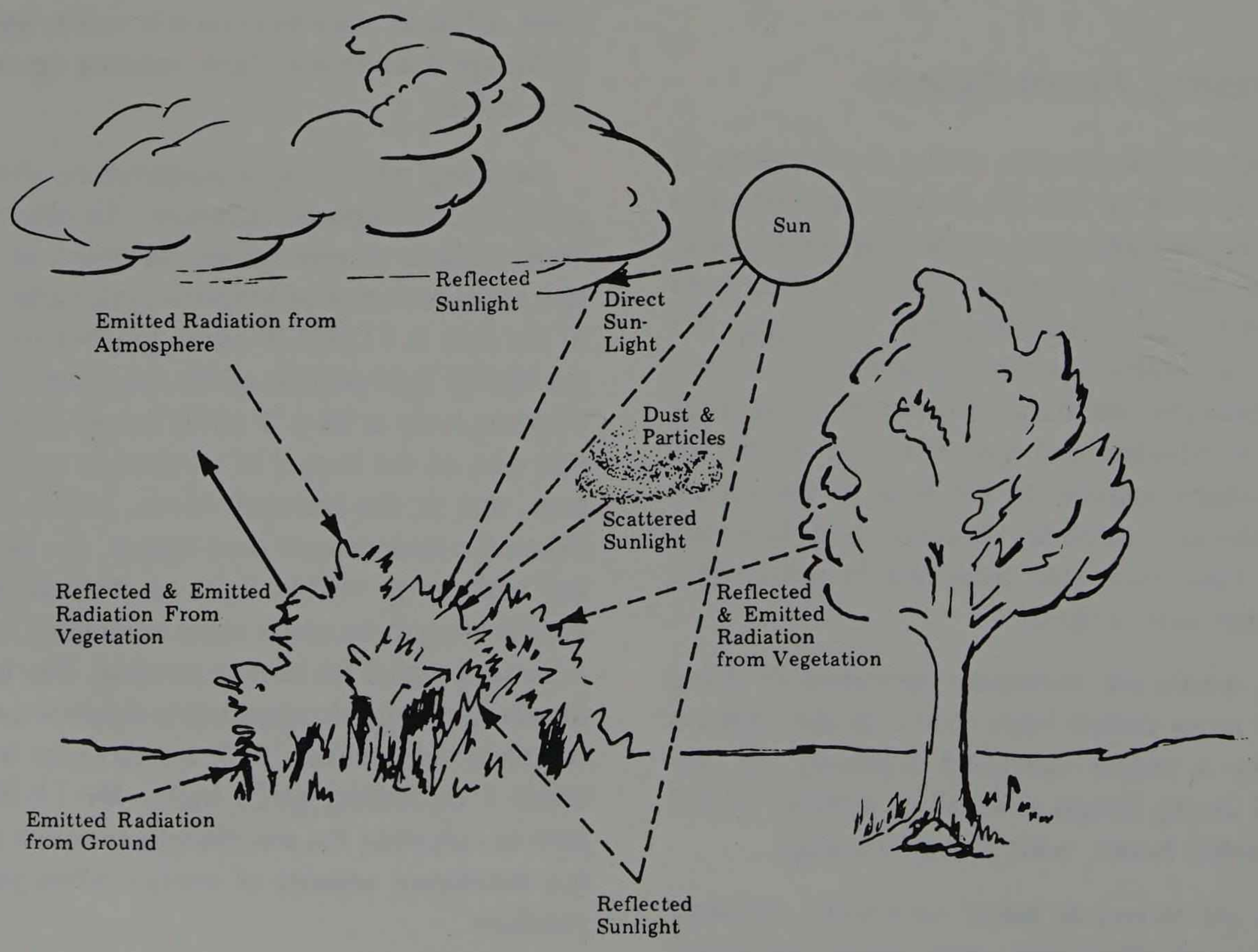


Figure 6.1 Emitted and reflected electromagnetic radiation surrounds us. *Courtesy of NASA.*

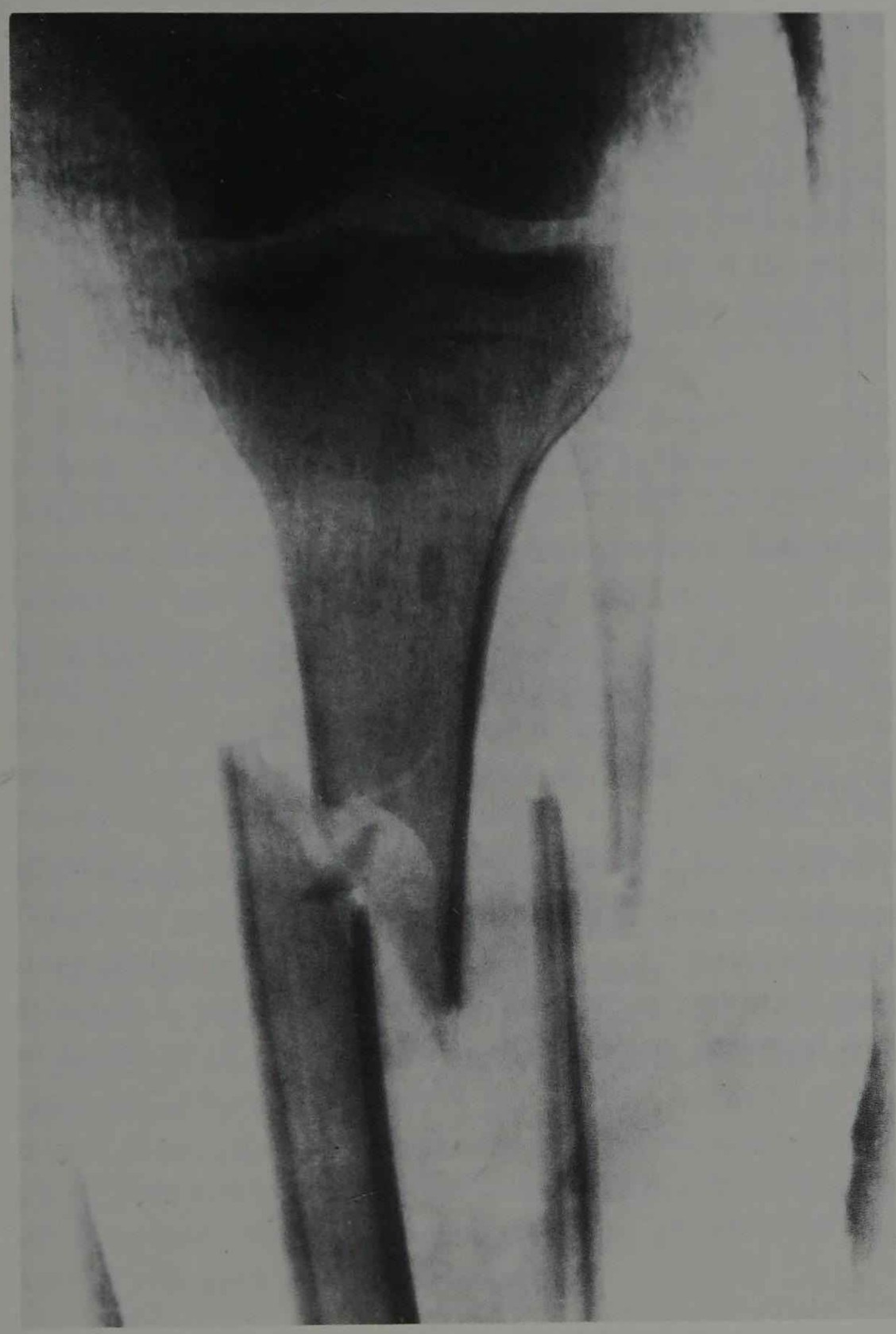


Figure 6.2 X-ray photo of a broken leg. Both the large bone (tibia) and the small bone (fibula) are broken through. The knee joint can be seen at the top. *Courtesy of C. Hudson.*

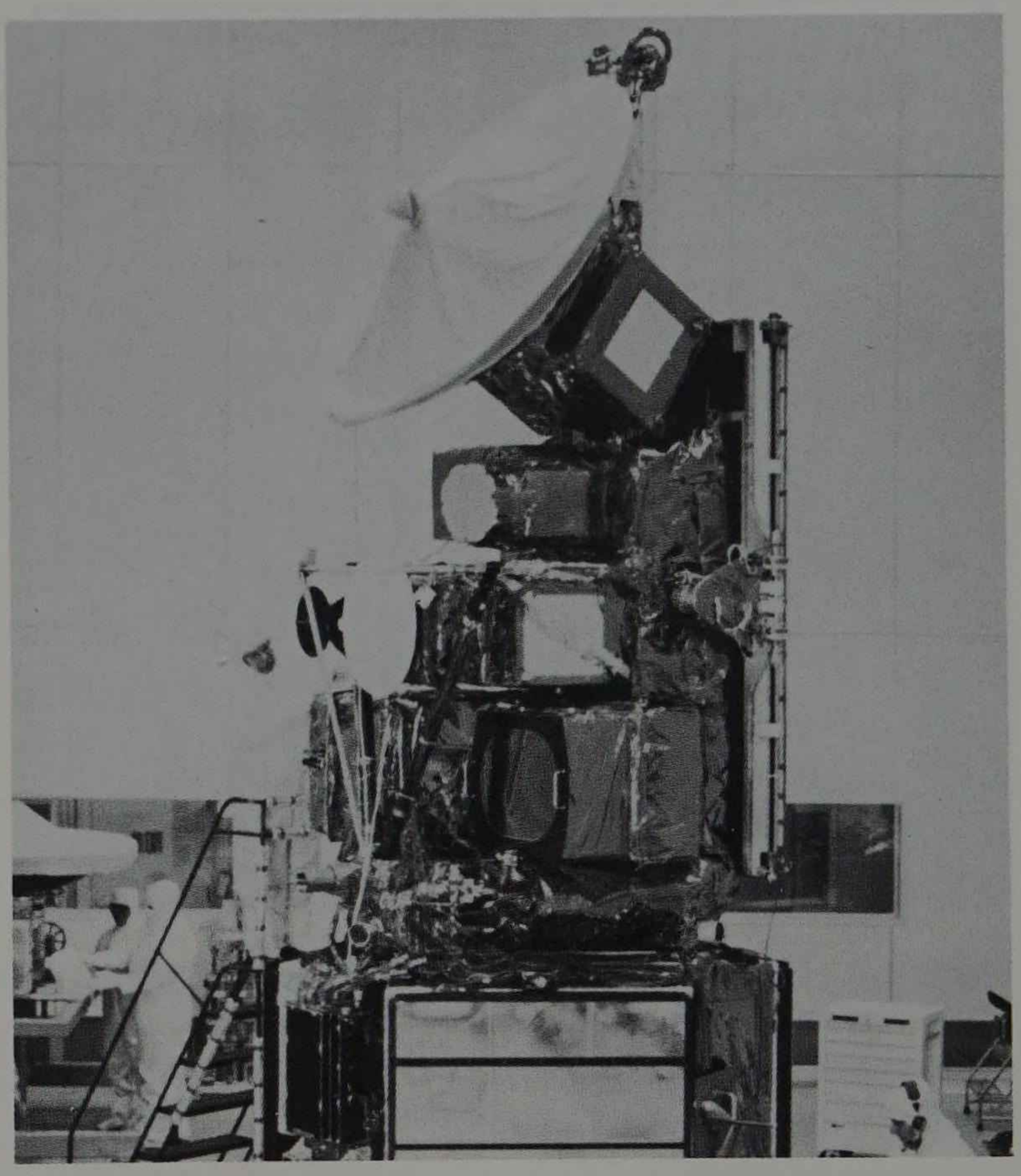


Figure 6.3 Landsat 5 during checkout in a clean room prior to launch. The communications antenna is covered with a shroud, and the solar cell panels are folded against the right side of the spacecraft. *Courtesy of EOSAT.*

them from other sources. A green leaf reflects green light; a red flower reflects red light. Most objects also reflect other wavelengths of the electromagnetic spectrum, such as ultraviolet or infrared, but human eyes are sensitive only to visible light so we cannot see these other wavelengths.

We are accustomed to viewing the world around us by the light emitted and reflected by objects surrounding us. See Figure 6.1. But that is not all there is. Using imaging devices which are sensitive to other wavelengths, we can get quite a different view of the world. Doctors use x-rays striking a piece of film to create an image of the inside of the body. X-rays pass through a body but are absorbed variably by tissue and bone on the way. When they strike a piece of film they create a shadowgram of the interior. Figure 6.2 shows an x-ray image of a broken leg.

Film sensitive to infrared is available at camera stores. Photographs made on infrared film look quite different from those made on regular film. With proper equipment it is possible to create an image of an object solely by the infrared heat waves that it gives off. However, for cooler objects which emit longer infrared waves, a mirror imaging

TABLE 6.1 Spectral Bands of Landsat Sensors

Band	Spectral Range	Color	Principal Applications
1	0.45–0.52 micron	Blue-Green	Coastal water mapping. Soil/vegetation differentiation. Deciduous/conifer tree differentiation.
2	0.52–0.60 micron	Green-Yellow	Reflected by healthy vegetation.
3	0.63–0.69 micron	Red	Chlorophyl absorption for plant species differentiation.
4	0.76–0.90 micron	IR	Biomass surveys. Water body delineation.
5	1.55–1.75 microns	IR	Vegetation moisture measurement. Snow/cloud differentiation.
6	10.4–12.5 microns	IR	Plant heat stress measurement. Thermal mapping.
7	2.08–2.35 microns	IR	Hydrothermal mapping.

(Note: A micron is a micrometer, one-millionth of a meter.)

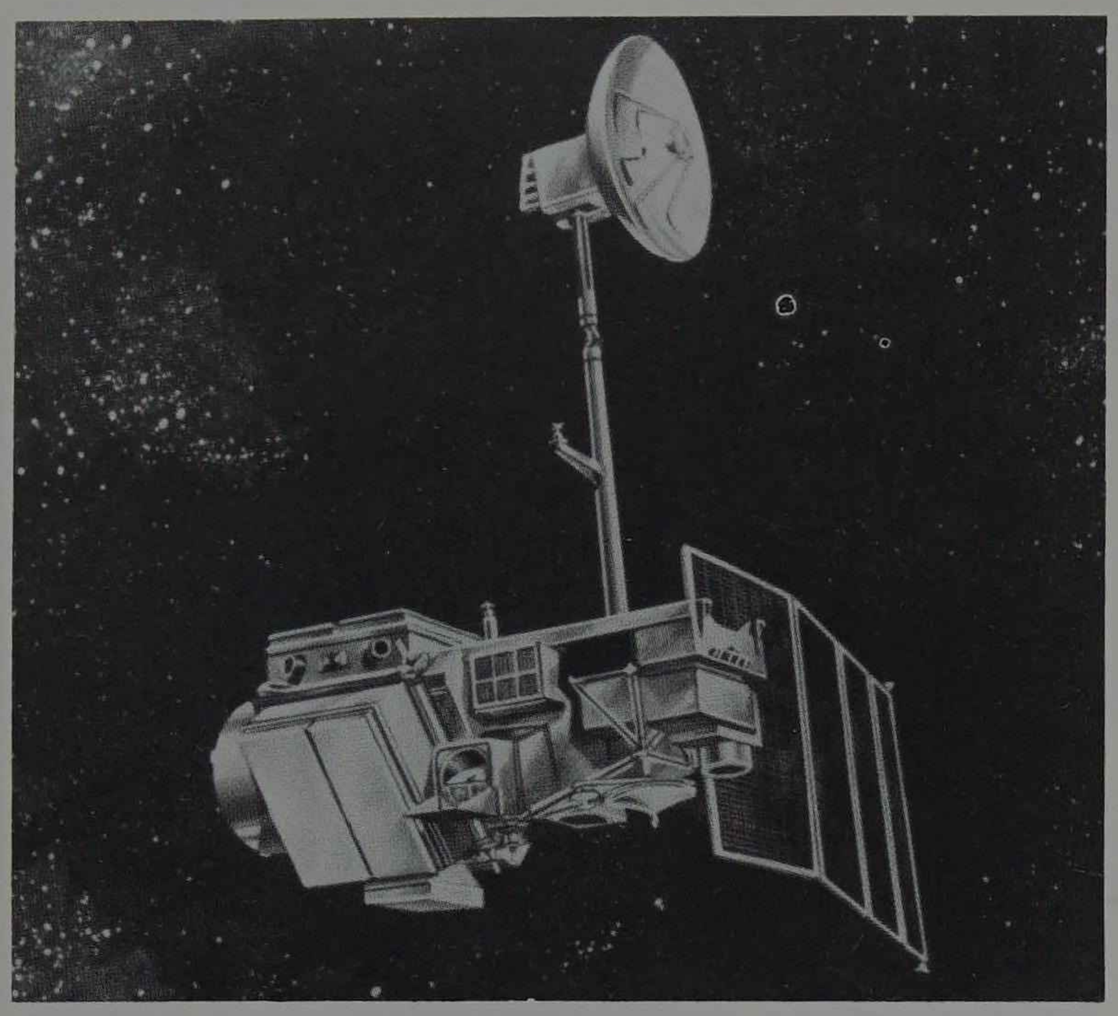


Figure 6.4 Landsat 5 in orbit. The antenna is pointed toward the TDRS communications satellite for relay of the data to receiving stations on the ground. Solar cell arrays are extended for power. *Courtesy of EOSAT; artist P. A. Bertolino.*

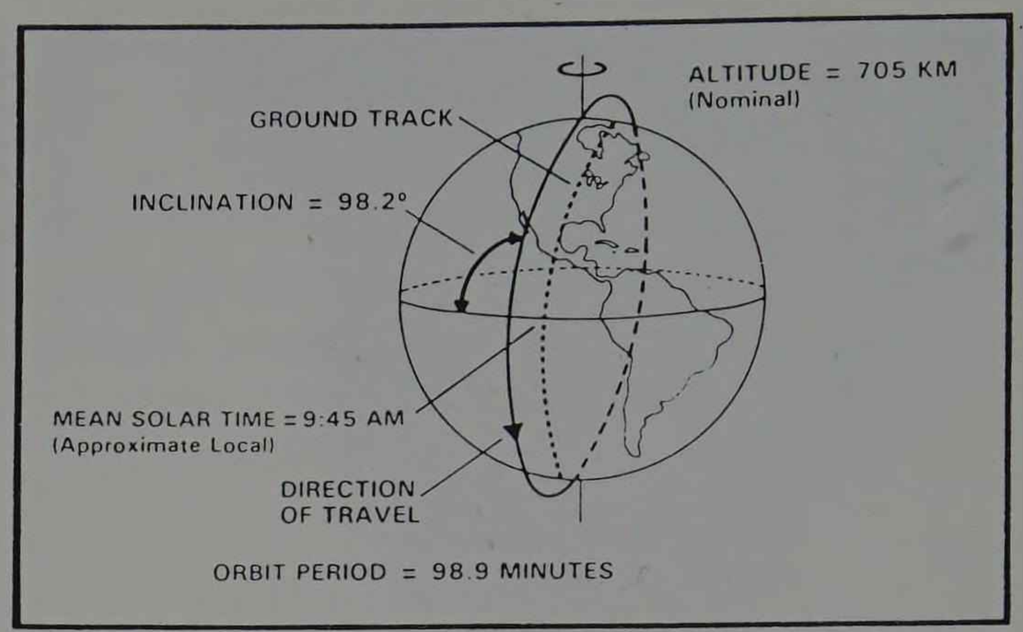


Figure 6.5 Orbit of Landsat 4. *Courtesy of EOSAT.*

system is used because the longer wavelengths are absorbed by glass lenses and do not reach the film.

Landsat

The exploration of space has led to an unprecedented and remarkable new exploration and understanding of Earth. For more than 15 years, a series of Landsat satellites have been recording pictures of the Earth's surface. Landsat 1 was launched in 1972. The latest, Landsat 5, is shown in

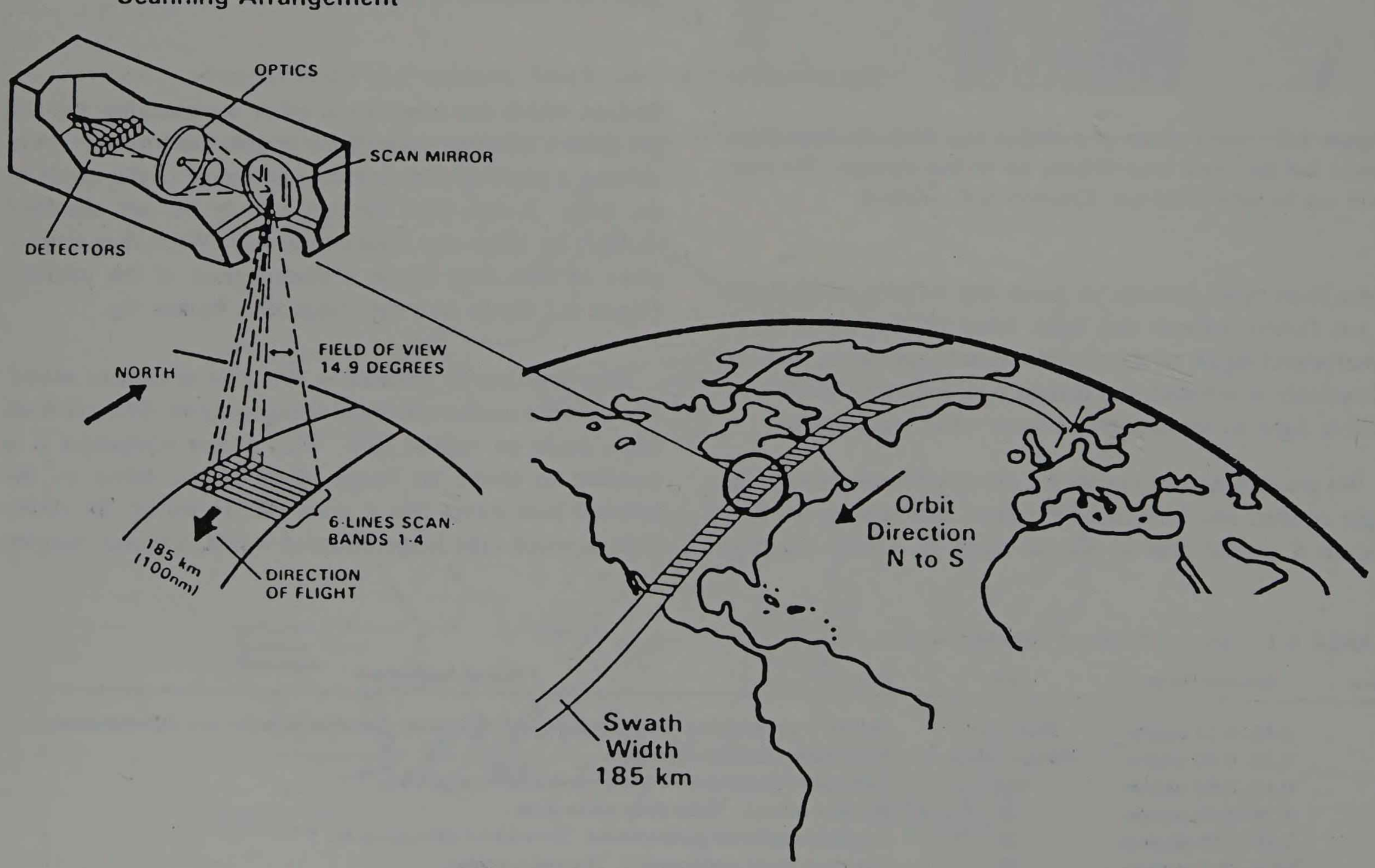


Figure 6.6 Scanning geometry of Landsat sensors. *Courtesy of EOSAT.*

Figure 6.3 being checked out prior to launch. Figure 6.4 is an artist's rendition of how it appears in space.

Landsat's orbit is shown in Figure 6.5. It is *Sun-synchronous* which means that it reaches the equator at the same local time on every pass, approximately 9:45 a.m. It takes pictures only on the north-to-south part of the orbit. The south-to-north part on the other side of the Earth is in darkness.

A rotating mirror produces east-west scan lines covering a swath 115 miles (185 kilometers) wide as shown in Figure 6.6 making a continuous strip picture. Instead of returning exposed film to the ground, Landsat satellites transmit a stream of numbers which represent the intensity of the electromagnetic radiation coming from the Earth below. Electromagnetic waves reflected from the mirror pass through a device which divides it into the six different *spectral wavelength bands* shown in Table 6.1. The six beams then pass into six detectors which measure their intensity. A seventh detector gives a broader heat measurement.

Scan lines are broken into short bits called picture elements or *pixels,* a 100 by 100 foot square, approximately a quarter of an acre, on the surface of Earth. Each pixel is represented by six numbers which tell the intensity of the waves in each spectral band, reflected and emitted from the pixel. This 100 foot resolution is less than one-third the area of a football playing field. Landsat 6, planned for the 1990s, will have a 50 foot resolution.

Figure 6.7 shows the strips covered by three consecutive orbits. Because of the rotation of the Earth, different areas

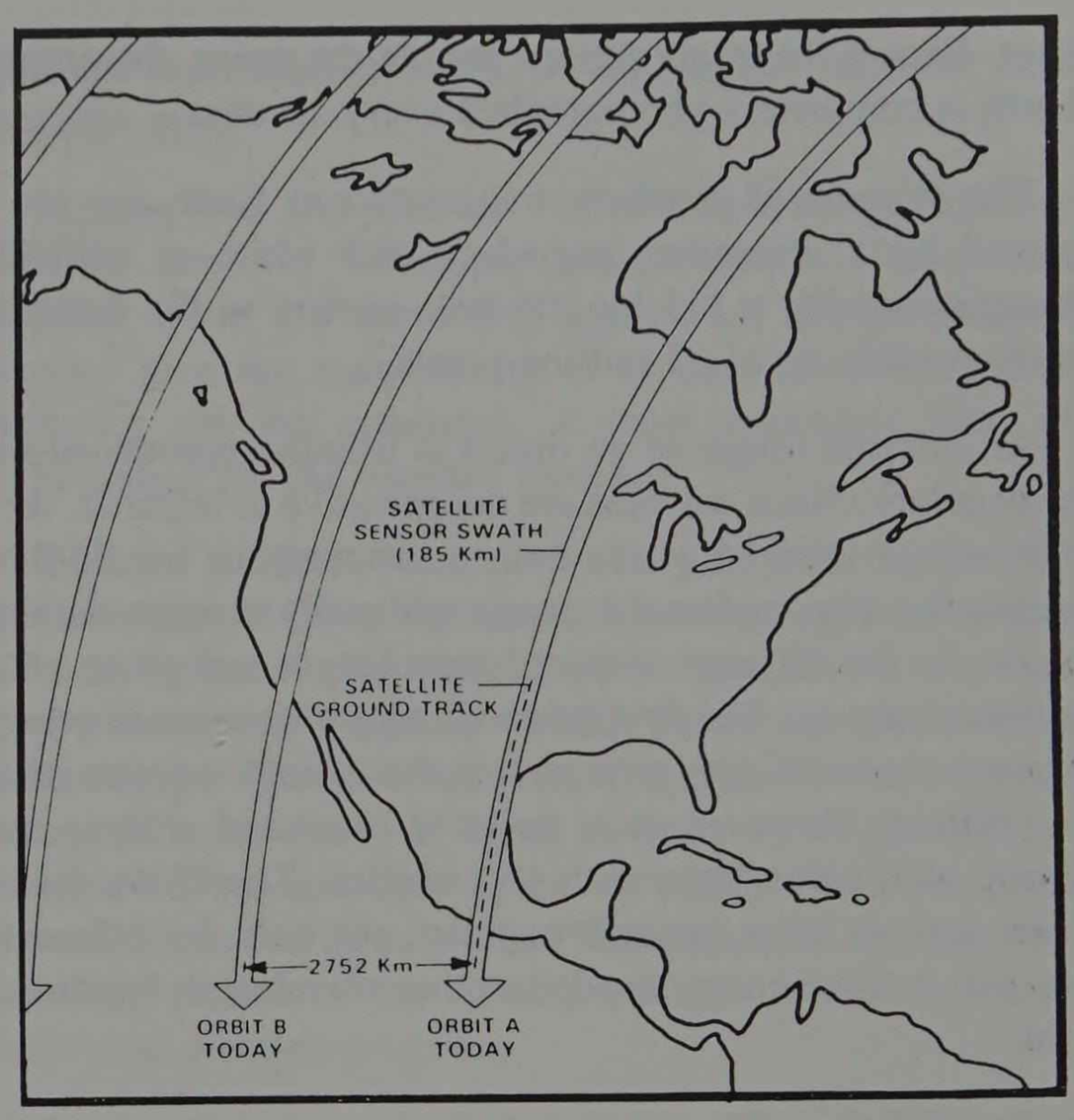


Figure 6.7 Landsat coverage on each orbital pass. *Courtesy of EOSAT.*

are covered on each orbit with gaps between them; on the following days the strips will fall in between until, after sixteen days the entire area is covered (Figure 6.8) and the pattern begins to repeat itself. Notice that on any pass, the strip covers an area just west of the strip produced one week earlier, and the next strip west will be covered one week



Figure 6.8 Landsat 4 and 5 coverage pattern. The pattern repeats itself over the entire Earth every 16 days. *Courtesy of EOSAT.*

later. Except for small regions around the poles, the entire Earth is completely photographed every 16 days.

The streams of numbers transmitted to Earth are processed by a computer into black and white or colored images showing a 115 by 105 mile section of the Earth's surface made up of 35 million pixels.

An infrared image of an object is usually reproduced in false colors. Since our eyes are not sensitive to infrared, the ''color'' of infrared waves has no meaning for us. So the technician who creates the image arbitrarily assigns visible colors to the different infrared wavelength and prints the picture that way. The first infrared images were made using various shades of grey to represent the various wavelengths of infrared. However, it is easier to view and analyze an image with colors than with grey shades. Therefore, false color images have become popular, not only for infrared images, but for images made in other wavelength bands as well.

Figure 6.9 in the color pages is a nearly natural color picture of Copenhagen, Denmark. Taken by Landsat 5, bands 1, 2, and 3 were used to make this image in approximately natural color, although the image was enhanced somewhat to increase the contrast between rural and urban areas. Water appears black; surf can be seen along the upper right beach. City streets, harbor docks, and the airport are clearly visible.

Compare this with the false color infrared images of Figures 6.10, 6.11, and 6.12 in the color pages Figure 6.10 is a Landsat infrared image of Denver, Colorado. Vegetation is printed in various shades of red; urban and commercial areas are light blue or grey; water is black. The mountains on the left are covered with evergreen trees. To the upper right are agricultural fields, some with growing vegetation, others lying fallow. The Platte River runs through the center of the city. Streets and grassy residential areas can be clearly identified.

Figure 6.11 shows winter wheat crops in Kansas. This infrared image was created from Landsat 5 bands 2, 3, and 4; red is used for vegetation. The circles are irrigated fields. Crops are irrigated by using a sprinkler system which is pivoted at the center of the field and moves in a circle on wheels. Red fields have actively growing crops; white and grey fields lie fallow. Rectangular fields are seen on the right. The Arkansas River runs from the bottom to the top on the left side of the picture. Garden City is the dark colored area left of the river.

Figure 6.12 is a Landsat image of communities in the Arizona desert. As with other false color IR images, vegetation is red, water areas are black, and housing, streets, and bare soil are grey or blue. The Agua Fria dry river bed runs through the center of the image. Sun City developments with parks and golf course are obvious. Interstate 89 and the city of Surprise are in the lower right corner. Colors can be adjusted to emphasize any particular land use, such as crops, vegetation, wetland, or sediment.

The data can be manipulated in a number of different ways. Unique patterns of light intensity across the seven bands can be used to identify features on the Earth which may not be apparent to the human eye. See Figure 6.13. For example, a corn field, once its spectral intensity pattern had been identified, can be located on a Landsat image. The light intensity levels of the various spectral bands of the corn field can be as unique as a person's handwriting. Other areas on the same image that have the same *''signature''* can be interpreted as consisting of the same type of corn fields. Finding the right combination of spectral intensities for a corn field in an image is done by computer evaluation of the pixel data. Fine details can be recognized in these spectral signatures, even to determining the health of crops. Wheat suffering from a drought has a different signature from normal healthy wheat. Using this data, estimates of crop production can be quickly assessed. Sediment and pollution in rivers give a different signature from clear water. Trees and lawns in a residential area, asphalt and

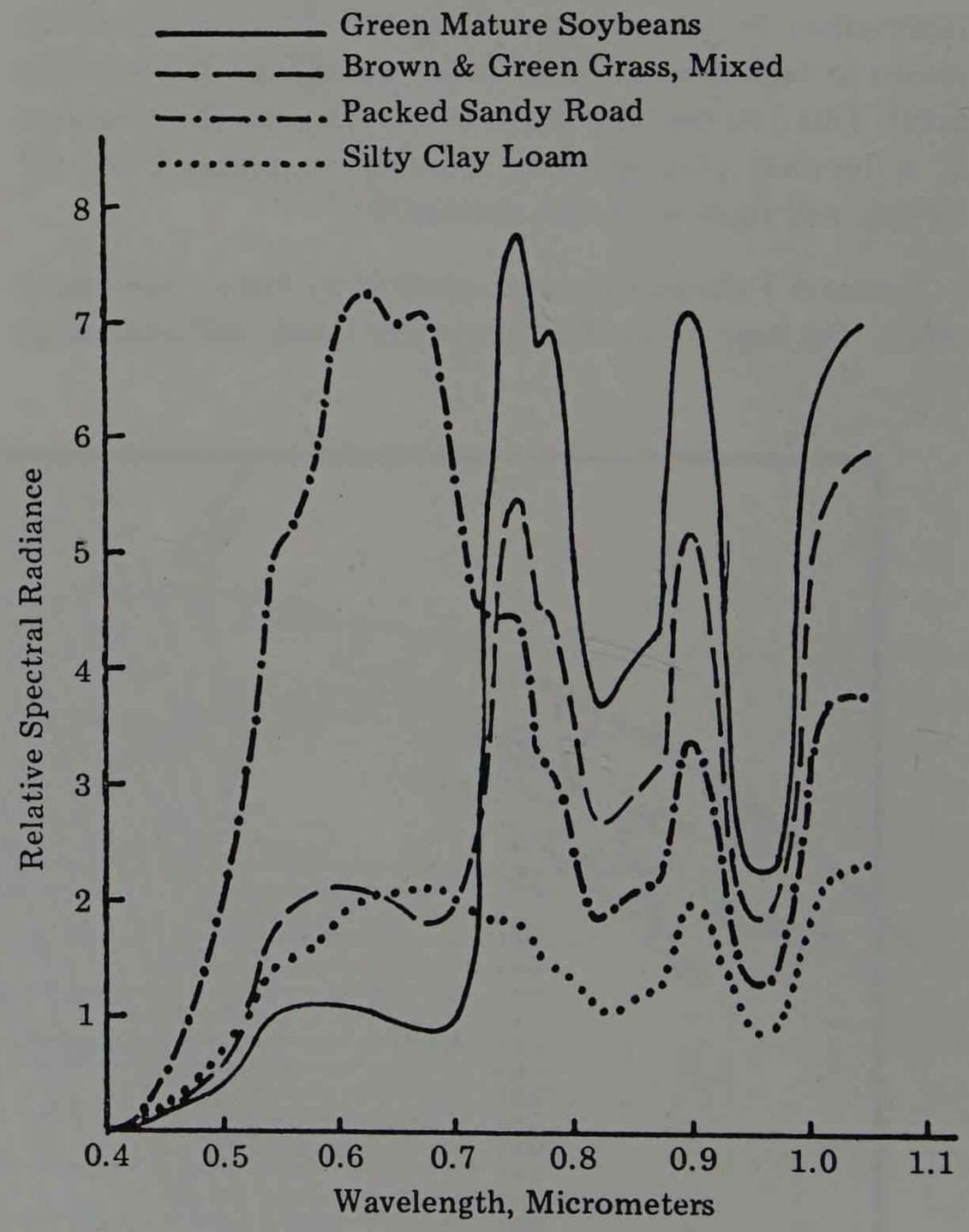


Figure 6.13 Signatures derived from Skylab data. Notice how each of the four different materials emits and reflects light and infrared differently. Although the soybeans and the grass have similar patterns, the intensities are different. The signatures for sand and loam are completely different. *Courtesy of EOSAT.*

cement areas, different kinds of exposed rocks, meadows and fields—all can be recognized.

To accomplish this kind of mapping of Earth resources by the older method of aerial photography would require 100 photographs and months or years to assemble and analyze a 100 mile square scene. Landsat could cover the same area in a single picture and the computer analysis could be done in a few hours. The timeliness of the data makes it especially useful in agricultural and environmental studies.

Weather Satellites

Tiros, the first true weather satellite, was launched on April 1, 1960, and carried television cameras that viewed Earth's cloud cover by visible and infrared light from a 450 mile orbit. A total of 10 Tiros satellites were launched over a five year period. Tiros 8 carried automatic picture transmission (APT) equipment so that anyone with a simple receiver and a facsimile recorder could receive the pictures. Nimbus was a second-generation weather satellite with improved cameras, an APT system, and an infrared sensor that allowed pictures to be made at night. Seven Nimbus satellites were put into orbit.

Figures 6.14 and 6.15 are visual images from a military weather satellite. Visual pictures of clouds, storms, and weather fronts are interesting and useful, but the infrared images give the temperatures of clouds. From this, their altitudes can be estimated, a most important kind of information for the weather forecaster.

Weather satellites were placed in geosynchronous orbit beginning in 1974 to transmit images almost continuously of selected areas. Earthbound meteorologists have a near real-time view of the broad weather patterns as they emerge and change. The satellite can also provide an enlarged image of a small area in which storms may be developing. A series of several dozen pictures taken over a period of several hours can be assembled into a speeded-up ''movie'' showing motion of the clouds, a display often shown on television weather programs.

It must be emphasized that the satellites are observing tools only; they do not make forecasts. Their capabilities,

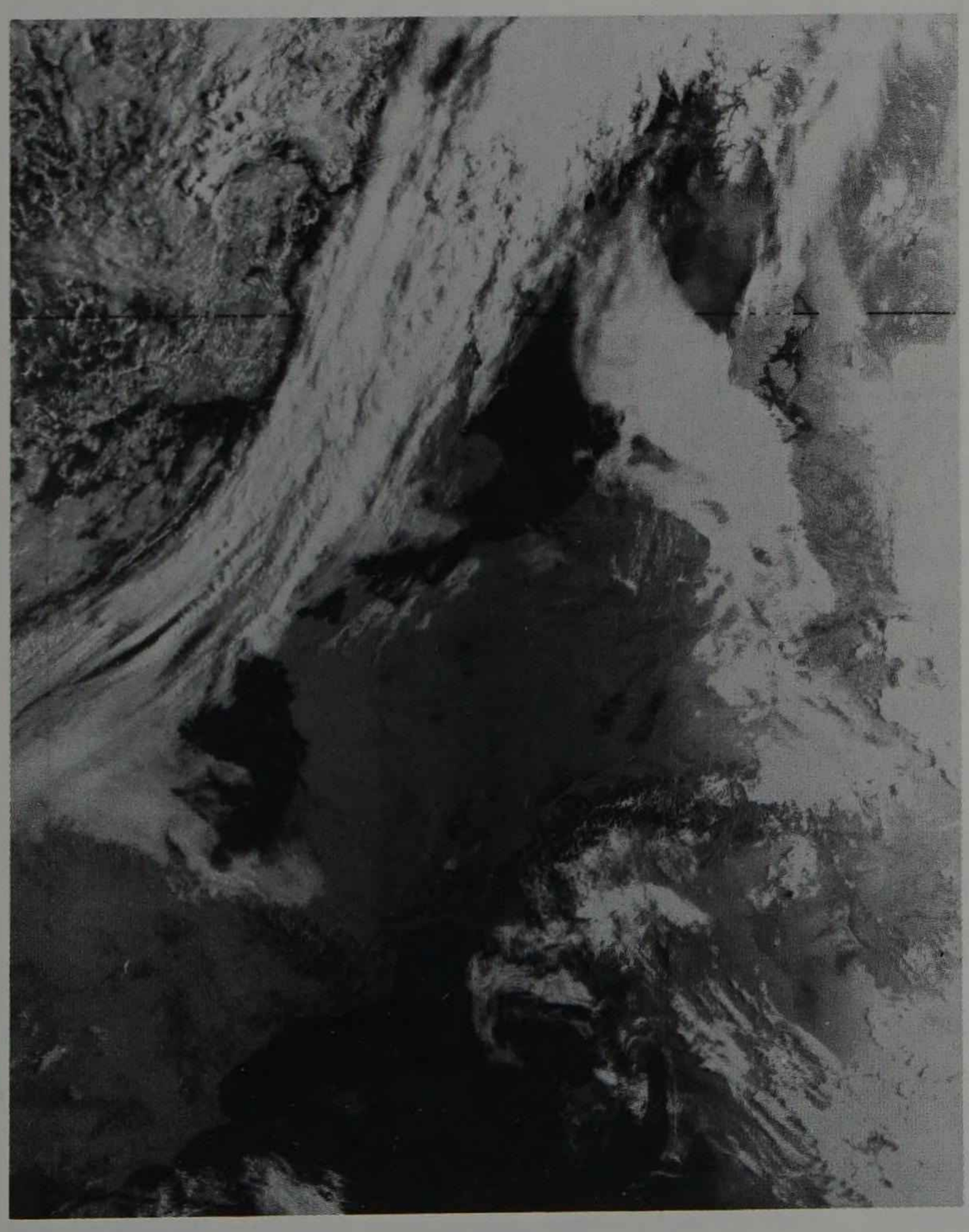


Figure 6.14 Defense Meteorological Satellite Program (DMSP) picture of central Europe. France is in the center, Spain is at the lower left; Great Britain is under the band of clouds at the left. Snow can be seen in the Pyrenees and the Alps as well as in the mountains of Norway at the top of the picture. *Courtesy of U.S. Space Command.*



Figure 6.15 Nighttime DMSP weather satellite picture of western Europe and North Africa. Clouds are illuminated by moonlight. Bright spots are city lights. Eastern Spain is covered by clouds, western Spain is clear. Madrid is at the edge of the clouds. The two brightest spots at the upper center are London and Paris. The ''cities'' in the desert of north Africa are oil well fires (bottom right). *Courtesy of U.S. Space Command.*

however, give the human forecaster a much broader, more complete, and more timely view of weather systems. Newly developing storms can be observed without delay and their motion monitored. Before the advent of satellites, meteorologists had to rely on ground based observations from weather stations. New storms developed and old storms intensified or weakened, often between ground stations where the changing pattern was not observed. Also, information concerning the patterns of windflow in the higher atmosphere, in particular the jet stream, came only from weather balloons sent aloft by a widely scattered network of observing sites. Data from mountainous areas, polar regions, and oceans was almost nonexistent. Weather satellites have changed all that. As a result, forecasters are able to make significantly more accurate analyses.

Astronomy From Space

Astronomers have learned about the universe by remote sensing, at first with naked eyes, then with telescopes, now with spacecraft. Spaceflight has aided astronomers in two ways: first by going to other celestial bodies, transporting sensors and men up close for a better look; and second, by carrying their instruments above the ''muddy'' and turbulent atmosphere of Earth. A spacecraft sent to another celestial body is remote sensing of the remotest kind! The sensors they carry are extensions of human senses which gather information and transmit it back to Earth.

Exploring the Moon

The greatest space spectacular of all time was undoubtedly the Apollo Moon landings. For the first time, humans left Earth, landed on another celestial body, and returned home. Astronauts walked on the Moon, photographed its surface, installed instruments for measuring moonquakes, and brought back hundreds of pounds of rocks. (See Figure 6.16.) From their work we have a clearer understanding of the origin of the Moon and the Solar System. The Apollo program was summarized in Chapter 1.

Thirteen unmanned flights preceded Apollo. Three Rangers transmitted close-up pictures of the lunar surface as they approached and crash landed. Five Surveyors soft-landed on the Moon, tested the composition of the soil, and transmitted more than 17,000 pictures from the lunar surface. Finally, five Lunar Orbiters made medium and high resolution photographs of 99 percent of the lunar surface to aid in selecting Apollo landing sites. When the Orbiters finished their job, they fired retrorockets and crash landed on the Moon so they would not interfere with Apollo activities.

Viking to Mars

Viking spacecraft both orbited and landed on Mars to examine it, determine its geology, and search for living

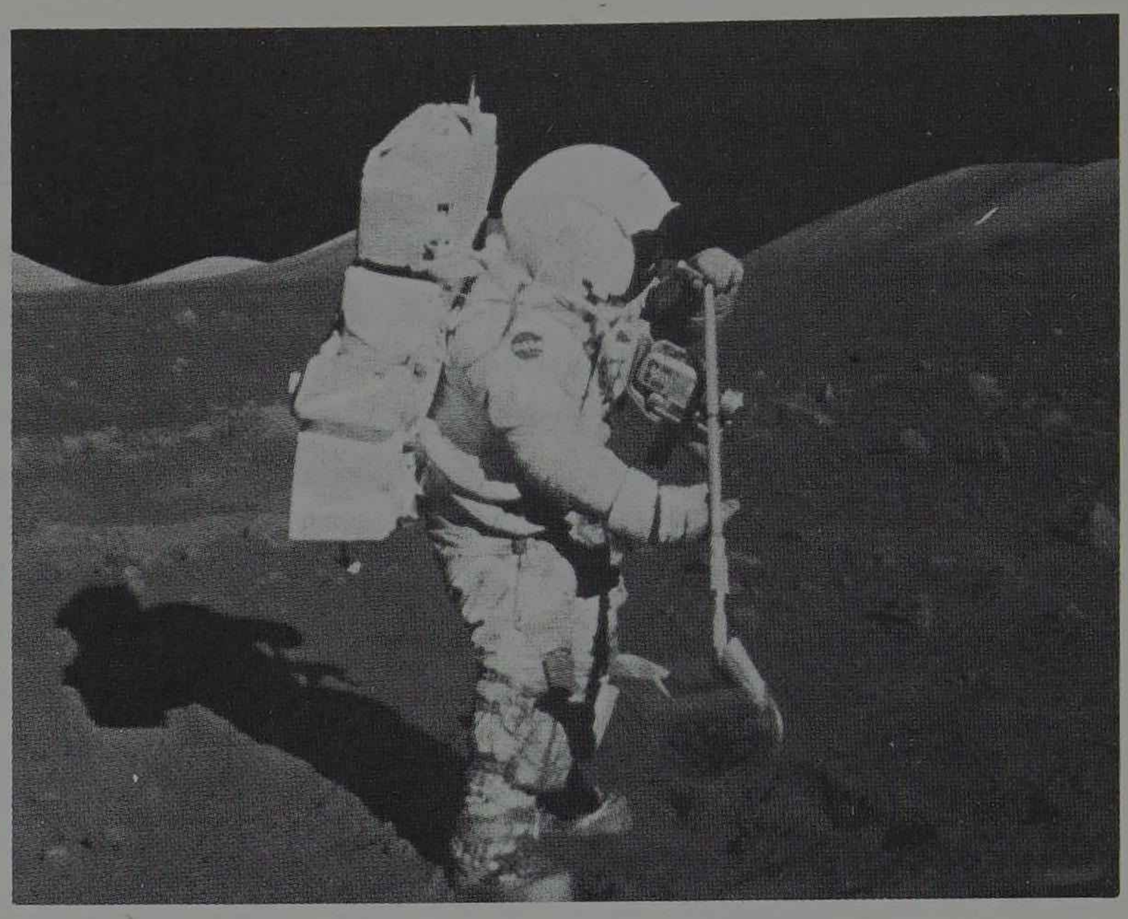


Figure 6.16 An Apollo scientist-astronaut scoops up rock and soil from the surface of the Moon. *Courtesy of NASA.*

organisms. They sent back spectacular and surprising information. Mars is no longer a point of light in the sky. We know it as a real place, a world that is both very much like Earth and very different from Earth. Chapters 12 and 13 will examine the Viking results, the planet itself, and the search for life.

Voyager

Perhaps the most successful planetary probe has been the pair of Voyager spacecraft that have made close passes to the outer planets, Jupiter, Saturn, Uranus, their moons, and their rings. Its last planetary encounter will be with Neptune on August 24, 1989.

Twelve Mariner and Pioneer spacecraft flew past Mercury, Venus, Mars, Jupiter, and Saturn from 1962 to 1978. They photographed the surfaces and cloud tops, detected magnetic fields, studied the atmospheres, and took measurements of the interplanetary solar wind. They were the forerunners of the later more sophisticated and technically capable Voyager spacecraft. Figure 6.17 is a diagram of Voyager.

Once every 175 years the outer planets line up on the same side of the Sun, making it possible to send one spacecraft to all of them on one flight. This ''Grand Tour'' was conceived and carried out by the Jet Propulsion Laboratory. The plan was that as Voyager fell toward Jupiter, the gravitational attraction would increase the spacecraft's speed sufficiently and curve its trajectory around the giant planet just properly so it would go on to Saturn, the next planet in line. Similarly, at Saturn Voyager would pick up enough speed and change course for Uranus, and so on to Neptune. These trajectories are shown in Figure 6.18.

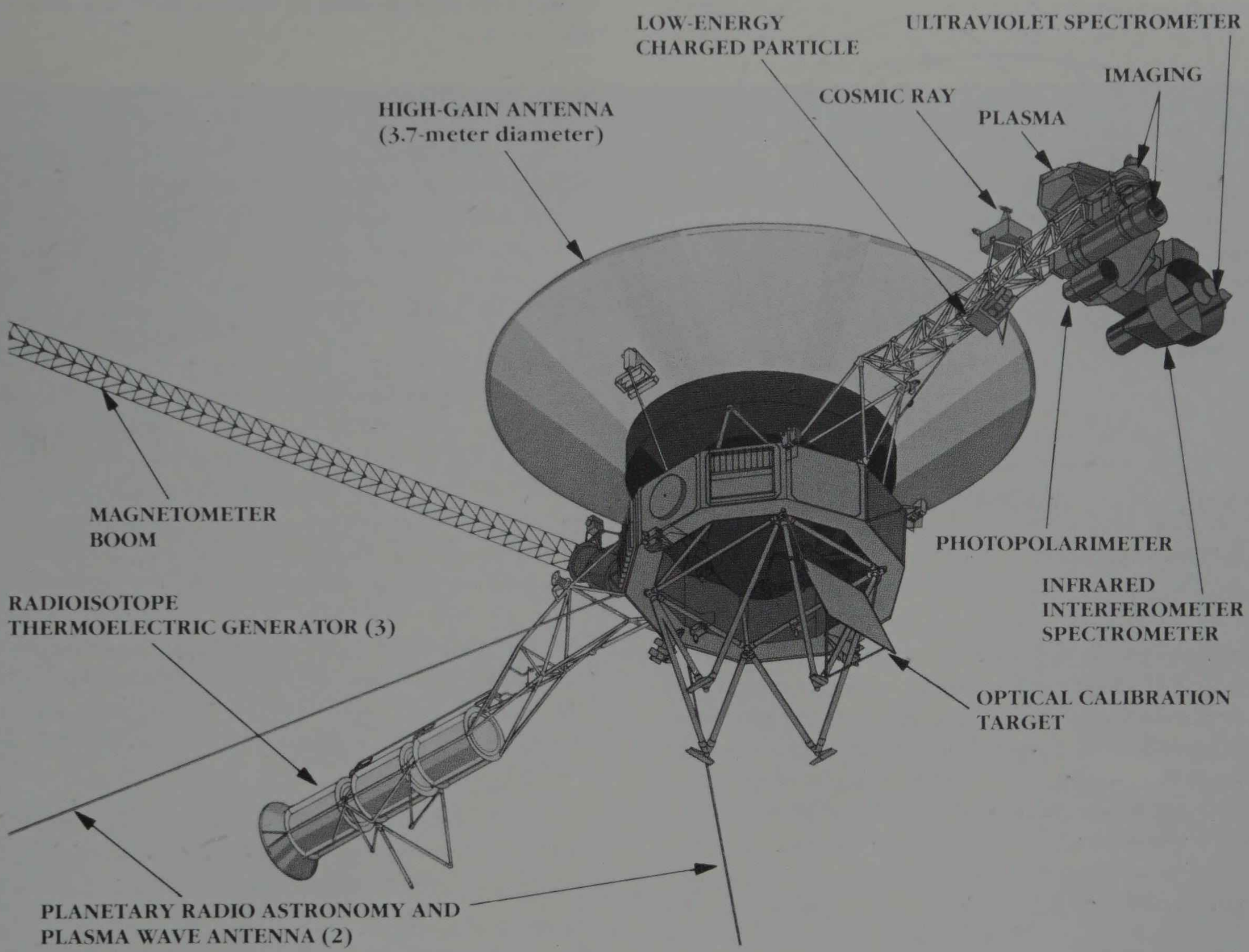


Figure 6.17 Voyager spacecraft. The spacecraft was powered by nuclear electric generators because the intensity of solar energy is so low at the outer fringes of the Solar System that solar cells cannot be used. The communications antenna is over 12 feet in diameter. Other components are sensors which measure particles and electromagnetic radiation in space and in the vicinity of the target planets. The imaging devices created spectacular photos of the planets and their moons. *Courtesy of NASA.*

Two Voyager spacecraft were sent on their way in 1977. Voyager 2 was launched August 20; Voyager 1 was launched into a faster trajectory on September 5 and reached Jupiter first on March 5, 1979. Voyager 2 arrived four months later on July 9.

Jupiter

The Voyager 1 trajectory past Jupiter is shown in Figure 6.19. What it found was awesome. Three of the 33,000 photographs returned are shown in Figures 6.20 to 6.22 in the color pages.

Figure 6.20 shows Jupiter as seen by Voyager from 12.4 million miles away. Swirls in the clouds are caused by wind and the rapid rotation of the planet, one rotation in only 10

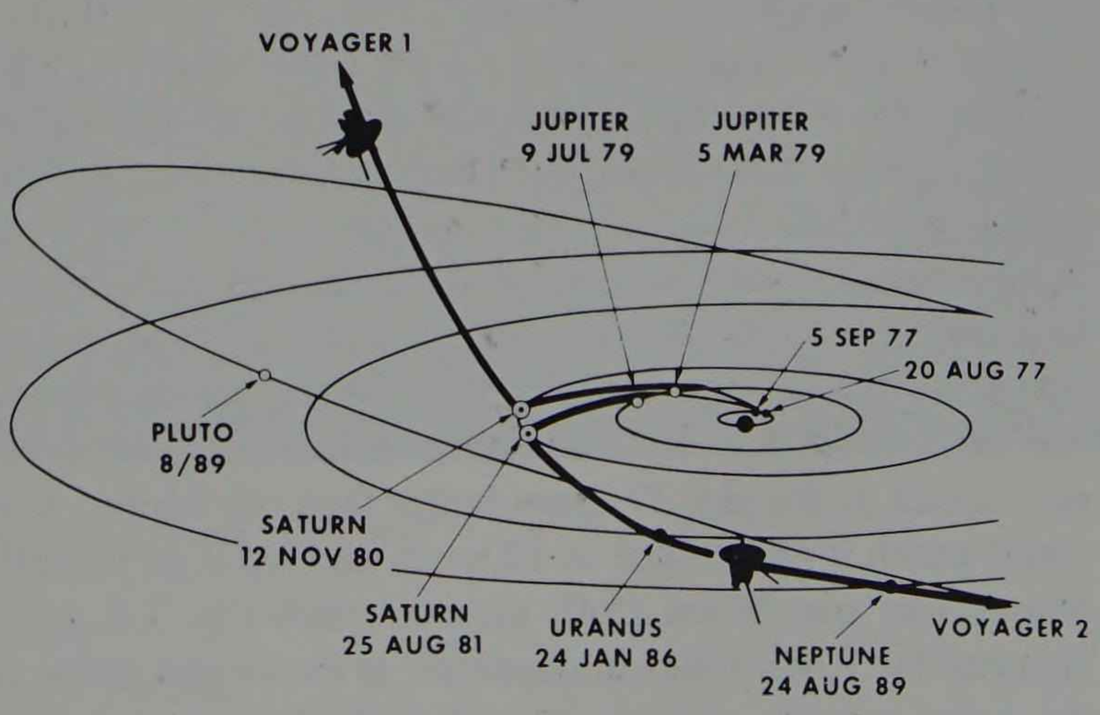


Figure 6.18 Voyager spacecraft "Grand Tour" of the outer Solar System. *Courtesy of NASA.*

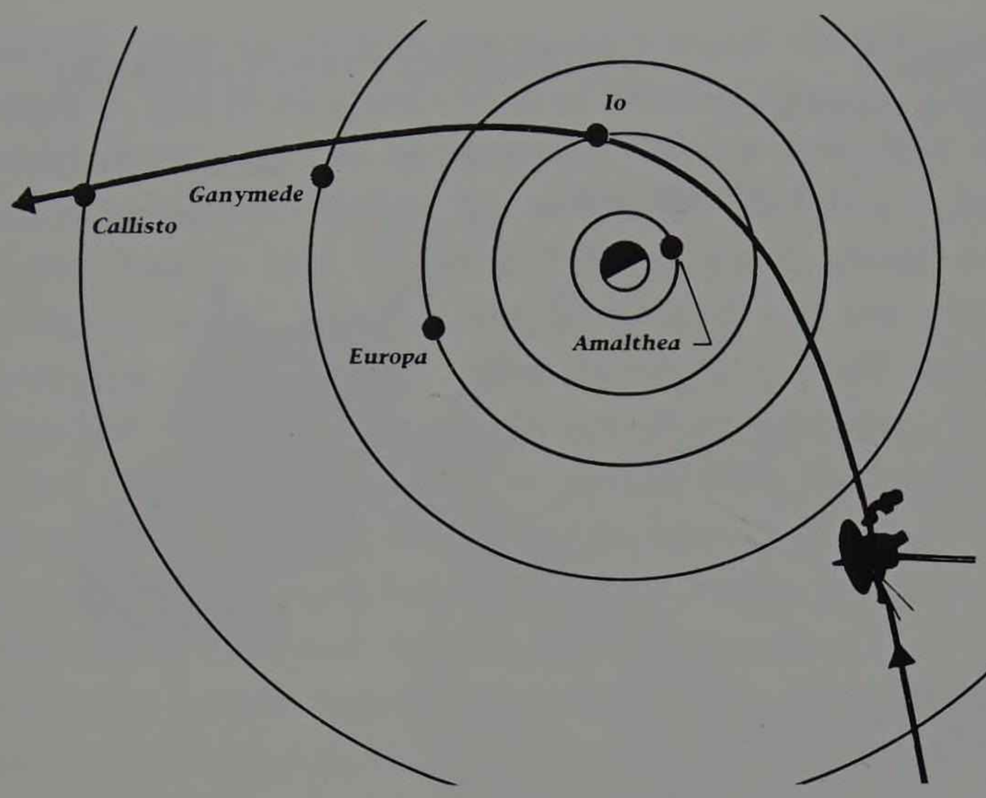


Figure 6.19 Voyager 1 track past Jupiter and its moons. The curvature of the trajectory is due to the gravitational force as Voyager approached Jupiter, which deviated the spacecraft from its elliptical orbit around the Sun. *Courtesy of NASA.*

hours. Two moons can be seen: red Io over the giant red spot and Europa just right of center. Sunlight comes from the right, so the left sides of the planet and the two moons are shadowed. The giant red spot in Jupiter's atmosphere had been observed for three hundred years. It was found to rotate counterclockwise, like a hurricane on Earth, once in 6 days at the outer edge. Data also verified the presence of lightning bolts, aurora, a magnetic field, and a magnetosphere. In addition, Jupiter was found to have a thin ring which could be seen only in the glare of the Sun, looking back from the opposite side.

The moons of Jupiter were spectacular. Planetary scientists had expected cold, rocky bodies riddled with craters. The surprises were many. Io, shown in Figure 6.21, is sometimes called the ''pizza planet'' for obvious reasons. The plume rising over the surface in the lower right comes from one of its at least eight active volcanoes. Io is the most geologically active body yet found in the Solar System, the only place with active volcanoes besides Earth. No impact craters are seen because lava flows constantly over the surface. The red-orange color is due to sulfur compounds in the lava, not tomato sauce. Covered with water ice, Europa is the smoothest body yet seen in the Solar System (see Figure 6.22). Dark and light lines on the surface are probably cracks in the ice where material from below squeezed up and froze. Europa's orbital period around Jupiter is about 3.5 days. Standing on Europa, you would see Jupiter in the sky 20 times larger than our Moon. You could watch it rotate once in 10 hours and see it go through phases like our Moon (full, crescent, new) in 3.5 days. Ganymede, 1,640 miles in diameter, is the largest moon in the solar system and is covered with both craters and grooved ice terrain. Callisto has wall-to-wall craters, probably the most intensely cratered body in the Solar System. Others were photographed as well and three new ones were discovered.

Voyager at Saturn

Voyager 1 arrived at Saturn on November 12, 1980, only 12 miles off course; Voyager 2 followed on August 25, 1981, 2.7 seconds early and 30 miles from the aim point. The Voyager 2 trajectory through the Saturnian system is shown in Figure 6.23. Photos are shown in Figures 6.24 and 6.25 in the color pages. Again the discoveries were many.

Figure 6.24 shows a view of Saturn that cannot be seen from Earth. Voyager 1 had passed the planet four days before and looked back toward the Sun to make this picture. The rings are composed mainly of small chunks of water ice; they are quite thin and the edge of the planet can be seen through them at the bottom. The image shows the shadow of the planet on the rings at the left and the shadow of the rings on the planet near the center of the picture. Figure 6.25 is a Voyager photograph of Saturn's moon Enceladus. The lower part of the picture shows many craters while the upper part has none at all. The grooves and ridges at the center and top are probably faults through which water from the interior flowed to wipe out the craters on that part of the moon.

Saturn's rings are so numerous they look like grooves in a phonograph record; spoke-like features were found in the rings. Small moons were found on the edge of some of the

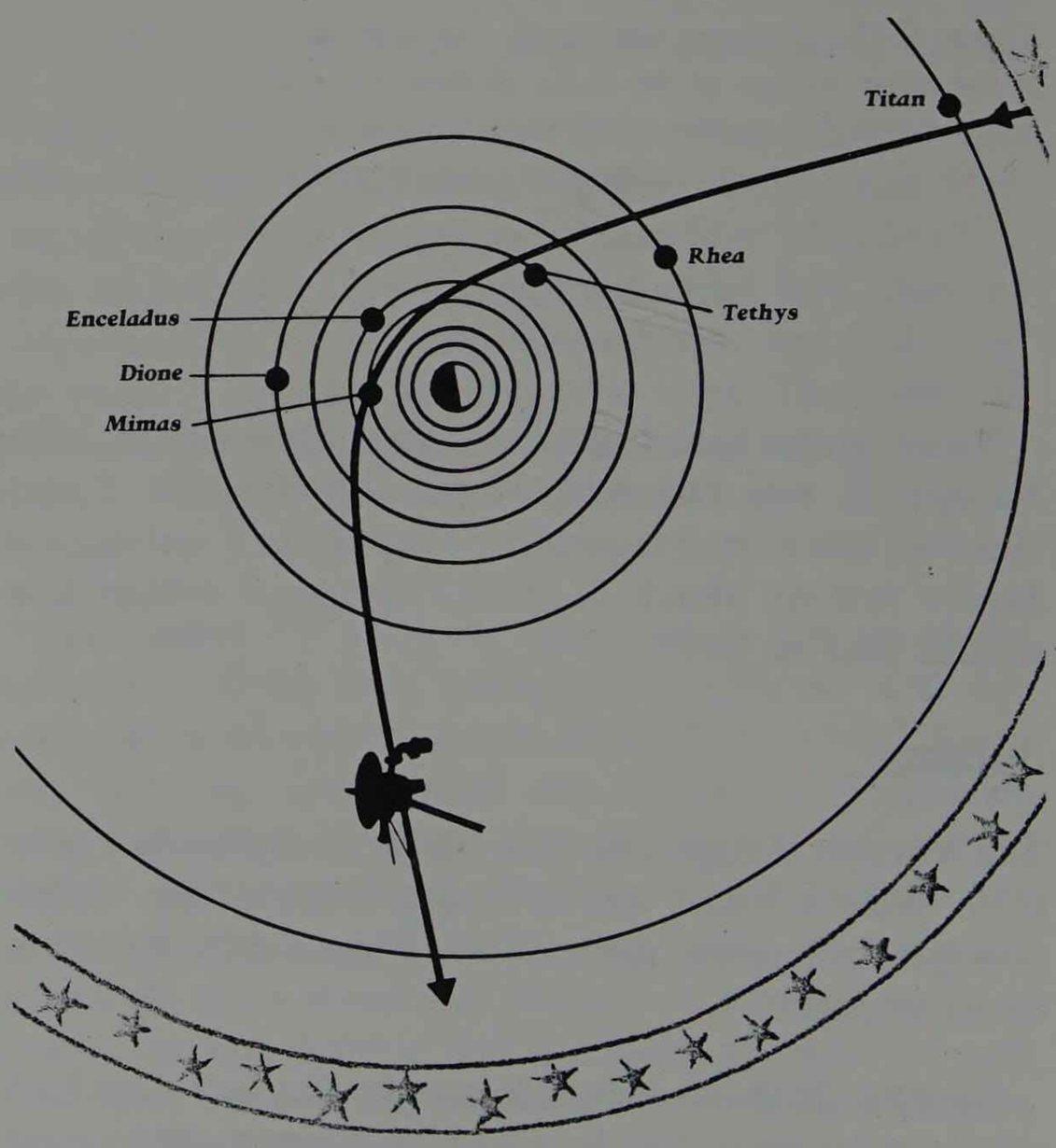


Figure 6.23 Voyager 2 trajectory through the Saturnian system.



Figure 6.9 Landsat 5 image of Copenhagen, Denmark. *Courtesy of EOSAT.*

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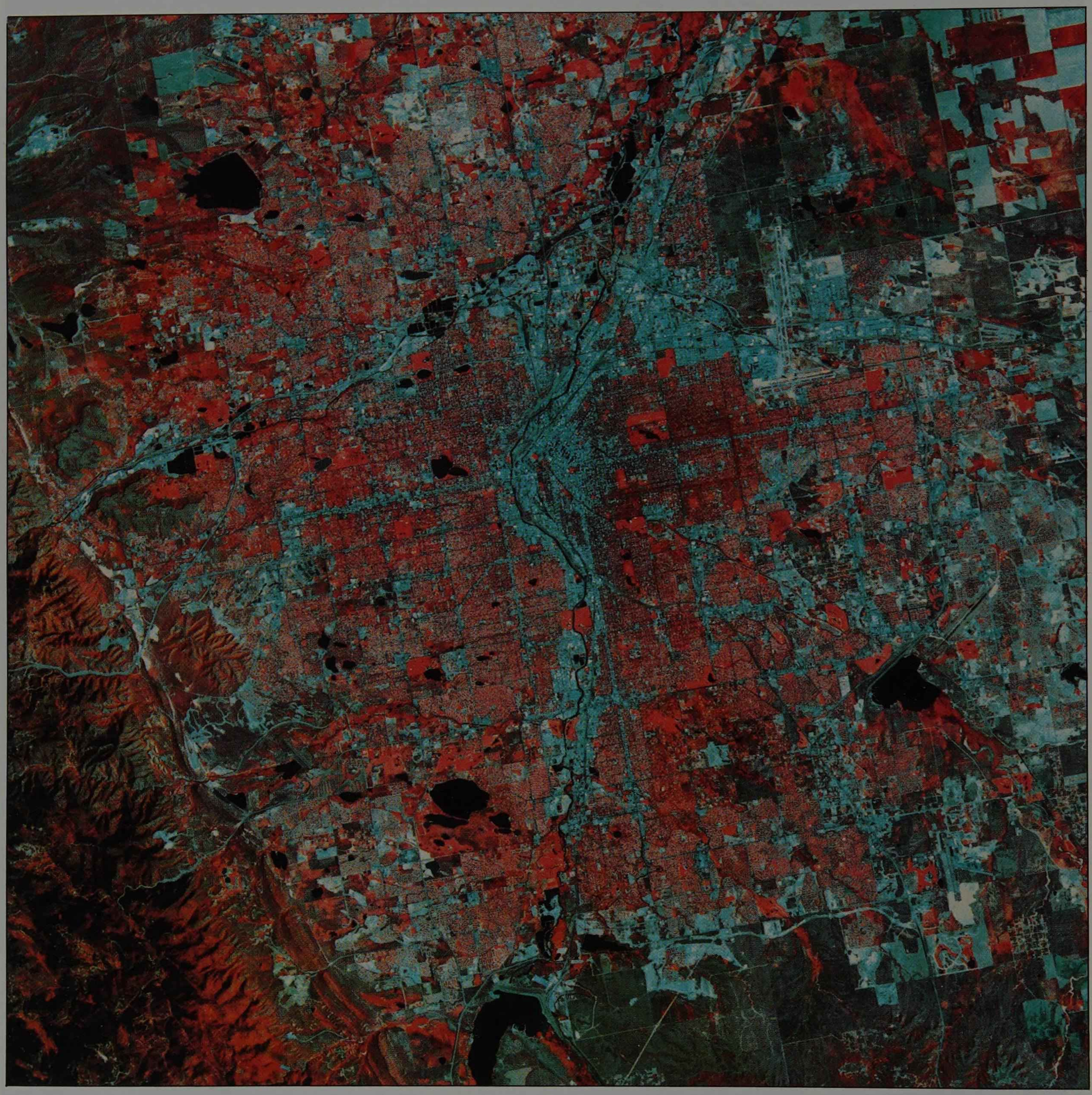


Figure 6.10 Landsat 5 color infrared image of Denver, Colorado, April 11, 1986. *Courtesy of EOSAT.*

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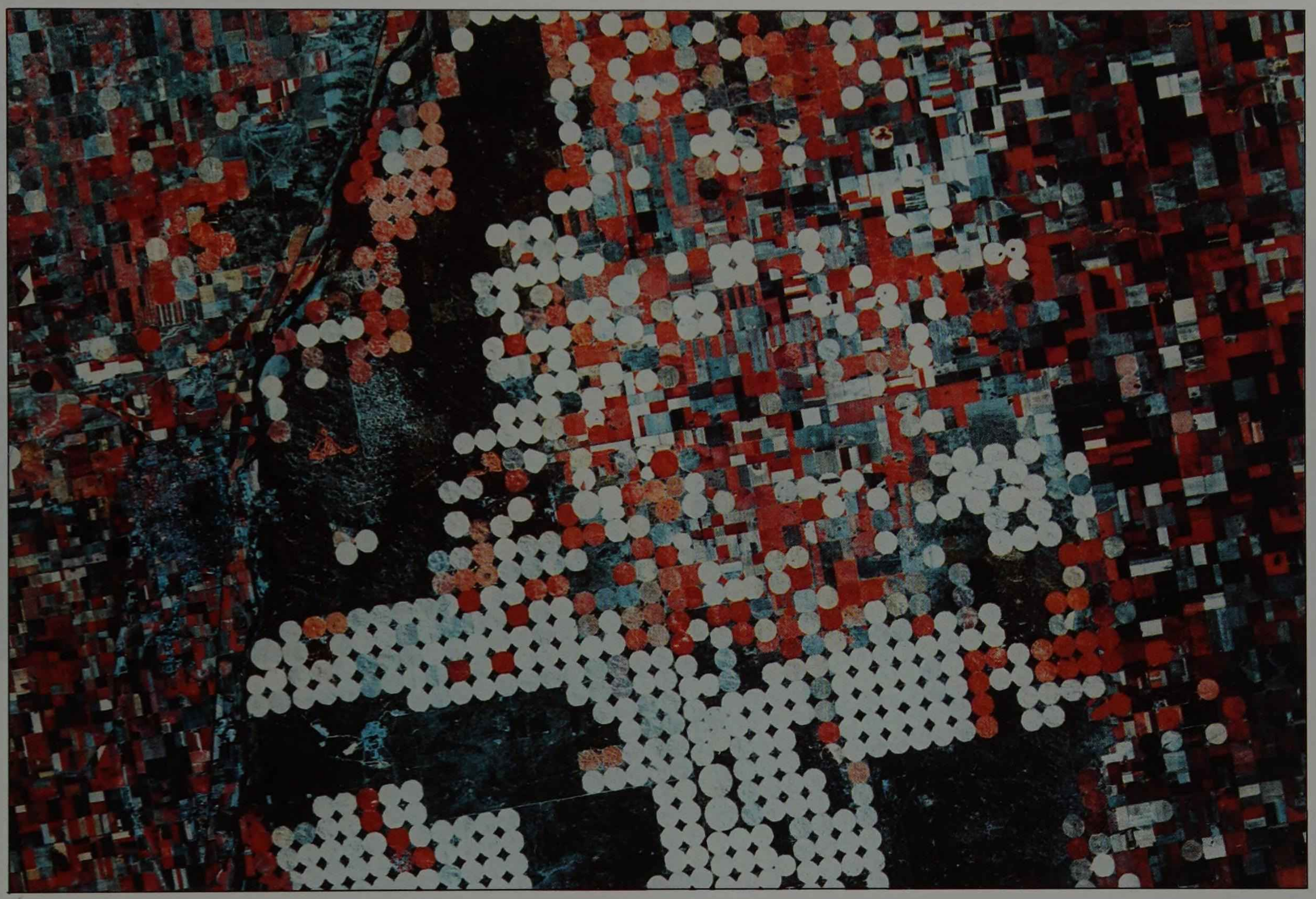


Figure 6.11 Winter wheat crops near Garden City, Kansas. *Courtesy of EOSAT.*

Same comment as fig 6.9



Figure 6.12 A Landsat 5 image of communities carved out of the Arizona desert, April 5, 1986. *Courtesy of EOSAT.*

Same Comment as fig 6.9



Figure 6.20 Jupiter as seen by Voyager from 12.4 million miles away. *Courtesy of NASA*.



Figure 6.21 Jupiter's moon Io. *Courtesy of NASA*.



Figure 6.22 Jupiter's moon Europa. *Courtesy of NASA*.

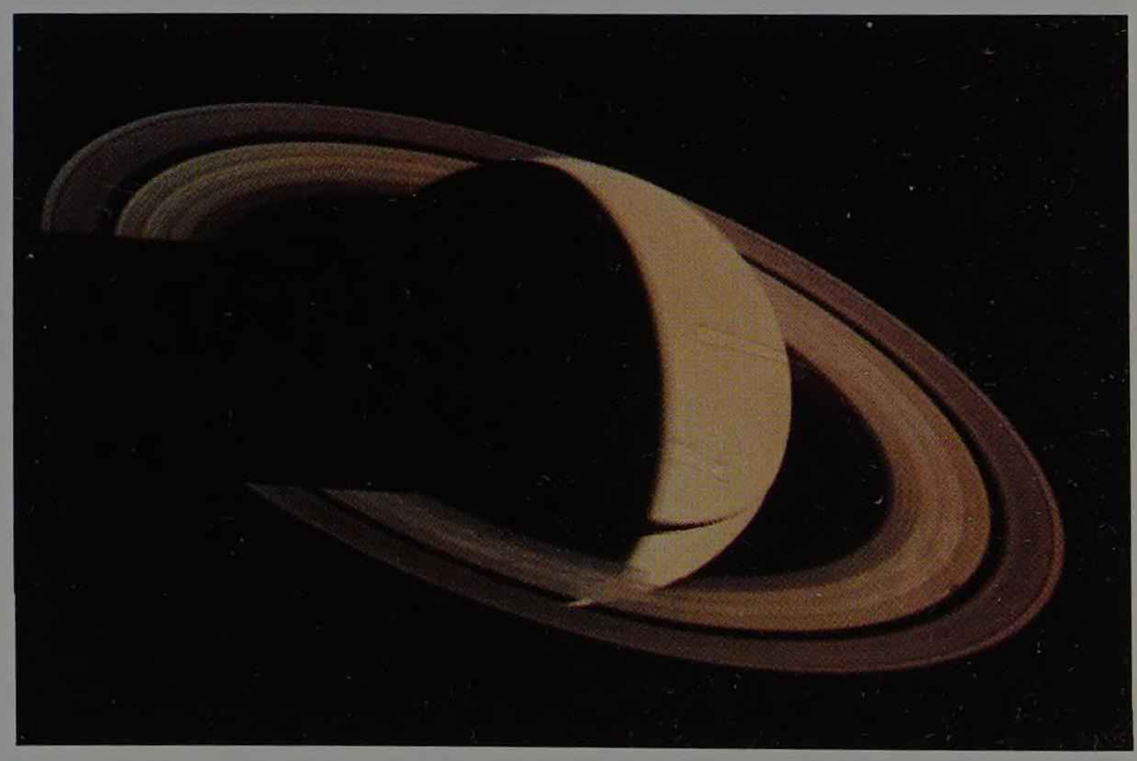


Figure 6.24 A view of Saturn taken by Voyager I. *Courtesy of NASA*.

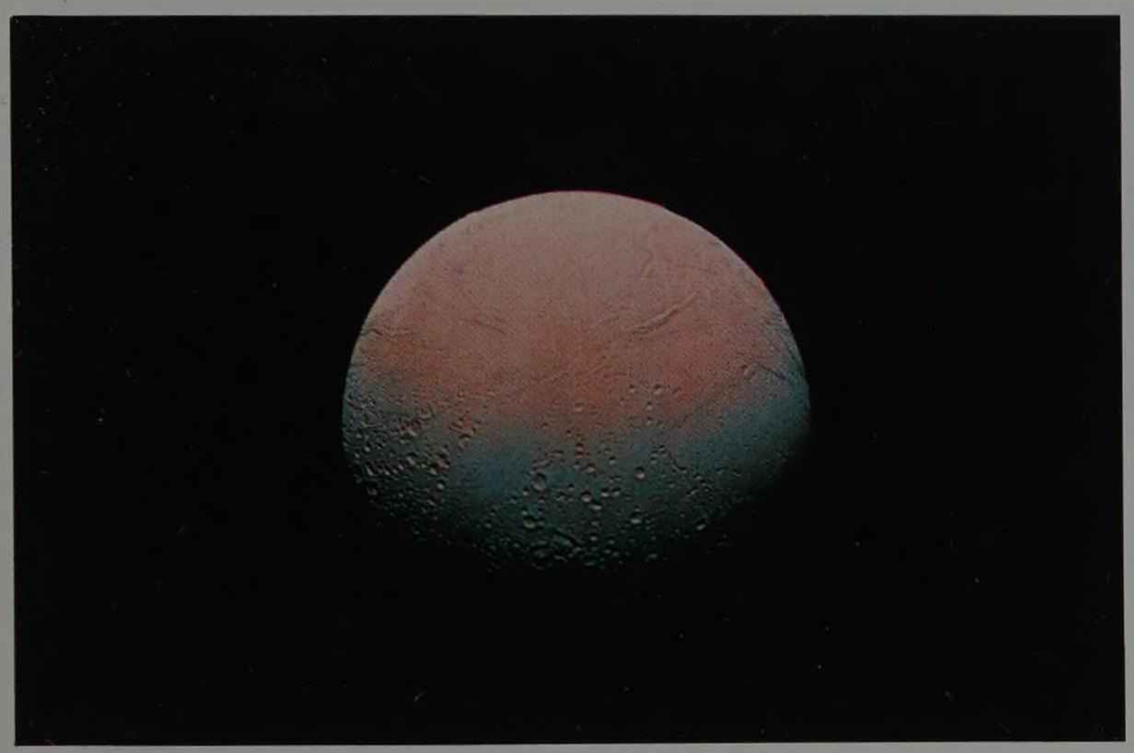


Figure 6.25 Saturn's moon Enceladus. *Courtesy of NASA.*

Figure 6.28 Galileo spacecraft passing Jupiter. *Courtesy of Harris Corporation; artist J. Harrelson.*



Figure 11.5 Later possible expansion of the space station. *Courtesy of Harris Corporation; artist J. Harrelson.*

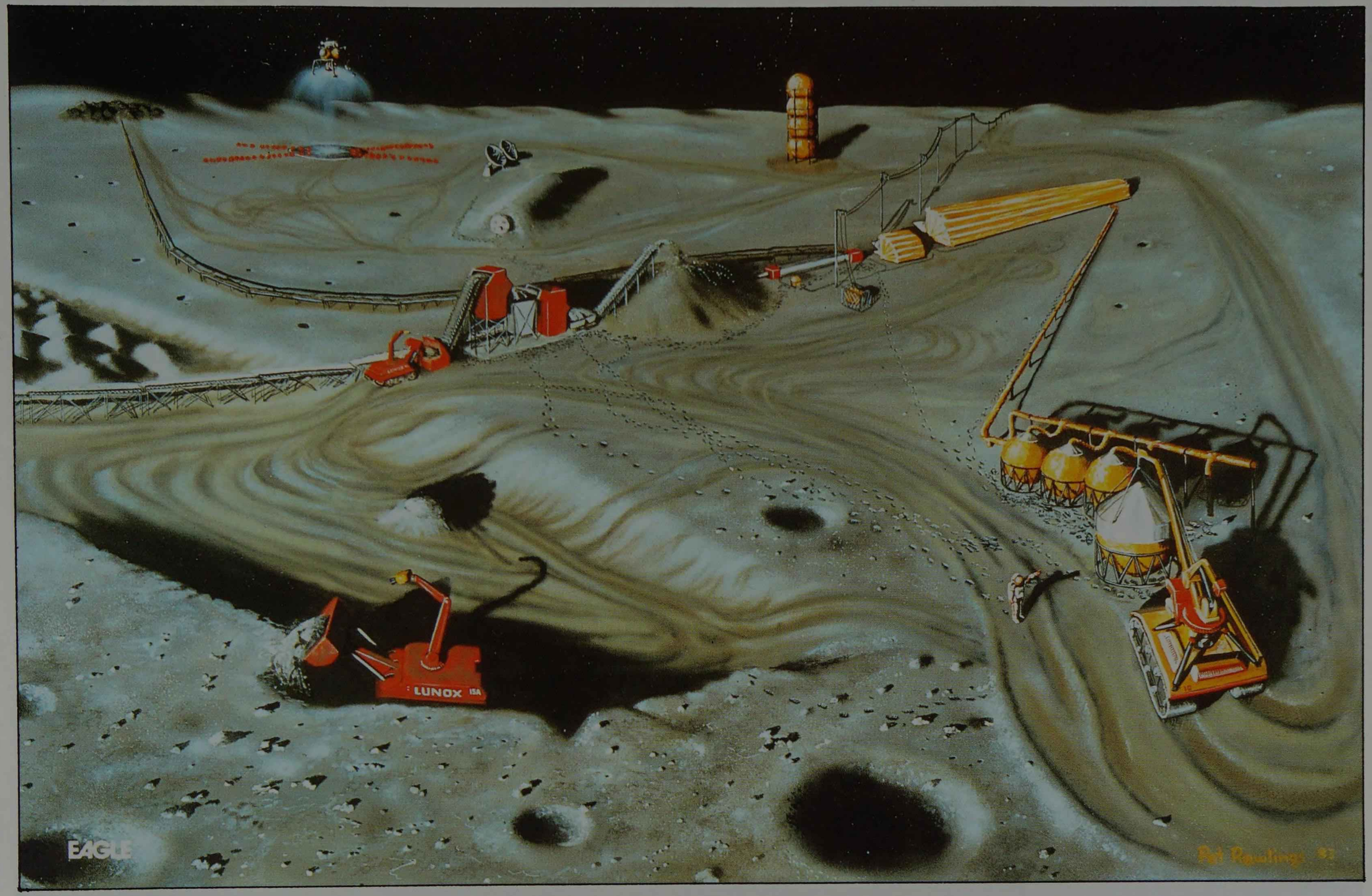


Figure 12.3 Artist's concept of a lunar mining base. Lunar soil is scooped up (red endloaders) and ground up (red structure to left); oxygen is extracted from the soil and liquified (yellow buildings), then piped to the yellow storage tanks. Waste tailings are carried away by a conveyer system. A rocket takes off in the background carrying several tanks of oxygen to a rendezvous point in lunar orbit. The habitat for a dozen technicians is just right of the communications antennas, covered by a mound of soil. Power lines come from a nuclear generator beyond the horizon. *Courtesy of Eagle Engineering for NASA; artist Pat Rawlings.*

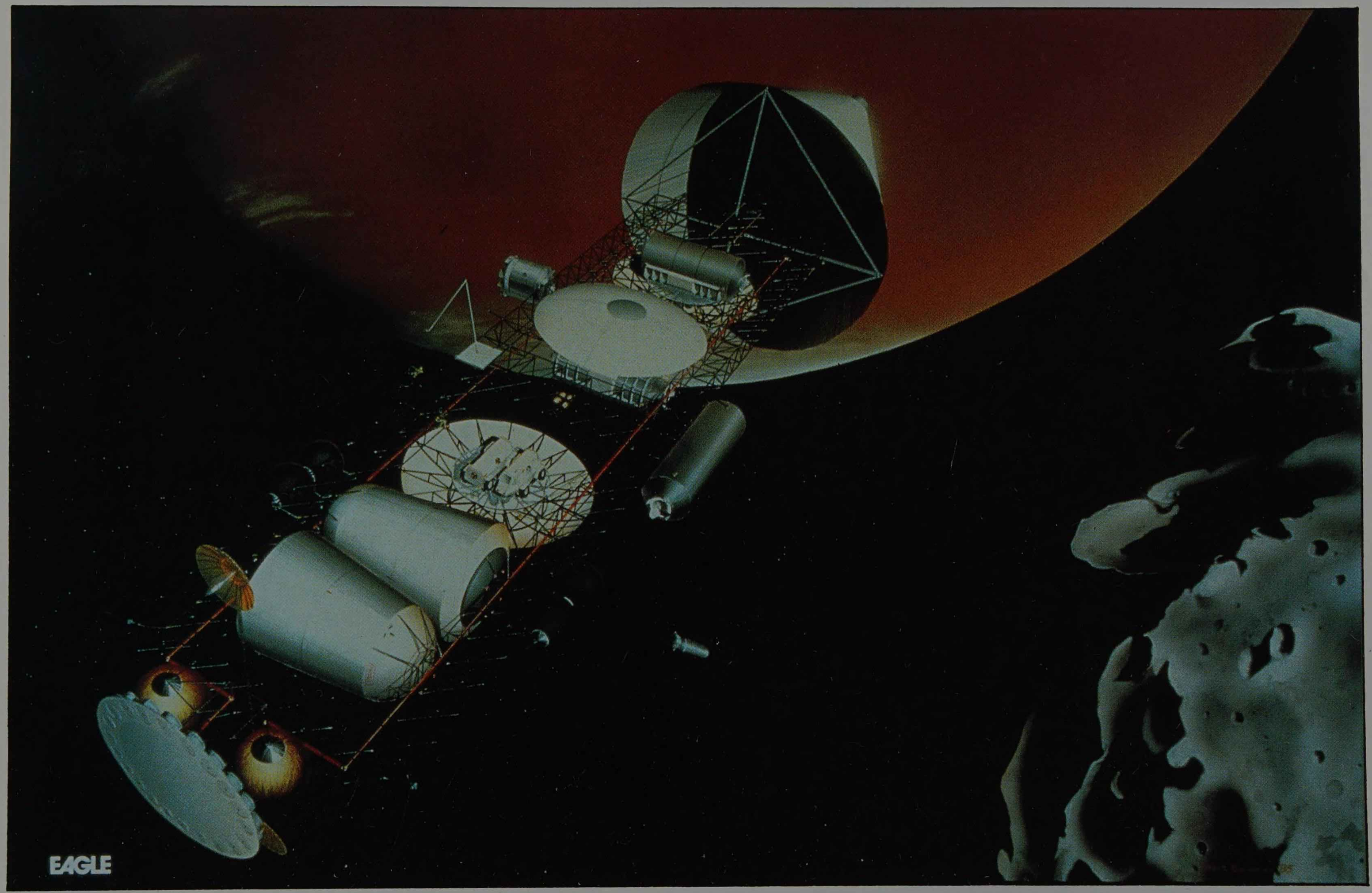


Figure 12.17 A space barge hauls a massive load of cargo from low Earth orbit to low Mars orbit. The Martian moon, Phobos, is visible at the lower right. *Courtesy of Eagle Engineering for NASA; artist Mark Dowman.*



Figure 6.26 Uranus's moon Miranda has features never before seen on Voyager's trek through the outer planets. The left and right edges show "racetrack" grooves. A large chunk seems to be missing at the bottom. V-shaped grooves are at the center. Only the top part looks like Earth's cratered Moon. Resolution is less than half a mile. Because of the low light level at Uranus (it is 19 times farther from the Sun than Earth is) long time exposures were necessary. To avoid blurred pictures, Voyager controllers instructed the spacecraft to fire thrusters causing it to spin in synchronization with its 43,000 miles per hour motion past Miranda. Without that trick, resolution would have been no better than about 16 miles. *Courtesy of NASA.*

rings. They act to keep the ring particles in place and the edge of the ring sharply defined. Cloud features are similar to Jupiter but not as pronounced in color. Wind at the equator was measured at 1,100 miles per hour. Saturn has a magnetic field and a magnetosphere.

Titan, the largest moon, has a dense nitrogen atmosphere, with haze layers formed from organic compounds such as methane, propane, and acetylene. The surface temperature on Titan is −288 °F. At that temperature methane could play much the same role as water does on Earth. The innermost moons are composed mostly of water ice.

Voyager 1 was steered under Saturn and allowed to accelerate to escape velocity from the Solar System. It is headed upward out of the plane of the ecliptic where the orbits of the planets lie. Voyager 2 took a trajectory around Saturn and on to Uranus, arriving there on January 24, 1986. Uranus showed a nearly blank ball. Its clouds were not as outstanding as the clouds of Jupiter and Saturn. The surprise of the encounter was the moon Miranda, shown in Figure 6.26. It has geological features and patterns never before seen in planetary exploration. One of the significant discoveries of Voyager is that, although they may look superficially alike, each body in the Solar System has unique features all its own, different from every other body..

Messages from Earth to whomever may find them are attached to the Voyager spacecraft. They are sounds and pictures recorded on a gold plated record carried in an aluminum case. Instructions on how to play the record are included. It is assumed that if anyone is smart enough to intercept Voyager they will be smart enough to decode the instructions. We will have more to say about this in Chapter 13. Science fiction has it that V—ger will be picked up by the crew of the starship *Enterprise* sometime in the twenty-third century!

Venus

Venus is constantly shrouded in cloud cover so dense that it is impossible to photograph its surface in the usual way with television type cameras. In 1978 a Pioneer spacecraft arrived to begin mapping 92 percent of the planet by radar with a resolution of 60 miles. High continents and low basins were found. Figure 6.27 shows the Pioneer map compared with a similar resolution map of Earth. The basins contain no water; water cannot exist in liquid form because of the extreme heat, 700 °F at the surface. The best map of Venus comes from a Soviet Venera spacecraft that had a resolution of 6,500 feet and covered about 30 percent of the planet. The Soviets also landed two spacecraft. They survived the 700 °F heat just long enough to send a few pictures of the dry, rocky surface.

Magellan, the next U.S. probe to Venus, will carry a high resolution imaging radar which can map the planet through the clouds. It will be able to distinguish objects as small as 800 feet across and measure altitudes with an accuracy of 100 feet. From its highly eccentric orbit with apoapsis of 4,823 miles and periapsis of 185 miles, the probe will record an image as it flies close to the planet at periapsis. Then, as it slows down approaching apoapsis, it will transmit its findings to Earth. It will require one Venusian day, 243 days long, to map almost the entire planet, missing only about 10 percent near the south pole.

Galileo Spacecraft

The Voyager data on Jupiter whetted the appetite of planetary scientists for more. Everything discovered by Voyager was so completely beyond expectations. Galileo is a U.S. spacecraft that will visit Venus and two asteroids, then end its trek in the Jovian system for a more thorough look. It is shown with its large communications antenna pointed toward Earth in Figure 6.28 in the color pages. At Venus, Galileo will search for lightning and measure atmospheric composition. Photos of the asteroid Gaspra will be made from a distance of 620 miles. The spacecraft

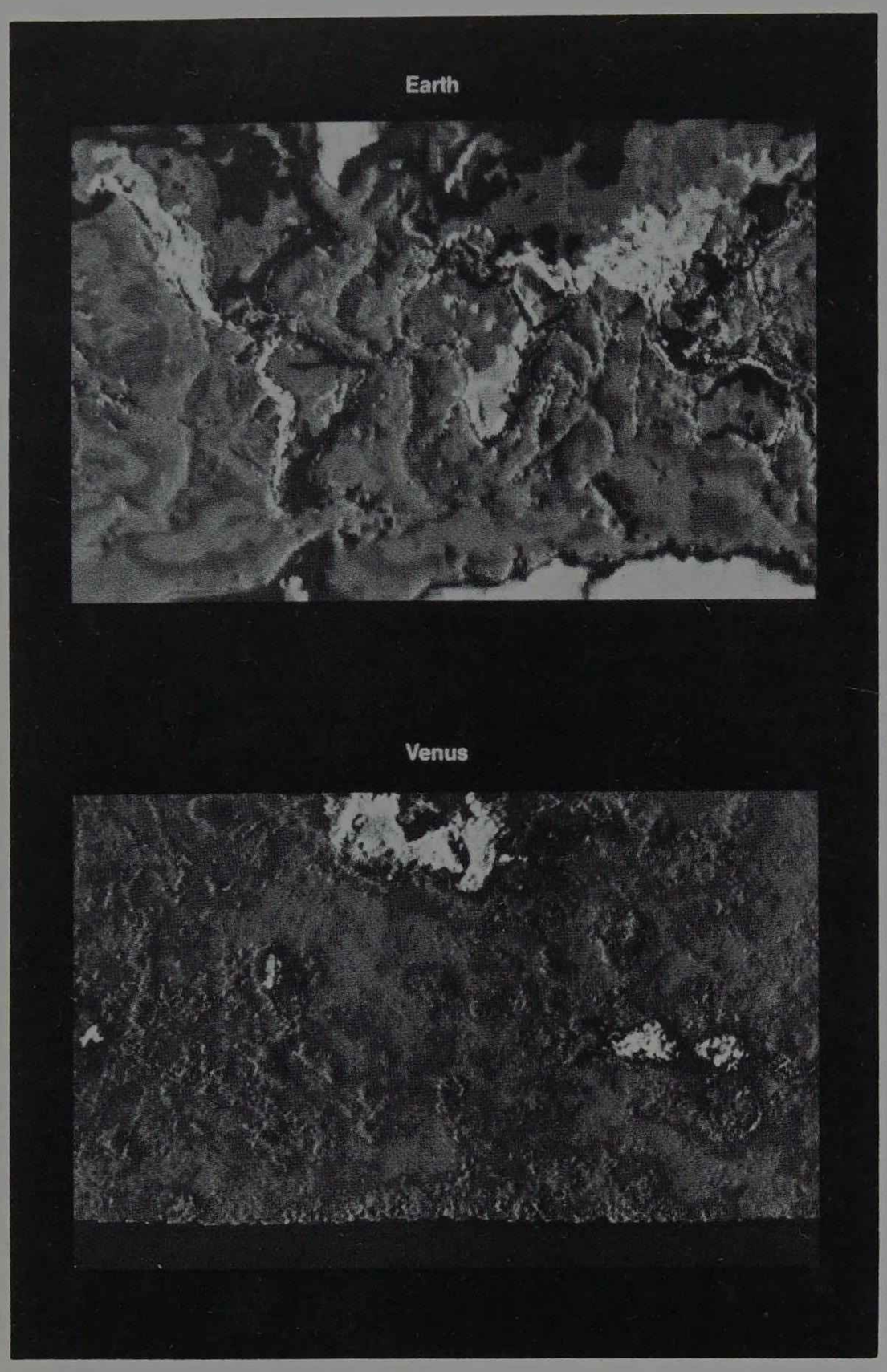


Figure 6.27 Venusian continents compared with Earth continents. *Courtesy of NASA.*

TABLE 6.2 Galileo Spacecraft Mission Events and Gravity Assisted Orbital Changes

Date	Event	Perihelion	Aphelion
November 1989	Launch	—	Earth
February 1990	Venus fly-by, gravity boost	Venus	Beyond Earth orbit
December 1990	Earth fly-by, gravity boost	Earth	Asteroid belt
October 1991	Asteroid Gaspra fly-by	No change	No change
December 1992	Earth fly-by, gravity boost	Earth	Jupiter
November 1995	Jupiter arrival	Jupiter capture	—

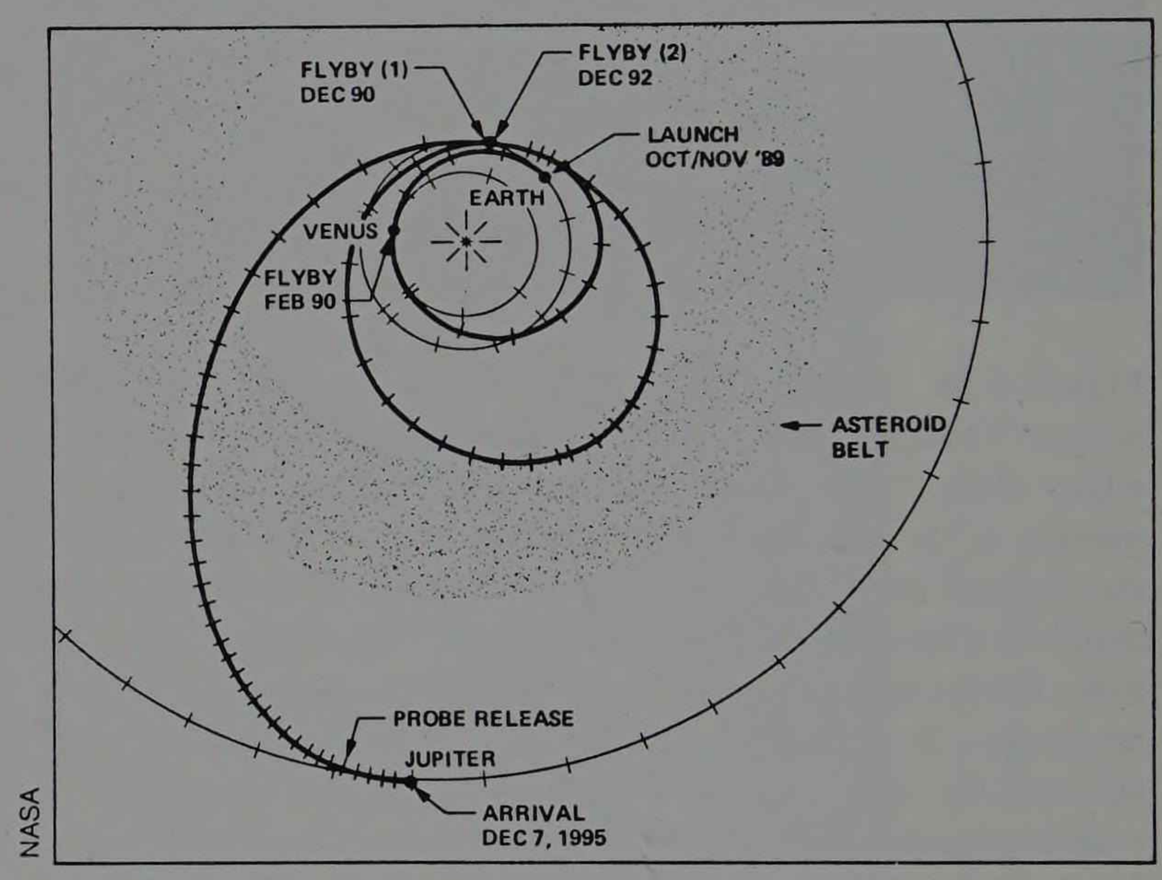


Figure 6.29 Galileo spacecraft trajectory to Jupiter via Venus and the asteroid belt.

will orbit Jupiter, drop a probe into its atmosphere, and make side trips to some of the many moons for closer looks than were made by the Voyagers in their quick fly-bys.

To minimize fuel requirements and at the same time expand its mission, Galileo will go to Jupiter by way of Venus, a long roundabout way to get there. The planets must be located in the correct positions at launch so each will be at the correct spot in space when Galileo arrives. The schedule is given in Table 6.2. At each encounter with Venus and Earth, the spacecraft falls toward the planet to increase its speed and extend its apogee until it reaches Jupiter. Figure 6.29 shows this complex trajectory; follow the path and notice the change in aphelion after each planetary encounter.

Earth's Muddy Atmosphere

One of the problems plaguing astronomers has always been that they have had to look through Earth's atmosphere. Light coming from the universe is refracted, bent by the air. That is why stars twinkle; above the atmosphere, they shine with a steady light. Air currents and bubbles of warmer or cooler air cause the light waves to refract as they pass through. Because the air is in constant motion, the refraction varies from moment to moment and the image in the telescope appears to shimmer and dance around.

In addition, atmospheric gases and particulate matter cause light to scatter away from a straight line. Sunlight is a mixture of all colors. As it penetrates the air, the longer wavelengths pass straight through while the shorter wavelength blue light scatters in all directions. That is why the sky is blue. The blue part of the sunlight comes at us from all directions. We cannot see the stars during the daytime because the sky is too bright from the scattered sunlight. Scattering is also the reason that the night sky is often rather bright. Starlight, moonlight, and city lights scatter and reflect from the gas and dust in the air, giving the sky a

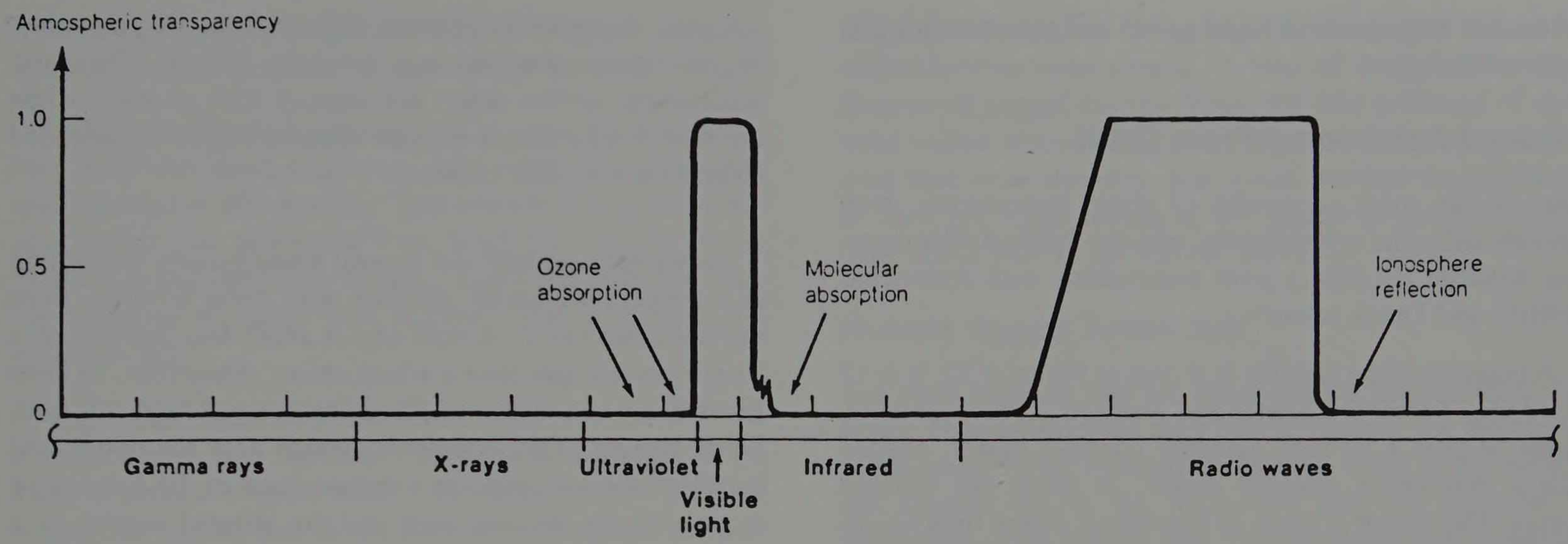


Figure 6.30 Transparency of Earth's atmosphere. *Courtesy of NASA.*

background glow which interferes with astronomical observations.

Another problem is that the atmosphere selectively absorbs many wavelengths of electromagnetic energy so they never reach the ground. This was pointed out in Chapter 4 and is shown in Figure 6.30. Ultraviolet, gamma rays, and x-rays are absorbed by the ionosphere and ozone layer. Certain infrared wavelengths are absorbed by molecules of water vapor and carbon dioxide. Some radio waves are absorbed by the ionosphere or reflected off its top. Some infrared and ultraviolet observations are possible from the tops of mountains or from balloons above the densest part of the atmosphere. But until the coming of the space age, Earthbound astronomers have had to be content with looking at the sky primarily by visible light, radio waves, and a few certain wavelengths of infrared, ''windows'' in which the atmosphere is partially transparent.

A final problem: as pointed out earlier in this chapter, everything emits electromagnetic waves and the atmosphere is no exception. It emits infrared. That fact is a boon to meteorologists whose satellites can detect variations in temperature of the ground and atmosphere from the infrared emissions. But that same fact is the bane of astronomers who would like to see the universe, not the atmosphere, with infrared sensors.

Before the days of spaceflight, astronomers used rockets and balloons to send their instruments above the atmosphere for short looks. Putting their observing equipment above the atmosphere allows astronomers to examine all wavelengths of electromagnetic energy coming from the universe. Many astronomy satellites were launched into orbit during the 1960s and 1970s. Uhuru discovered many x-ray sources in its four year lifetime. Explorer 53 discovered, among other things, stars that produce enormous bursts of x-rays every few hours. Two Orbiting Astronomical Observatories and the International Ultraviolet Explorer searched the universe for ultraviolet sources. Three High Energy Astronomy Observatories further studied x-ray sources. One of them searched out cosmic ray particles and gamma ray sources.

X-ray Telescopes

Because x-rays penetrate most substances, the normal telescope design cannot be used for x-rays. They will, however, reflect from a surface if they strike it at a very shallow angle, a glancing blow, so to speak; see Figure 6.31. To accommodate this phenomenon, the reflecting surfaces of an x-ray telescope are not flat, but are curved

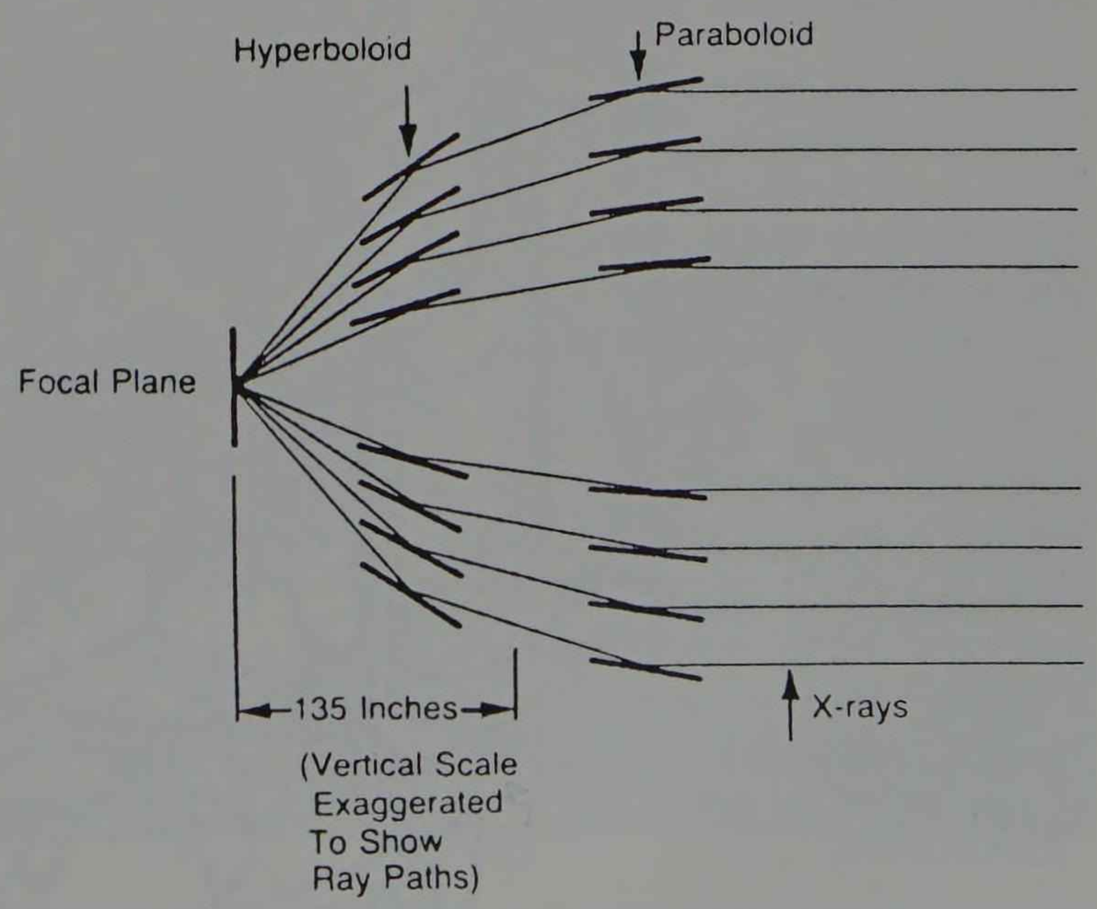


Figure 6.31 Diagram of an x-ray telescope. X-rays enter the telescope from the right, skip off two reflecting surfaces, and converge at the focal plane. ''Paraboloid'' and ''hyperboloid'' refer to the shape of the surface. The reflectors are actually rings; we see them edgewise in the diagram. The telescope is about 2 feet in diameter at the entrance. *Courtesy of NASA.*

concentric rings made of fused quartz and coated with a thin layer of nickel.

Infrared Astronomy From Orbit

One of the most successful of these instruments, both operationally and scientifically, was the Infrared Astronomical Satellite (IRAS), a joint undertaking with American, British, and Dutch scientists.

A diagram of the satellite is shown in Figure 6.32. It is 12 feet long, 7 feet in diameter and weighed 2,365 pounds on Earth. It uses a 22 inch diameter concave mirror, shaped like a shaving or makeup mirror, to focus the infrared waves. The mirror is made of beryllium, a very lightweight but strong metal. A secondary mirror reflects the waves to the focal plane where the 62 silicon arsenide and germanium gallium detectors are positioned. The detectors are sensitive to four wavelength bands from 119 microns to 8.5 microns, designed to observe objects from 15 Fahrenheit degrees above absolute zero to about 230 °F. The short wavelength sensors detect hot sources such as stars, while the longer wavelength sensors observe cooler or extended objects such as dust clouds.

As we have pointed out several times before, everything at a temperature above absolute zero emits infrared, even the telescope itself. A cold object emits less infrared at a longer wavelength than a warm object. Therefore, to keep interference to a minimum, the telescope was kept cold with liquid helium. This *cryogenic* system kept the optics and barrel of the telescope at a temperature of 10 Fahrenheit degrees above absolute zero and the infrared sensors at a lower temperature of only a few degrees above absolute zero. All the liquid helium needed for the lifetime of the spacecraft had to be put aboard before launch. The 125 gallons carried in a ''thermos jug'' was expected to be a six

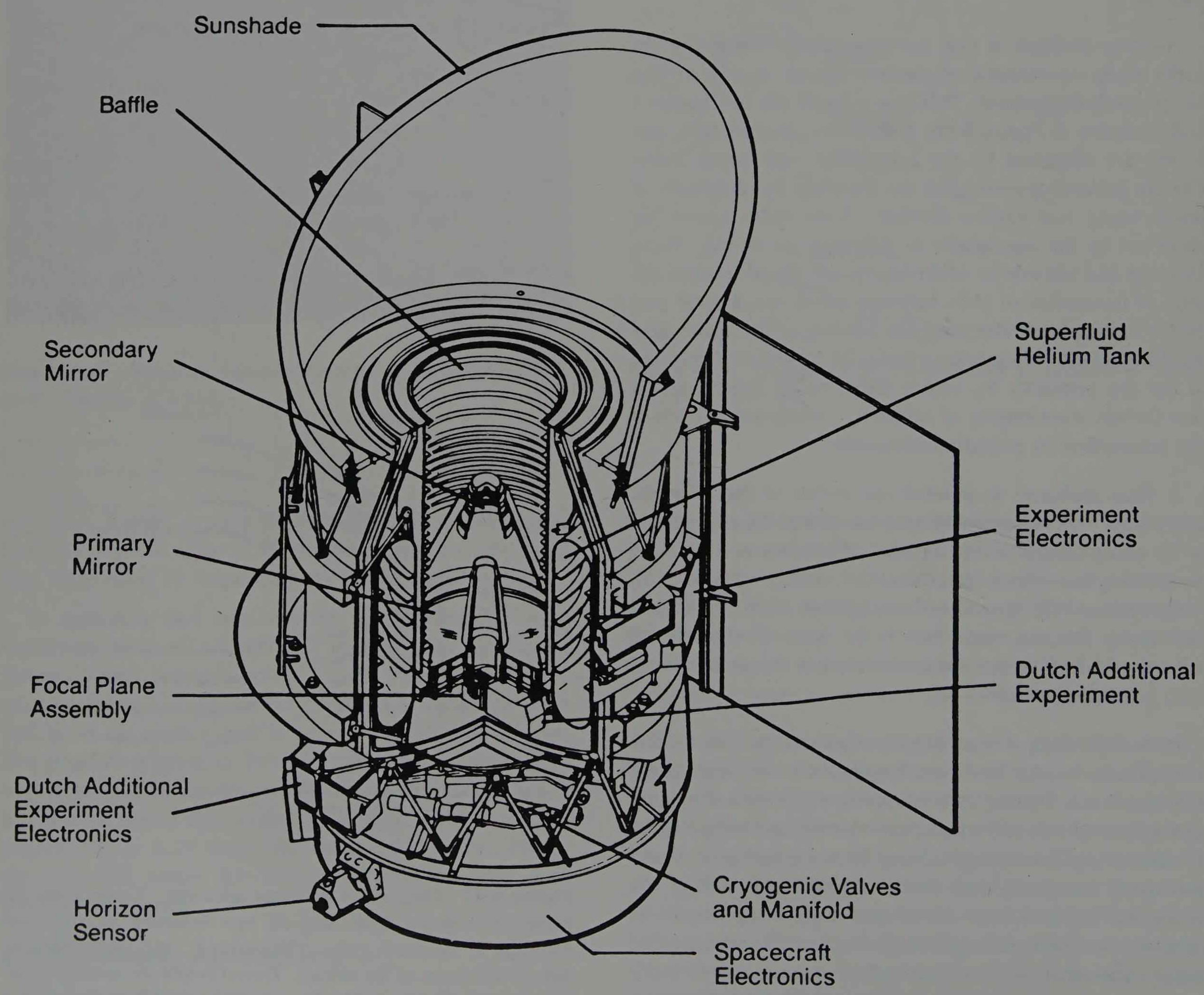


Figure 6.32 Anatomy of the Infrared Astronomical Satellite (IRAS). *Courtesy of NASA.*

months supply, but it evaporated more slowly than expected and the satellite continued to operate for ten months.

IRAS was launched on January 25, 1983, from Vandenberg Air Force Base, California, into a 560 mile polar orbit with a period of 100 minutes. That altitude is well above the atmosphere, but below the Van Allen belts except in the South Atlantic Anomaly region. There the data becomes contaminated by many false readings from protons in the radiation belts.

The orbit was oriented over the *terminator*, the sunrise-sunset line between daylight and darkness on Earth's surface (Figure 6.33). The orbit rotated about 1 degree per day so that as the Earth moved around the Sun the satellite remained over the terminator. It was important to keep the orbit oriented in that direction because the spacecraft had to point more than 60 degrees away from the Sun and more than 88 degrees from the Earth's horizon so the sensors would not pick up the Sun or Earth. A sunshade and baffle aided in keeping stray infrared from reaching the sensors.

The spacecraft scanned a one-half degree wide strip on each orbit which overlapped the previous strip by one-fourth of a degree. It did a complete survey of 95 percent of the sky. IRAS catalogued 250,000 individual sources within the limits of sensitivity of its detectors. Most of them are stars in our Milky Way galaxy, some surrounded by cooler material. The nucleus of the Milky Way is readily discernible in the data, giving further proof that we live in a spiral galaxy. At least 10,000 galaxies outside the Milky Way were also observed. A few sources were seen to move and therefore had to be nearby. Some turned out to be asteroids, five were comets. A ring of dust particles was discovered around the star Vega, the first evidence of cool solid matter around a star other than the Sun. Some newly born stars were also seen, hot bodies that had not turned on as stars yet. From launch of the vehicle to analysis of the data, IRAS was an unqualified success.

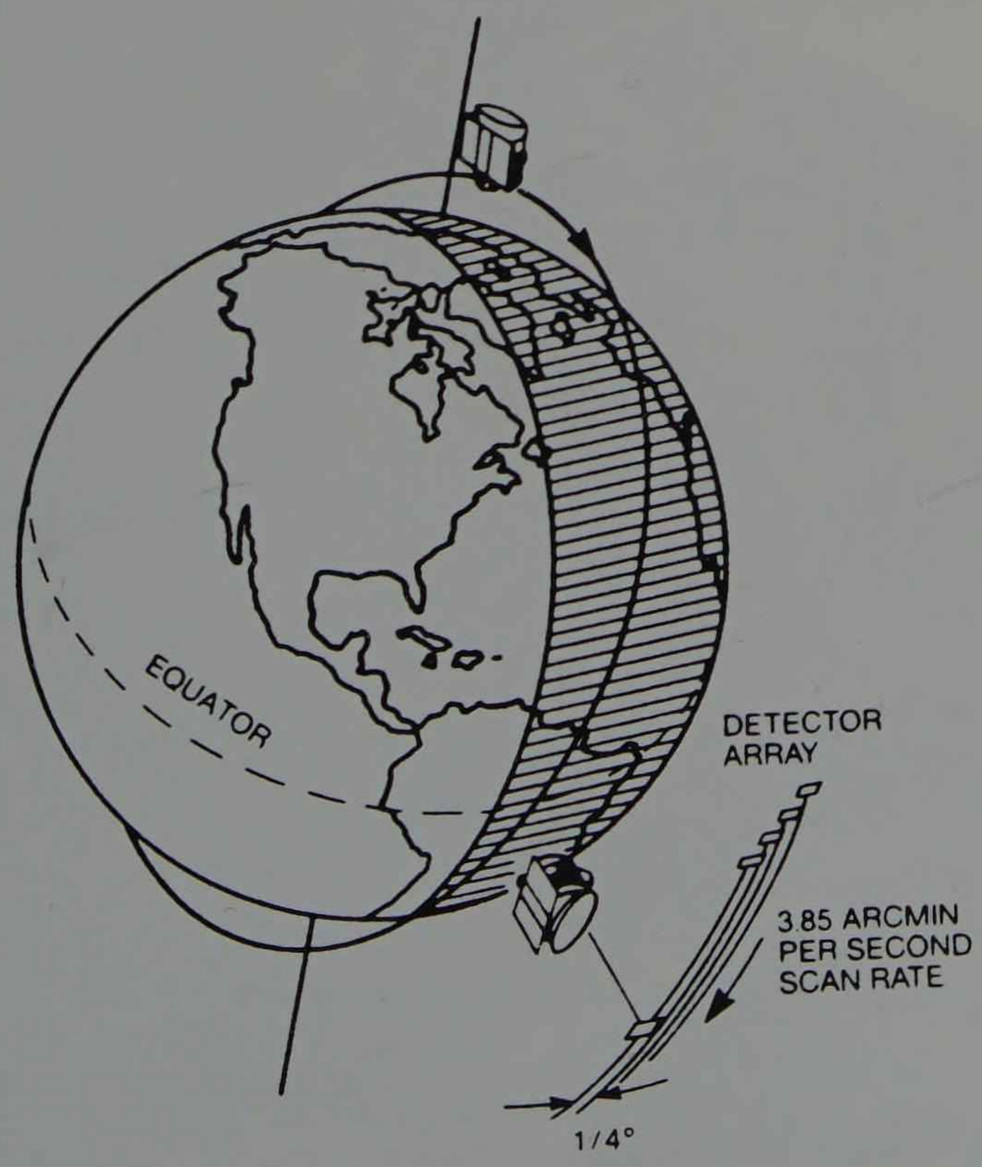


Figure 6.33 IRAS orbit. *Courtesy of NASA.*

Hubble Space Telescope

The most exciting tool for observational astronomy is the Space Telescope named after Edwin Hubble, the American astronomer whose research on galaxies early in the twentieth century led to the realization that the universe is expanding. This newest and most sophisticated telescope ever built is 43 feet long and weighs (on Earth) about 25,000 pounds. It is shown in Figure 6.34 being checked over in a clean room.

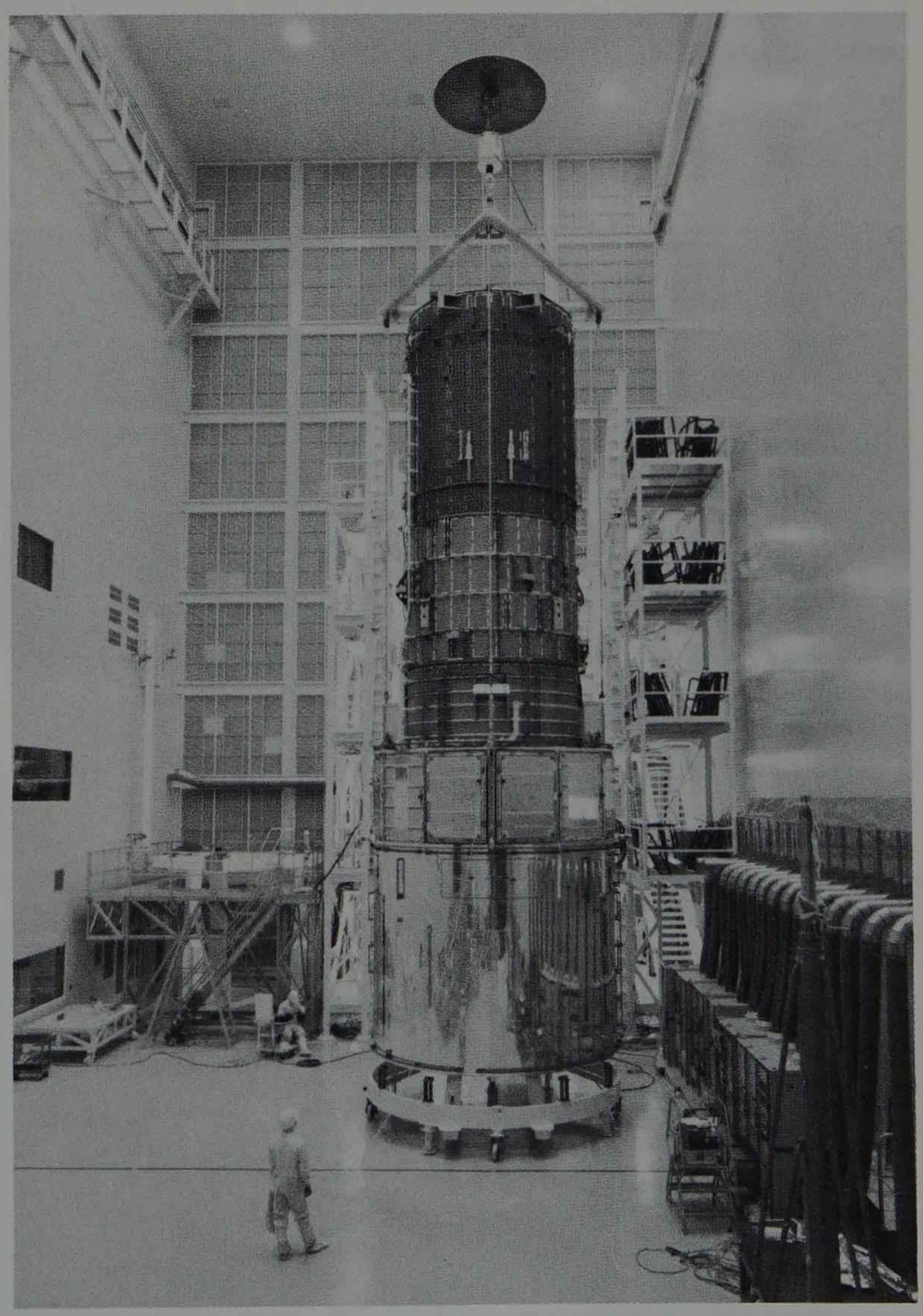


Figure 6.34 Hubble Space Telescope being assembled in the world's largest clean room. Note the size of the telescope compared to the technician in the lower left. The clean room is 85 feet high, 50 feet wide, and 120 feet long. Air is moved through the filters in the back wall at the rate of 8,500 cubic feet per second, giving a complete filtration of the half-million cubic feet in the room every minute. *Courtesy of Lockheed.*

The working end of the telescope is an 8 foot diameter mirror (Figure 6.35) which brings electromagnetic waves from space into focus. The size of this mirror makes it one of the largest instruments ever built; the precision of its construction makes it one of the best ever built; but its location in orbit above the atmosphere is what makes it unique and more powerful than any other telescope (Figure 6.36). The Space Telescope will be able to observe the entire sky, not limited by a horizon. It will observe for longer periods of time unhindered by scattered sunlight, up to 4,500 hours per year compared with perhaps 2,000 hours per year at the best ground observatories.

Figure 6.37 is a diagram of the Space Telescope and Figure 6.38 shows the light path through the instrument. The telescope is a Cassegrain design, a common design for Earth-based telescopes. The aperture door is opened and light from the object under study enters. A system of baffles keeps stray light out. The light rays reflect from the large primary mirror to a 12 inch secondary mirror mounted in the center of the tube, 16 feet from the primary. The light beam is reflected back from the secondary mirror and passes

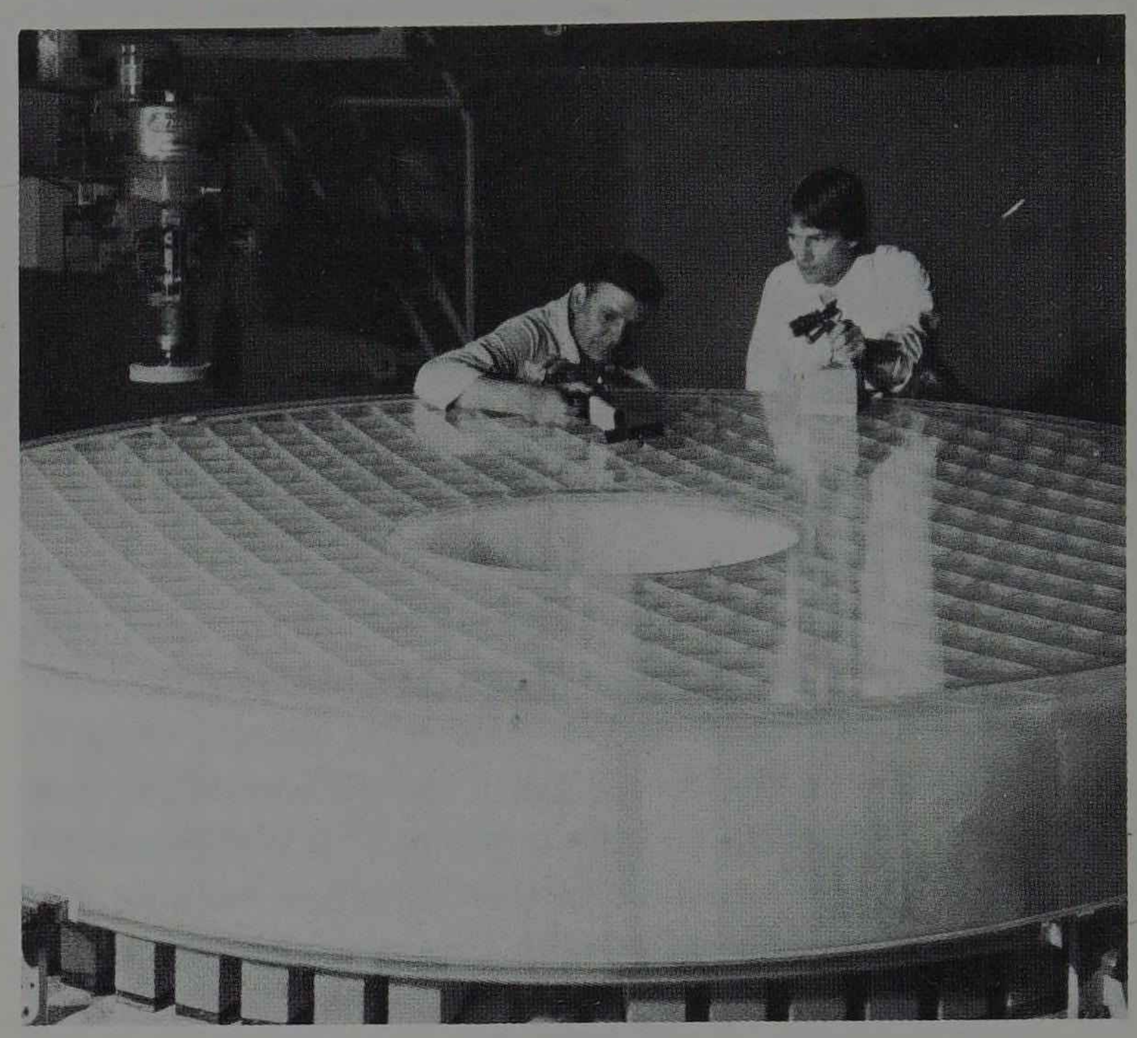


Figure 6.35 Technicians check the 8 foot diameter mirror of the Hubble Space Telescope. It is made of a lightweight honeycomb glass core fused between two plates of glass. A reflective aluminum coating topped with magnesium fluoride is applied later. Earth weight is 1,827 pounds. *Courtesy of NASA.*

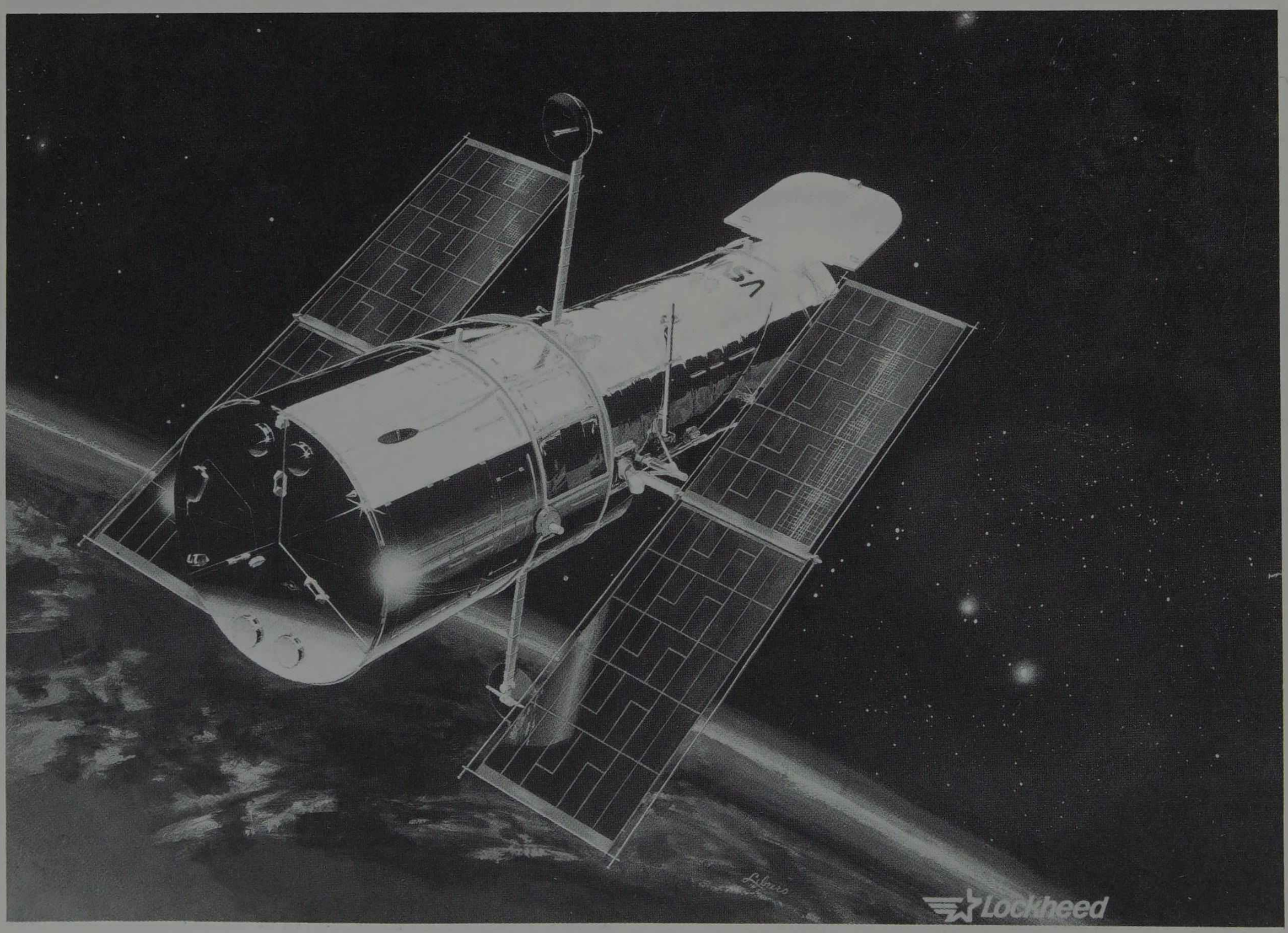


Figure 6.36 Artist's concept of how the Hubble Space Telescope appears in orbit. *Courtesy of Lockheed.*

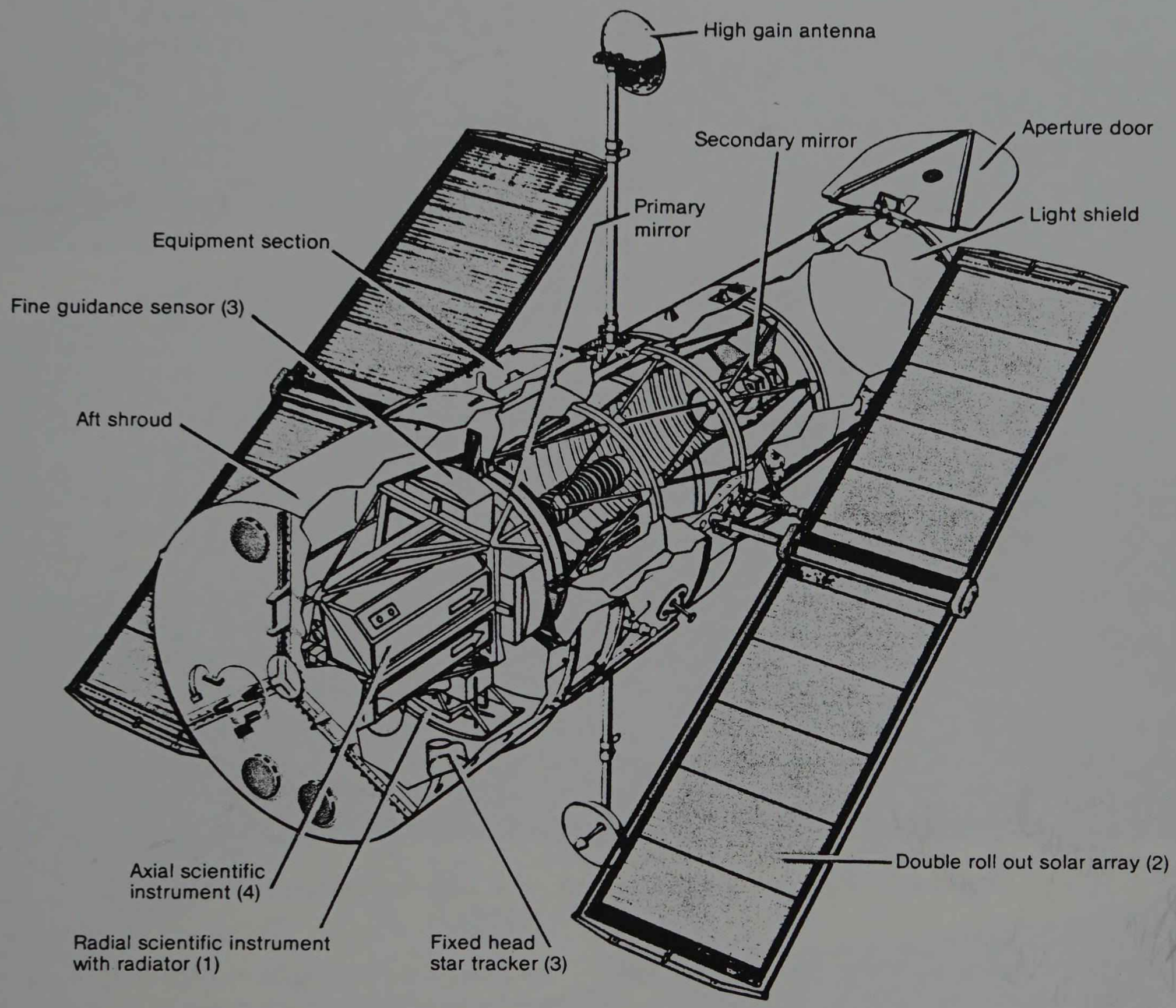


Figure 6.37 Main components of the Hubble Space Telescope. *Courtesy of NASA.*

through a 24 inch hole in the center of the primary mirror to the instruments enclosed in the aft shroud.

Five different instruments for analysis of the light are mounted behind the primary mirror. Two of them are spectrographs which break up white light into its rainbow of colors, two are cameras for wide angle and planetary photography and for faint object photography, and the fifth is a photometer which measures light intensity.

The Space Telescope is powered by six nickel-cadmium (NICAD) batteries kept charged by two arrays of solar cells, each providing up to 2,000 watts of power when the instrument is in the sunlight. This operates much like an automobile electrical system where the battery is kept charged by an alternator attached to the engine. The batteries charge when the telescope is in sunlight and provide power to the equipment when it is on the dark side of Earth. This charge-discharge cycle will recur 16 times each day as the telescope orbits Earth every 90 minutes. An average of 2,400 watts of electrical energy will be required by the telescope and its associated instrumentation.

Star trackers and fine guidance sensors will keep the telescope pointed with unprecedented precision. It could remain locked onto a dime at 450 miles.

The Hubble Space Telescope will be carried by the Space Shuttle to a 320 mile circular orbit with an inclination of 28.5 degrees. That is about the highest altitude the Shuttle can attain with it. The launch was originally scheduled for August 1986, but the *Challenger* accident has delayed it for at least two years. On reaching orbit, it will be removed from the cargo bay by the remote manipulator arm and deposited in space. A specialist aboard the Shuttle will give it a thorough checkout before departing for home.

Once in place and ready to go it will be remotely controlled from the ground. Earth-bound astronomers at the Space Telescope Science Institute at The Johns Hopkins University in Baltimore will evaluate proposed research

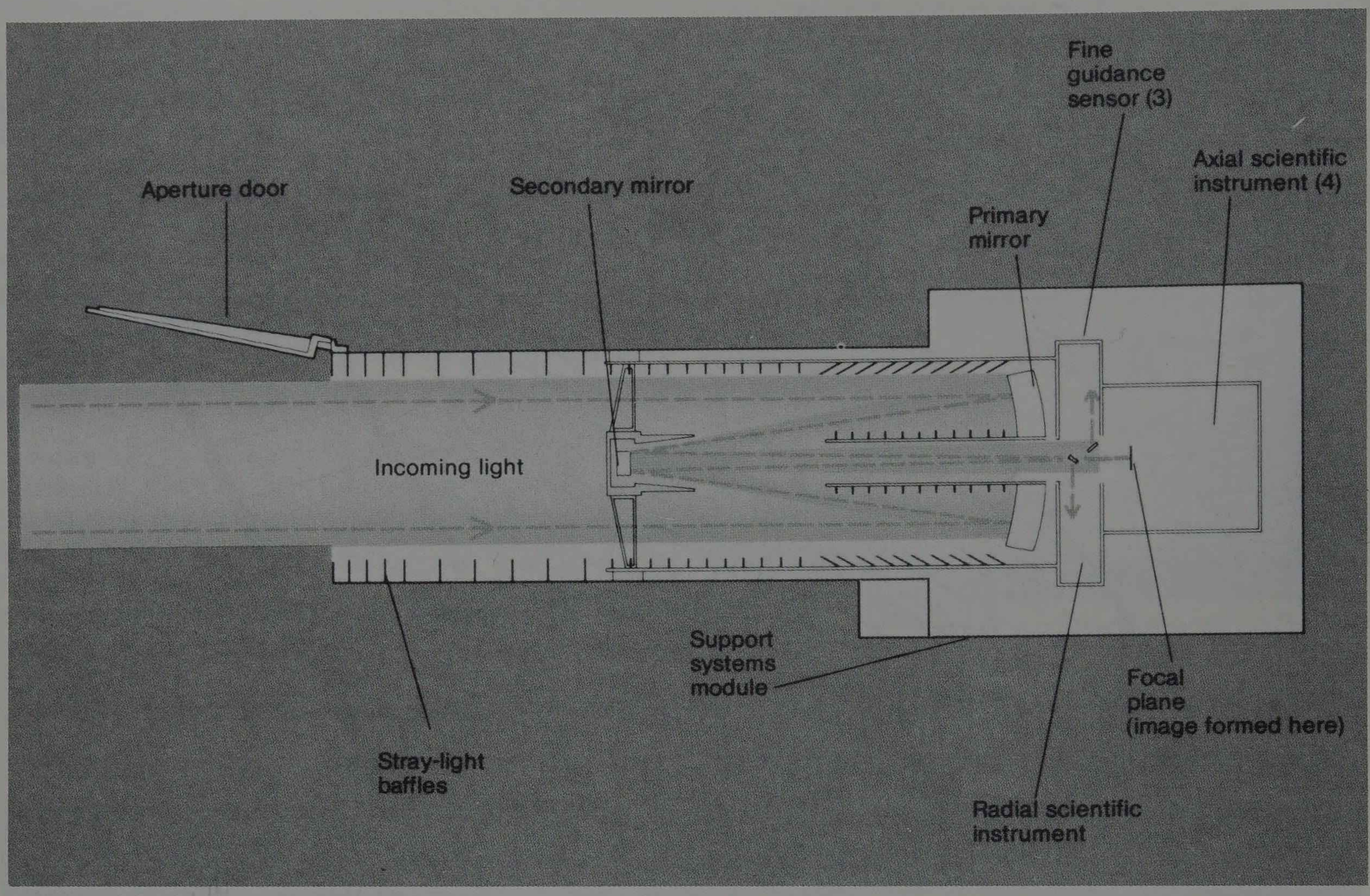


Figure 6.38 Light path through the Hubble Space Telescope. *Courtesy of NASA.*

projects from astronomers worldwide and will set the schedule for observing time.

Atmospheric drag will gradually lower the orbit as with any other satellite. When it gets down below 300 miles, the pointing accuracy will be degraded by the air drag and it will have to be boosted to a higher orbit again. During the peak of solar cycle when the atmosphere is at its greatest expansion, the telescope may require a boost as often as every nine months.

The Space Telescope is designed to be serviced and repaired in orbit by astronauts in space suits. A Shuttle would rendezvous with the instrument and pull it into the cargo bay with its manipulator arm (Figure 6.39). Astronauts could then repair inoperable electronic or mechanical parts and replace the instrument packages when necessary or when new ones are designed. The original plans included bringing the instrument back to Earth for a complete overhaul every few years. The idea of routine maintenance and overhaul has been reconsidered because of possible damage and contamination on a return to Earth. The intention now is to fix it in orbit only when it needs fixing. There is even some concern over on-orbit repair. The Shuttle attitude control system and orbital maneuvering systems use hydrazine fuel and the exhaust gases could contaminate the instrument by depositing on the optics. It may be better for the space station to have prime responsibility for repair, maintenance, and overhaul of the Space Telescope and for boosting it to a higher orbit than the Shuttle can. We will discuss this further in Chapter 11.

The instrument is expected to detect objects only one-fiftieth as bright as can be seen from the ground. It will therefore be able to see objects seven times farther away than ground based telescopes. (The square root of 50 is about 7. See MATHBOX 6.2.) Ground based telescopes can detect objects 2 billion light years away; the Space Telescope will observe objects as far away as 14 billion light years. (A light year is the distance light travels in a year, about six trillion miles.) Since the universe is thought to be about 15 billion years old, the objects seen by the Space Telescope will be observed as they were at the beginning of time, shortly after the big bang. It will expand the observable volume of space to 350 times that which is now observable. (Seven cubed is about 350. See MATHBOX 6.3.) The resolution of the telescope will be ten times sharper than ground based instruments. The Space Telescope will be able to make photographs of Jupiter and its moons from Earth orbit with the same clarity as the closeup Voyager images shown in Figures 6.20 to 6.22



Figure 6.39 Hubble Space Telescope being repaired on orbit. Two astronauts can be seen in the picture, one on the manipulator arm and one in the cargo bay. *Courtesy of Lockheed; artist Gordon Raney.*

in the color section. It will also be able to determine whether there are planets orbiting other stars. Planets cannot be detected from the ground because the glare from the starlight coming through the atmosphere blocks the view. The Hubble Space Telescope should be able to see them. One astronomer said he expected that we will learn more about the universe in one year with the orbiting telescope than we learned in all the previous history of astronomy.

DISCUSSION QUESTIONS

1. What is the value of using remote sensing to study Earth resources?
2. Do you see any objection to the use of high resolution satellite photographs by the news media?
3. Referring to Figure 6.18, what forces are acting on Voyager at each point along the trajectory?

MATHBOX 6.2

Light Intensity

Light waves expand outward from their source spherically in all directions. The area of a sphere is $a = 4\pi R^2$ where R is the sphere's radius.

Refer to Figure 6.2.1. Sphere A has a radius of 1 mile and an area of 4π. Sphere B has a radius of 3 miles and an area of 36π.

Although the radius of sphere B is three times as large, its area is nine times larger: $3^2 = 9$.

As it expands from sphere A to sphere B, light energy from a source at the center would spread out over nine times the area and would therefore be only one-ninth as intense by the time it reached sphere B.

Thus, light intensity decreases as the square of the distance from the source. If a light source is 7 times farther away it is only 1/49 as bright. If two lights are actually of the same intensity but one appears 49 times fainter, then it must be 7 times farther away.

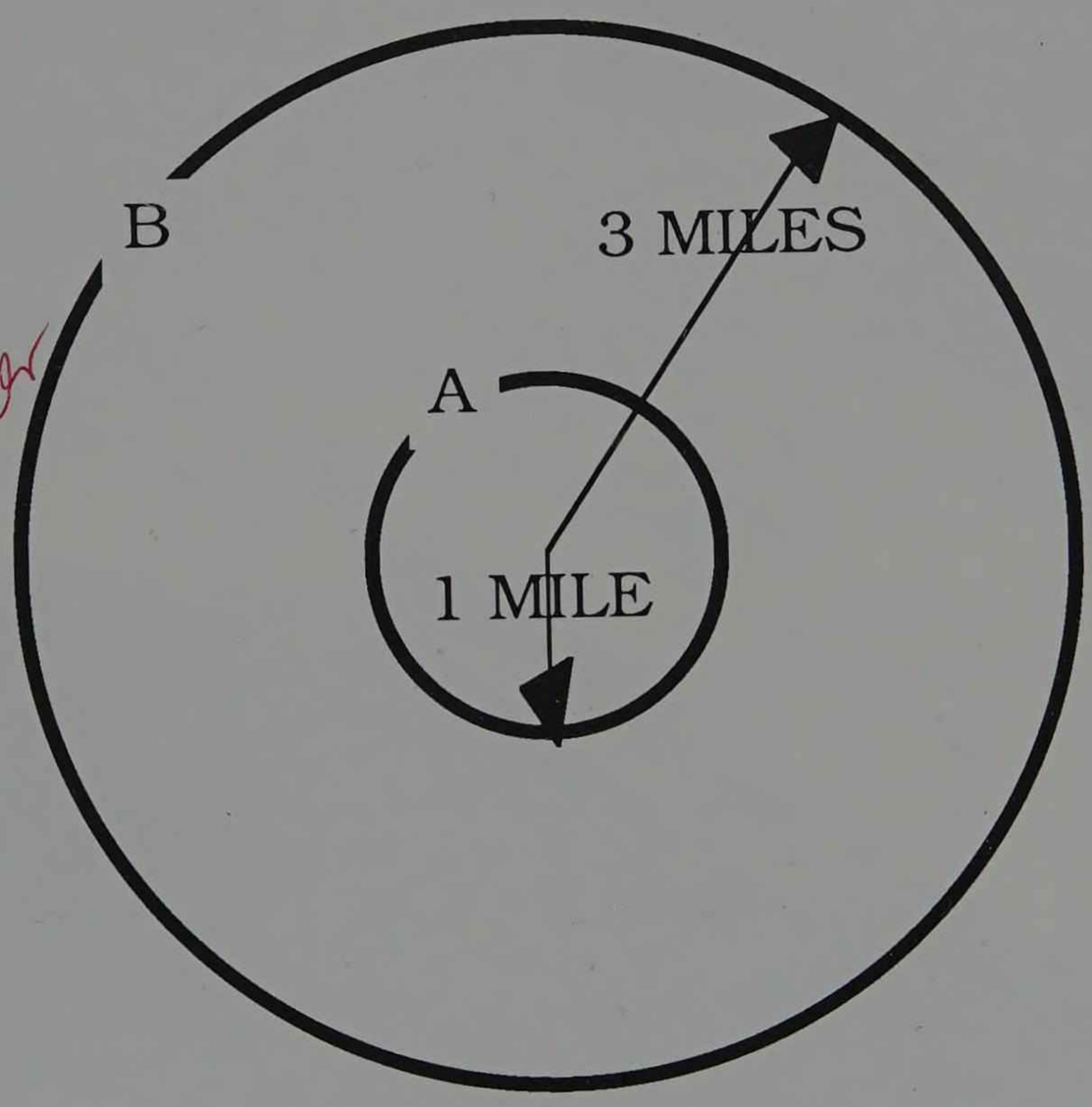


Figure 6.2.1 Spherical expansion.

4. Why is there so much interest in astronomy?
5. Why was IRAS oriented carefully so it was never pointed toward Earth or the Sun?

ADDITIONAL READING

Giacconi, Riccardo. "The Einstein X-Ray Observatory." *Scientific American,* February 1980. Results from HEAO-2 spacecraft.

Habing, Harm, J., and Gerry Neugebauer. "The Infrared Sky." *Scientific American,* November 1984. IRAS results.

Laeser, Richard P., et al. "Engineering Voyager 2's Encounter with Uranus." *Scientific American,* November 1986. How spacecraft problems were solved.

NASA. *Landsat Tutorial Workbook, Basics of Satellite Remote Sensing*. Government Printing Office, 1982. Comprehensive reference book.

MATHBOX 6.3

Volumes of Spheres

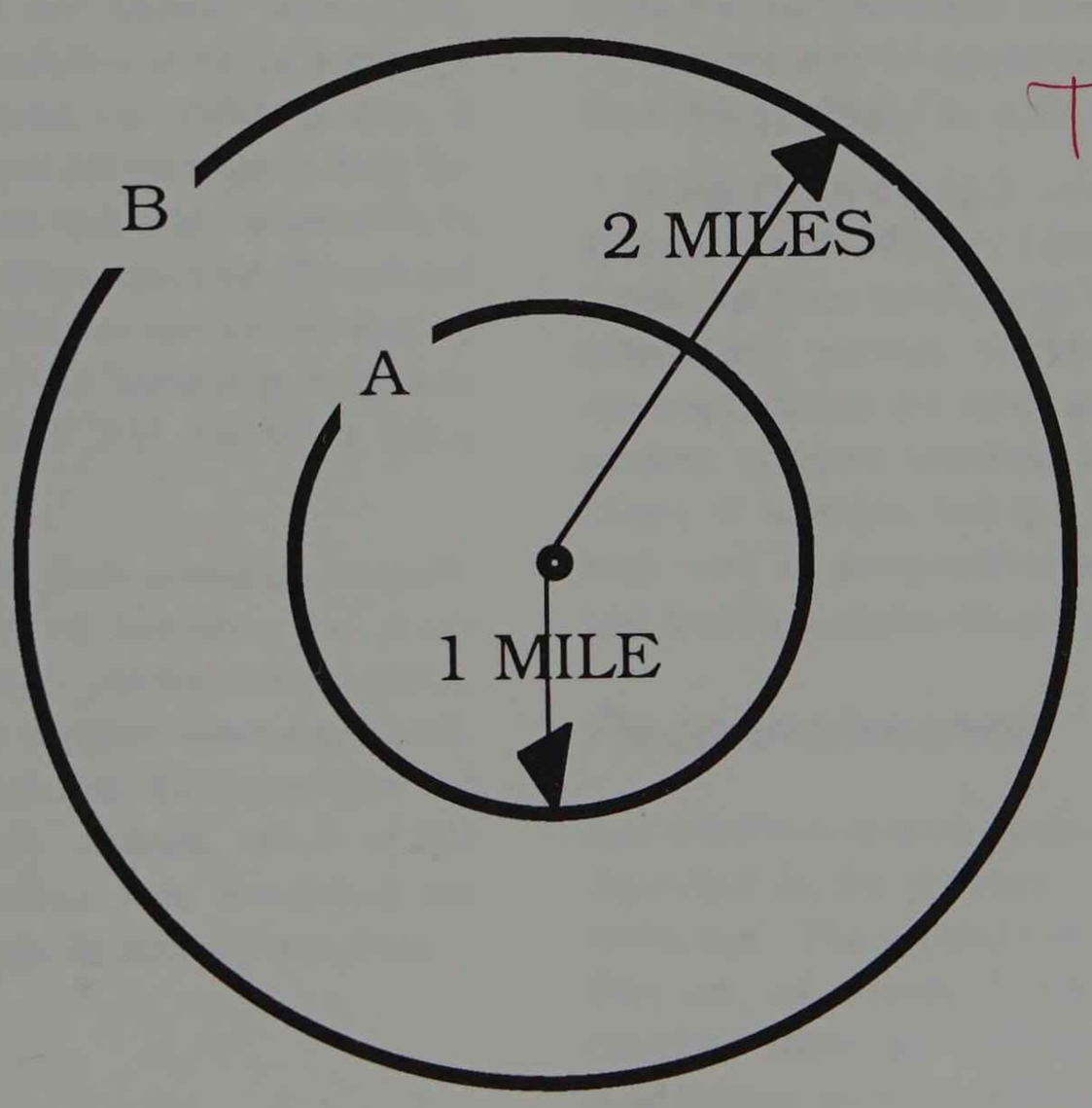
The volume of a sphere is $V = 4\pi R^3/3$ where R is the radius of the sphere.

Refer to Figure 6.3.1.

Sphere A has a radius of 1 mile and a volume of $4\pi/3$. Sphere B has a radius of 2 miles and a volume of $32\pi/3$.

Although the radius of sphere B is twice as large, its volume is eight times larger: $2^3 = 8$.

If the Space Telescope can see objects 49 times fainter than are now visible from Earth, then it can see seven times farther and can examine a volume of space $7^3 = 343$ times greater.



This figure should be a lot smaller also

Figure 6.3.1 Spherical volume.

NASA. *Planet Earth Through the Eyes of Landsat 4*. NASA Facts NF-138, Government Printing Office, March 1983. Pamphlet, select example images in color.

Weaver, Kenneth F. "Remote Sensing: New Eyes to See the World." *National Geographic*, January 1969. Somewhat dated, but excellent fundamentals.

Chapter 7

Space Defense

We have saved a discussion of defense activities in space until now, even though space defense operations have been conducted since the very beginning of the space age. We often hear slogans against the militarization of space; but it is naive to think that space is not already militarized. Nuclear tipped intercontinental ballistic missiles were operating before the first satellite went into orbit. In fact, it was the development of those heavy-lift missiles in both the United States and the Soviet Union that made it possible to launch satellites. When the Russians successfully orbited their first Sputnik, President Eisenhower announced that we had a satellite in preparation, but our highest priority was the continued development of the ICBM and other space activities had a secondary role.

In addition to ballistic missiles, both countries immediately recognized the advantages of satellites for many purposes: communications relay, photoreconnaissance, electronic intelligence gathering, weather observing, navigation, and warning of missile launches. Such satellites had highest priority in the early days. Indeed, much of the spacecraft technology in use today was developed for defense purposes and had its origin in military satellites.

Communications

The defense communications relay satellites are similar in operation to their civilian counterparts. To prevent outsiders from listening in, however, the messages are generally encoded electronically before transmission to the satellite and automatically decoded at the receiving station.

The United States is probably more dependent on satellites for military communications than the U.S.S.R. There are two reasons. First, American forces are spread around the globe on all continents, so worldwide positive command and control is essential. Soviet forces, however, are located mostly in Europe and Asia where landline communications interconnect them. Second, the northern perimeter of the Soviet Union is located too far north to use geosynchronous satellites effectively. We have previously discussed the Russian development and use of the Molniya orbit for communications relay to the far northern regions. In addition, the Soviets use numerous communications satellites in circular orbits inclined at 74 degrees, about 930 miles high. Eight satellites are launched on one booster and placed into orbits with periods differing by a few seconds so they slowly drift apart and spread themselves around the Earth. Over 300 such satellites have been launched since 1970 and 30 or more may be operational at any time to assure that at least one is always in sight of the ground stations.

In the 1990s the U.S. military will have a new satellite system called Milstar. Four satellites in geosynchronous orbits and three satellites in highly elliptical (Molniya-type) orbits will provide worldwide command, control, and communications for land, air, sea, and undersea forces. A number of spare satellites will be placed in 100,000-mile orbits. It is easier and quicker to move a satellite from a high orbit to geosynchronous altitude than it is to prepare and launch a replacement from the ground.

Reconnaissance

Spy satellites operate somewhat like the Landsat satellites described in the previous chapter, but with much higher resolution. The capabilities of intelligence-gathering satellites are, of course, highly classified. However, rumors circulate about spy satellites with sufficient resolution to read license plates and identify people from a one hundred mile orbit. Current U.S. photoreconnaissance spacecraft probably have a resolution of about 4 inches.

The camera on one U.S. satellite, called Big Bird, photographs the area of interest, the film is processed like a Polaroid snapshot, and the picture is transmitted to the ground. If still higher resolution is needed, Big Bird can eject a capsule containing the film itself. The capsule deorbits like a miniature Apollo spacecraft, and an airplane flies out to the landing point to catch its parachute in midair before it reaches the water. The Soviets recover the entire satellite and its load of film when a mission is completed.

Film returned to Earth yields higher resolution images than pictures transmitted to the ground by radio. The difficulty in transmitting very high resolution images is the quantity of data that must be sent. A picture covering only one mile square with one foot resolution requires nearly three million pixels (and a very high pointing accuracy to

photograph the area desired). Saving images from a large area or many smaller areas for subsequent transmission to a ground station may strain the storage capability of the spacecraft. Newer reconnaissance satellites will undoubtedly overcome these problems and will be able to transmit images as fast as they are taken, with higher resolution, in several spectral bands, and perhaps with radar to make images through clouds.

For best resolution it is necessary, of course, to operate as low as possible, down to 90 miles, which means rapid decay of the orbit due to atmospheric drag. Therefore, spy satellites are equipped with thrusters and fuel to periodically boost them back up to higher altitudes. Big Bird has a lifetime of six to seven months. The Soviet satellites operate at lower altitudes and remain in orbit for about two weeks. That explains why the United States launches about 3 per year while the Russians usually launch more than 30. Newer Soviet photoreconnaissance satellites are highly maneuverable, changing orbit frequently, dropping to a low perigee over a place of interest, taking their photos, then returning to a higher orbit before atmospheric friction does them in. They have also been seen to change apogee which changes the local time over the target for better lighting for their photography.

Electronic intelligence satellites have listening devices which tune in on telephone conversations, radio messages, radar signals, and data transmissions during missile launches. The United States keeps several such satellites in low orbit and at least two in geosynchronous orbit. The Soviets use a constellation of satellites in six different orbital planes, 400 miles high, at about 82 degrees inclination.

Ocean surveillance is another major effort on both sides. Watching the activities of naval surface fleets is relatively easy by radar and ELINT satellites. Keeping track of nuclear submarines with their load of ballistic missiles is more difficult, but several factors make it possible. Although the submarines remain under water for weeks at a time, when they are under power they leave a trail of hot water which may be followed by infrared sensors. They also leave a small wake which may be detectable by radar or by the glint of sunlight from the surface.

Russian cosmonauts in space stations probably have intelligence-gathering duties. Salyuts carried telescope-cameras with 33 foot focal length lenses. While solar observing is their announced purpose, such cameras in low orbit are more useful for Earth observing.

Whatever their capability, the intelligence community has become highly dependent on the information satellites gather. Just knowing that the other side is probably monitoring your every move is a stabilizing influence. It is unlikely that either side could mount any large scale military activity without detection. The fact that the other side is watching and listening is a strong deterrent against any actions which may appear offensive.

Early Warning

Several U.S. early warning satellites located in geosynchronous orbit continuously watch the Soviet ICBM launch complexes; their space launch Cosmodromes at Tyuratam (Baikonur), Plesetsk, and Kapustin Yar; and the Atlantic and Pacific Ocean areas from which submarines could launch missiles. Continental launch sites are shown in Figure 7.1. Submarines are always in place just off the U.S. coasts in the Atlantic and Pacific Oceans. Early warning satellites carry infrared sensors which respond instantaneously to the enormous quantity of heat emitted when a rocket engine is burning (Figure 7.2). Within a few seconds the detection is reported to the North American Aerospace Defense Command (NORAD) inside its Cheyenne Mountain Complex near Colorado Springs, Figure 7.3. Computer analysis and human interpretation of the intensity, duration, and location of the infrared signal make it possible to determine what kind of launch is taking place.

The infrared sensors also respond to the heat from nuclear explosions worldwide for the purpose of monitoring treaty compliance and for damage assessment.

The prime purpose of the early warning system is to detect a mass missile raid against the United States or its allies. When its engines burn out, a missile follows an elliptical orbit just like a satellite, except that the missile's trajectory intersects Earth after only part of an orbit. See Figure 7.4. The partial orbit over the north pole from the Soviet Union to the United States or vice versa takes about 20 minutes. The 20 minute or so warning time given by the detection system would enable us to take some actions of our own, such as to get our nuclear bombers airborne so they are not destroyed on the ground and to launch retaliatory missiles. The country would not be saved from



Figure 7.1 Location of Soviet ICBM launch sites. The 60 degree latitude line is shown.

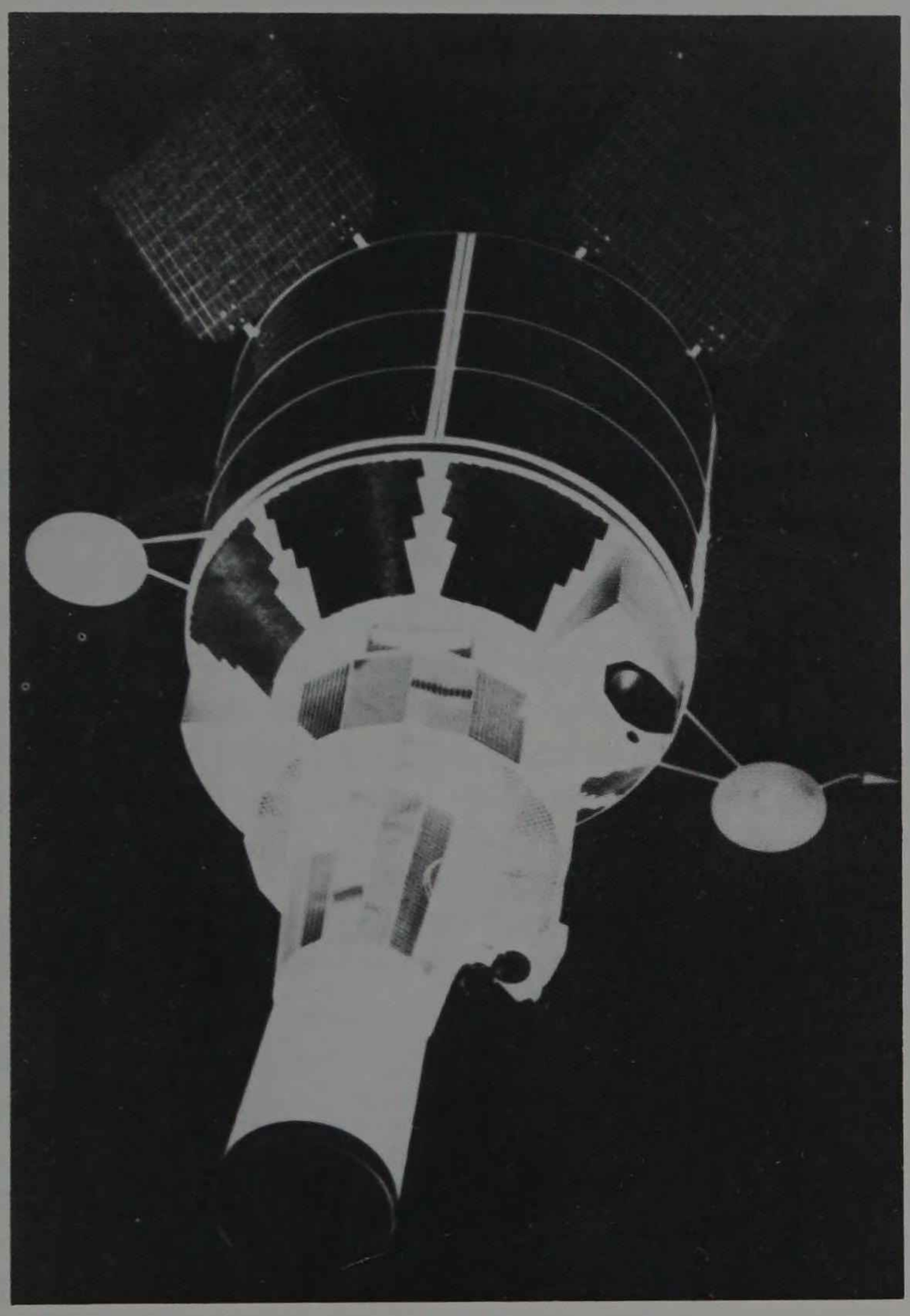


Figure 7.2 Early warning satellite for detection of missile and space launches. Several of these satellites are parked at strategic locations in geostationary orbit. The telescope is pointed slightly off axis so that as it rotates it scans a wide area with its infrared sensors. *Courtesy of U.S. Space Command.*

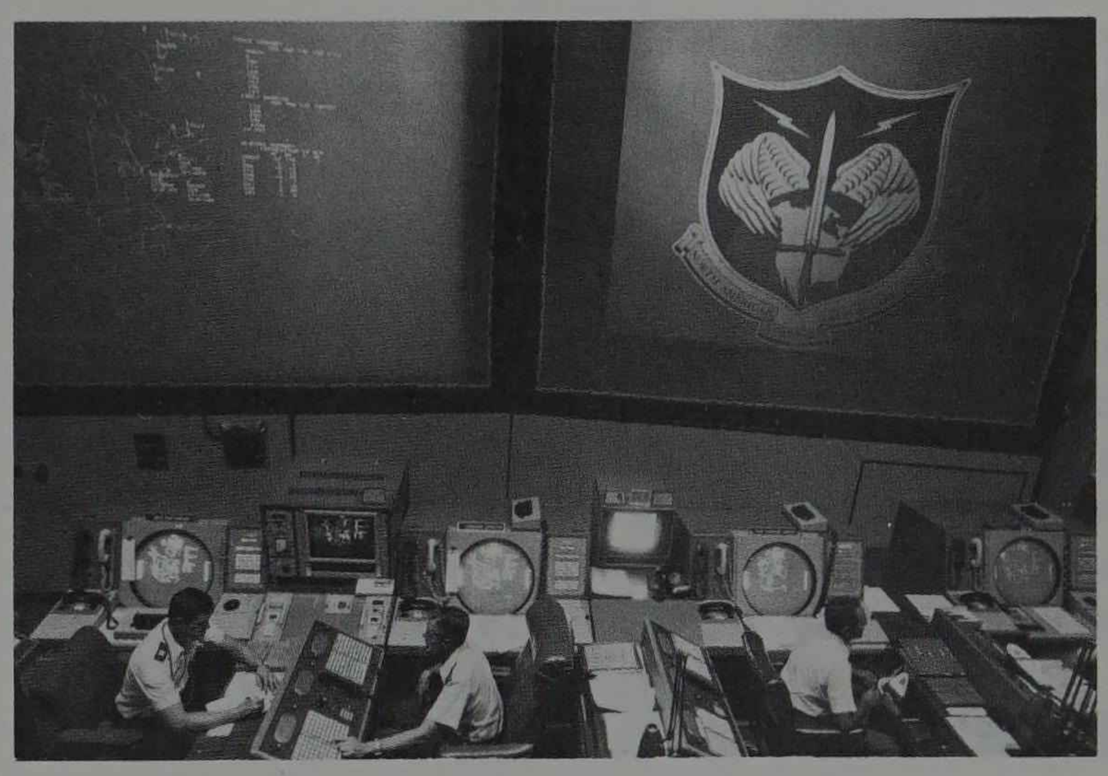


Figure 7.3 NORAD Command Post inside Cheyenne Mountain near Colorado Springs. The Space Surveillance Center and Missile Warning Center receive data from satellites and ground sensors 24 hours a day to keep track of every object launched into space by any country worldwide. *Courtesy of U.S. Space Command.*

nuclear destruction, however. We have no defense against a missile attack.

The Soviets have a similar satellite early warning system. Like intelligence satellites, early warning systems are a strong stabilizing influence in the "cold war." Knowing that a missile attack would be immediately detected and retaliatory forces would be launched is a strong deterrence against a first strike.

Weather and Navigation

Weather satellites have been discussed previously. Because the National Weather Service geosynchronous satellites are designed and read out with civilian needs in mind, the Defense Department has its own dedicated weather satellite. See Figures 6.14 and 6.15. The spacecraft fly in polar orbits at lower altitude for greater resolution and can observe the weather anywhere on Earth. Pictures may be read out immediately as the satellite passes overhead, or the images are recorded and played back when the satellite is in sight of a ground station. Readout equipment in mobile vans can be quickly moved by aircraft to any point where military action requires weather information.

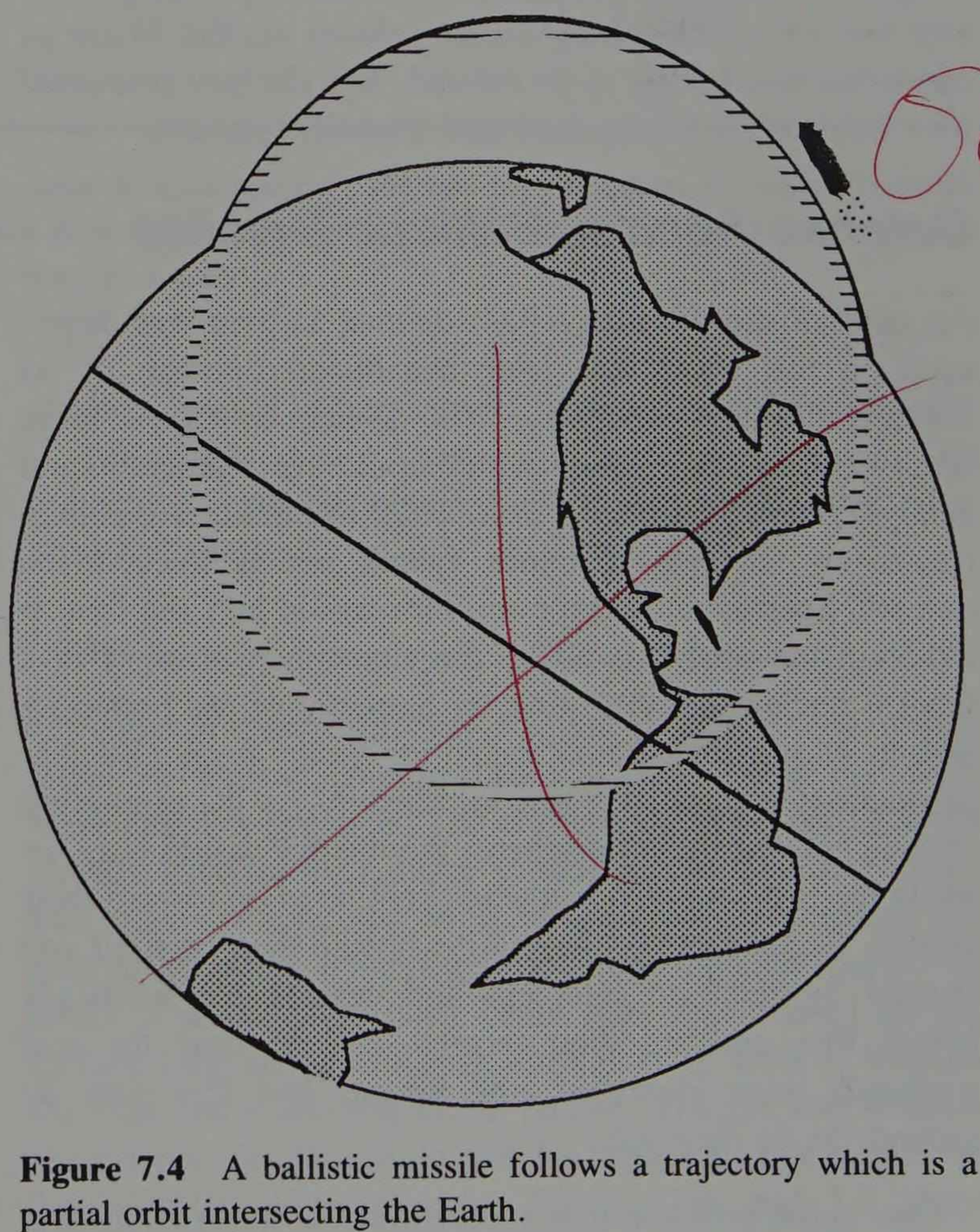


Figure 7.4 A ballistic missile follows a trajectory which is a partial orbit intersecting the Earth.

Navigation satellites were discussed in Chapter 5. Certain communications with the satellite are encoded so that an adversary cannot transmit erroneous information to them.

Also, they are protected against damage from nuclear and laser weapons which might be used against them.

The obvious use is for aircraft, ships, and tanks to know where they are and where they are going. But perhaps ICBM warheads could also be equipped with small receivers to keep track of their location and, using small rocket thrusters to adjust their trajectories, find their targets with greater accuracy. Consequently, smaller weapons could replace the large megaton nuclear bombs currently carried on ICBMs, and could strike military targets without devastating the entire countryside.

Limits

These defense activities in space are obvious, contribute substantially to national security, and are accepted by all adversaries. International agreements on the uses of space do not preclude any of these defense satellites; all sides take advantage of their capabilities. Some things have been prohibited by international agreement, however. Nuclear weapons in orbit are prohibited but nuclear power generators are not. Establishing military bases on the Moon or other celestial bodies is prohibited, but military personnel may be used for exploration and scientific pursuits.

Defense Against Ballistic Missiles

An antiballistic missile (ABM) defense system was developed in the 1960s but later abandoned because of its severely limited capability. The system involved large northward pointing radars which could see warheads (and decoys) rising over the horizon. Their information was then passed to terminal guidance radars which tracked the objects. Spartan antimissile missiles would be fired first to intercept the warheads above the atmosphere using x-rays from a nuclear bomb to destroy as many of the incoming objects as possible. Lethal range for x-rays from a nuclear detonation in space is a few kilometers. As the remaining objects entered the atmosphere, the decoys would burn up while the heat shielded warheads continued on toward their targets. Sprint antimissile missiles would then be fired and steered by radar to intercept and destroy the warheads before they reached their targets. By the time the real warheads were identified, the Sprints had less than 30 seconds to do their job.

One major problem that apparently was never overcome is that x-rays produced in a nuclear weapon explosion above the atmosphere will cause increased ionization in the ionosphere which could reflect radar waves and black out the ground radars. Another problem is that unless the destroyed warheads vaporized completely, their radioactive residue would scatter over northern United States and Canada.

The 1972 ABM treaty with the U.S.S.R. allowed for the deployment of a single system to protect an ICBM missile complex and one to protect its seat of government. The Soviets elected to deploy an ABM system around Moscow. In the United States, the original intent was to construct a system to protect some of our missile silos. Because of its limited capability and for other political reasons, the project was abandoned.

Strategic Defense Initiative (SDI)

New scientific and technological developments have opened up other approaches to defense against nuclear ballistic missiles. A topic of great controversy is the Strategic Defense Initiative (SDI), sometimes called "Star Wars." President Reagan announced in 1984 that it appeared to be technologically possible to destroy ICBMs during their launch phase and that the United States would undertake a research program to investigate the feasibility of developing a defense against nuclear missiles.

In particular, an ABM system stationed in space may be able to destroy an ICBM over enemy territory while it is still in the boost phase with engines running. Figure 7.5 shows the various stages of a missile flight launched from a land site. A submarine launched ballistic missile has a similar but much shorter flight. Boost phase lasts two minutes, warheads separate two minutes later and coast for seven minutes, reentry phase lasts only a minute. There are numerous advantages to attacking the missile while it is still under power. First, it is easier to detect and track using infrared sensors. Second, the missile and its bus carrying the payload are only one target. Later, up to 10 warheads and 100 decoys may separate from the bus, becoming a multitude of targets. Third, a rising missile under power and full of fuel is particularly vulnerable.

The whole purpose of SDI is to detect and destroy a mass ICBM raid on the United States. SDI would have three major components: the detection and tracking component, the command-control component, and the antimissile weapons.

The SDI detection and tracking system must be able to detect *and track* hundreds of launches simultaneously from about 20 launch sites. A space-based early warning detection system now operates, as described previously, but the present system does not track the missiles with the precision required to aim and fire a weapon. It only detects them and gives some information on their trajectory. It would saturate during a mass raid; but, then, that is its present purpose—to detect a mass raid.

The heart of the command-control system must be an automated computer which receives information from the detection system to aim and fire the weapons. A mass raid would take place too rapidly for human decision making. Hundreds of missiles each carrying several warheads and decoys would be launched in a few minutes, each having a

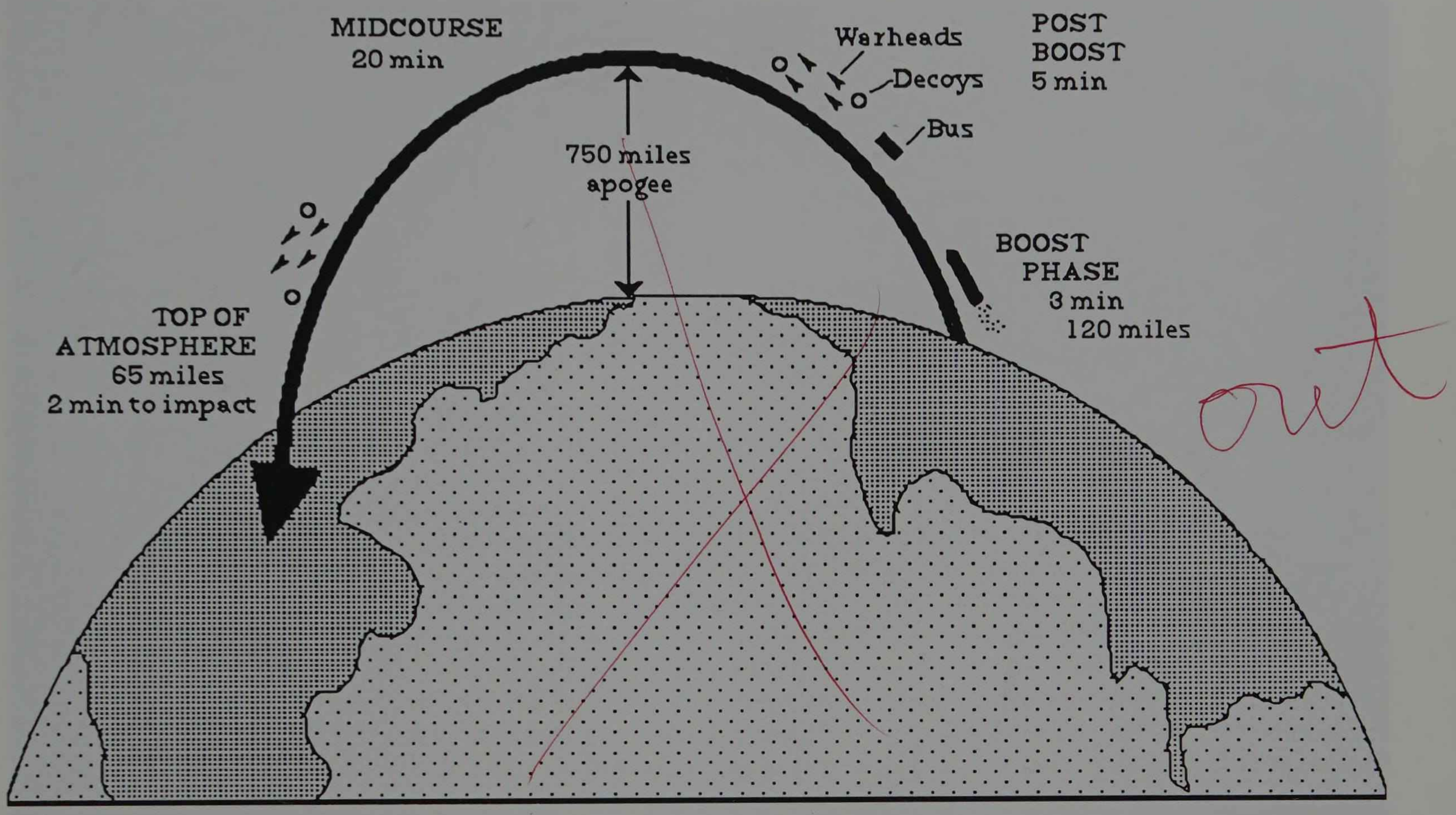


Figure 7.5 Typical ballistic missile trajectory. For about 10 minutes after booster burnout, the bus uses thrusters to aim and release warheads and decoys. On reentry into the atmosphere, shielded warheads glow with heat; lighter decoys slow and fall behind. *After Office of Technology Assessment, A. Carter.*

slightly different trajectory from its launch site to its target a third of the way around the globe. A computer program would have to be written which would completely and automatically manage such a battle. It could not be tested under actual battle conditions; it would be written for a one time use and would have to be 100 percent reliable.

Some computer scientists doubt that a 100 percent reliable computer program could be written for SDI. It must be noted, however, that computers are now doing things reliably that were undreamed of only 20 years ago. For example, extremely complex programs handle our charge cards and our banking; we can withdraw money from our bank account via a computer driven machine anywhere in the country. Industrial computer programs control machines that build everything from automobiles to computer chips. The NORAD computers have never had to operate under real battle conditions. Yet, simulations are routinely run which give credibility to their ability to operate properly should a mass raid occur. In addition, rapid advances are being made in artificial intelligence techniques for programming computers and the construction of reliable programs is a major area of research in computer science.

Two types of antimissile weapons are being considered for SDI: *directed energy weapons* and *kinetic energy weapons*. Directed energy weapons send a beam of electromagnetic waves to heat up and burn through the outer skin of the missile, while kinetic energy weapons would fire projectiles or pellets into the path of the missile, destroying it by collision.

Lasers

One type of directed energy weapon is actually a powerful laser. A narrow intense beam of light with a single wavelength is produced and focused on the target. Lasers are now used for microsurgery, spot welding, cutting metal, and other applications. Most of them involve heating the area or shocking it with a short, high intensity pulse. To attack a missile, the laser beam must be focused on the surface long enough to burn through or at least to weaken the skin and cause explosive failure. The nuclear weapon aboard the missile would not be triggered, but would be destroyed in the explosion. Figures 7.6 and 7.7 show artists' concepts of possible laser weapons in orbit. They have a very large advantage: their destructive beam travels at the speed of light.

Lasers with sufficient power to destroy a missile pour out tremendous quantities of power—tens of millions of watts—and require very large power supplies. At least two concepts are being considered. First, the laser and its power supply could be stationed in orbit where it would shoot at



Figure 7.6 Artist's concept of a constellation of directed energy weapons on station in orbit. The energy is reflected and focused by the mirror onto the ICBM to destroy it. Only the mirror moves, not the entire spacecraft, so it can attack several missiles in quick succession. *Courtesy of Lockheed.*

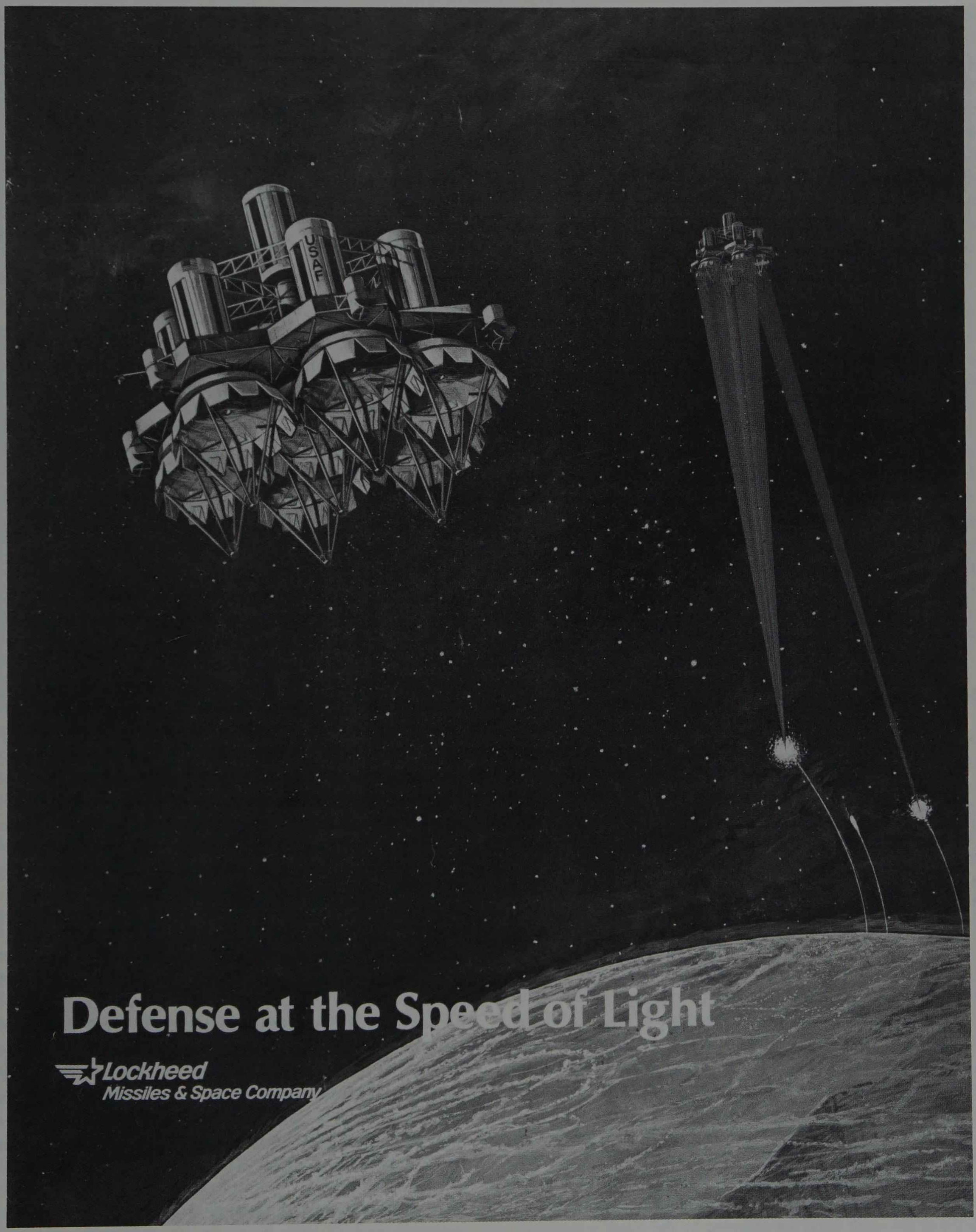


Figure 7.7 Artist's concept of an SDI laser weapon in orbit. To increase the intensity of the beam striking the target, seven lasers are phased together, focusing their energy simultaneously on one spot on the missile. *Courtesy of Lockheed.*

rising missiles. An orbiting laser weapon would be about 80 feet long and weigh 50 tons. Second, it could remain on the ground with mirrors in orbit to reflect and focus the laser beam. This concept saves placing the power supply in orbit, but requires many mirrors. One mirror would be positioned at geosynchronous altitude, stationary like a communications satellite, and other mirrors would be in low orbit to redirect the laser beam to the targets. The laser could be located on United States territory and the constellation of mirrors could direct the energy to an attacking missile anyplace on Earth.

Shorter electromagnetic waves carry more energy so research is being done to design an x-ray laser. X-rays to drive the laser would be produced by a small nuclear bomb and the amplified and directed x-ray beam would be focused on the rising missiles. Obviously an x-ray laser antimissile weapon could not be based on the ground. Not only are the nuclear explosions a problem, but the x-rays are absorbed by the atmosphere within a hundred feet or so. Such a weapon would necessarily be based in space and could work from geosynchronous orbit. Each laser could be used only once; it is destroyed in the explosion. Thus one laser weapon must be placed in orbit for each missile to be shot down. International agreement prohibits placing nuclear weapons in space. Whether that applies to a nuclear driven laser for defense, not offense, requires interpretation.

Particle Beams

Another type of directed energy weapon uses a particle beam accelerator. Electrically charged negative hydrogen ions, that is, hydrogen atoms with an extra electron, are accelerated by injecting them into the field of an electromagnet. Because charged particles in motion also have a magnetic field, the two fields interact which causes them to accelerate. Other magnets focus and steer the beam in the desired direction.

The electron gun in a television picture tube works the same way. Electrons are accelerated through the neck of the tube by an electromagnet wrapped around it. When the electrons strike the fluorescent coating on the face of the tube, they cause it to glow. Varying the electrical current in the electromagnet deflects the beam back and forth and up and down the face of the tube, creating the picture.

A particle accelerator in space will not hit a missile by firing charged particles directly at it, however; the particle beam would be deflected from its intended path by Earth's magnetic field. Recall from Chapter 4 how charged particles in the solar wind are affected by the Earth's magnetic field. Therefore, the particles must be neutralized by removing the extra electron from each hydrogen ion. This is done by passing the beam through a thin gas. The electrons are stripped off by the collisions with the gas atoms. The beam then consists of neutral hydrogen atoms.

The beam diverges and loses its intensity if the particles collide with other atoms such as atmospheric gases. Therefore it is effective only when the target missile is well above the atmosphere. When a high speed hydrogen atom hits the skin of the missile, it splits into a proton and an electron. The proton penetrates deeply into the metal and does the damage. Even a small dose would disrupt the electronics; very heavy doses would be needed to melt the aluminum skin.

Kinetic Energy Weapons

Exotic laser weapons get a lot of attention but are still in the beginning phases of research and development. Meanwhile, kinetic energy weapons would most likely be the first elements of a missile defense system to be deployed. Kinetic energy weapons are ''old fashioned rifle bullets'' that damage a missile by hitting it. There are two general types of kinetic energy weapons: those which accelerate the ''bullets'' with rockets and those which use electromagnetic devices to fire the projectiles.

The first type operates rather like a retrorocket by taking the projectile out of a higher orbit to intercept either the rising missile on its ballistic path or the warheads after they have been separated from the bus. The interceptor carries sensors so it can home in on its target and may be able to differentiate between warheads and decoy. It does not carry any explosive, but simply collides with the target (see Figure 7.8). Research is underway to miniaturize the rockets so an orbiting platform can carry a large number of such interceptors. Rocket powered interceptors are also under consideration for a ground based system which would attack warheads just before they reenter the atmosphere. This is the favored technology for the first ''layer'' of missile defense because it is the best known and farthest advanced.

One type of electromagnetic accelerator is the rail gun. It has two parallel rails carrying a high electric current. When a piece of metal shorts across the rails, the high current flowing through it causes it to suddenly evaporate to a high pressure gas which accelerates a projectile out the barrel. Velocities of over 50,000 miles per hour may be achievable in space. A barrage of small plastic projectiles fired into the path of the missile could destroy it by collision. Rail guns involve difficult technology. Problems with handling the high current, damage to the rails and barrel of the gun, and the effects of rapid repeated firing must be overcome.

Constellation of Orbiting Weapons

Figure 7.9 shows the 24 hour ground trace over the Soviet Union of an orbit with an inclination of 90 degrees. It passes over the poles on every orbit and covers high latitudes well.



Figure 7.8 Artist's concept of a kinetic energy weapon in space. A number of interceptor rockets are carried in the platform at the center. The spacecraft at the right is a radar which tracks the rising missile and directs the interceptor on a collision course. *Courtesy of Lockheed; artist Louis De La Torre.*

Figure 7.10 shows the ground trace of an orbit inclined 65 degrees to the equator. Compare these with Figure 7.1 and notice that a 65 degree orbit covers the Soviet missile fields better than the 90 degree orbit.

But spacecraft do not stand still, and are not everywhere at once. When located in a high orbit, spacecraft travel slower and can cover a larger area. Since the intensity of a laser beam decreases with distance to the target, a tradeoff between altitude and laser power must be made. ''Bullets'' from a kinetic energy weapon would have farther to travel from a higher orbit, requiring a longer travel time. A constellation of many antimissile weapons would be needed to assure that one is within range of each launch site at all times. How many are needed depends on the type of weapon and its effective range. According to one study, nearly 200 orbiting weapons are required when using 20 megawatt infrared lasers equipped with 33 foot diameter mirrors in 600 mile orbits. This is based on the provision that the mirrors can be retargeted in one second. If 25 megawatt ultraviolet lasers with 85 foot mirrors are used in

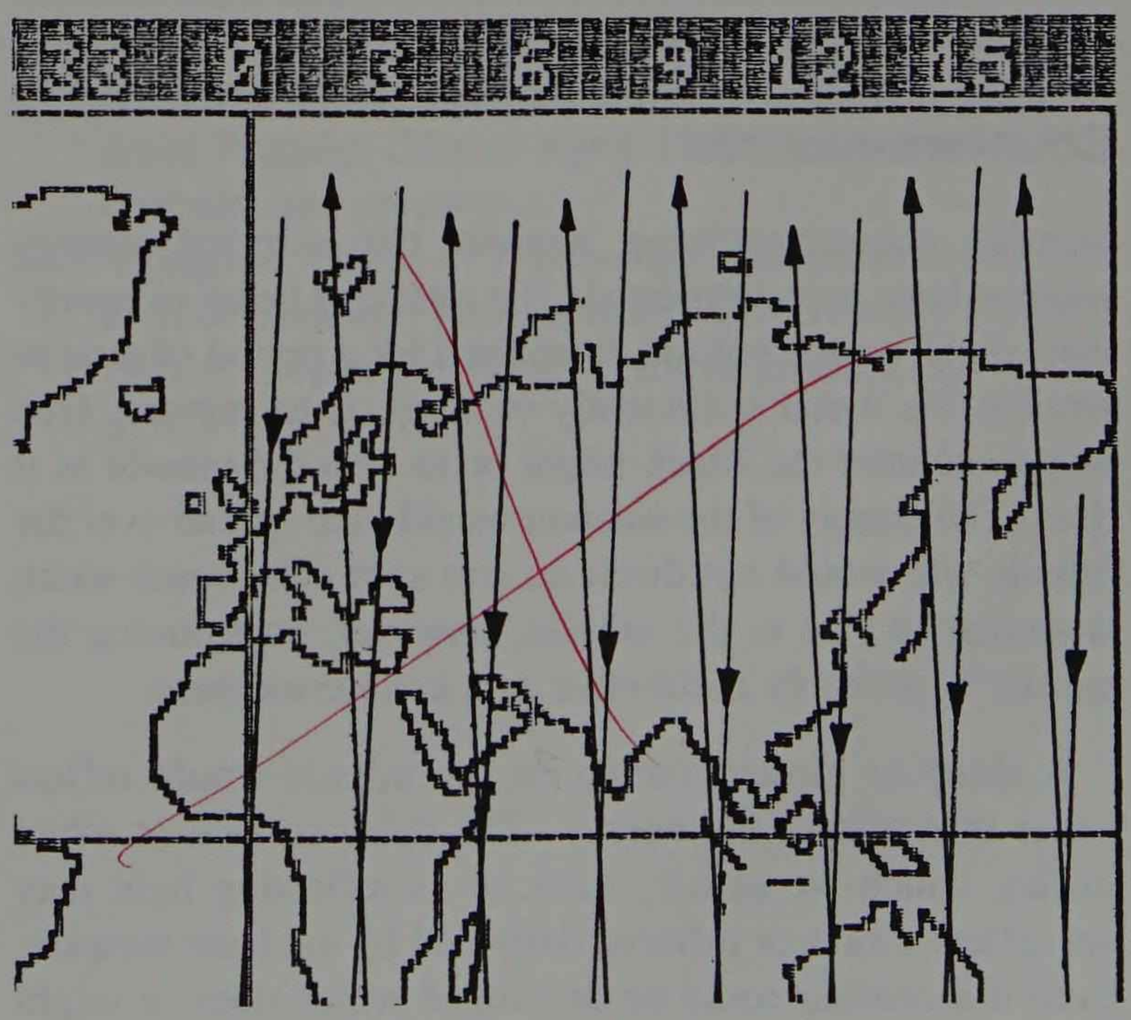


Figure 7.9 Ground trace of a 375 mile orbit with a 90 degree inclination, i.e., it passes over the poles. Of 15 orbits per day, 6 pass within range of at least one Soviet launch site. See Figure 7.1.

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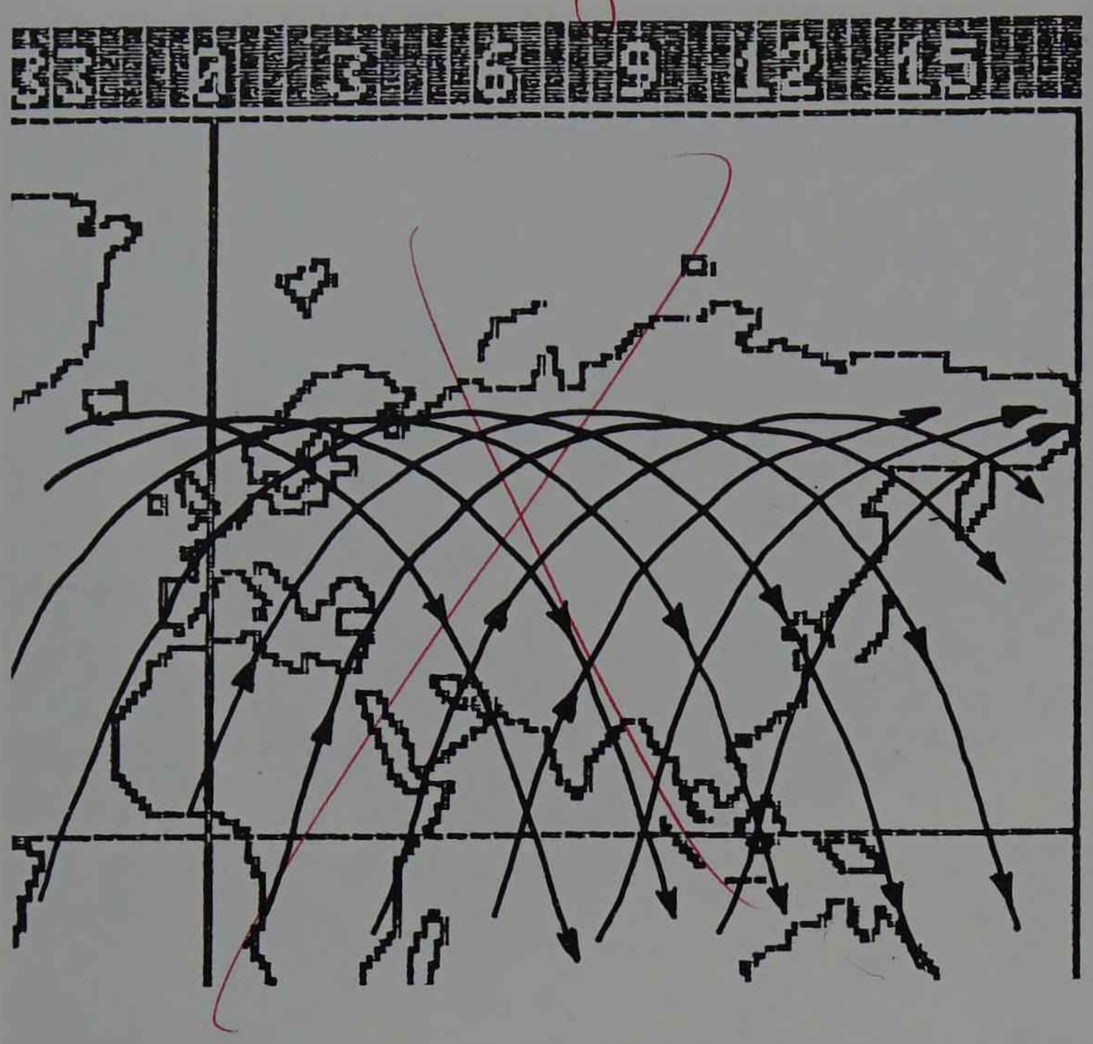


Figure 7.10 Ground trace of a 300 mile orbit with a 65 degree inclination. Of 15 orbits per day, 11 pass within range of one or more Soviet launch sites.

1,800 mile orbits, 40 weapons are needed. Using kinetic energy weapons such as space based rocket interceptors, 250 to 350 platforms would be needed in low Earth orbit to assure continuous coverage of launch areas worldwide with a capability of attacking missiles during both boost and postboost phases.

A new heavy lift launch vehicle capable of orbiting 70,000 pounds or more will have to be developed to deploy SDI. An estimated 40 to 50 launches per year would be necessary. The current boosters could do the job, but over a longer time and at greater overall expense.

Countermeasures

Several countermeasures against the directed energy weapon have been suggested. The attacking beam of energy must dwell on the missile outer shell for a period of time to weaken the metal sufficiently to cause it to rupture. One way to counter the attack might be to spin the missile as it rises. The energy of the weapon would then spread over the missile and would not dwell on one spot. The beam width is similar in size to the missile, however, so spinning the missile is probably ineffective as a countermeasure.

A shiny or glossy coating on the missile would reflect rather than absorb the energy. The shiny surface or white surface which we usually think of as reflecting light may not reflect x-rays or infrared delivered by the laser weapon. Even if a coating could be developed which does, it might lose its protective surface during takeoff and high speed flight through the atmosphere.

A skirt over the rocket engine's nozzle to hide the heat of the flame from the infrared detectors has been suggested as a way to prevent the tracking of the rising missile. However, the hot exhaust plume is larger than it appears and the added weight of a large skirt would reduce the effective payload of the missile.

Because the missile is best attacked when it is in the boost phase before the warheads and decoys separate from the bus, the use of rapidly burning boosters would be an effective countermeasure. They would be more difficult to attack if they burn out in, say, 90 seconds, before they leave the dense part of the atmosphere. However, replacing the entire fleet of operational missiles with fast burn boosters would be extremely expensive.

So, while there are possible countermeasures against these weapons, those currently being suggested are either ineffective or too expensive to consider.

Antisatellite Weapons

With the high value placed on defense systems in space, it is not surprising that both superpowers have developed means of disabling an opponent's spacecraft. Compared to missile defense, it is relatively easy to ''shoot down'' a satellite. Once its orbit is determined, its exact position in space can be predicted with great accuracy, unless it is maneuvered into another orbit.

For many years the Soviets have had the capability of damaging or destroying a satellite in orbit. A rocket interceptor is launched so as to rendezvous with the target spacecraft and, using a high explosive warhead, blast it with pellets. If rendezvous is accomplished during the interceptor's first orbit, the target spacecraft does not have much warning time to make an evasive maneuver. Twenty tests of their antisatellite weapon have had a 64 percent success rate. The Soviets are also working on the same technologies that the United States is developing for SDI. They already have a powerful ground based laser which may be capable of damaging optical sensors and electronics on orbiting satellites.

The United States has tested a satellite interceptor. A two-stage rocket was carried to high altitude by an F-15 airplane and launched to rendezvous with the target spacecraft. It carried a homing device and destroyed the satellite by collision. Congress has forbidden any further testing.

Conclusion

The problems in developing a space-based antimissile system are enormous, as with any other undertaking that has never been done before. The present objective of SDI is to complete enough research and development by 1992 to enable the president and Congress to decide whether or not to actually build a space defense system.

Cost estimates of such a system run into the trillions of dollars, depending on whom you talk to and whether you are talking about development or deployment, space-based or ground-based, conventional or nuclear, directed energy or kinetic energy weapons. Even if each of the various components prove to be technologically feasible, many notable scientists doubt that a reliable working system could be developed at any price. A system that would guarantee protection of the entire United States against all attacking missiles, they argue, would be entirely too complex and could not be realistically tested to see if it worked. And, they add, anything less than complete protection would not be justifiable. However, scientists are not invariably correct. Such criticisms have frequently been voiced against just about every new state-of-the-art undertaking. As late as the 1920s one prominent scientist said that a rocket ship would not work in space because there was no air for the exhaust to push against. A friend of Dr. Edward Teller, father of the hydrogen bomb, once said, "If Edward says something can be done, it can be done. If he says something cannot be done, he is frequently wrong."

Policy considerations may prevent SDI from ever coming into being. A major consideration is the 1972 ABM treaty in which the United States and the U.S.S.R. agreed not to develop, test, or deploy space-based ABM systems or components. A provision of the treaty lets either country back out with six months notice to the other party, stating the reason for withdrawal. There is little doubt, however, that the Soviets are developing the technologies for space-based missile defense with at least as much vigor as the United States.

DISCUSSION QUESTIONS

1. Could very high resolution photoreconnaissance satellites of the future be considered an invasion of your privacy?
2. Should the United States continue to develop a defense against nuclear missiles?
3. How might an effective defense against nuclear missiles change international relations?
4. How might it be possible to distinguish between a warhead and a decoy after they have been released from the bus?
5. What factors might be considered in determining whether or not to deploy an antimissile weapons system in orbit?

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Chapter 8

Space Shuttle

The Space Shuttle is probably the most complex machine ever built. It is the first reusable vehicle for carrying people and cargo into orbit and returning them to Earth. Part of the Space Transportation System—the Shuttle—takes off like a rocket, orbits Earth as a spacecraft, and lands like an airplane. It is the outgrowth and merging of two technologies . . . the Mercury-Gemini-Apollo ''man-in-the-can'' approach to spaceflight combined with the experimental rocket-powered aircraft. Instead of a capsule sitting atop a heavy-lift booster rocket, this new approach has a rocket-powered airplane, the Orbiter, attached to a large external fuel tank and two solid propellent booster rockets. All except the external tank are recovered, reconditioned, and reused. The Orbiter was designed for 100 missions; the solid rocket boosters were designed for 20 flights.

The Space Shuttle is the backbone and workhorse of the U.S. space program in the 1980s and beyond. It was expected to be a low cost bus-truck service to space for 7 to 30 day missions. It can carry satellites into orbit and drop them off; pick up satellites and repair them on site or return them to Earth; conduct scientific, technological, and industrial research; or act as a platform for construction of large objects in space. All of these tasks were done in 24 successful flights from April 1981 to January 1986, when the *Challenger* accident occurred. The flights are cataloged in Table 8.1.

The Shuttle carries a crew of up to seven. It was designed to open space to men and women who do not have the test pilot background and training that previous astronauts had.

TABLE 8.1 A List of Space Shuttle Flights

Flight	Dates	Orbiter	Missions
STS-1	Apr 12–14, 1981	*Columbia*	First test flight
STS-2	Nov 12–14, 1981	*Columbia*	Test remote manipulator system; Earth survey instruments
STS-3	Mar 22–30, 1982	*Columbia*	Test manipulator arm; materials processing
STS-4	Jun 27–Jul 4, 1982	*Columbia*	Test manipulator arm with scientific payload; materials processing; first DOD payload
STS-5	Nov 11–16, 1982	*Columbia*	Launch two communications satellites
STS-6	Apr 4–9, 1983	*Challenger*	First EVA spacewalk; deploy NASA TDRS satellite
STS-7	Jun 18–24, 1983	*Challenger*	Launch two communications satellites; release and recapture tests
STS-8	Aug 30–Sep 6, 1983	*Challenger*	Deploy comm satellite; test remote manipulator arm
STS-9	Nov 28–Dec 8, 1983	*Columbia*	First Spacelab
41-B	Feb 3–11, 1984	*Challenger*	First test of manned maneuvering unit, backpack propulsion system; launch two comm satellites (boosters failed to send them to synchronous altitude)
41-C	Apr 6–13, 1984	*Challenger*	Retrieve, repair, redeploy Solar Maximum Mission spacecraft using MMU; deploy Long Duration Exposure Facility
41-D	Aug 30–Sep 5, 1984	*Discovery*	Launch three comm satellites; extend and retract large solar array
41-G	Oct 5–13, 1984	*Challenger*	Launch Earth Radiation Budget Explorer; test Earth imaging radar
51-A	Nov 8–16, 1984	*Discovery*	Launch two comm satellites; retrieve two failed satellites from flight 41-B
51-C	Jan 24–27, 1985	*Discovery*	DOD payload
51-D	Apr 12–19, 1985	*Discovery*	Deploy two commercial satellites (one booster failed)
51-B	Apr 29–May 6, 1985	*Challenger*	Spacelab; materials processing
51-G	Jun 17–24, 1985	*Discovery*	Deploy three communications satellites; deploy and retrieve Spartan science experiment
51-F	Jul 29–Aug 6, 1985	*Challenger*	Spacelab, solar physics, astrophysics, plasma physics, materials processing
51-I	Aug 27–Sep 3, 1985	*Discovery*	Deploy three comm satellites; retrieve, repair, redeploy failed satellite from 51-D
51-J	Oct 3–10, 1985	*Atlantis*	DOD mission
61-A	Oct 30–Nov 6, 1985	*Challenger*	Spacelab, materials processing
61-B	Nov 26–Dec 3, 1985	*Atlantis*	Deploy three comm satellites; assemble large structures; study EVA dynamics
61-C	Jan 12–18, 1986	*Columbia*	Deploy comm satellite; deploy hitchiker satellite; IR imaging experiment; images of Comet Halley
51-L	Jan 28, 1986	*Challenger*	The accident

Adapted from the Presidential Commission on the Space Shuttle *Challenger* Accident, *Report to the President*.

Any person in reasonably good health with the need to go into space for scientific or commercial ventures could do so.

Maximum altitude for a Shuttle orbit is 600 miles. If a satellite must be delivered to a higher orbit, it is equipped with a two stage solid rocket booster called the inertial upper stage (IUS). When the Shuttle reaches orbit, the satellite with its IUS is released from the cargo bay, checked out, and left. At the proper time a command from the ground ignites the IUS and the satellite is carried to its higher orbit, often to geosynchronous altitude.

A robotic mechanical arm is used to move things in and out of the cargo bay and to assist in other work. Astronauts in space suits leave the cabin through an airlock to work outside. A rocket-powered backpack called the manned maneuvering unit is used to fly away from the Shuttle to repair satellites or other jobs. Spacelab is a laboratory which is carried in the cargo bay to provide a shirt-sleeve environment for scientific research. All of this and more will be described in detail in Chapter 10. This chapter is concerned with the structure and flight profile of the Shuttle.

The Space Shuttle has three major components: the *Orbiter,* a pair of *solid rocket boosters* (SRBs), and the *external tank* (ET). See Figure 8.1.

Solid Rocket Boosters

The two solid propellant booster rockets provide most of the initial thrust, along with the three engines in the Orbiter, to lift the 4.4 million pound vehicle from the launch pad and boost it to an altitude of about 28 miles. While resting on the launch pad, the entire weight of the vehicle is supported by the two booster rockets.

The solid rocket boosters of the Space Shuttle are the largest ever flown, the first designed for reuse and the first to power a manned spacecraft. Figure 8.2 shows SRB structure and Table 8.2 lists its statistics. Overall each booster is nearly 160 feet long and 12 feet in diameter, constructed of half-inch thick steel. Because of their size, it is not possible to manufacture the motors and ship them to Kennedy Space Center in one piece. They are made in eleven pieces at a factory in Utah, then partially assembled, filled with propellant and shipped in four segments on special flatbed railway cars to Florida for final assembly.

The propellant is composed of aluminum powder fuel, ammonium perchlorate oxidizer, a polymer binder, an epoxy curing agent, and iron oxide catalyst. When hardened into a grain, it looks and feels like a hard rubber typewriter eraser. To ignite the propellant, a small rocket motor is fixed at the upper end of the perforation. A hollow core runs up the center of the grain. When the small motor is ignited, its flames ignite the entire exposed inner surface of the perforation, and the booster comes up to full thrust in less than half a second.

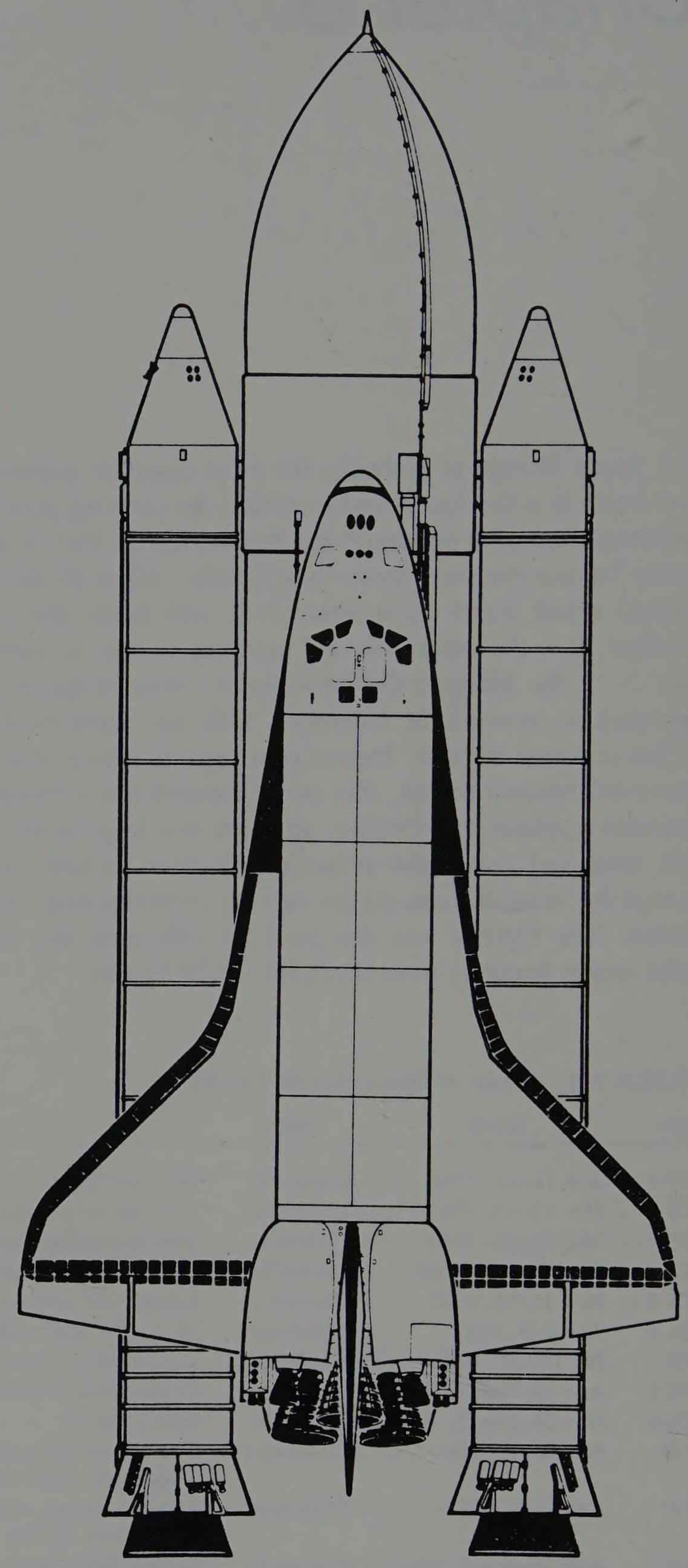


Figure 8.1 Space Shuttle: the Orbiter is attached to the external fuel tank and flanked on each side by a solid propellant rocket booster. *Courtesy of NASA.*

Each booster contains about 1.1 million pounds of propellant and develops a thrust at liftoff of 2.65 million pounds. As the fuel burns, the weight of the booster decreases. As it rises into less dense atmosphere, the drag decreases, and as it leaves the surface of the Earth, the gravitational force decreases. All these contribute to an increase in acceleration. The Shuttle is designed to with-

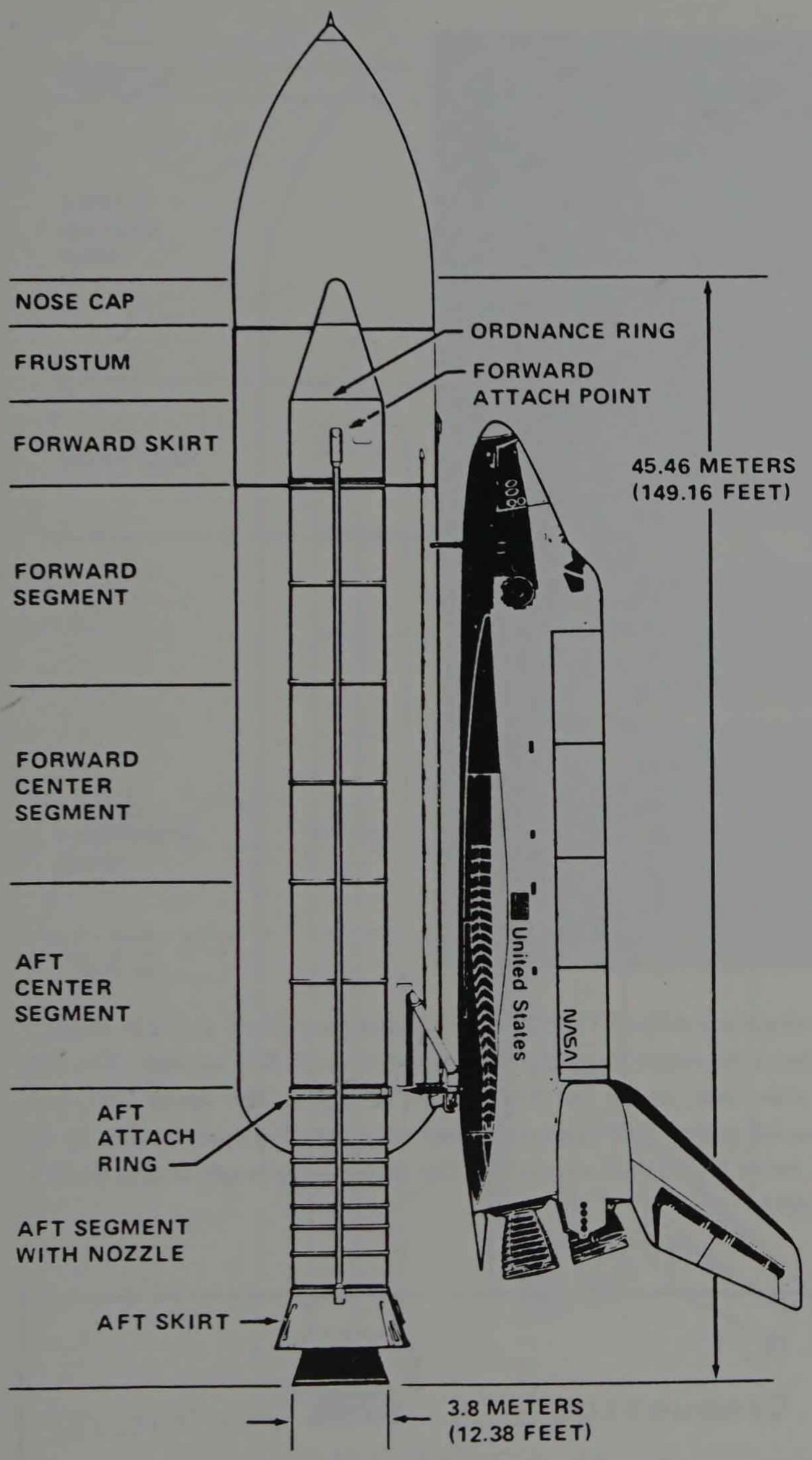


Figure 8.2 Details of the solid rocket booster. *Courtesy of NASA.*

TABLE 8.2 Solid Rocket Booster Statistics

Overall dimensions	
Height	149.2 feet
Diameter	12.4 feet
Propellant composition	
Aluminum powder (fuel)	16.0 percent
Ammonium perchlorate (oxydizer)	69.8 percent
Iron oxide (catalyst)	0.2 percent
Polymers (binder)	12.0 percent
Epoxy (curing agent)	2.0 percent
Weight each booster	
Empty	193,000 pounds
Propellant	1,107,000 pounds
Total	1,300,000 pounds
Thrust at liftoff	
Both boosters	5,300,000 pounds

stand acceleration of up to three g. Therefore, grains are cast in such a way as to produce a regressive burn 55 seconds into the flight to keep the acceleration from exceeding the three-g design limit. This also keeps stress on the astronauts within tolerable limits. Figure 8.3 shows the grain structure.

The exhaust nozzle can be swiveled up to 6.65 degrees from the central axis of the booster to change the direction of thrust and help steer the Shuttle during ascent. Guidance system sensors inform the control computer of the speed and direction of motion of the vehicle. The computer signals the booster when a change in direction of the nozzle is required. Electric power is supplied to the booster through a cable from the Orbiter's electric system.

External Tank

The external tank serves two purposes: it carries the propellants for the Orbiter's three main rocket engines and it is the support structure that connects the Orbiter and solid rocket boosters together during ascent to orbit. Figures 8.4 and 8.5 show its structure and Table 8.3 tells its statistics. It is 154 feet long and 27 feet in diameter.

Because it carries both liquid hydrogen fuel and liquid oxygen oxidizer, the external tank is really two inner tanks in one outer shell. The upper tank carries the liquid oxygen, 1.36 million pounds of it at −297 °F at liftoff. Its 19,500 cubic foot (143,000 gallon) volume is greater than that of a 2,000 square foot house. The lower tank is about 2.5 times larger (383,000 gallons) and carries about a quarter of a million pounds of liquid hydrogen at −423 °F. If these proportions do not seem to make sense, see MATHBOX 8.1.

Both inner tanks are constructed of aluminum and tita-

TABLE 8.3 External Tank Statistics

Dimensions	
Diameter	27.5 feet
Overall length	154.2 feet
Liquid oxygen tank	53.3 feet
Liquid hydrogen tank	97.0 feet
Intertank	22.5 feet
(Intertank overlaps propellant tanks)	
Total weight	
Empty	78,100 pounds
Loaded	1,668,000 pounds
Propellant weight	
Liquid oxygen	1,359,000 pounds
Liquid hydrogen	226,000 pounds
Total	1,585,000 pounds
Propellant volume	
Liquid oxygen tank	143,000 gallons
Liquid hydrogen tank	383,000 gallons
Total	526,000 gallons
Propellant densities (per cubic foot)	
Liquid oxygen	71.1 pounds
Liquid hydrogen	4.2 pounds

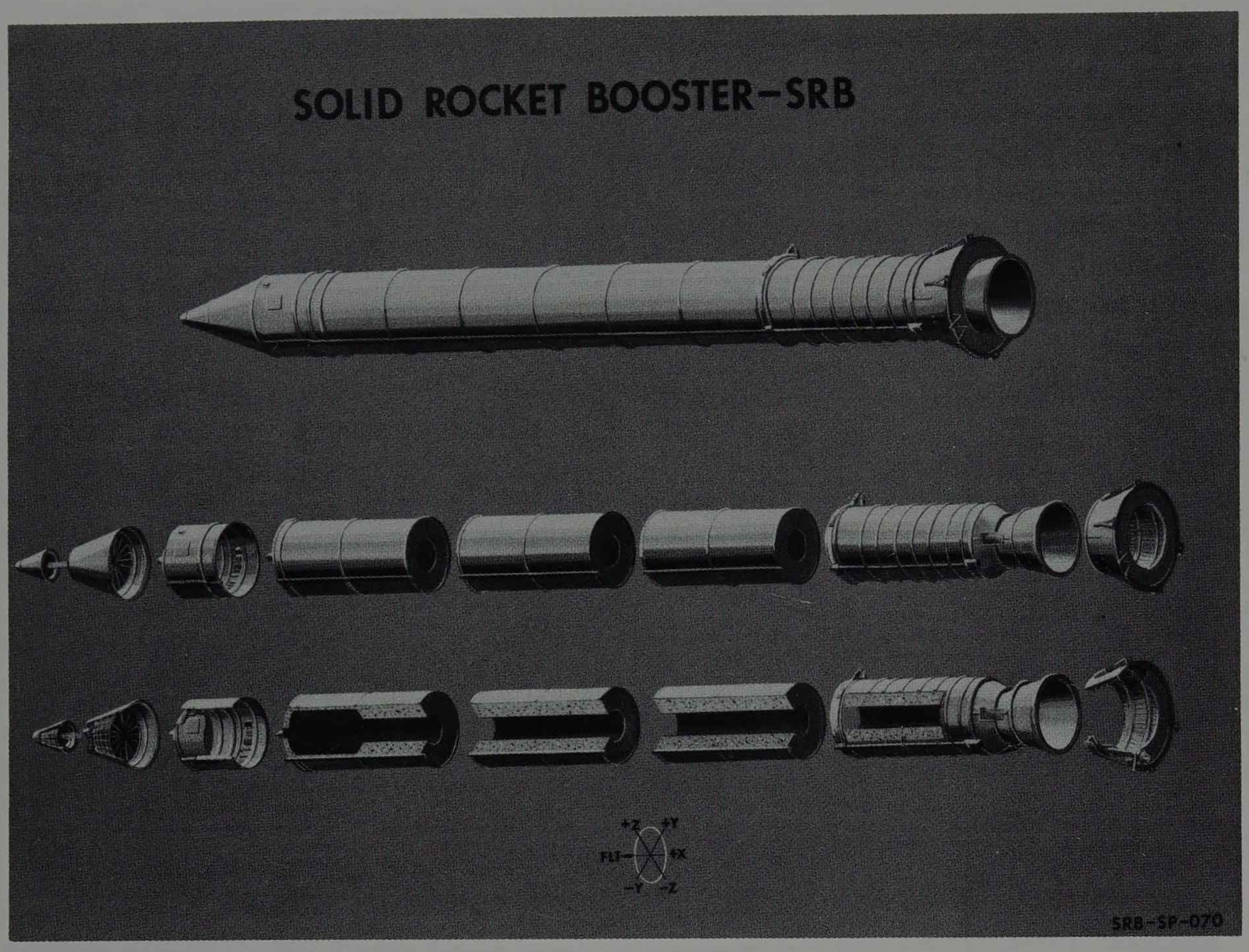


Figure 8.3 Grain design of the solid rocket booster. Four segments contain propellant. The bottom (right) propellant grain is slightly tapered and flared out at the end with the nozzle attached; exhaust gases from the entire engine must escape through this section. The two center segments have cylindrical grains which produce increasing thrust with time, as the burning surface enlarges. The upper (left) half of the topmost section contains less propellant and has slots like a star-shaped grain. This segment burns very rapidly, contributing to the high thrust needed at liftoff but burns out quickly so the maximum desired thrust level is not exceeded. The thrust-time graph is also shown. *Courtesy of NASA.*

MATHBOX 8.1

Hydrogen-Oxygen Combustion

An atom of oxygen has an atomic weight of sixteen; an atom of hydrogen has an atomic weight of one. When the two react chemically (burn) they produce water.

$$2H + O \rightarrow H_2O$$

For complete combustion, then, it is necessary to have twice as many hydrogen atoms as oxygen atoms. Therefore, the hydrogen tank has more than twice the volume of the oxygen tank.

A water molecule has a molecular weight of 18 (2 for the hydrogens + 16 for the oxygen). Therefore the weight of the oxygen atoms is eight times the weight of the hydrogen atoms. If the external tank starts with 1,359,000 pounds of oxygen, then, for complete combustion it will need 1,359,000/8 = 170,000 pounds of hydrogen.

Actually, it carries more hydrogen than that (226,000 pounds) because it burns a hydrogen-rich mixture, only six parts of oxygen to one part of hydrogen, instead of the 8 to 1 ratio for perfect, complete combustion.

Thrust depends on the mass of the exhaust and its velocity out of the nozzle, so the extra hydrogen in the exhaust contributes to the thrust even if it is unburned.

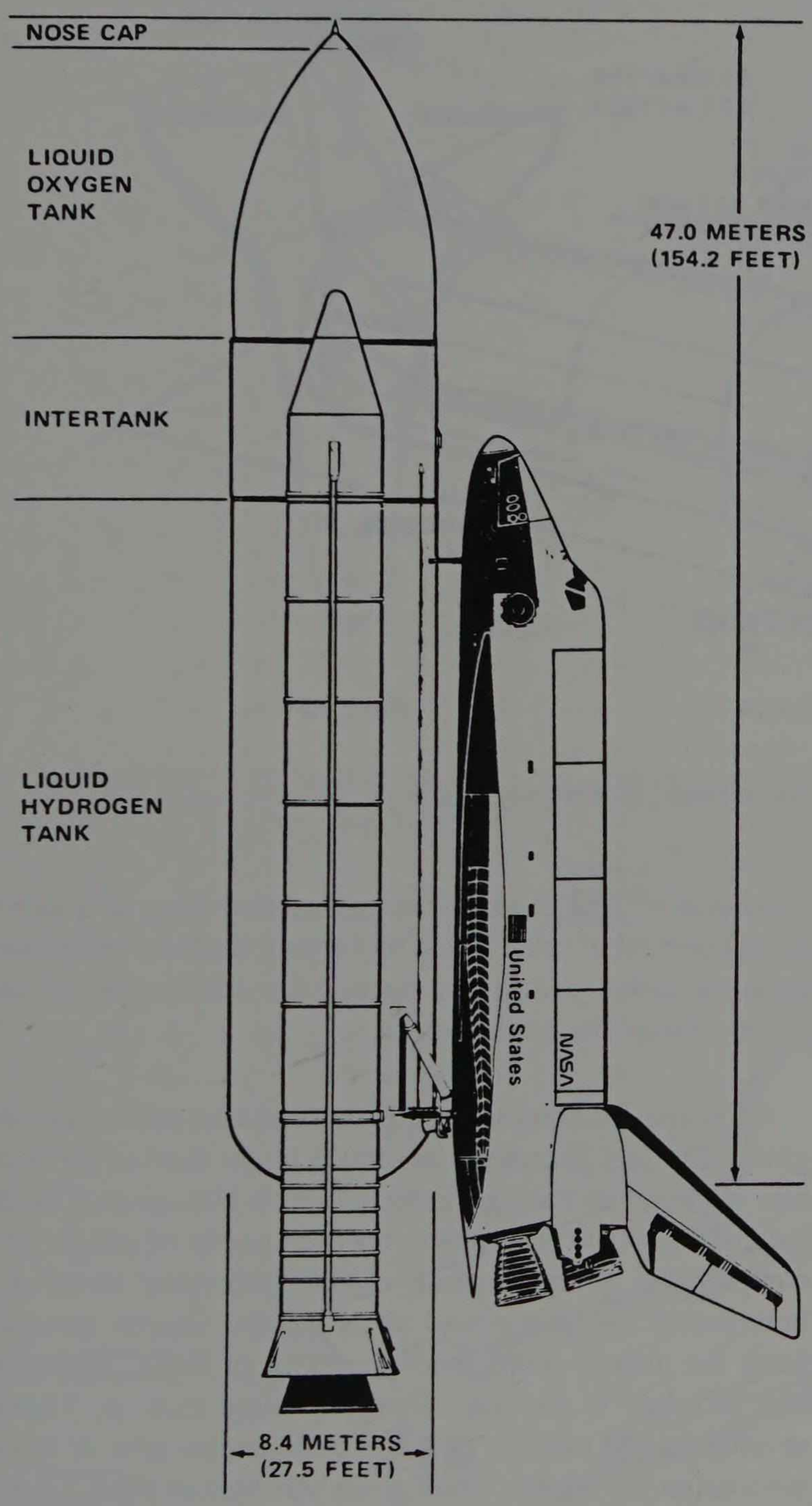


Figure 8.4 The external tank. *Courtesy of NASA.*

nium alloys up to 2 inches thick. The oxygen tank contains baffles to keep the liquid oxygen from sloshing around during flight and throwing the Shuttle off course. The density of liquid hydrogen is so low that sloshing is not a problem. An intertank collar connects the two propellant tanks together and provides space for most of the electrical components. Since the first tank was built, the manufacturer has made some design changes, substituted titanium for aluminum in some components, and eliminated the white exterior paint. As a result, the weight of the newer tanks has been reduced by more than 6,000 pounds, allowing the Shuttle to carry a heavier payload.

To reduce atmospheric drag, the oxygen tank curves to a point at the upper end of the structure. The entire outer surface of the external tank is insulated with a half-inch thick cork/epoxy layer covered with 1 to 2 inches of spray-on foam. Insulation is necessary for two reasons. The propellants are very cold: liquid oxygen boils at −287 °F and liquid hydrogen at −420 °F. An uninsulated tank would absorb heat from the surroundings causing uncontrolled boiling of the propellants. This poses two problems: excessive loss of hydrogen and oxygen through vent valves and buildup of excessive pressure in the tanks. Controlled boiling is necessary on the launch platform to keep the tanks pressurized for structural strength and also to assist the pumps in moving the propellants out to the engines. During flight, the tanks are pressurized by gases from the engines. In addition, because of the cold temperatures, if the tank were not insulated, water vapor in the air would readily condense as ice on the sides. At liftoff, the ice would break loose and damage the Shuttle.

Propellants flow to the engines through 17 inch pipes: oxygen at a rate of about 64,000 gallons per minute and hydrogen at nearly 50,000 gallons per minute.

The Orbiter

The *Orbiter* is the airplane-rocket ship shown in Figure 8.6 and its dimensions are given in Table 8.4. It is about the size of a DC-9 jet airliner as seen in Figure 8.7. The main structure of the Orbiter is constructed of aluminum, similar to the way an airliner is built. There are three main sections: the forward fuselage with the crew compartment; the midsection which includes the payload bay and its clamshell doors; and the aft fuselage which includes the engines, pods, and vertical tail. Empty it weighs about 150,000 pounds.

Payloads are carried in the cavernous cargo bay. The maximum payload weight depends on the direction of

TABLE 8.4 Orbiter Dimensions

Total length	122.2 feet
Height	56.6 feet
Rudder height	26.3 feet
Wing	
Span	78.1 feet
Maximum thickness	5.0 feet
Body Flap	
Width	20.0 feet
Area	135.8 square feet
Aft fuselage	
Length	18.0 feet
Width	22.0 feet
Mid fuselage	
Length	60.0 feet
Width	17.0 feet
Crew cabin	2525 cubic feet
Payload bay	
Length	60.0 feet
Diameter	15.0 feet

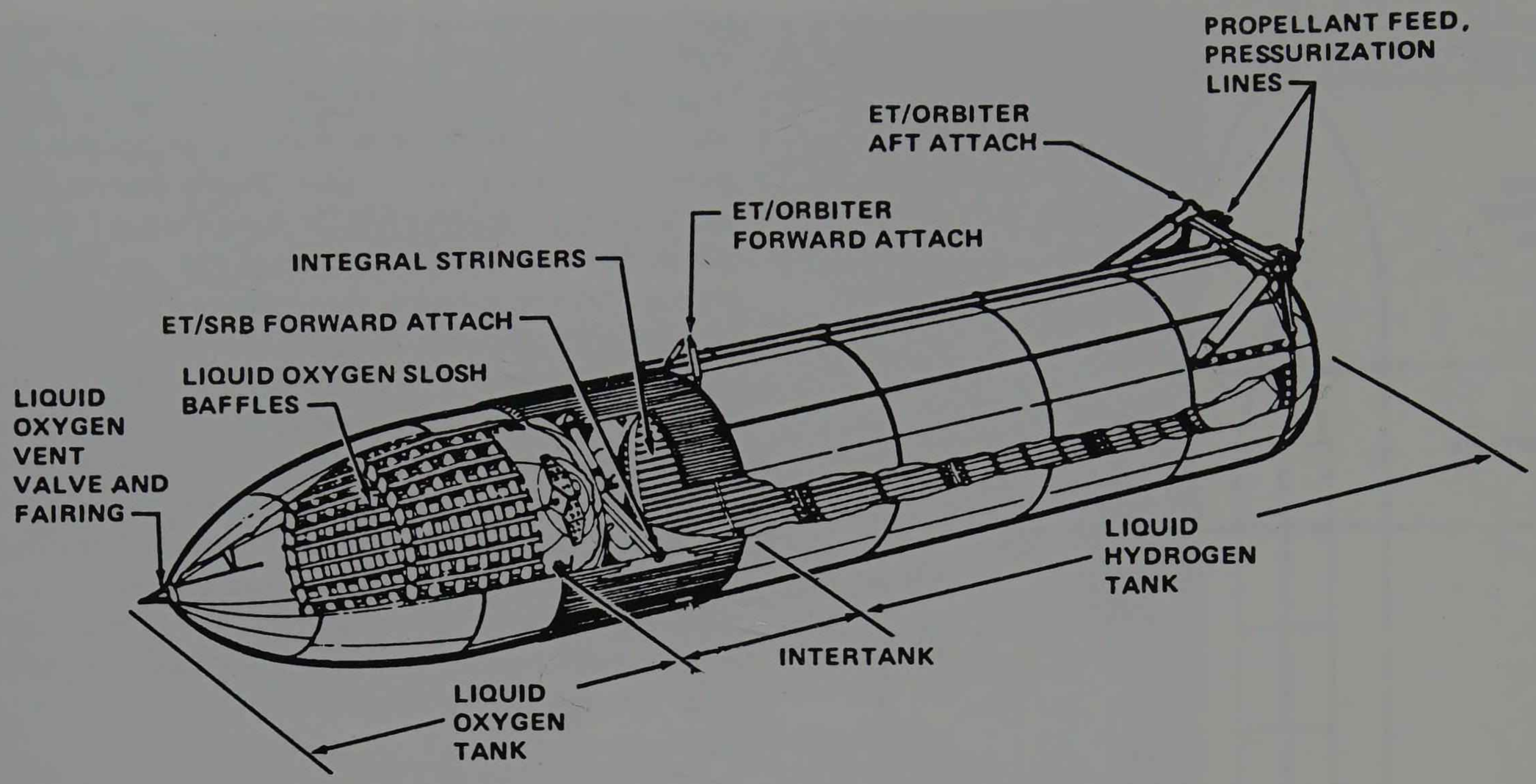


Figure 8.5 Internal structure of the external tank. *Courtesy of NASA.*

launch. Eastward launches take place from Kennedy Space Center in Florida. Polar launches were planned from Vandenberg Air Force Base, California. To date, no shuttles have been launched from Vandenberg and after the *Challenger* accident in 1986 the facility was placed in ''caretaker'' status. Polar launches do not take place from Florida because the spacecraft would overfly land areas while under power. Because of the rotation of the Earth, Kennedy Space Center (at about 29° north latitude) is moving eastward with respect to space at a speed of 914 miles per hour. Given that initial speed while still on the launch platform, the Shuttle can carry a payload of 65,000 pounds into low Earth orbit on an eastward launch from Kennedy Space Center. A maximum of 39,700 pounds can be carried into polar orbit because the initial eastward velocity of Earth's rotation does not help in a polar launch. Up to 32,000 pounds of cargo can be returned from orbit to Earth.

The cargo bay is not pressurized. Its doors open like a clamshell to expose the Orbiter's cooling radiators (Figure 8.8). The front radiators tilt so that heat may escape from both sides. It is absolutely essential that the doors be opened immediately on achieving orbit and that the radiators be exposed to space. Otherwise the Orbiter would overheat within a few orbits and the mission would have to be aborted. On the other hand the doors must be closed for reentry or air friction would quickly destroy them, and probably the entire cargo bay. If the automatic door opener should fail, a manual method can be used.

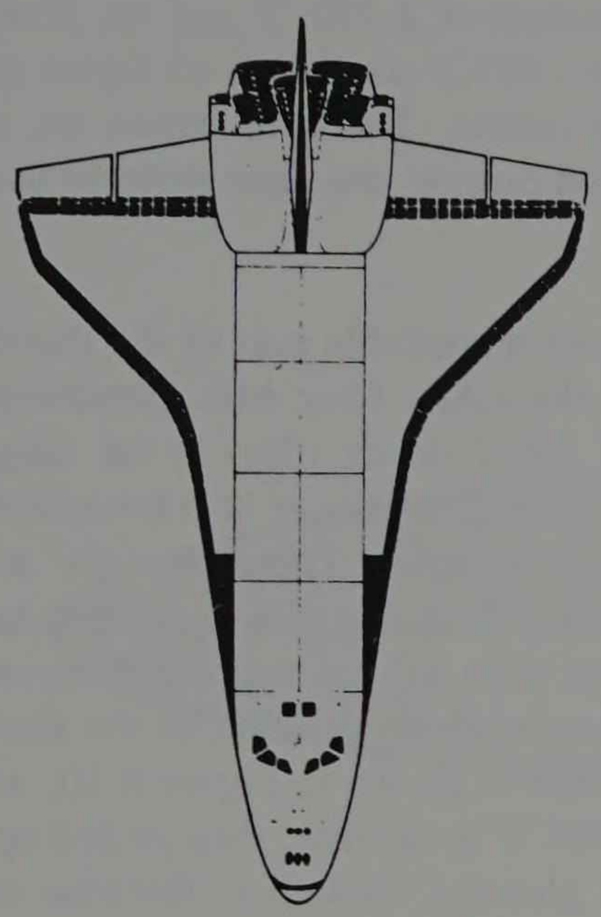
The Orbiter's three main engines are the most advanced liquid fueled rockets ever built. Propellants are liquid hydrogen and liquid oxygen carried in the external tank. Each develops 375,000 pounds of thrust at 100 percent rated power. The engines can be throttled from 65 percent to 109 percent of rated thrust by varying the flow of the fuel from the tanks, just as you operate the accelerator in your car to change the engine speed.

Rockwell International built these remarkable main engines. The fuel pumps are not much larger than an automobile engine, yet they generate as much horsepower as 28 locomotives, 100 horsepower for each pound of weight. By comparison, an automobile engine generates about 1/2 horsepower for each pound of its weight. Output pressure from the pumps could send a column of liquid hydrogen 180,000 feet in the air. The fuel pump runs at 37,000 revolutions per minute; an automobile engine runs at 3,000 revolutions per minute when going 60 miles an hour. Liquid hydrogen at −423 °F is the second coldest liquid on Earth (liquid helium is colder). When it burns in the combustion chamber, the temperature reaches 6,000 °F, higher than the boiling point of iron. The three engines empty the half-million gallon external tank in 8.5 minutes.

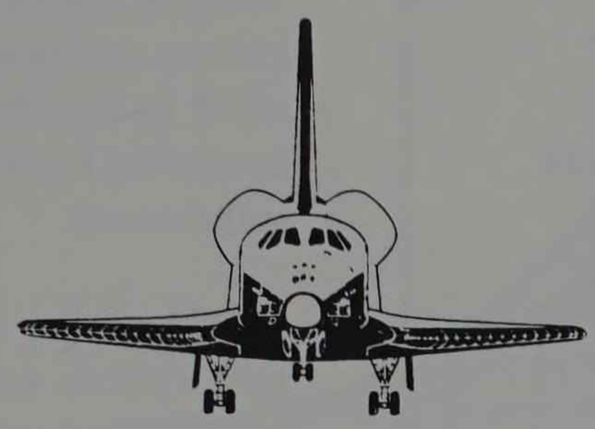
The Orbiter engines are mounted in such a way that they can be gimbaled, moved to change the direction of the thrust. In conjunction with the solid rocket boosters, this provides the means for steering the Shuttle during powered flight.

Orbiter Thermal Protection

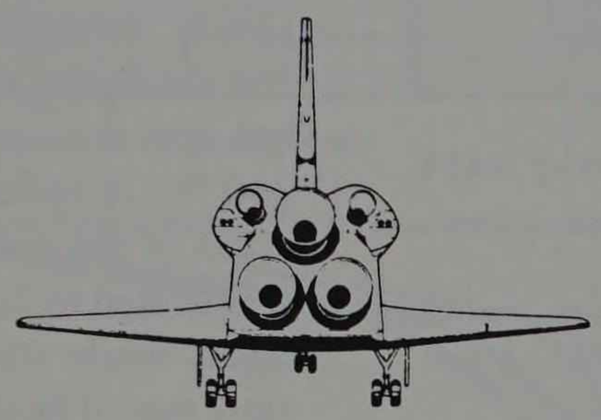
When returning to Earth, the Orbiter must reduce its speed from 18,000 miles per hour in orbit to 200 miles per hour landing speed. Its kinetic energy of motion must be dissi-



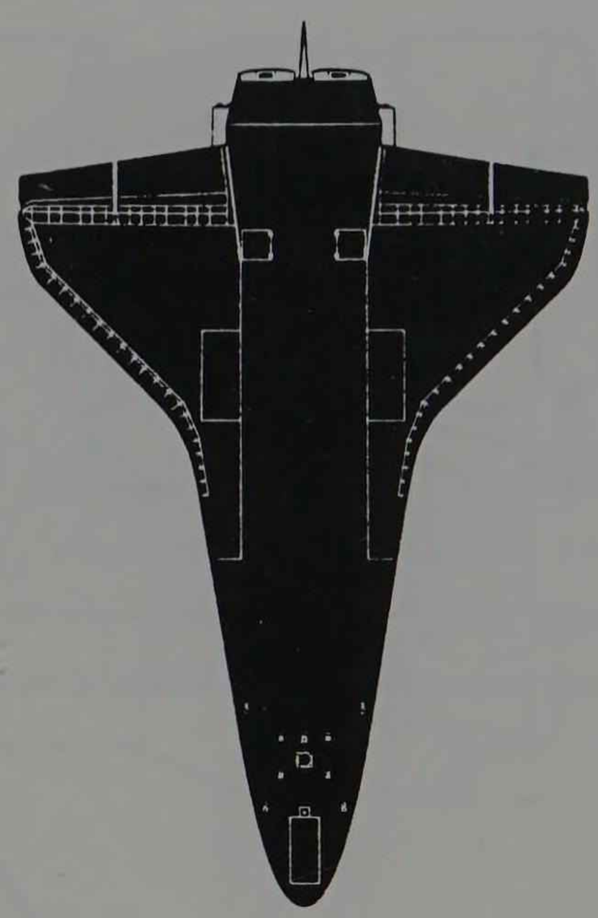
TOP VIEW



FRONT VIEW



REAR VIEW



BOTTOM VIEW

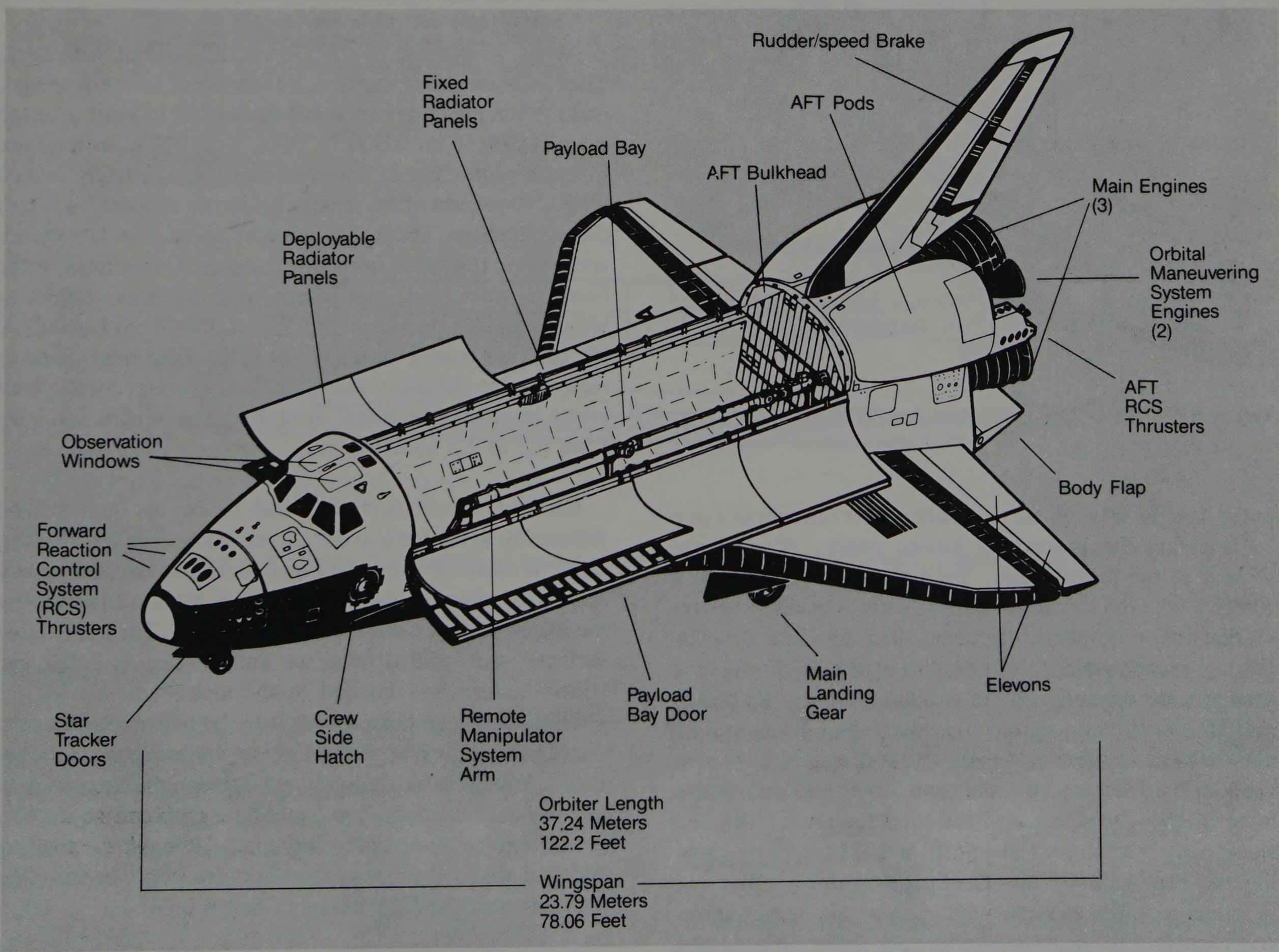


Figure 8.6 The Space Shuttle Orbiter. *Courtesy of NASA.*

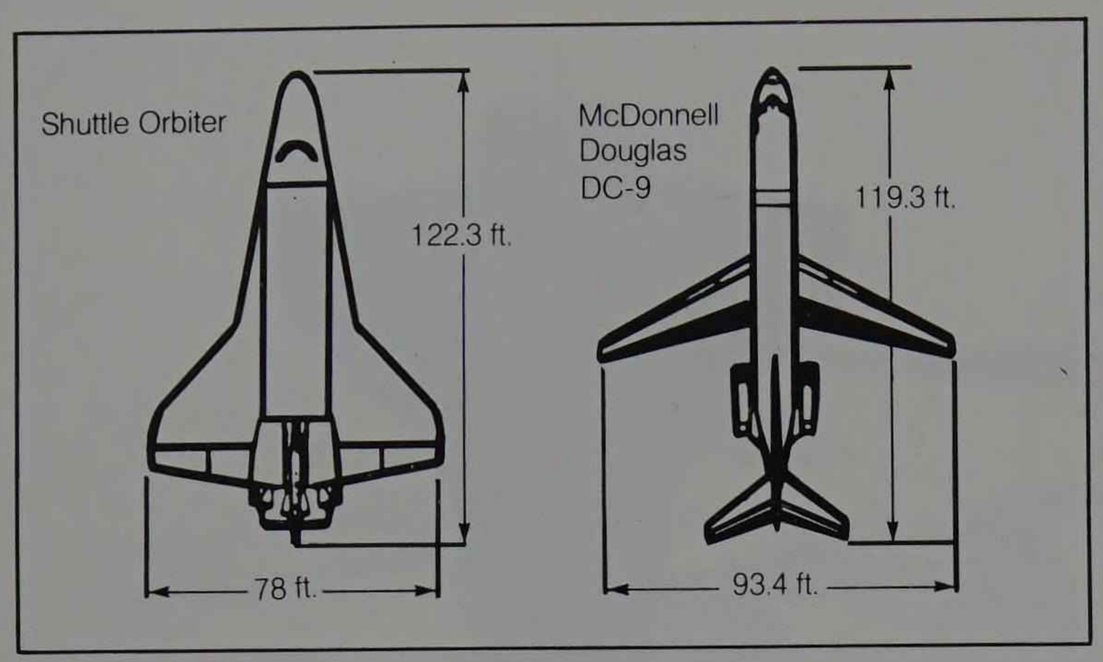


Figure 8.7 Size comparison of the Orbiter. *Courtesy of NASA.*

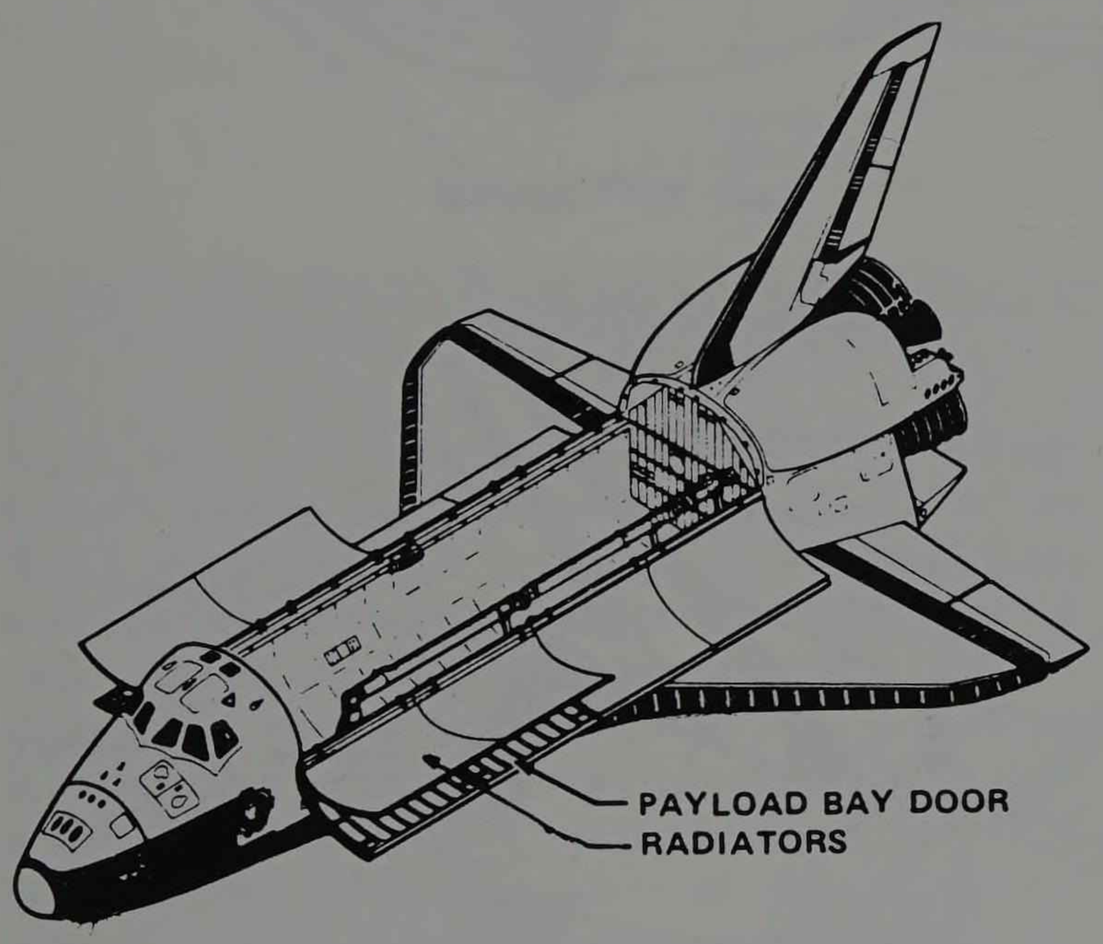


Figure 8.8 The Orbiter radiators. *Courtesy of NASA.*

pated in some way. When an automobile is brought to a stop by applying the brakes, its kinetic energy is converted to heat in the brake lining. Similarly with the Shuttle; it reenters with the large, flat bottom surface leading the way so that the atmospheric frictional drag acts like a brake. During reentry into the atmosphere, the frictional heat produces temperatures on the Orbiter varying from 600 °F to 2,750 °F. Without a protective covering of insulation, the aluminum structure would melt. Ablative heat shields were used on the Mercury, Gemini, and Apollo spacecraft, but none of those vehicles was intended for reuse. The heat shield simply charred, flaked off, and ablated away carrying the heat with it. But the Space Shuttle Orbiter was designed as a 100 mission vehicle. It would be too expensive to replace the heat shield after each flight, so a reusable one had to be developed.

Figure 8.9 shows how the various areas of the Orbiter are covered by different types of insulation. The nose tip and leading edges of the wings are subject to the greatest heat stress at a temperature of 2,750 °F and are protected by a carbon composite (RCC) consisting of layers of graphite cloth in a carbon matrix. The outer layers are chemically converted to silicon carbide, the same material used to make grindstones.

Perhaps the most remarkable part of the thermal protection system are the silica fiber tiles identified as LRSI (white tiles) and HRSI (black tiles) in the diagram. This material absorbs great quantities of heat but transfers it very slowly through its interior. Therefore, the atmospheric friction during reentry heats the tiles to as much as 2,300 °F, but the aluminum skin of the spacecraft never exceeds 350 °F. A spectacular demonstration of the thermal properties of the material is shown in Figure 8.10, where a tile was heated to 2,300 °F in an oven, then picked up with bare hands while still glowing white hot. Because of the very slow rate of heat flow through the tile, the outer surface had cooled in a few seconds to near room temperature while the interior was still 2,300 °F.

About 70 percent of the Orbiter is covered with tiles. Tiles on the bottom surface, the front part of the fuselage, and the leading edge of the tail are subject to heating in the range 1,200 °F to 2,300 °F (648–1,260 °C), so they are given a shiny black boron-silicate glass coating which allows 90 percent of the reentry heat to be radiated back into the atmosphere. These tiles measure about 6 inches square and vary in thickness from 1 to 5 inches. On sections of the fuselage sides, tail, and upper wing surfaces subject to temperatures in the range 750 °F to 1,200 °F (371–648 °C), the tiles are coated with a shiny white aluminum oxide to reflect solar radiation and help keep the spacecraft cool while in orbit. These are about 8 inches square and vary from 0.5 to 2.5 inches thick.

Each of the 30,000 tiles had to be cut and shaped differently to conform to the curved surfaces of the Orbiter. Some of them are shown in Figure 8.11. No two are exactly alike. Groupings of about 20 tiles were set into a frame after the outer surfaces were cut and coated. Then the inner surfaces were milled to shape and bonded to a felt pad which in turn was bonded to the aluminum skin of the Orbiter using a silicone resin glue. The felt pad isolates the tiles from strain due to the Orbiter's vibrations as it flies into and out of orbit. Excess weight due to the absorption of rain water or condensation could be a problem, so the tiles are also given a waterproofing coat. Although the tiles are soft and easily damaged, they are also easily repaired by spraying scratches and plugging larger holes.

The parts of the Orbiter not subject to excessive heating are covered with a flexible felt material (FRSI) which affords protection where the temperature does not exceed 700 °F. These areas include the cargo bay doors, most of the upper wing surface, lower rear fuselage sides, and pods.

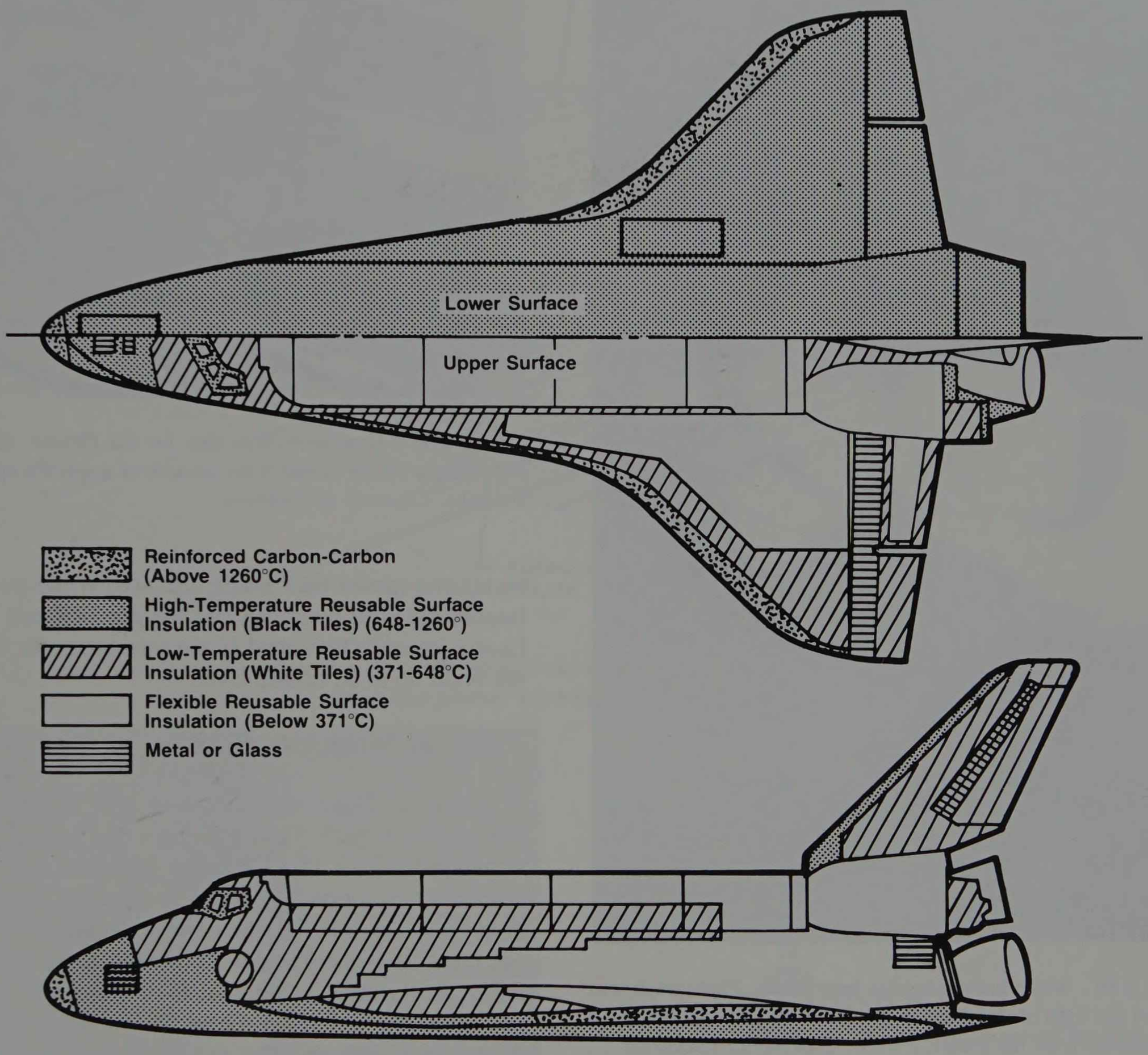


Figure 8.9 Four different kinds of insulation cover the surfaces of the Orbiter. *Courtesy of NASA.*

Electric Power

Electricity for the Shuttle and its payload is produced by three fuel cells which use hydrogen and oxygen, combining them into water and generating electricity in the process. In a car battery, electricity is produced by the chemical reaction of lead and lead dioxide plates in a solution of sulfuric acid contained within the battery. In a fuel cell, however, the hydrogen and oxygen are brought in from the outside.

Fuel cells were invented in 1959 and were used in the Apollo program. Shuttle fuel cells are about the same size as those used in Apollo but generate six times as much electric power. Sufficient hydrogen and oxygen are carried to generate 1,530 kilowatt-hours of electrical energy. Additional fuel can be carried in the cargo bay if needed for a particular mission. The water produced as a by-product in the fuel cells supplies all human needs with plenty left over. The excess is dumped overboard into space at intervals.

Assembly

At Kennedy Space Center, Florida, the various parts of the Space Shuttle are brought together and assembled inside one of the largest buildings in the world, the vehicle assembly building (VAB). It covers eight acres, stands 525 feet tall, 716 feet long, and 518 feet wide. The large doors operate in two sections. The upper section, 342 feet high

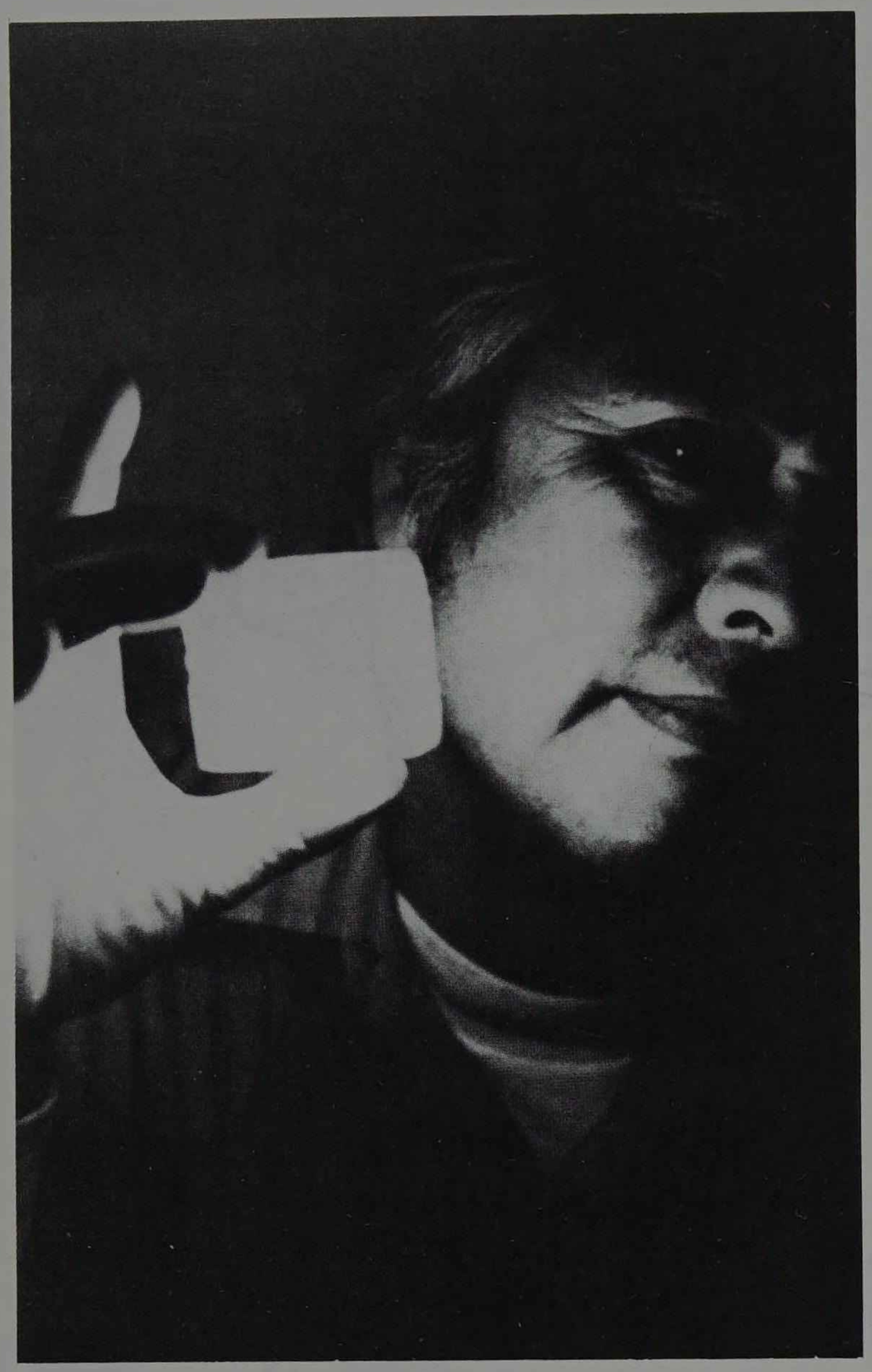


Figure 8.10 White hot tile held in bare hands. Photograph was taken by the light of the glowing tile less than 10 seconds after it was removed from the 2,300 °F oven. *Courtesy of Lockheed.*

and 76 feet wide, consists of seven leaves which move vertically to open. The lower section is 114 feet high and 152 feet wide with four leaves which move horizontally. More than 70 lifting devices are in the building, including two 250-ton cranes.

The entire Space Shuttle is put together on a mobile launch platform. First the solid rocket boosters are assembled and attached to the platform. Next the external tank is attached to the boosters and finally the Orbiter is connected to the external tank. Each of these components is tested individually. Then, when mated together, the entire vehicle is thoroughly checked out. A crawler-transporter (Figure 8.12) is then attached to the mobile launch platform with the Shuttle resting on top. This moves out through the doors along a 130 foot wide roadway to one of two launch pads 3.4 or 4.2 miles away. Its maximum speed is 1 mile per hour (Figure 8.13). The launch platform with the Shuttle is deposited on the pad (Figure 8.14) and the crawler-



Figure 8.11 Heat protection tiles for the Orbiter. Each tile is individually milled to match the contour of a specific spot; no two are alike. *Courtesy of Lockheed.*

transporter moves back a safe distance. While awaiting the launch, the cold hydrogen and oxygen boil and vaporize. Excess gas must be vented so the pressure in the tanks does not build up to an unsafe level.

Typical Mission Profile

A typical sequence of events during a Shuttle launch is tabulated in Table 8.5 and a diagram of a typical mission is shown in Figure 8.15. (Check the table and diagram as we describe the action.) By one hour prior to liftoff the propellant tanks are full, the crew is aboard, and computers and crew have checked out all systems to be sure they are ready. In the final minutes of the countdown the engines and nozzles are checked for proper operation and set into their launch position. The Orbiter is switched to internal electric power supplied by the fuel cells.

There are several opportunities for holding the countdown if something does not appear to function properly. If an emergency occurs while the crew is in the Orbiter on the launch pad, the crew can leave the vehicle to a safe location by means of the escape system shown in Figure 8.16.

Ignition and Liftoff

The three main rocket engines in the Orbiter ignite one at a time at intervals of 0.12 second, the first at T − 3.46 seconds. By time T the engines have reached 90 percent thrust. The entire vehicle lurches forward about 40 inches in the direction of the tank, straining against the eight holddown bolts which attach the solid rocket boosters (the entire Shuttle) to the launch platform. It takes 2.64 seconds for the vehicle to rock back to a vertical position. The booster engines then ignite and come to full power by T + 3 seconds. The holddown bolts are triggered and the Shuttle lifts off (Figure 8.17).

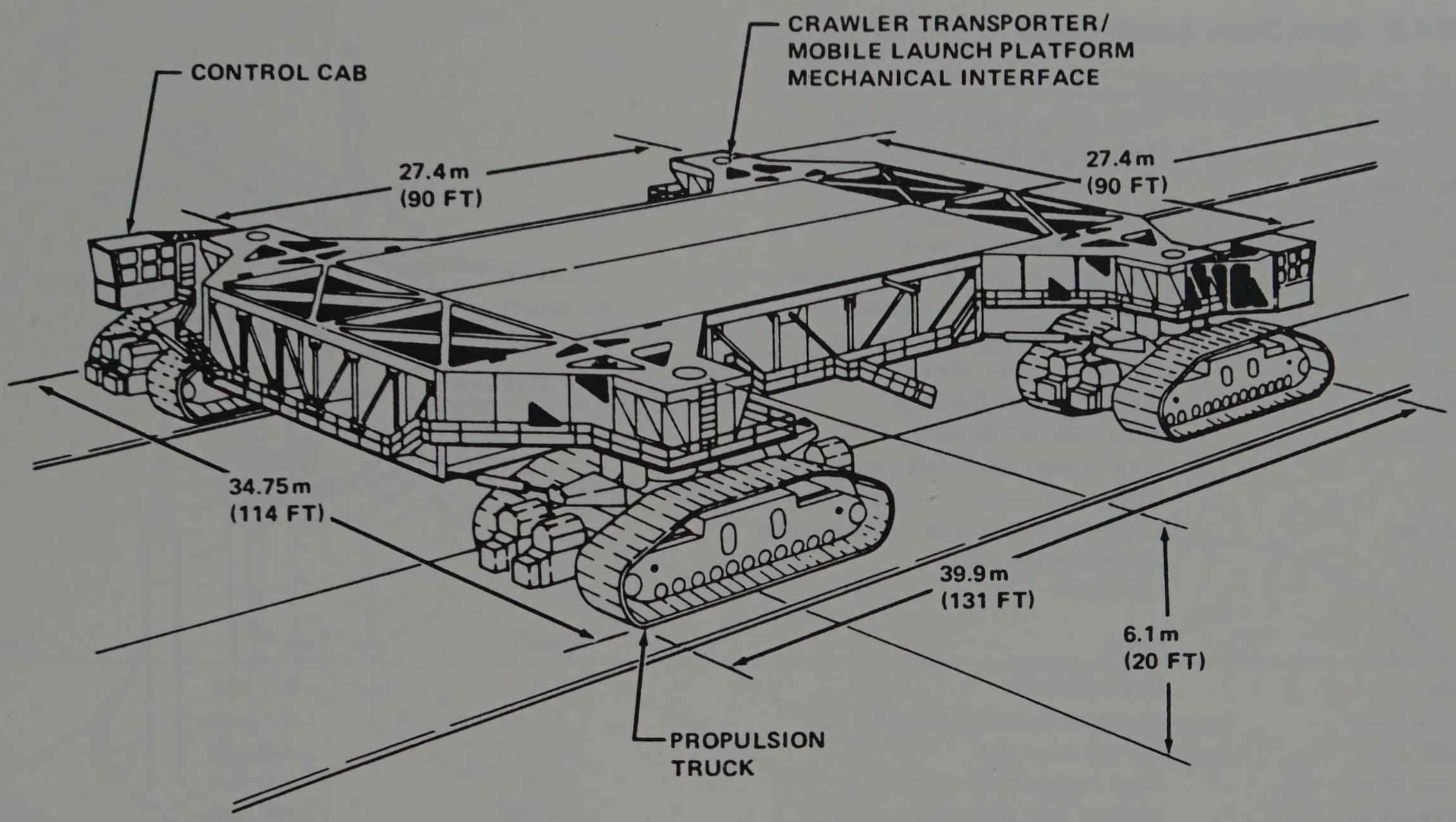


Figure 8.12 Space Shuttle crawler-transporter. Note the dimensions; the tracked drive trucks stand 10 feet tall. The entire vehicle weighs six million pounds unloaded. *Courtesy of NASA.*

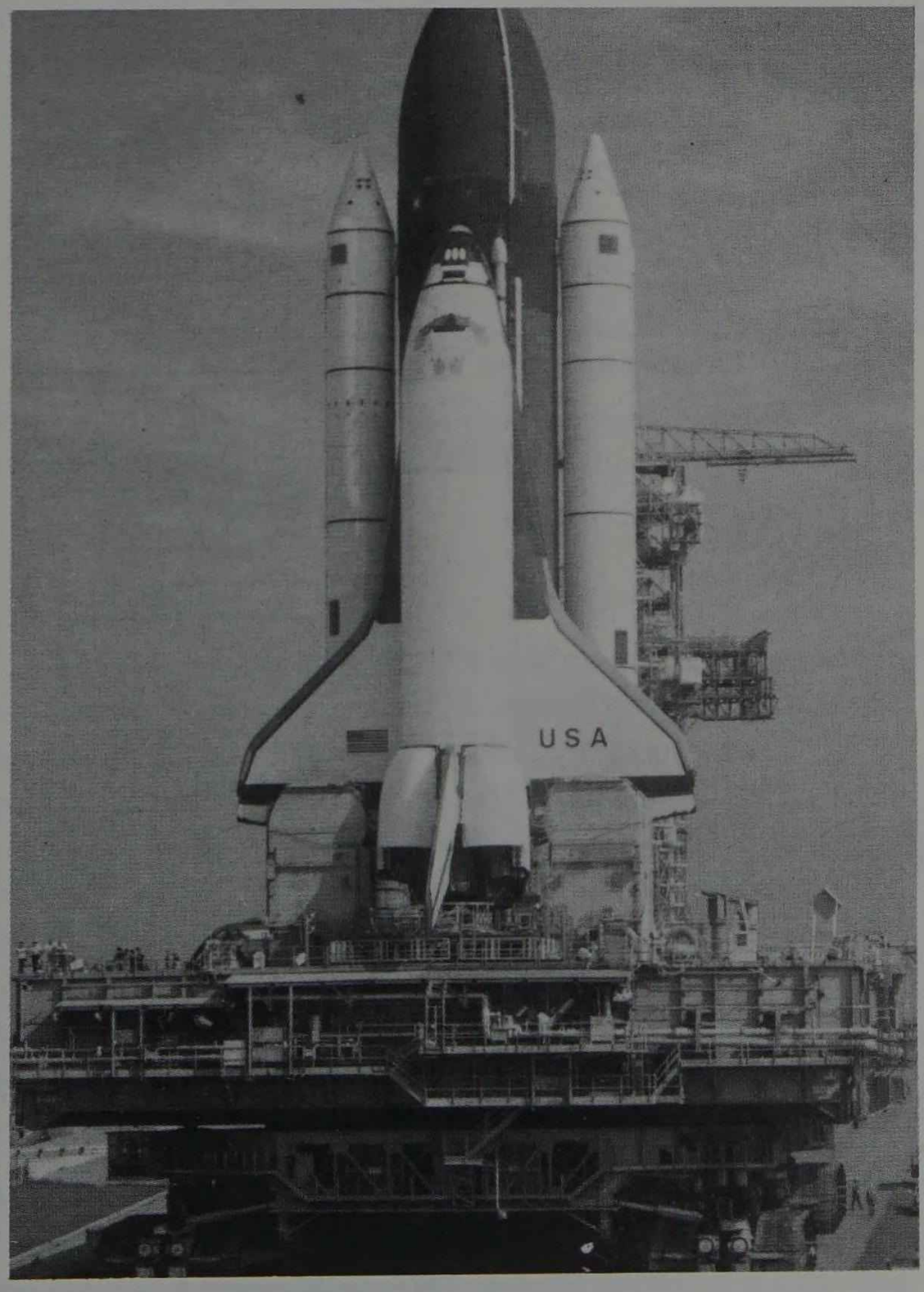


Figure 8.13 Assembled Space Shuttle ''speeds'' to the launch site at 1 mile per hour. It rests on a mobile launch platform atop a crawler-transporter. *Courtesy of NASA.*

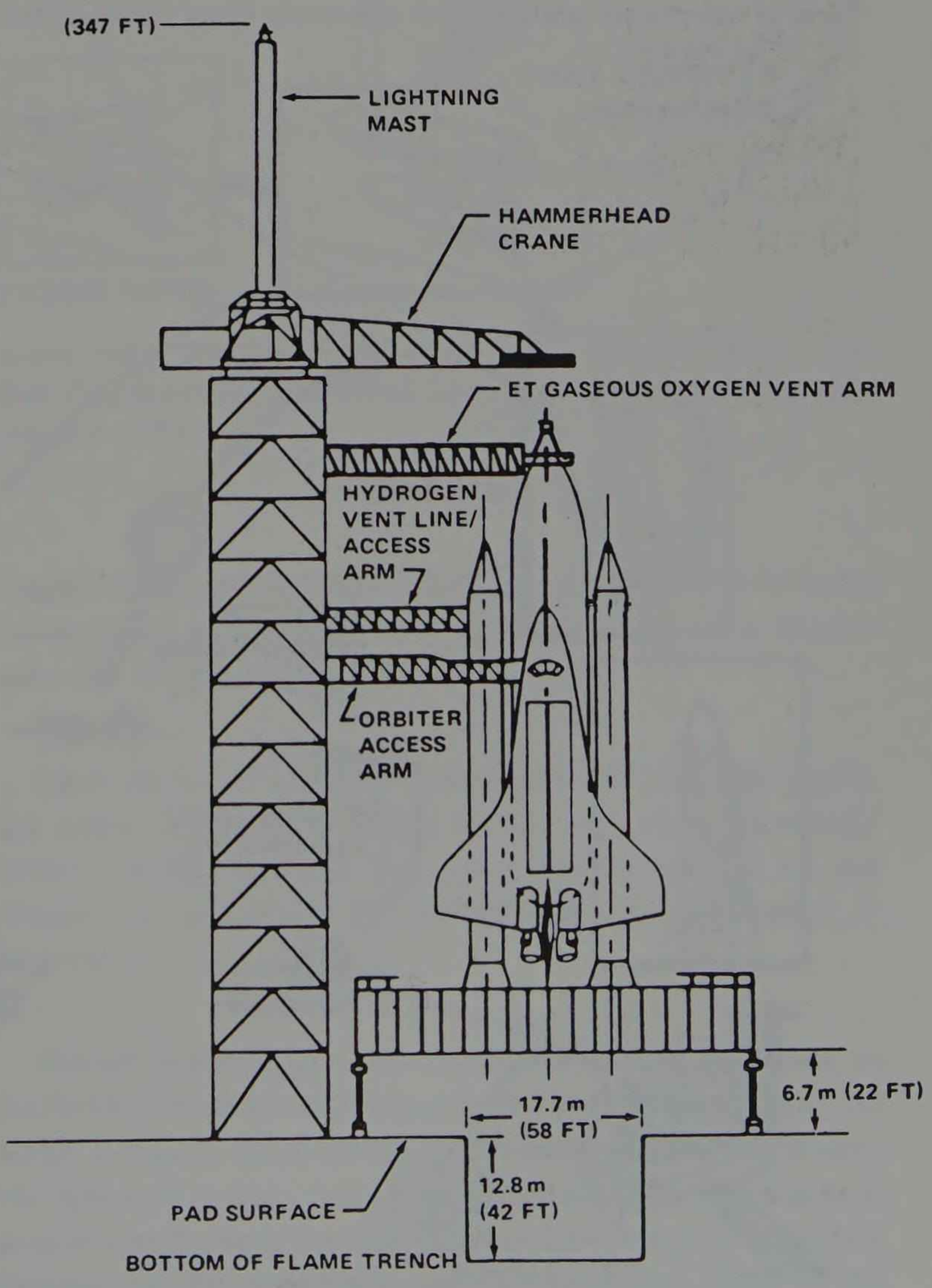


Figure 8.14 Shuttle launch pad. *Courtesy of NASA.*

TABLE 8.5 Space Shuttle Launch Events

Time	Event
T − 4 hr 30 min	Begin filling liquid oxygen tank
T − 2 hr 50 min	Begin filling liquid hydrogen tank
T − 1 hr 5 min	Crew aboard, hatch closes
T − 9 min	Automatic launch sequence starts
T − 4 min 30 sec	Orbiter on internal power
T − 3 min	Main engines move to start position
T − 2 min 55 sec	Oxygen tank at flight pressure
T − 1 min 57 sec	Hydrogen tank at flight pressure
T − 3.46 sec	First main engine starts
T − 3.34 sec	Second main engine starts
T − 3.22 sec	Third main engine starts
T − 0	Main engines reach 90% power
	Delay timer set for 2.46 sec
T + 2.46 sec	Command to start solid rocket boosters
T + 3 sec	Boosters reach 100%
	LIFTOFF

Time	Event	Altitude	Speed*	Range
T + 7 sec	Begin pitchover	545 ft	914 mph	0
T + 1 min 9 sec	Maximum dynamic pressure	8.3 mi	1,654 mph	4 mi
T + 2 min 4 sec	Booster separation	29.4 mi	3,438 mph	23.7 mi
T + 8 min 38 sec	Main engine cutoff (MECO)	73 mi	17,500 mph	829 mi
T + 8 min 50 sec	External tank separation	73.5 mi	17,498 mph	886.6 mi
T + 10 min 39 sec	OMS 1 ignition	78.3 mi	17,479 mph	1,380 mi
T + 12 min 24 sec	OMS 1 cutoff	83.2 mi	17,591 mph	1,860 mi
T + 43 min 58 sec	OMS 2 ignition	173.6 mi	17,201 mph	9,775 mi
T + 45 min 34 sec	OMS 2 cutoff	174.2 mi	17,321 mph	10,269 mi

*Speed is with respect to space. Earth at Kennedy Space Center is rotating eastward at 914 miles per hour.

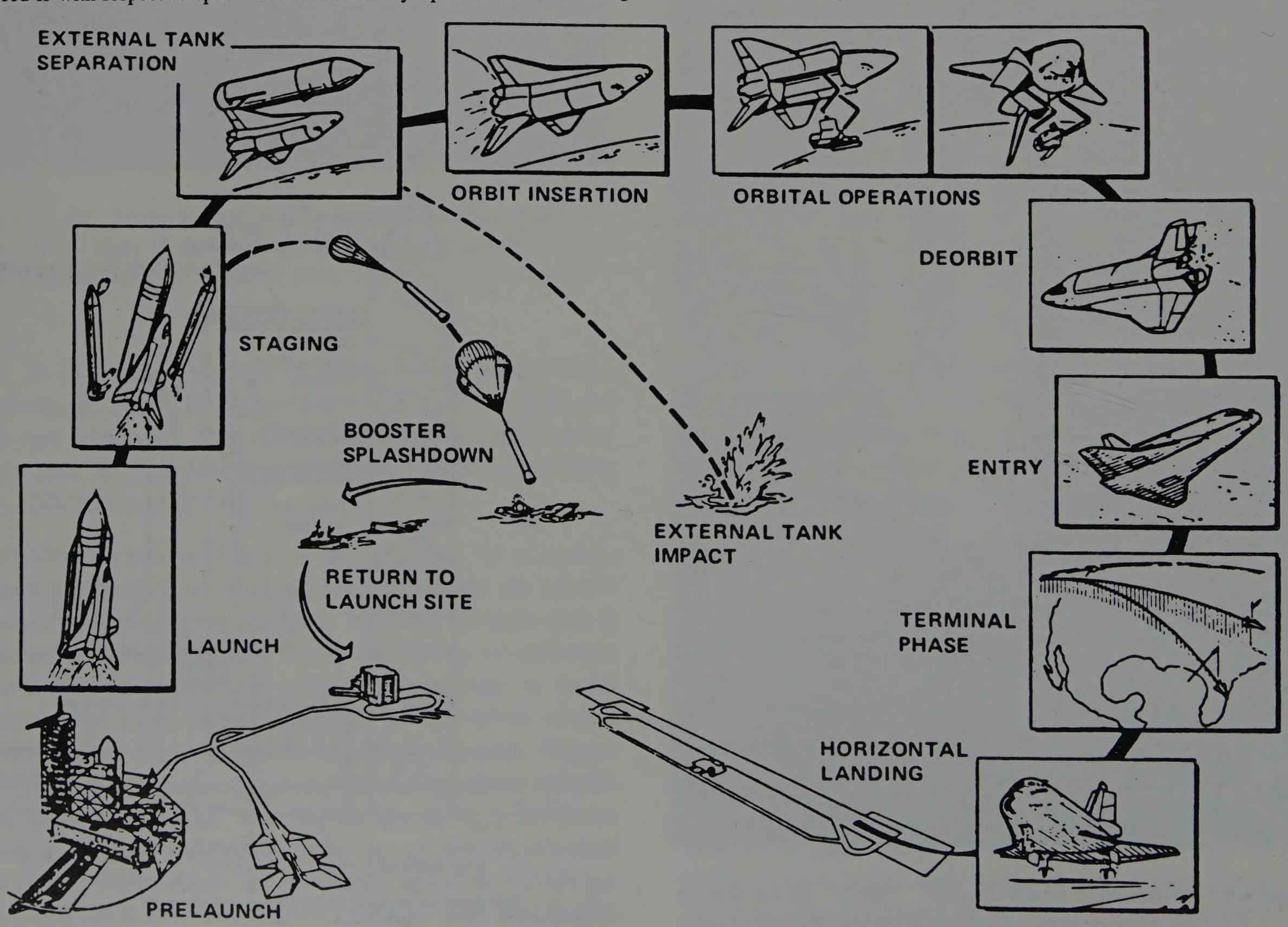


Figure 8.15 Typical launch-to-landing mission profile. *Courtesy of NASA.*

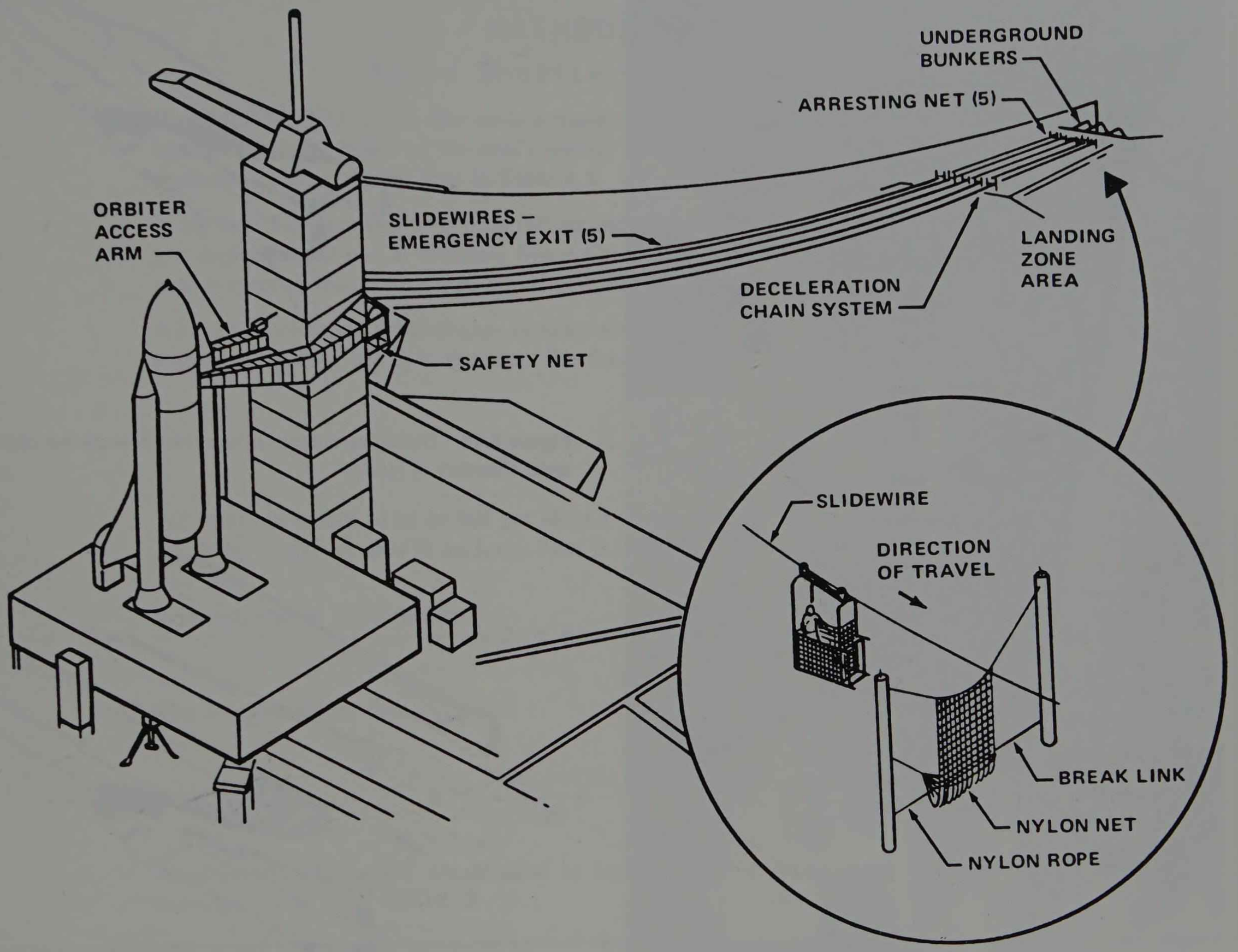


Figure 8.16 Emergency escape while on the launch pad. Crew leaves Orbiter, enters baskets on slide wires, two people per basket. Near the bottom, the baskets catch and drag chains to decrease their speed before they reach the nets which stop them completely. Crew then takes cover in bunkers. *Courtesy of NASA.*

Clouds of smoke and water vapor engulf the area. Much of it comes from water which is poured onto the launch pad area to suppress the intense sound waves produced by the rocket engines. Without sound suppression the Orbiter could be damaged by the acoustic energy. The solid rocket boosters also contribute a great amount of smoke to the scene, but the three main rockets on the Orbiter produce very little visible exhaust. Recall that they are burning hydrogen and oxygen and the product of this combustion is plain water, so hot that the vapor is nearly invisible.

This sequence obviously must be computer controlled; human reaction time is not fast enough to carry it out. Sensors on the main engines continuously send their data to the computer. As long as all readings are satisfactory, the countdown continues. If any sensor gives a reading which is out of acceptable limits, the countdown stops automatically. The liquid propellant main engines can be shut down by simply cutting off the flow of propellant, but once the solid booster engines ignite there is no way to stop. The Shuttle must lift off the launch pad.

Up to the point when the vehicle lifts off the launch pad, the entire operation is under the control of the Kennedy Space Center. Immediately upon liftoff, control of the mission is transferred to the Johnson Space Center in Houston.

Almost immediately after liftoff the vehicle rolls over so the Orbiter is underneath the external tank (Figure 8.18). At about 1 minute after launch the vehicle reaches mach one, the speed of sound, and experiences maximum strain as it accelerates through the dense lower atmosphere. The main engines are throttled back and the regressive grain of the solid boosters decreases their thrust to keep the acceleration

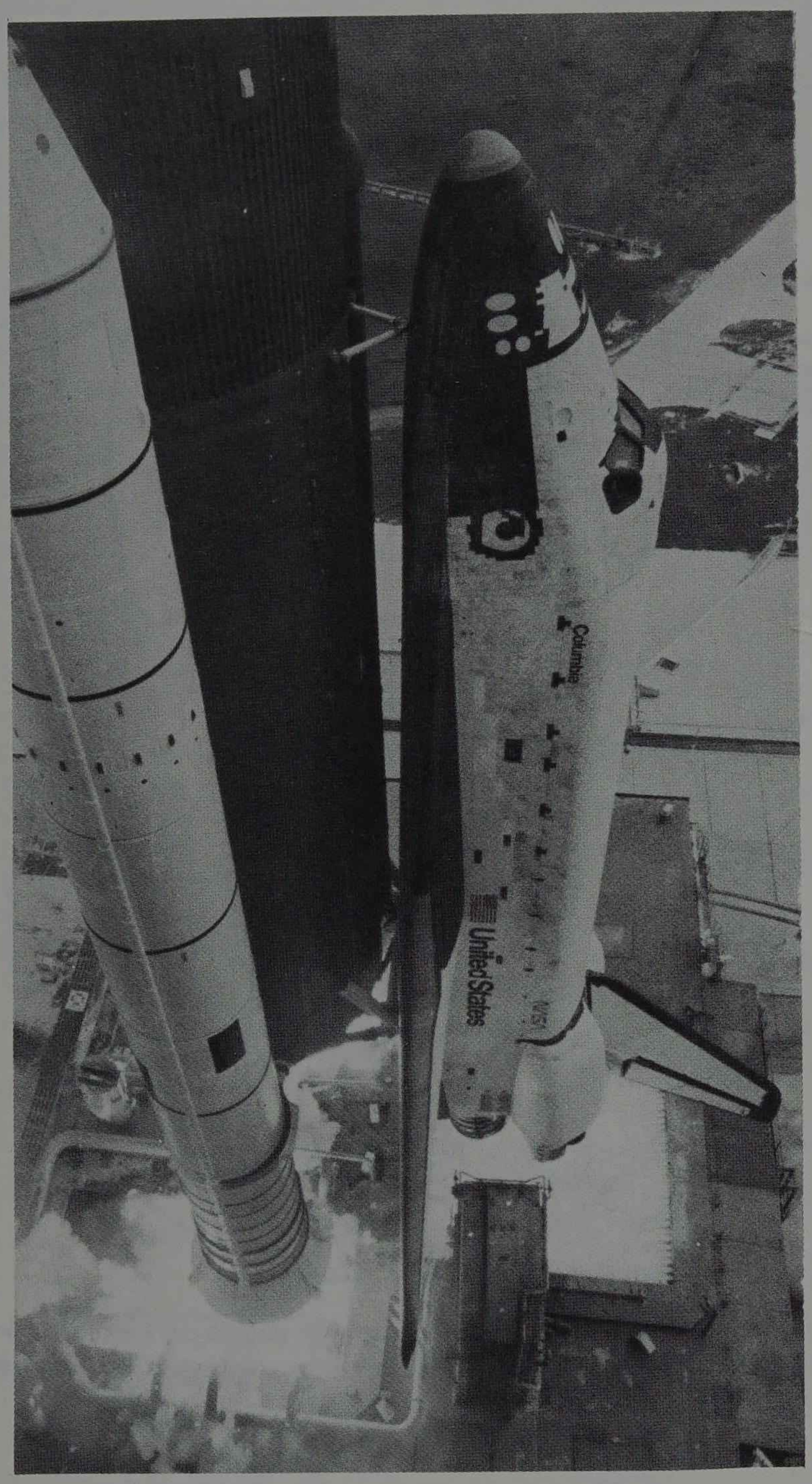


Figure 8.17 Space Shuttle *Columbia* lifts off from the mobile launch platform. *Courtesy of NASA*.

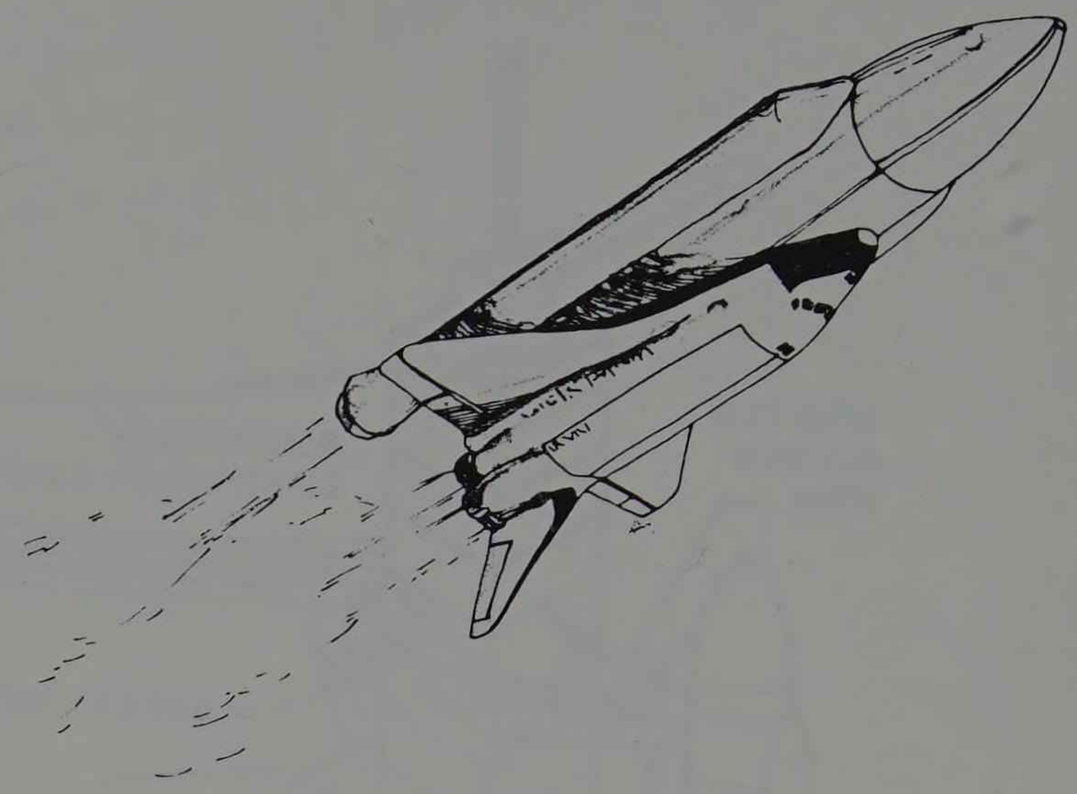


Figure 8.18 During ascent the Orbiter rides beneath the external tank. *Courtesy of NASA*.

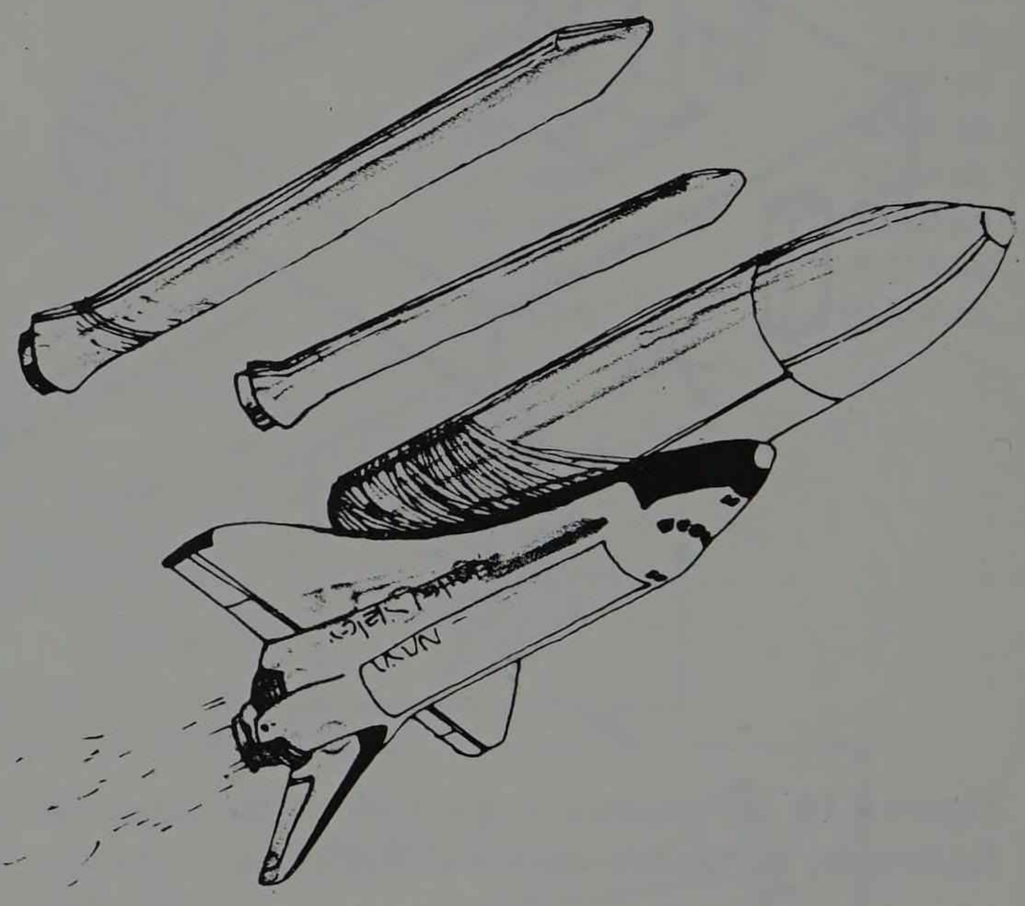


Figure 8.19 Solid rocket booster separation. *Courtesy of NASA*.

below the three-g limit. MATHBOX 8.2 shows how to calculate the average acceleration during this period.

Solid Booster Rocket Operation

The boosters burn out about 2 minutes into the flight at an altitude of about 28 miles and a speed of over mach four. The boosters are jettisoned (Figure 8.19). To prevent a collision, they are moved away from the Orbiter and external tank by a one-half second burn of eight small separation rocket motors, four at the top and four at the bottom of each booster. Even though the boosters have separated, they are still travelling at the same forward speed as the rest of the vehicle. But, because they are no longer under power, they follow a ballistic path arcing upward, then falling back downward into the more dense atmosphere. A barometer-altimeter switch ejects the nosecap at 15,400 feet altitude and the parachutes deploy, first a pilot chute which carries away the nose cap, then a drogue chute which carries the upper conical shaped frustum. Finally three main parachutes open to lower the booster into the ocean. The main chutes, each one 115 feet in diameter, become fully inflated at 2,200 feet altitude. Initially they are falling at over 230 mph, but by the time they reach the water they have slowed to 60 mph.

The booster rockets hanging from their parachutes strike the water bottom end first, forcing water into the empty interior and trapping air in the upper portion. Thus, they float upright in the ocean. The parachutes disconnect

MATHBOX 8.2

Space Shuttle Acceleration

Recall MATHBOX 2.2. We made a rough calculation of the acceleration of the Space Shuttle at takeoff based on Newton's second law of motion. Now let us find the actual acceleration based on the data in Table 8.5.

In the first 1 minute and 6 seconds (66 seconds) after liftoff the Shuttle accelerates from rest on the launch pad at Kennedy Space Center, an initial speed of 914 miles per hour with respect to space, to a final speed of 1,654 miles per hour.

Average acceleration is the change in speed divided by the time interval required to make that change. If we use S_f to represent the final speed and S_i for the initial speed, then

$$a = \frac{S_f - S_i}{t}$$

We want our results to be in feet per second so we multiply by 5,280 feet in a mile and divide by 3,600 seconds in an hour. That is,

$$S_f = \frac{1654 \text{ miles/hr} \times 5280 \text{ ft/mile}}{3600 \text{ sec/hr}} = 2426 \text{ ft/sec}; \; S_i = \frac{914 \text{ ft/sec} \times 5280 \text{ ft/mile}}{3600 \text{ sec/hr}} = 1341 \text{ ft/sec}.$$

The acceleration is, then

$$a = \frac{2426 - 1341}{66} = 16.4 \text{ ft/sec}^2.$$

As expected, the actual acceleration is higher than we found using our simplified assumptions in MATHBOX 2.2.

automatically, beacon lights are turned on, and a radio transmitter begins sending a signal to assist aircraft and ships in finding and recovering the spent motor. A ship tows the rocket to shore where it is disassembled and sent back to Utah to be refurbished and refueled for another flight.

Main Engine and External Tank Operation

Meanwhile, the Orbiter and external tank continue on their way, the three main engines accelerating the vehicle upward. During the first part of the flight, the emphasis is on gaining altitude, getting through the dense part of the atmosphere. Now it is necessary to increase horizontal velocity to reach orbital speed. When the Shuttle reaches an altitude of about 80 miles, it begins a long shallow dive to 73 miles during which its speed approaches the 17,500 mph needed for orbit.

When the hydrogen and oxygen in the external tank are nearly consumed and the vehicle is just short of orbital velocity, the Orbiter's main engines cut off (MECO). A vent valve at the top of the external tank opens and oxygen escapes through the nose cap. A few seconds later the tank is disconnected (Figure 8.20), the venting oxygen causing it to pitch away from the Orbiter and start to tumble. Tumbling assures that atmospheric drag will cause it to break up as it falls back to Earth and lands in the Indian Ocean. There is some uncertainty as to where it will land because of the way it tumbles. The designated impact area is an oval 2,100 miles long by 62 miles wide.

Incidentally, many people feel this is a waste of a valuable resource. External tanks are large, airtight, and structurally capable of being used as living quarters, workshops, or storage tanks. NASA has been urged to stockpile them in a parking orbit for possible future use. The tanks already reach 99 percent of orbital velocity and only a little extra boost would inject them into orbit. There are several objections. One, the payload of the Shuttle flight would be reduced by several thousand pounds. Also, if left in low Earth orbit, the tanks would have to be periodically boosted to higher altitudes to keep them from becoming a hazard to traffic and from eventually burning in. A costly alternative is to strap on rockets and boost them to a higher stable parking orbit. Some planners envision them clustered together as a space station, fitted with rockets and launched to the Moon for a lunar colony, or refilled a little at a time and

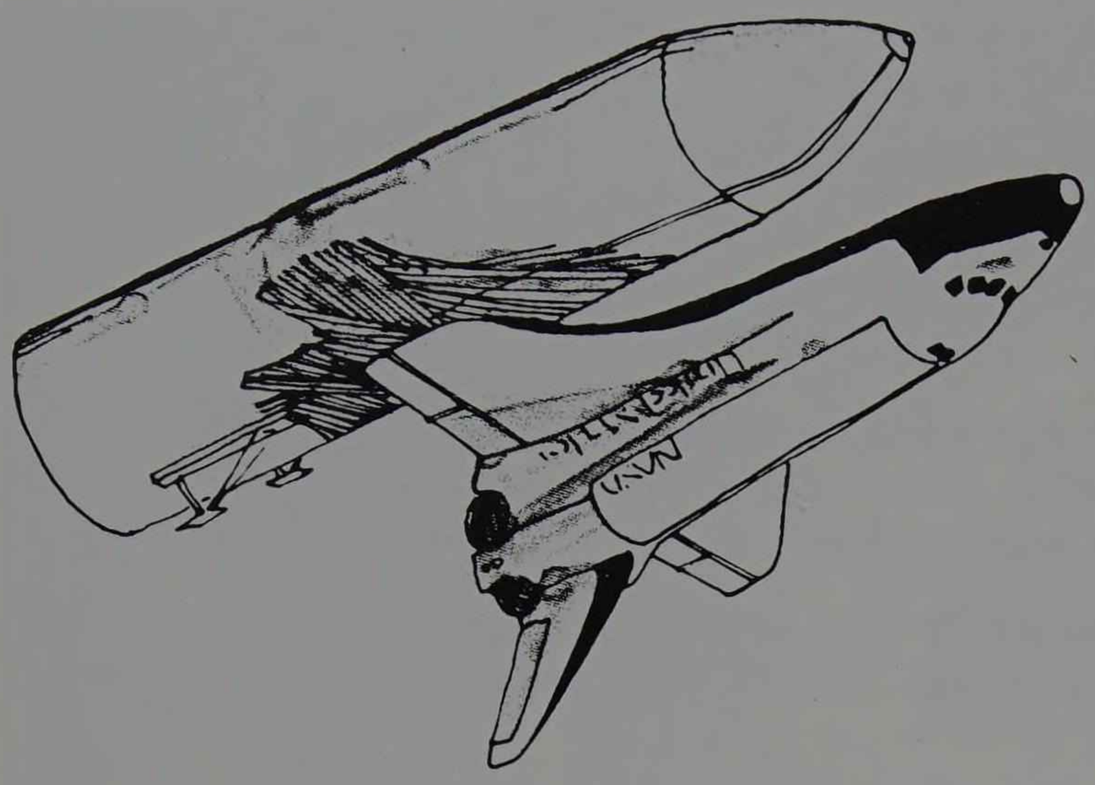


Figure 8.20 Orbiter separates from external tank. *Courtesy of NASA.*

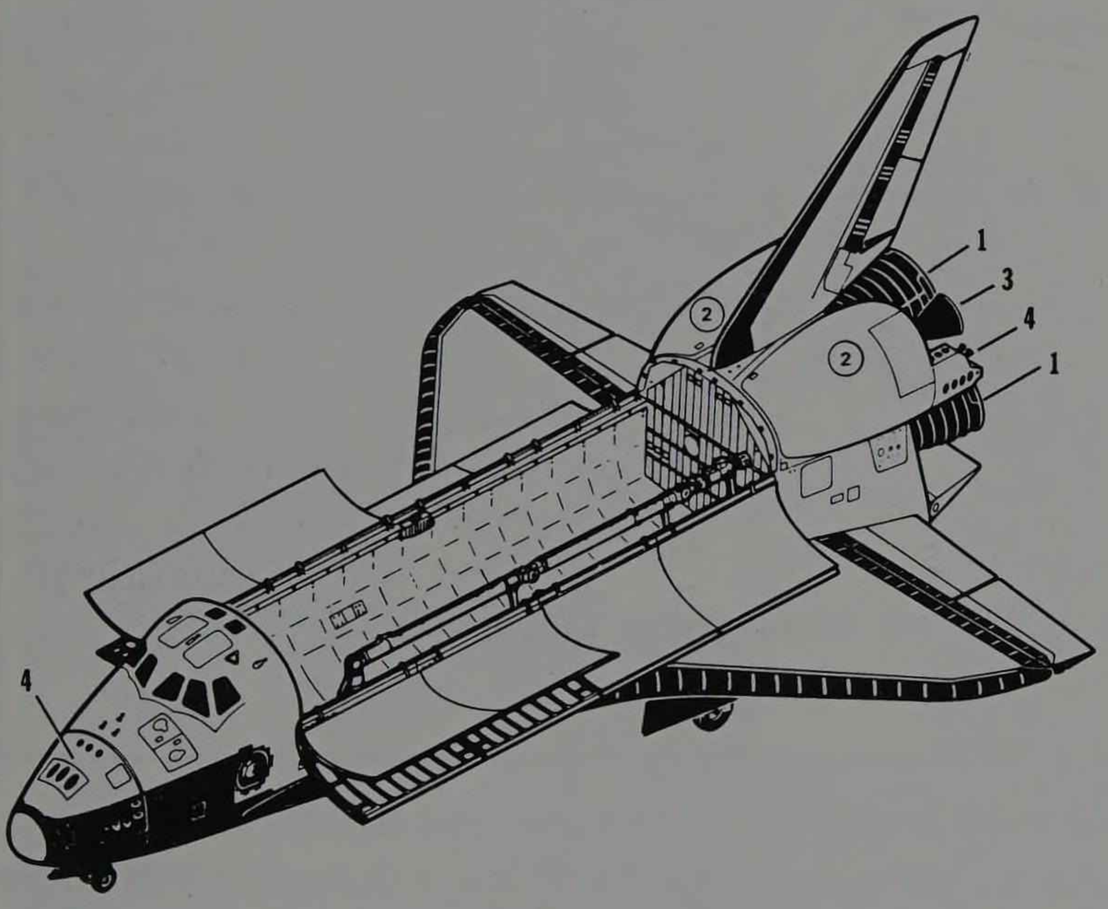


Figure 8.21 Orbiter's propulsion systems: three main engines (1), two orbital maneuvering system (OMS) engines (3), and the reaction control system (RCS) clusters of thrusters in the nose and tail sections (4). Two pods in the rear of the Orbiter (2) hold the OMS engines and their fuel tanks. *Courtesy of NASA.*

used as orbiting ''gas stations'' for vehicles heading to the outer reaches of the Solar System.

Orbit Insertion

A couple of minutes later after the external tank separates, the orbital maneuvering system (OMS) engines are ignited to inject the vehicle into orbit. The two OMS engines, located in the pods just above the main engines on either side of the tail (Figure 8.21), produce 6,000 pounds of thrust each. They are propelled by monomethyl hydrazine fuel and nitrogen tetroxide oxidizer stored in two large pods, one on each side of the tail. These propellants are hypergolic; that is, they ignite and turn to hot gas on

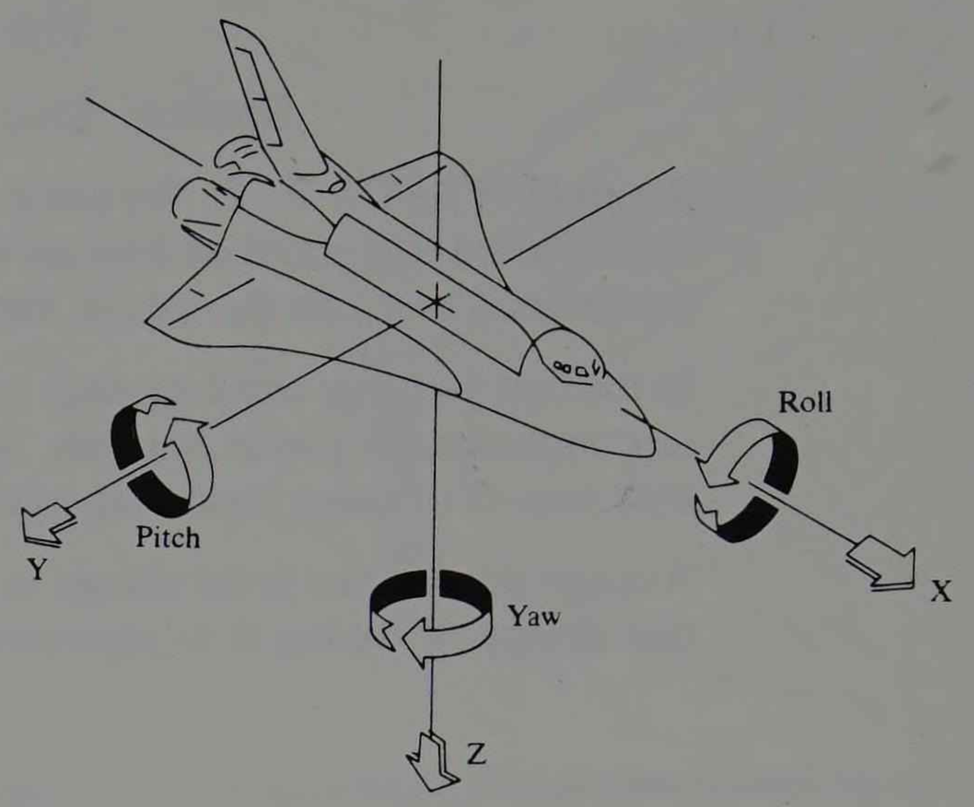


Figure 8.22 Pitch, yaw, and roll. *Courtesy of NASA.*

contact. Since no ignition system is needed, this system is highly reliable. The fuels are forced out of their storage tanks and into the engines under pressure supplied by liquid helium stored in nearby containers.

The length of this OMS burn determines the height of apogee; a longer burn means a higher apogee. Typically the engines are fired for about 2 minutes which increases the speed by a hundred miles an hour. With engines off, the Orbiter coasts to apogee, near 174 miles in the example of Table 8.5. The orbit is now completely determined. After passing apogee the Orbiter will return to the point where the OMS engines cut off, about 83 miles. This will be perigee. However, atmospheric drag on the vehicle is sufficient at that altitude to rapidly decay the orbit. Energy (speed) is lost to friction each time the Orbiter passes perigee. With less speed at perigee, the vehicle will not be able to reach as high at apogee. Thus, apogee lowers with each orbit, increasing the drag even more, until finally the vehicle no longer has sufficient speed to remain in orbit. To prevent this from happening, the OMS engines are ignited again at apogee, a procedure called ''apogee kick.'' This increase in energy raises the height of perigee above the altitude of excessive atmospheric drag. If the apogee kick is of just the right duration, perigee is raised to the same height as apogee and the orbit becomes a circle. Table 8.5 shows an OMS 2 burn of 96 seconds to circularize the orbit at about 174 miles.

Attitude Control Thrusters

While in orbit the attitude (not altitude) of the Orbiter, that is, its orientation with respect to Earth, is controlled by the 44 thrusters of the reaction control system (RCS). As shown in Figure 8.21, 14 primary thrusters and 2 vernier thrusters are located in the nose; 24 primary and 4 vernier thrusters

are located in the rear, on the back of the two pods. Primary thrusters produce 870 pounds of thrust; vernier thrusters, used for ''fine adjustment,'' produce just 24 pounds.

Firing the proper combination of thrusters causes the Orbiter to pitch (nose up or nose down), yaw (swing nose left or right), or roll (Figure 8.22). Recall Newton's law of action and reaction. For example, firing a thruster pointed upward from the nose causes the nose to pitch down. Firing a rear end thruster toward the right causes the tail to move left and the nose to yaw to the right. The Orbiter can automatically keep itself in any position, such as tail pointed straight down toward Earth and nose straight up at the sky. Different jobs require different orientations. For tasks which must be carried out without vibration, the Orbiter is allowed to drift free without firing any of the thrusters. If no particular attitude is necessary for the job at hand, the Orbiter is usually oriented with the white top side toward the Sun to reduce solar heating and reduce the energy consumption of the air conditioners.

Propellants for these thrusters are monomethyl hydrazine and nitrogen tetroxide, the same propellants as the OMS. In fact, propellants from the OMS tanks can be fed to the reaction control system if needed. See Figure 8.23 for a diagram of one of the pods.

Because their thrust is so small, operating the reaction control system has little effect on the size or shape of the orbit. Small orbital adjustments in velocity are possible with the reaction control system, but if a large orbital change or rendezvous with a satellite is needed, the OMS engines (6,000 pounds thrust each) are used.

Reentry and Landing

To leave orbit and return to Earth, the Orbiter must again fire the OMS engines. Sixty minutes before touchdown, over the Indian Ocean, the Orbiter is turned by the reaction control system so the engines are pointed in the direction of motion. Engines are fired in that position, against the motion, in order to slow the vehicle down and transfer it to a new orbit in which perigee lies inside Earth, that is, the orbit intersects the ground. As the Orbiter begins to ''fall'' toward Earth, its speed once again increases by two or three hundred miles per hour. The thrusters turn the vehicle again so it is falling underside first with a nose-high attitude.

Twenty-five minutes later, at an altitude of 50 miles, the Orbiter encounters sufficient atmospheric drag to act as a brake. During the next 20 minutes, it drops to 15 miles altitude and slows to about 1,700 mph, as its kinetic energy of motion is transformed to heat energy. Maximum heating occurs at around 42 miles while moving at 15,000 mph. The heat ionizes the surrounding air by tearing electrons from the atoms so that a sheath of oxygen ions, nitrogen ions, and electrons, called a *plasma,* encloses the descending Orbiter. It is not possible to transmit radio signals through the plasma sheath so for 13 minutes the Orbiter has no communications with the ground. It can easily be tracked by radar during that time, however.

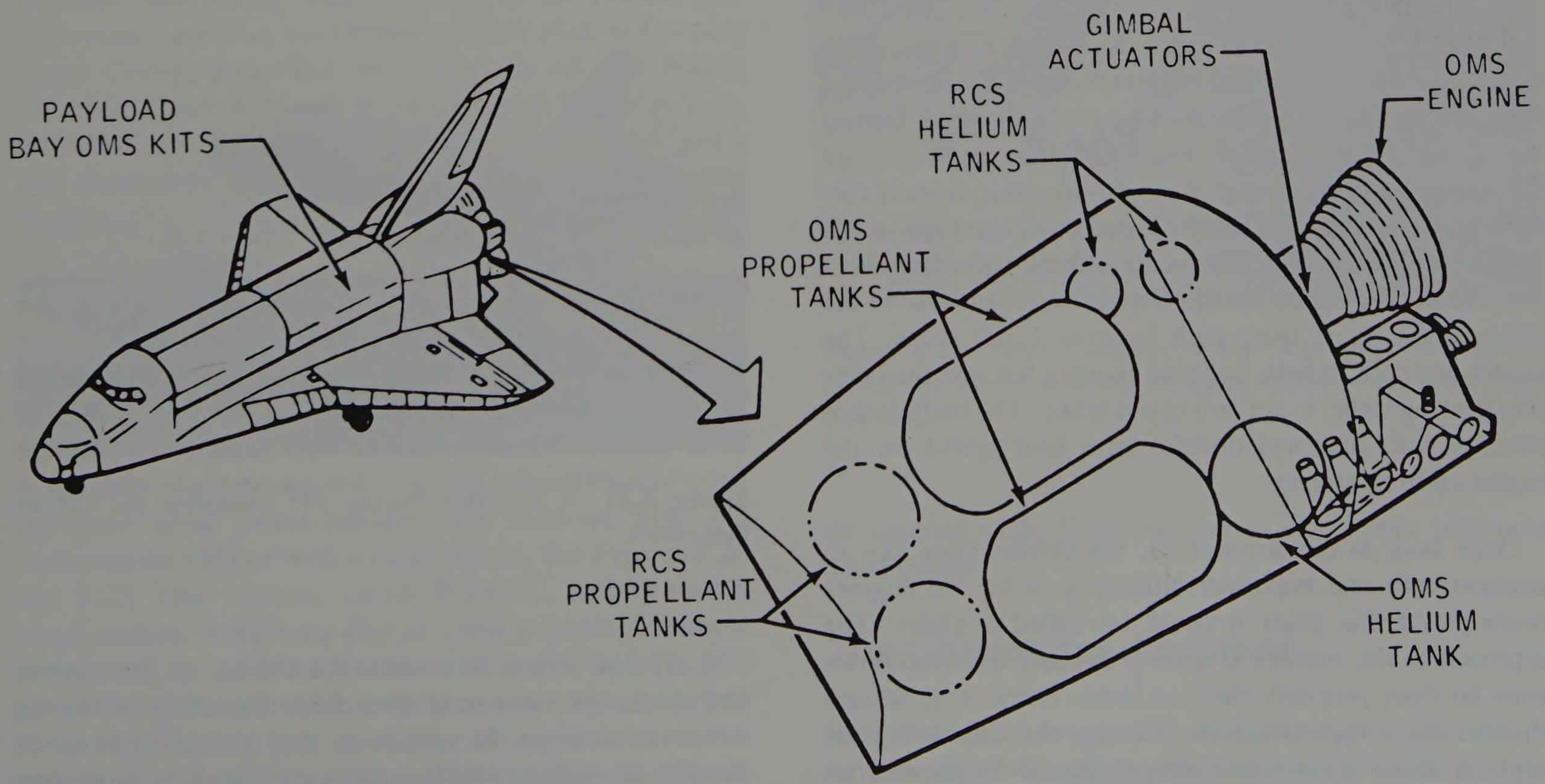


Figure 8.23 Left pod at rear of Space Shuttle. Propellants for the OMS and RCS engines are forced from their tanks under pressure supplied by the helium tanks. OMS and RCS are interconnected so the propellants from either system can feed the other. *Courtesy of NASA.*

Figure 8.24 Space Shuttle *Columbia* approaching Edwards AFB, California, for a landing. *Courtesy of NASA.*

While in the vacuum of space the wings, elevons, body flap, vertical stabilizer, and rudder (Figure 8.6) are ''excess baggage''; without air they serve no useful purpose. During reentry the Orbiter's altitude and speed decrease as it enters the denser atmosphere and these aerodynamic control surfaces begin to operate. Unlike the earlier manned spacecraft of the Apollo era which followed a ballistic trajectory like a cannonball, the Space Shuttle Orbiter can maneuver to the left or right of its entry path by over 1,200 miles. The rudder can split in half, one side moving left and the other side moving right, to act as a speed brake. The body flap is covered with tiles and doubles as a heat shield for the engines during reentry.

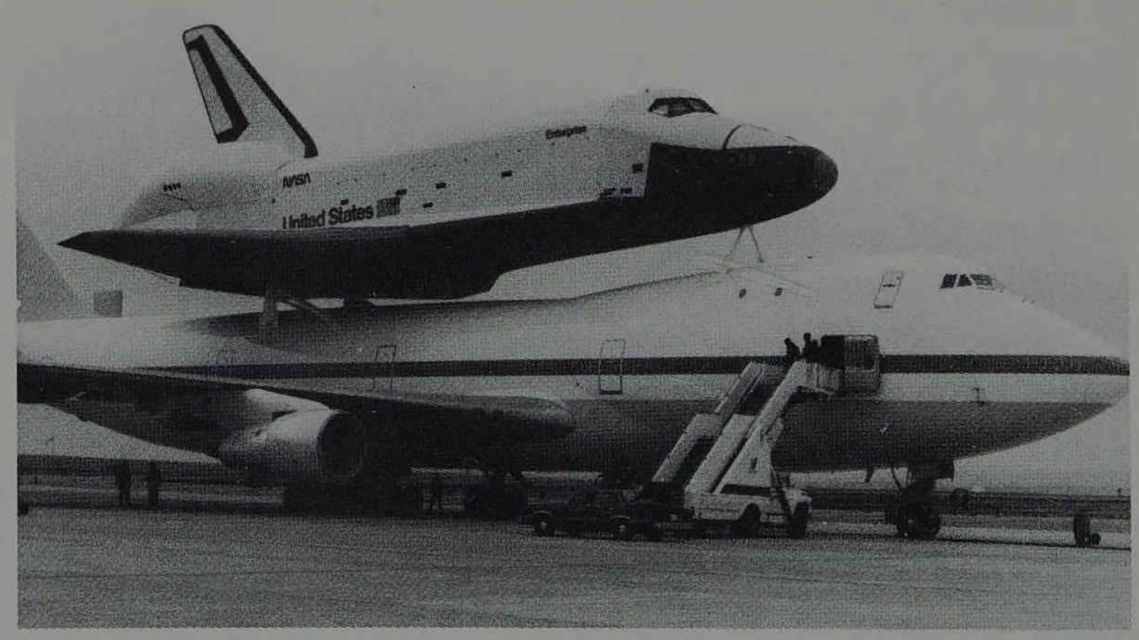


Figure 8.25 A modified Boeing 747 transports the Orbiter piggy-back.

Once back in the atmosphere, the Orbiter flies like an airplane with one important difference: it has no engines running. At this point it could be called a glider. The approach to the runway (Figure 8.24) and the touchdown must be done precisely the first time. There is no second chance. As it approaches the runway, the Orbiter's glide angle is about seven times steeper than a commercial jet liner. At touchdown its speed is a little more than 200 miles per hour.

A crew of technicians meets the Orbiter on the runway and checks the exterior of the vehicle for safety before the astronauts emerge. In particular, they use instruments to ''sniff'' around the OMS engines and thrusters to be sure there is no leakage of toxic propellants. Also, it takes time for the Orbiter to cool off so it can be touched. Temperature

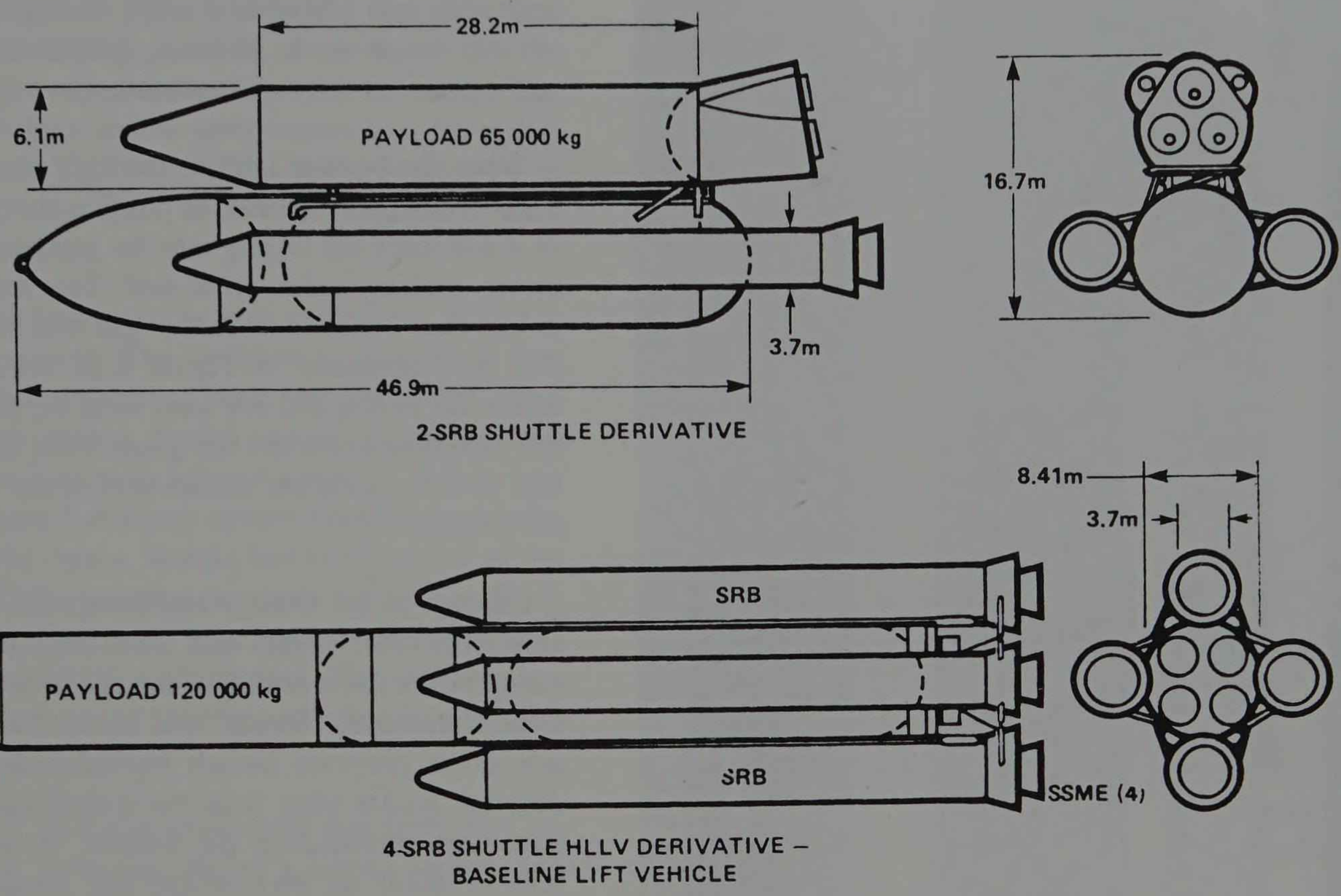


Figure 8.26 Cargo vehicles derived from the Space Shuttle. Solid rocket boosters and external tank are identical to the Shuttle; the Orbiter is replaced by a cargo vessel. *Courtesy of NASA.*

of the top surface of the Orbiter is about 200 °F and the hatch cover is 300–350 °F after landing!

Most Orbiters have touched down in the desert at Edwards Air Force Base, California. Relatively few Shuttle missions have ended with a landing at the Florida site. Following a mission, the Orbiter is flown back to Kennedy Space Center, piggyback on a specially adapted Boeing 747. See Figure 8.25. At Kennedy Space Center it is refurbished, mated to a pair of reconditioned boosters and a new external tank, checked out, and made ready for another flight.

Unmanned Shuttle Derivatives

Some missions may not need a crew. For example, building the space station will require depositing many loads of building materials in orbit for later assembly by astronauts. A freighter could be derived from the present Shuttle using the same solid rocket boosters and external tank, but replacing the Orbiter with a cargo vessel. See Figures 8.26 and 8.27. One version, called Shuttle-C, simply uses a cargo canister something like an Orbiter fuselage without wings, tail, or crew compartment. It could haul 140,000 pounds to a 100 mile orbit, more than twice the capacity of the Orbiter payload bay. In another Shuttle derivative, two additional solid rocket boosters are strapped on and a cluster of four main engines is attached to the external tank. The 260,000 pound payload leads the way at the forward end of

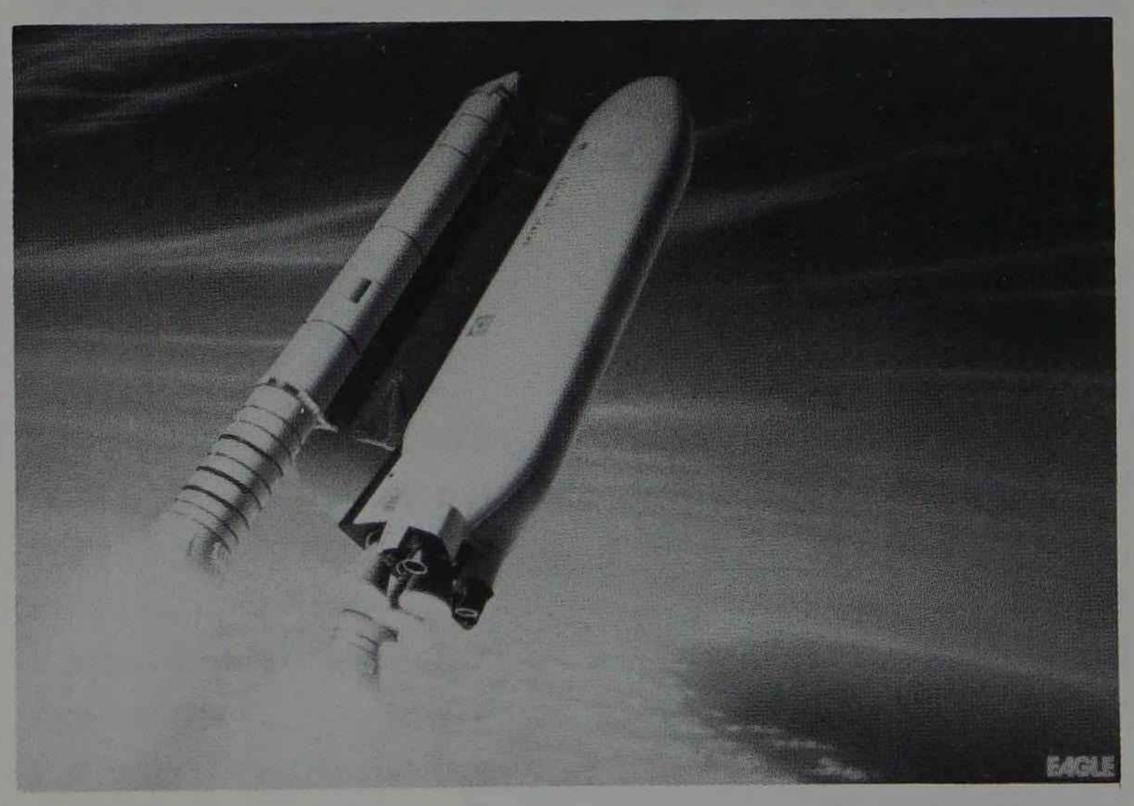


Figure 8.27 Artist's concept of the cargo ship, Shuttle-C, a 2-SRB derivative. *Courtesy of Eagle Engineering; artist Mark Dowman.*

the external tank. Such vehicles would require minimum development.

The Challenger *Accident*

So, what went wrong with this marvelous machine on January 28, 1986, when, after 24 successful flights, the Shuttle blew up on its way to orbit, destroying the Orbiter *Challenger* and its crew?

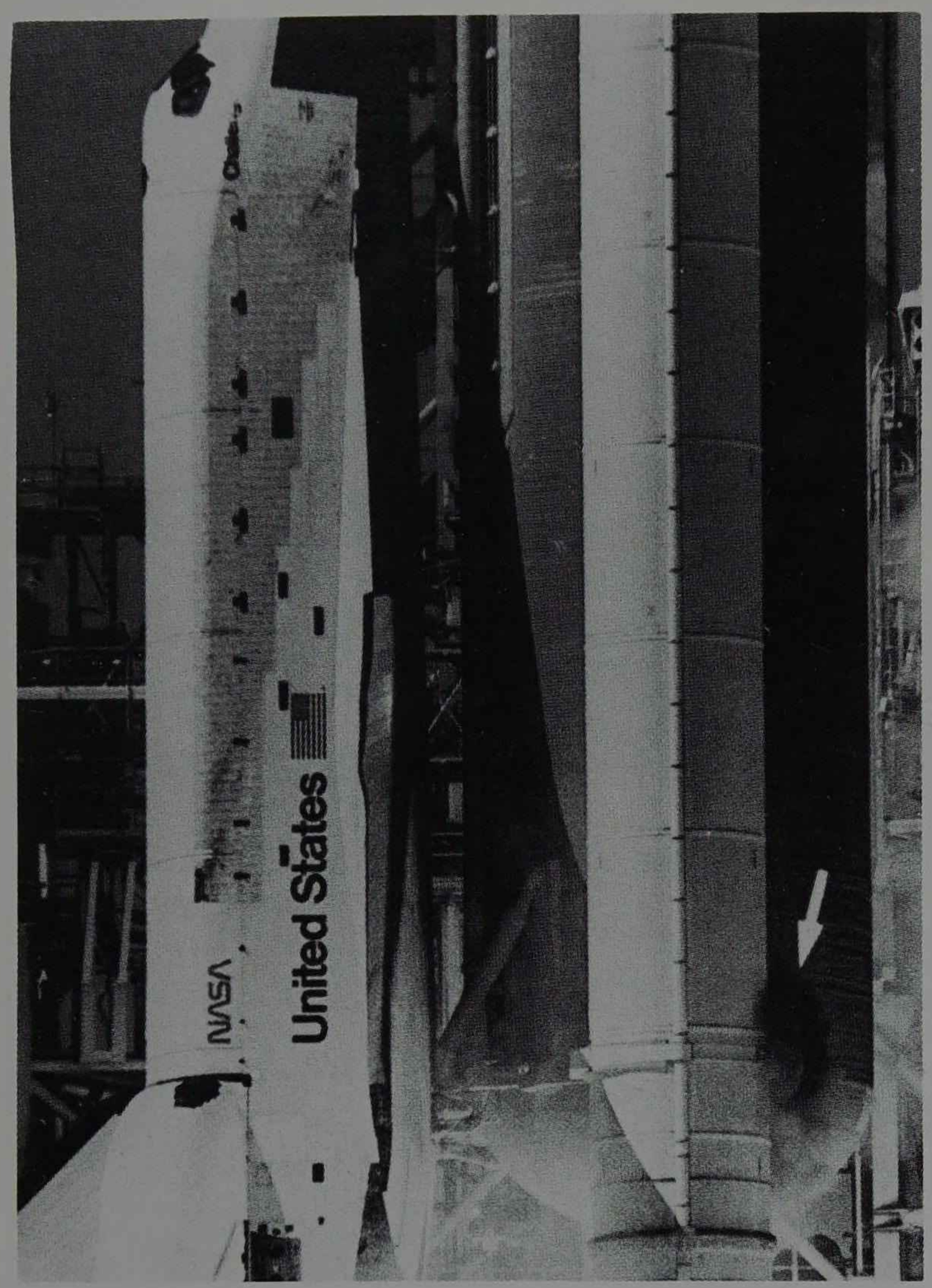


Figure 8.28 The puff of smoke when boosters ignited shows where the seal failed and hot gases leaked through the joint. *Presidential Commission Report, NASA photo.*

A Presidential Commission studied all aspects of the *Challenger* flight and published a report of its findings. The Commission determined that the primary cause was the failure of a joint between two segments of the solid rocket booster. Figure 8.28 is a photograph of the *Challenger* a second or so after the boosters ignited; a puff of smoke can be seen escaping at the failure point. Eventually the hot gases from the burning propellant burned through the side of the booster and flames impinged on the external tank. The bottom of the external tank ruptured about 1 minute into the flight, spilling out the hydrogen which burned violently in the air. The entire vehicle broke up about 15 seconds later.

As pointed out before, the four segments of the solid rocket booster are assembled at Kennedy Space Center, one stacked on top of another. To assure a tight fit, sealed against the enormous pressure of the combustion taking place inside, the top of each segment has a U-shaped groove, called a *clevis,* into which the bottom of the next segment, called a *tang,* fits. Figure 8.29 is a simplified diagram of the joint. Because metal against metal does not seal well, two rubber-like seals, *O-rings,* are set into slots cut into the clevis. In addition, zinc chromate putty fills the space between the two segments.

When the booster ignites, the high pressure gas inside is supposed to push against the putty to compress the air ahead of it and force the O-ring into the gap between the tang and clevis, making a leak-proof seal. This seal must take place in less than 1 second or the hot gas will blow by the O-ring. The puff of smoke in Figure 8.28 occurred at the point where the O-ring did not seal. First the putty came through the gap, then came the hot gases from the burning propellant which caused the destruction of the external tank and the Orbiter.

Damage to the O-rings had been seen in boosters recovered from other flights and some engineers had expressed concern. On the morning of the accident the temperature at Cape Canaveral, Florida, was below 30 °F, colder than at any other previous launch by more than 25 Fahrenheit degrees. Icicles hung from the mobile launch platform and structures surrounding the Shuttle. A work crew had to remove them so they would not break free during the vibrations of takeoff and damage the vehicle, particularly the soft tiles on the Orbiter. At lower temperatures both the

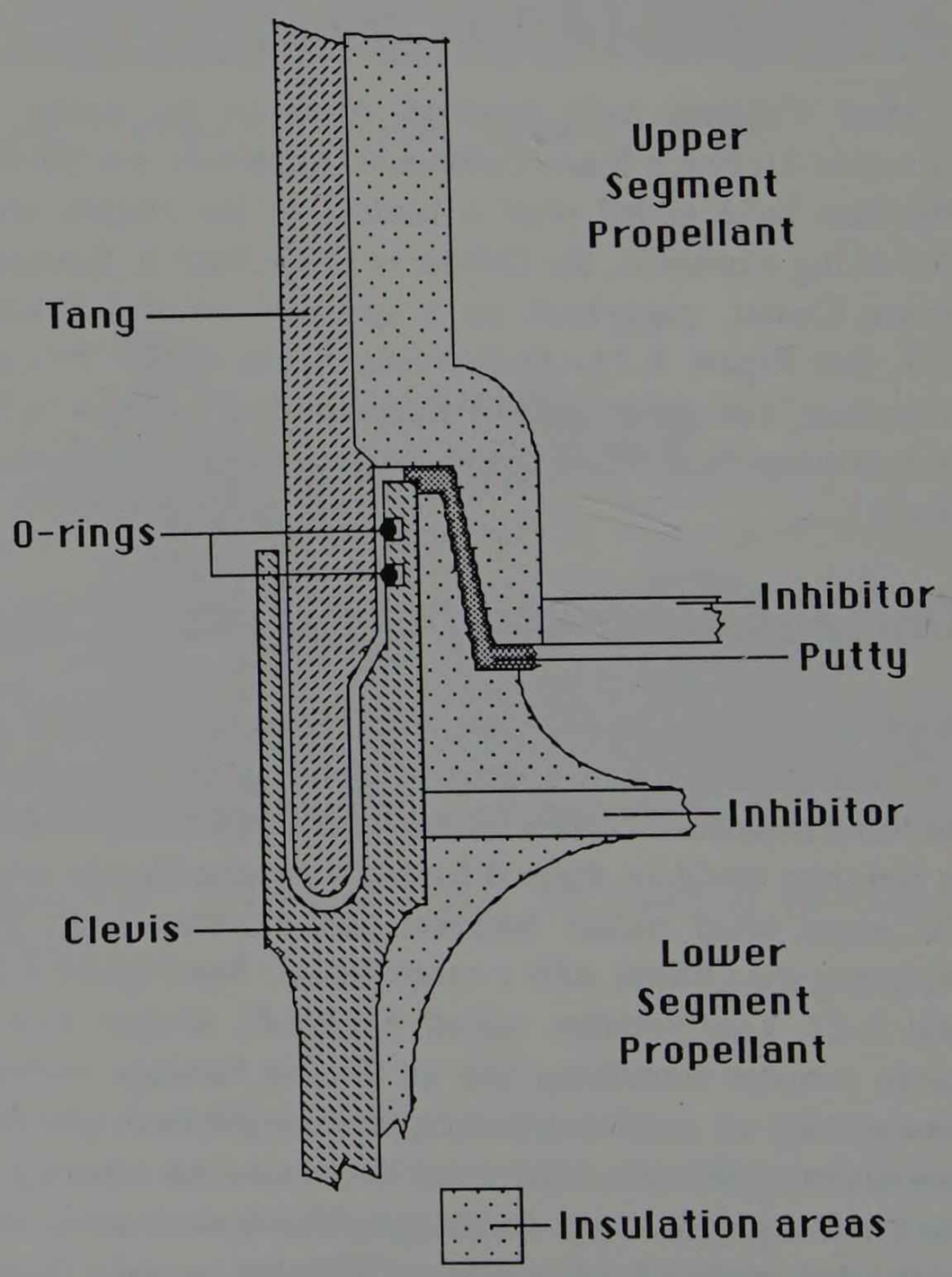


Figure 8.29 Original design of joint connecting two segments of the solid rocket booster. *After NASA diagram.*

O-rings and the putty are less flexible and the seal takes longer to complete. They had not been tested at the temperatures that prevailed at the Cape that morning. The performance of O-rings at low temperature had been discussed by NASA and Thiokol officials in the hours prior to launch. Over the objections of several engineers, they decided to go anyway.

The Presidential Commission was critical of NASA's decision-making process. The decision to launch on that fateful morning was certainly a poor one. Although there was no outside intervention, NASA people, in general, felt pressure among themselves to achieve a goal of 24 launches per year. In retrospect that seems to have been an unrealistic flight schedule. The Space Shuttle had been touted as the primary means of transportation to space for both military and civil missions. Therefore, development of unmanned, heavy lift vehicles had been terminated. The country was completely dependent on the Shuttle, and when it failed, the space program was grounded.

The Commission was also concerned that there was no means for the crew to escape during a launch failure. On the initial test flights, the Orbiter *Columbia* was equipped with ejection seats for the two pilots. When testing was completed, they were replaced with the operational seats to save space and reduce weight. It would not have been possible to supply an entire seven person crew with ejection seats and exit hatches for each one. In case of failure of one or more engines, the plan was to ride the Orbiter to a landing back at the launch site, in southern Europe, in north Africa, or, as a last resort, to ditch in the ocean, depending on the speed of the vehicle when the emergency occurred. Even with an ejection system, it is doubtful that the crew could survive a catastrophic explosion. There was no warning of trouble either at mission control or in the *Challenger* until the external tank ruptured. Then it was too late.

Since the accident, all of the Commission's findings have been acted on by NASA. The redesigned joint is shown in Figure 8.30. Weather stripping and heat tape will cover the joint, also.

For crew escape, an experimental extraction system, usable during a controlled glide at altitudes between 5,000 and 20,000 feet, at a speed of about 200 miles per hour, is shown in Figures 8.31 and 8.32. A small rocket is expelled from its storage canister by gas pressure. When it reaches the end of a 10 foot lanyard, the 2,000 pound thrust rocket motor fires for a tenth of a second to pull the crew member, parachute, and survival pack free of the Orbiter, clearing the wingtip by 30 feet. A different type of escape system (not shown here) makes use of a 21 foot telescoping rod extending from the side of the hatch opening. The crewmember clips a ring onto the rod and slides down and out away from the vehicle before opening the parachute.

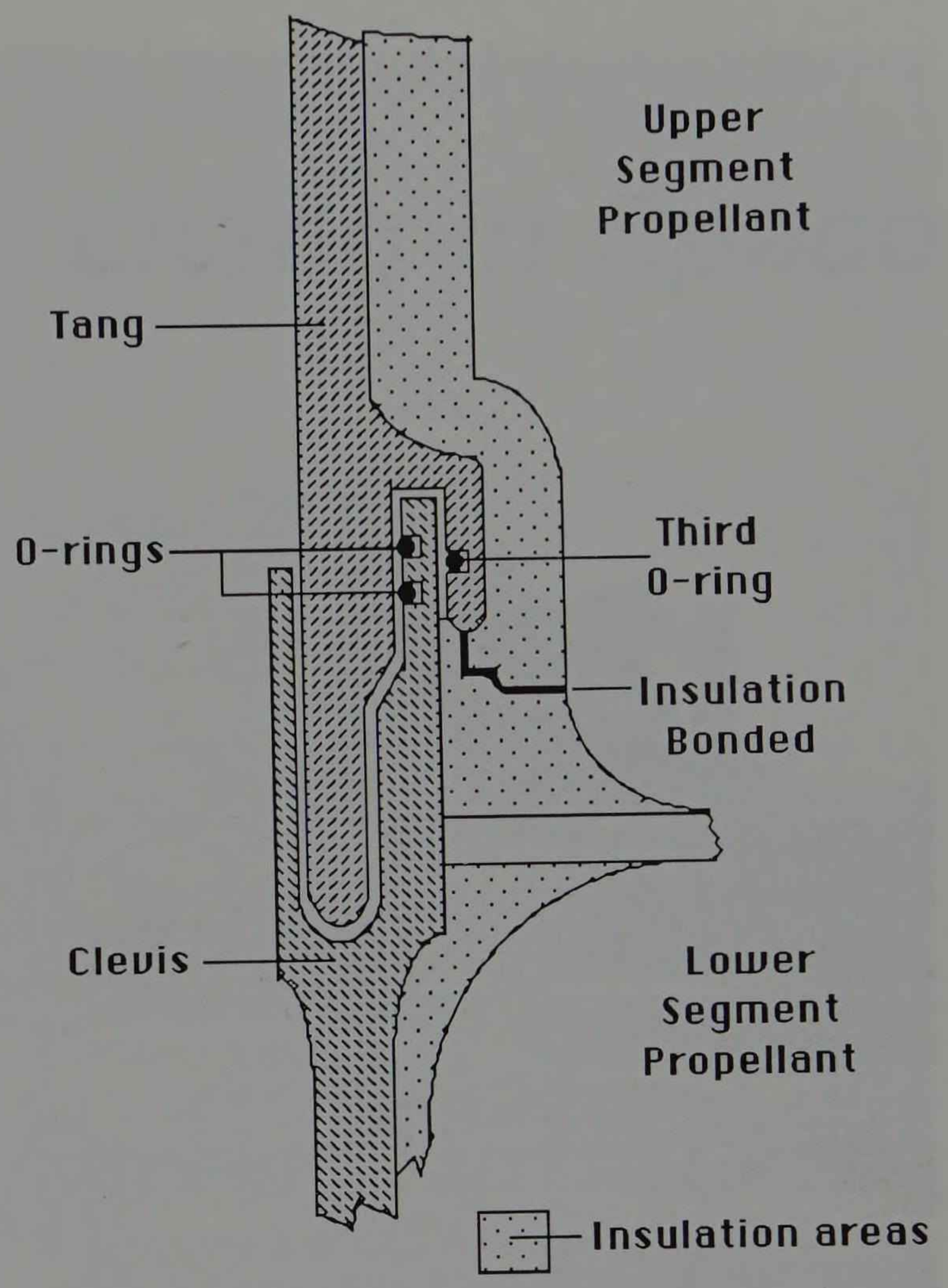


Figure 8.30 Redesigned joint for solid rocket boosters. A third O-ring is added and bonded insulation replaces the zinc chromate putty. This may not be the final design. *After NASA diagram.*



Figure 8.31 Crew escape system under test by NASA. A dummy is in place in a mockup of the Orbiter's hatch area. The television camera records the ejection. *Courtesy of NASA.*

These and other actions by NASA should result in a safer, more reliable Shuttle.



Figure 8.32 Test of crew escape system. A tractor rocket is fired to pull the astronaut out of the Orbiter. In this test, the dummy is pulled out of the mockup of the Orbiter hatch and over the side of a cliff on Hurricane Mesa, Utah. *Courtesy of NASA.*

DISCUSSION QUESTIONS

1. Why are the main engines started first? Why not fire the solid rocket boosters first?
2. How is the Orbiter steered when it is on its way to orbit? when it is in orbit? when it returns to Earth?
3. Why, do you suppose, does the Orbiter fly under the external tank on its way to orbit?
4. In assembling the booster rockets, why not just bolt the segments together?
5. At what points in a flight would it be infeasible to bail out of a disabled Orbiter?

ADDITIONAL READING

Allaway, Howard. *The Space Shuttle at Work*. NASA SP-432, Government Printing Office, 1979. Easy reading, written before first flight.

Joels, Kerry M., and Gregory P. Kennedy. *The Space Shuttle Operator's Manual*. Ballantine Books, 1982. Very detailed and complete, popular reading level.

NASA. *Space Shuttle News Reference*. Government Printing Office. Everything you always wanted to know about the Shuttle.

Presidential Commission on the Space Shuttle *Challenger* Accident. *Report to the President*. Government Printing Office, 1986. Thorough investigation and report.

Chapter 9

Living in Space

For millions of years the human body has adapted to living on Earth with the normal force of gravity, where up and down are clearly defined. The atmosphere is 21 percent oxygen and 78 percent nitrogen at 14.7 pounds per square inch pressure. Food and water are available in abundance. All these things are absent in space. If people are to survive in space, they must take a suitable environment with them, particularly air at a proper temperature and pressure. If they are to remain for an extended period of time, they must have food and water. In weightlessness the body begins to deteriorate in a number of ways and some arrangement must be made to keep physically fit by exercising or perhaps by creating artificial gravity. Protection from cosmic and solar radiation is necessary. In addition, being cooped up in a small space with a few other people for a long time can lead to sociological and psychological difficulties. All these factors must be considered in designing spacecraft and in planning missions.

Cabin Atmosphere

The Space Shuttle Orbiter cabin is shown in Figure 9.1. Living space is in the middeck, and life support equipment is mostly in the lower deck, accessible through hatches in the floor of the middeck.

A life support system must provide oxygen to breathe, remove exhaled carbon dioxide and other gases, and maintain a comfortable temperature. Poisons can accumulate in the spacecraft atmosphere. Excess methane gas could be a problem if the air purification system failed. More serious would be an increased level of exhaled carbon dioxide. At first the astronaut's breathing rate would increase noticeably. Then hearing ability would be reduced, followed by dizziness, nausea, mental confusion, convulsions, and unconsciousness.

In the Space Shuttle Orbiter, the atmosphere is a dupli-

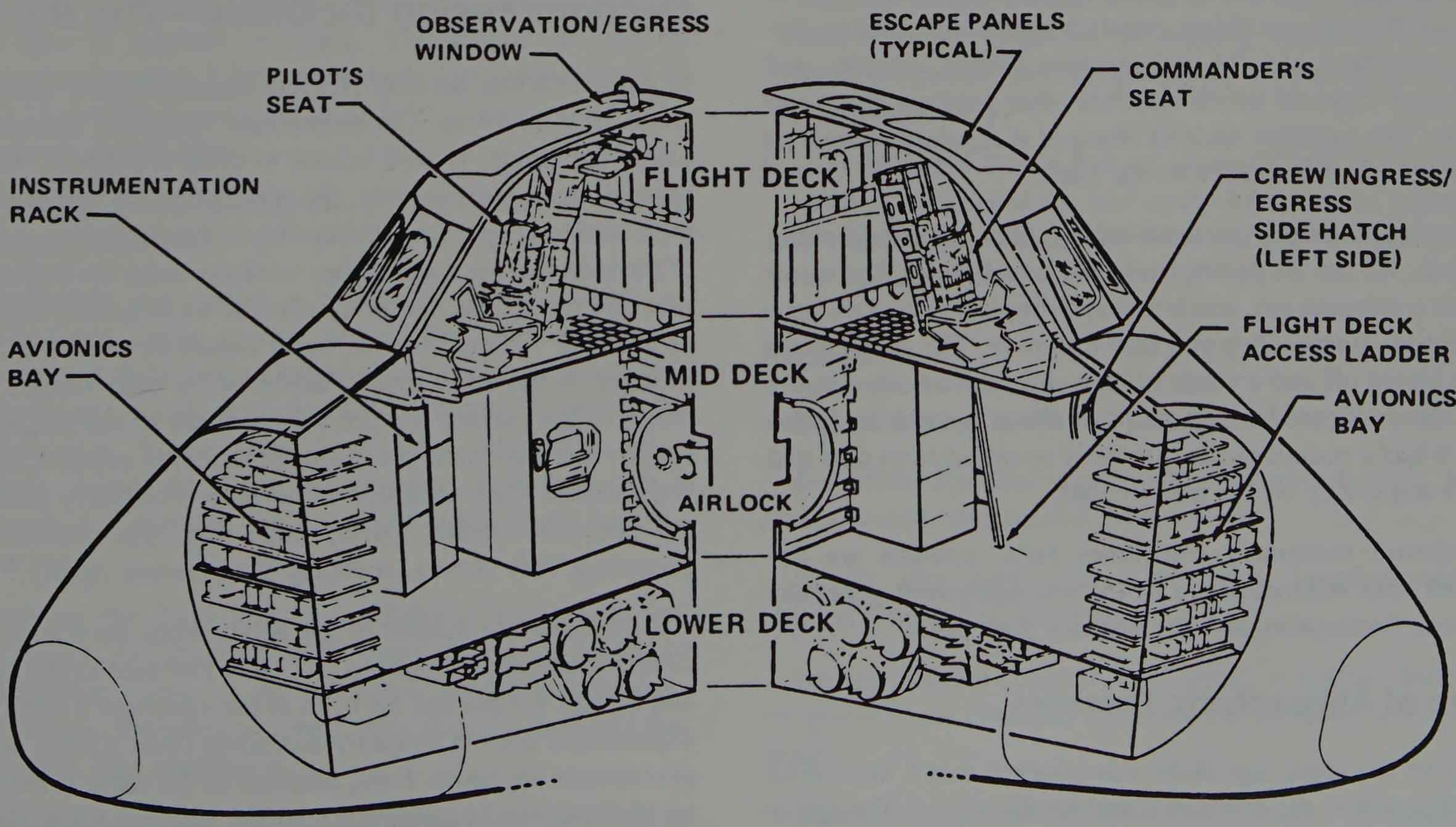


Figure 9.1 Space Shuttle Orbiter cabin. *Courtesy of NASA.*

cate of the atmosphere on Earth at sea level: 21 percent oxygen, 78 percent nitrogen, 14.7 pounds per square inch (psi) pressure. The Apollo spacecraft used a pure oxygen atmosphere at 5 psi pressure. Pure oxygen is very reactive and the launch pad fire (Chapter 1) showed the danger of using it unless the spacecraft is made absolutely fireproof and the pressure is kept lower than normal. The Skylab space station had an atmosphere of 75 percent oxygen and 25 percent nitrogen at a pressure of 5 psi. Other inert gases such as argon have been considered as a substitute for nitrogen.

An automatic system maintains the proper oxygen-nitrogen ratio. It senses the amount of oxygen in the air and adds more oxygen or more nitrogen, as necessary, from storage tanks.

Maintaining a comfortable temperature, in the range 65 °F to 80 °F, requires cooling, not heating. Body heat, solar heat, and heat generated by the equipment are removed by a refrigerator air conditioner. Excess heat is dumped into space via radiators located inside the cargo bay doors. The doors must be opened and the radiators exposed to space for the system to work. Your refrigerator does the same job, removing heat from the box and dumping it into the kitchen via a radiator on the back or bottom. Notice how hot the radiator gets when the refrigerator is running.

On Earth, air circulates because warm air is less dense than cold air. Gravity causes the cooler, denser air to sink while the warm air rises. But in orbit, when weightless, air will not circulate of its own accord, and blowers must be used to keep it from stagnating. These blowers also move the air through purifying canisters containing lithium hydroxide which absorbs and removes carbon dioxide, and activated charcoal which removes other noxious gases and odors. The canisters must be changed at regular intervals as they become saturated with the gases.

Excess moisture is removed by the air conditioning system. As the air passes over cold metal plates, the water vapor condenses out, much as water droplets collect on your bathroom mirror when you take a shower. The droplets are then blown off into a waste storage tank. Soviet cosmonauts use the condensed water, but American astronauts found that it had a peculiar taste, probably acquired from dust and other impurities on the metal plates.

Because machinery sometimes fails, systems are designed with redundancy. Life-critical equipment generally has two backups in case the primary goes out.

Loss of Atmospheric Pressure

Early in the space age there was concern that a meteoroid could puncture the spacecraft and let the air out. Complete loss of the atmosphere from the cabin would, of course, kill everyone. Although the concern over meteoroid impacts proved to be exaggerated, an underlying and realistic concern is that mechanical failure of some component of the spacecraft, space suit, or helmet could be disastrous. Three Russian cosmonauts died in 1971 when a valve in their Soyuz II failed.

Death comes quickly and quietly when the atmospheric pressure is suddenly reduced to almost zero as it is in the near vacuum of space. First, air in the lungs would be expelled in one quick exhalation. As blood flowed through the lungs, the oxygen in the blood would also be released to space. Symptoms of hypoxia (the lack of oxygen)—dizziness and blurred vision—would be evident. Without a continuing fresh supply of oxygen, the brain would die in 2 to 4 minutes.

Early in the space age it was thought that the blood would boil and a body would literally explode when exposed to near zero atmospheric pressure. Water boils at 212 °F at sea level. But at Colorado Springs, where atmospheric pressure is only about 80 percent of sea level pressure, water boils at about 190 °F. Ascending to higher altitudes, one would eventually reach the point where the pressure is so low that water would boil at 98.6 °F, body temperature. This fact led to the false conclusion that, in the near vacuum of space, blood would boil and a body would explode. Skin is a strong membrane, however, and it is more likely that the body fluids would evaporate slowly rather than explosively. The skin would blister and some blood vessels would rupture producing bruises. But the astronaut would have been brain-dead long before.

Decompression Sickness—The Bends

In extravehicular activity (EVA), decompression sickness could be a problem. Decompression sickness, commonly called the bends, is well known to deep sea divers. When descending in a diving suit, the pressure in the suit must be increased to keep it from collapsing under the great pressure of the surrounding water. After working under the higher air pressure for a time, the body absorbs an excessive amount of nitrogen. Oxygen is used up in metabolic processes, but nitrogen in the air is simply absorbed by body tissues. On rising to the surface the pressure reduces to normal atmospheric pressure and the nitrogen bubbles expand in the body tissue. This condition is not only extremely painful, but can cause death. Divers cope with this problem by ascending very slowly, reducing the pressure slowly.

Astronauts are subject to the bends when they leave the cabin, where the pressure is 14.7 psi. Pressure in the space suit is only 4.3 psi and nitrogen in the astronaut's body will expand as it does in a rapidly ascending diver's body unless precautions are taken. First, pressure in the cabin is reduced to 10.2 psi for 24 hours prior to the planned EVA. Thus, astronauts become acclimated to a lower pressure over a period of time. Second, they breathe pure oxygen for a time

before leaving the cabin to allow the body to eliminate most of the nitrogen. NASA has been developing a space suit which will hold an atmosphere at 8.2 psi. If one can be successfully built, bends will be less of a problem. It has been noted that women are at a greater risk than men.

Food

The first American to eat in space was John Glenn in 1962, squeezing applesauce through a tube into his mouth. Before the flight, some experts were concerned that, in weightlessness, food would be difficult to swallow and would collect in the throat. The concerns were unfounded, however, and Glenn had no problem except that the food was not very appetizing. When another astronaut heard about the unappetizing meal, he smuggled a ham sandwich aboard his flight.

For present day spaceflights, all food must be taken along. No running down to the corner convenience store for something you forgot! In the future, on large space stations and interplanetary spacecraft, food will undoubtedly be grown in greenhouses aboard the craft. It would be difficult to carry all provisions necessary for very long trips; the weight at liftoff would be enormous. Soviet cosmonauts have already attempted to grow food on their space stations with mixed results. Concepts for doing this will be discussed further in Chapter 11.

Five main problems and considerations arise in preparing food for Shuttle flights.

1. Achieving proper nutrition. Astronauts often experience a loss of appetite in space. The menus are strictly regulated to give 2,800 calories per day, consisting of 16 to 17 percent protein, 30 to 32 percent fat, and 50 to 54 percent carbohydrate.
2. Preserving food from spoilage. Five basic methods are described below.
3. Preparing and eating a variety of foods in zero g. Bite-sized cubes carried aboard the Mercury flights crumbled and crumbs floated about the cabin. The cubes were later coated with an edible gelatin to control the crumbling. Freeze-dried foods were difficult to rehydrate. Improved plastic packs were developed with a means for inserting the nozzle of a water gun into the package.
4. Making the food and its packaging lightweight and compact. At first some foods were pureed and placed in aluminum tubes to be squeezed out like toothpaste. However, the tubes weighed more than the food and that concept was abandoned.
5. Developing meals that are appetizing and pleasing to eat. There were early complaints that the food tasted bland.

Water supply aboard the Shuttle is not a problem. It is produced by the fuel cells which generate electricity from hydrogen and oxygen. Water is a by-product, made at a rate of nearly 2 gallons per hour. This is more than needed for life support, so much of it is dumped overboard. With an abundance of water, dehydrated foods are a natural choice. The food is rehydrated as needed.

Food Preparation

Five basic methods are used to prepare food for use in a spacecraft.

1. Rehydratables. These foods have been dehydrated by freeze drying, air drying, spray drying, or other methods. This is the most commonly used method and is likely to remain so. The astronauts rehydrate some of them by simply putting them in their mouth, such as bananas. Others, such as shrimp cocktail, scrambled eggs, and beverages are rehydrated with water.
2. Intermediate moisture. Some foods are partially dehydrated, such as dried apricots and dried peaches.
3. Thermostabilized. Foods are sealed in cans or aluminum laminated pouches and cooked at temperatures that destroy bacteria. Foods processed this way can be stored while retaining their original moisture. These foods include canned peaches, ground beef with relish, and stewed tomatoes.
4. Irradiated. As with thermostabilized food, bacteria are destroyed to allow food to be kept at room temperature with its natural moisture. But in this case, the bacteria are killed by exposure to ionizing radiation. Corned beef, beefsteak, and smoked turkey are among the foods treated this way.
5. Natural form. Foods that are naturally low in moisture, such as nuts, cookies, and candy bars, can be taken on the spacecraft in the same form that they are purchased at the supermarket.

Menus

A typical menu aboard the Space Shuttle may include:

Breakfast: Peaches, beef patty, scrambled eggs, bran flakes, cocoa, and orange drink.

Lunch: Hot dogs, turkey tetrazzini, bread, bananas, almond crunch bar, and apple drink.

Dinner: Shrimp cocktail, beef steak, rice pilaf, broccoli au gratin, fruit cocktail, butterscotch pudding, and grape drink.

Substitutes are allowed from the ''pantry,'' a supply of favorite foods requested by the astronauts. There are nearly 100 foods and beverages to choose from.

Food tends to taste bland in space, perhaps because of the nasal congestion often experienced by the astronauts or perhaps because the air circulation is low in zero g. Therefore, a number of condiments are provided, such as ketchup, mustard, liquid salt and pepper, and hot sauce.

The galley aboard the Orbiter is shown in Figure 9.2. To prepare a meal, the first step is to add water to the dehydrated food through a small opening in the pouch. The pouch is then kneaded thoroughly. If it is to be heated, it is placed in the oven. When ready, the packages are set into a tray and cut open with a knife or scissors. The Shuttle food tray is shown in Figure 9.3 and a meal in weightlessness aboard the Orbiter *Columbia* is shown in Figure 9.4.

Food in gravy, heavy syrup, or sauce sticks together and to the container. The forces of adhesion and cohesion keep it from floating away. It also sticks to forks and spoons so eating is almost normal. There are some cautions, however. Food sticks to the side and bottom of the utensils as well as the top, so you get twice as much in a forkfull. Sudden moves will send the food floating off into space. For example, a straw inserted into a covered container must be used for beverages. Otherwise, when you bring the container to your lips and stop, the liquid keeps going. Spilled water does not fall down, but gathers into floating globules. Salt sprinkled on the food may scatter into the air. Bread crumbs also scatter everywhere, so crumbly food is avoided.

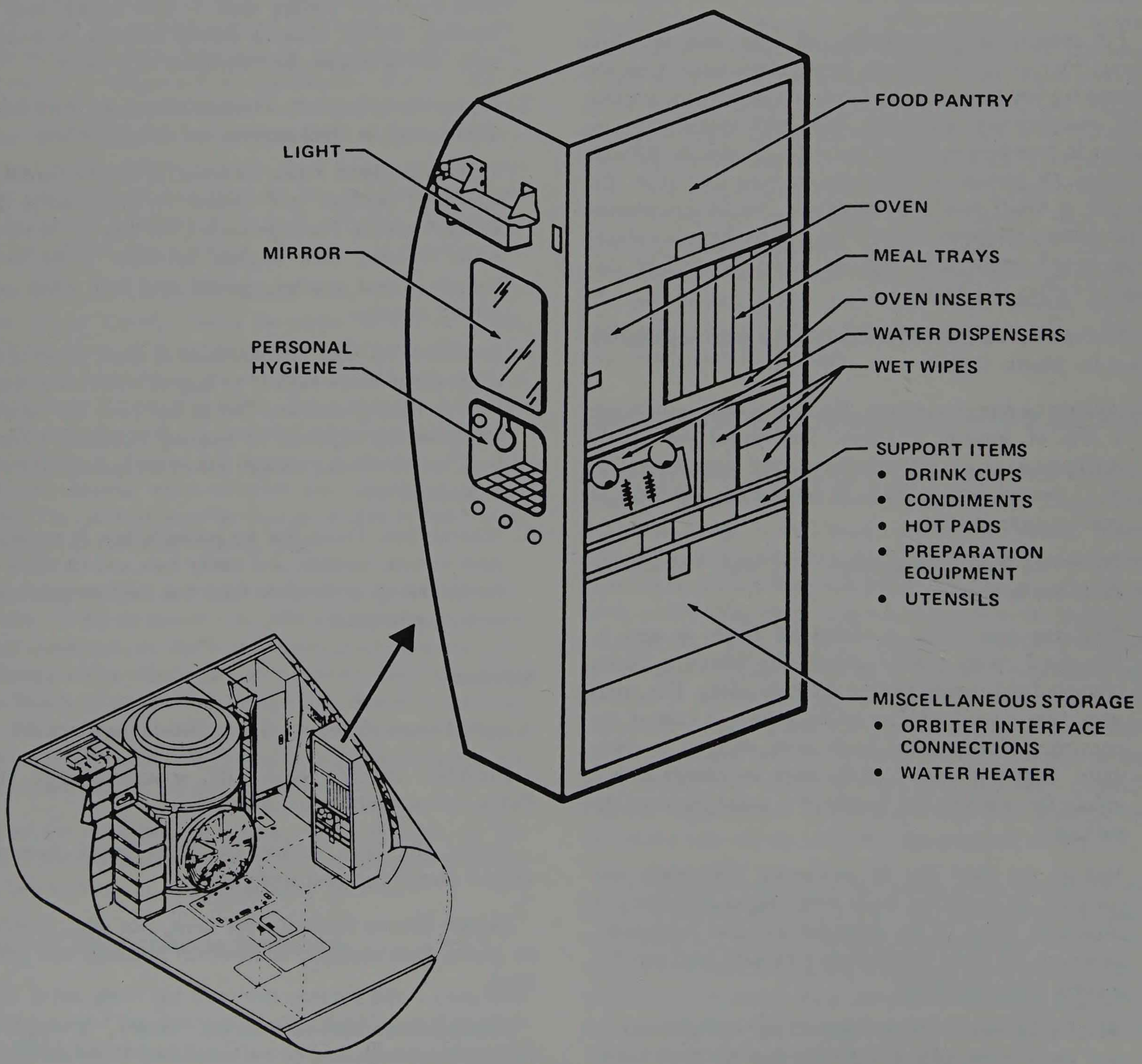


Figure 9.2 Space Shuttle pantry and personal hygiene station. *Courtesy of NASA.*



Figure 9.3 Shuttle food tray. This meal consists of (left to right, top row) fruit punch, butterscotch pudding in the can, smoked turkey in the foil bag, (bottom row) strawberries, mushroom soup, and mixed vegetables. *Courtesy of NASA.*



Figure 9.4 Mealtime aboard the Orbiter *Columbia*. A full meal tray floats at the right while an empty pudding can floats at the center. *Courtesy of NASA.*

Sleep

When you are weightless you do not have to lie down to sleep. Some astronauts have slept while simply floating in the cabin. The problem is, of course, that they drift around and get in the way of the rest of the crew.

There was concern in the early days that a person would not be able to sleep while weightless, and some astronauts have had difficulty. After sleeping for a short time, some tried to roll over and woke themselves up flailing their arms and legs. Waking with a dizzy feeling resulted from the head bobbing around. Others could not sleep well without the firm feeling of a mattress under them. In the Orbiter, sleeping bags are attached to the bunks to keep them from floating away. A waist strap presses the body against the bunk to give the sensation of lying on a mattress. Slipping the hands under the waist strap keeps them from floating in space.

Figure 9.5 shows the arrangement of bunks in the Space Shuttle. One person sleeps on the top bunk, a second one on the lower bunk, a third on the bottom side of the lower bunk facing down, and the fourth vertically at the end of the other bunks. Of course, the words ''top'', ''down,'' and ''vertical'' are only in reference to the Orbiter's top and bottom. They are meaningless in zero g.

In a 200 mile orbit, the Sun rises and sets every hour and a half. Eye shades and earmuffs are available to reduce disturbing noise and light for those who want to use them.

Personal Hygiene

The personal hygiene station is part of the galley, shown in Figure 9.2. A globular shaped chamber with two openings is used for washing hands without getting water all over the place. The Skylab space station was equipped with a shower. A curtain enclosed the astronaut. He used a spray to squirt water on his body and lather up, then used a vacuum cleaner device to remove it from his body, the curtain, and walls. It didn't work very well. Some water escaped from the shower stall and had to be chased around and vacuumed up. There is no shower on the Space Shuttle, so astronauts wash up by hand. Water clings to the body in weightlessness and makes the job easier than you may think. One sponge is used to soap up and a second to rinse off. Waste water goes into a storage tank beneath the floor.

Dry shaving with an electric shaver in weightlessness caused problems because the whiskers floated off around the cabin causing eye and lung irritation and getting into equipment. A wind-up electric shaver with a vacuum cleaner attached to suck up the whiskers helped, but didn't give a comfortable shave according to at least one astronaut. Shaving cream and safety razors seem to work best. Some astronauts gave up and grew a beard.

Figure 9.6 is a diagram of the Earth-like commode for collecting human waste. It had to be carefully designed, of course, for use in weightless conditions by both male and female astronauts. Toe holds and a waist restraint, like an

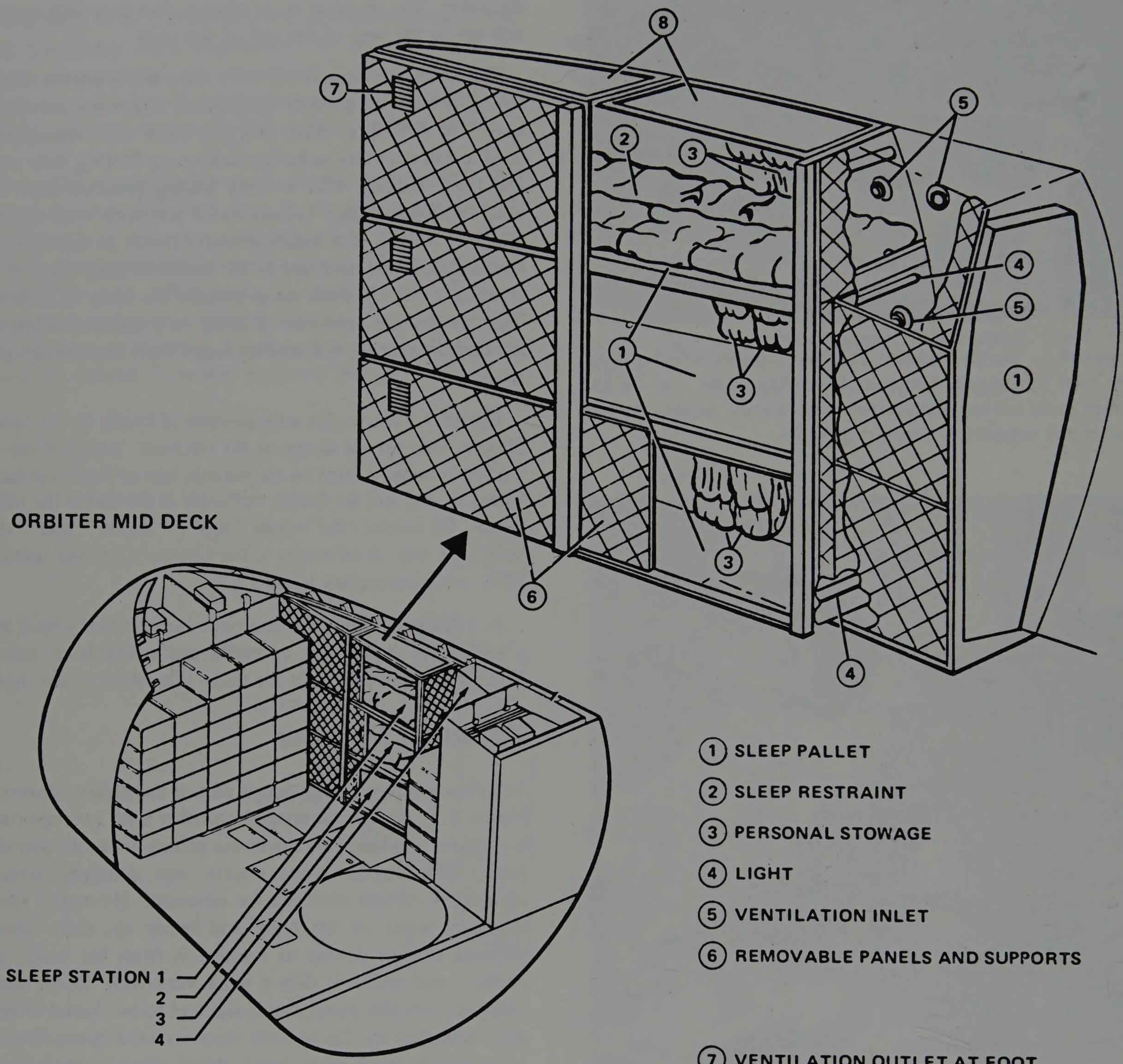


Figure 9.5 Orbiter sleep stations. *Courtesy of NASA.*

automobile seat belt, hold the occupant firmly in place to assure a good seal between the user and the seat. The commode has separate receptacles for feces and urine. In the absence of gravity, high speed air streams carry the solid and liquid waste downward into their respective receptacles. Solid waste is vacuum dried, chemically treated to prevent odor and the growth of bacteria, and stored. Liquid waste joins other waste water in the storage tank beneath the floor. When the tank fills up, it is dumped overboard.

A reading light, a nearby window, and privacy curtains are part of the commode area.

Waste is not recycled in present day spaceflight. Everything is saved in the Shuttle and returned to Earth. On longer trips to other planets and beyond, it may be advantageous to recover whatever can be reused in order to reduce the weight of the vehicle on the launch pad. Whether or not there is an advantage to recycling depends on the weight of

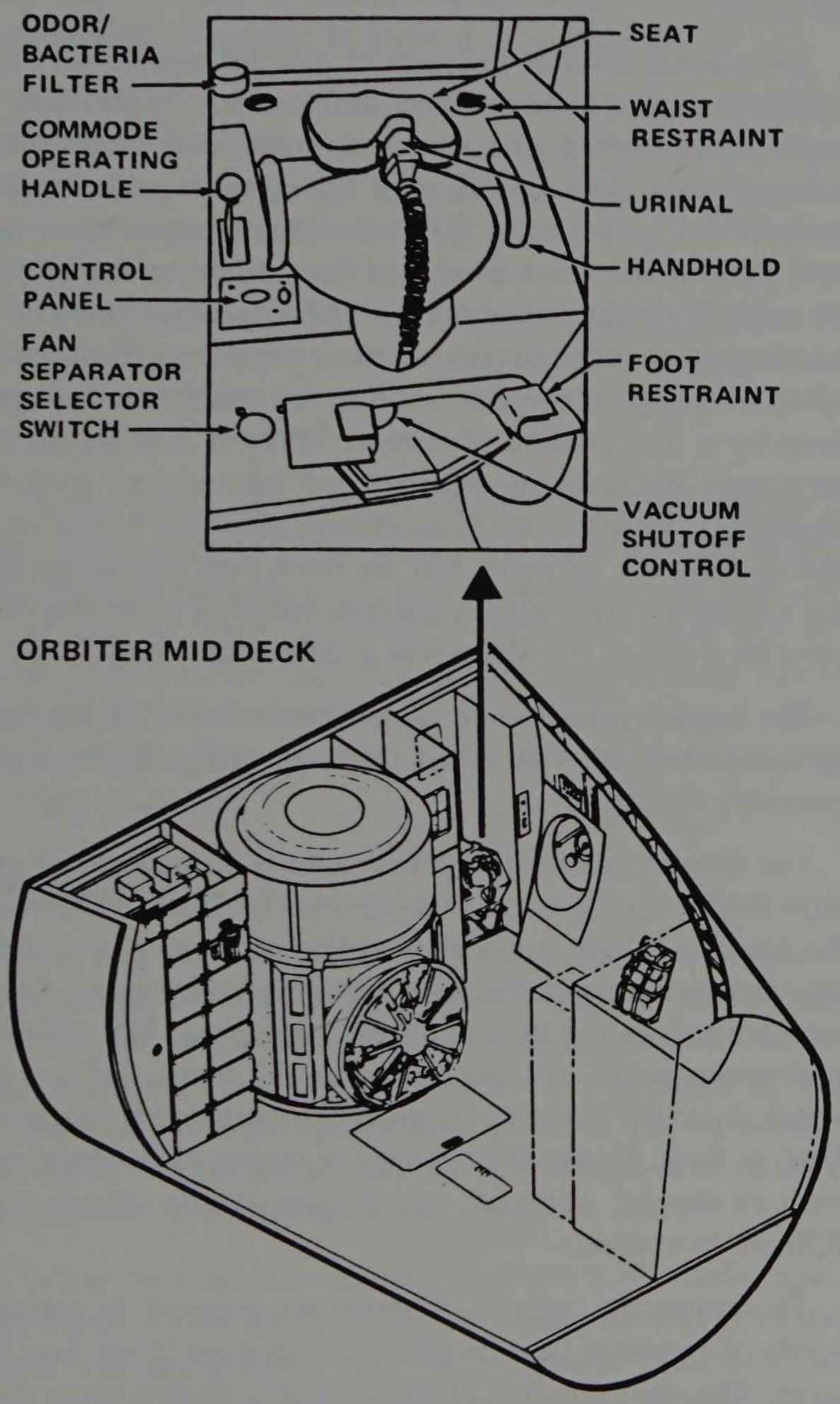


Figure 9.6 Orbiter waste collection system. *Courtesy of NASA.*

the equipment plus initial supplies compared to the weight of use-once-and-throw-away materials. Present recycling technology gives no weight advantage for flights less than two years in duration. This will be discussed in more detail in Chapter 11.

Radiation

Radiation in space consists of electromagnetic waves from the Sun, high speed protons and electrons in the solar wind, cosmic rays from outer space and from the Sun, and trapped particles in the Van Allen belts. (Recall Chapter 4.) Some of these pose a serious threat to human life. On the ground, we are protected from this radiation by the Earth's atmosphere and magnetic field. The cabin of a spacecraft provides protection from electromagnetic waves and some protection from the particles. However, when a primary cosmic ray strikes the vehicle walls, it produces secondary radiation by ionizing the materials of which the walls are made. This secondary radiation penetrates into the cabin. (Secondary radiation is produced in the upper atmosphere of Earth, also. Few primary cosmic rays reach the ground, but the secondaries do.)

When high energy protons, cosmic rays, x-rays, or gamma rays enter a living cell, they ionize the atoms and split apart the molecules of the cell, disrupting its operation and perhaps killing the cell. Recall that cosmic rays are the nuclei of atoms which have lost all their electrons. They are mostly hydrogen and helium nuclei (protons and alpha particles) with a few nuclei of heavy atoms such as carbon, oxygen, and iron. One of these heavy cosmic ray particles does more damage than a proton because it carries more positive electrical charge and can cause more ionization in the cell. A single heavy cosmic ray particle will destroy a cell. In total, though, protons do more damage simply because there are so many more of them.

The human body is continuously manufacturing new cells and the loss of a few is no big thing, but exposure to high dosages of radiation results in the destruction of many cells in a short time. Then the body has a problem, particularly if the cells are in a vital organ.

A particular problem of a woman exposed to high radiation dosages is that one or more of her latent egg cells may be damaged. A woman is born carrying all the eggs she will ever have. They develop at the rate of about one per month during her reproductive years. If one is damaged and later is impregnated, the fetus may be malformed. Male sperm are produced frequently and are not subject to the same lifelong concern as a woman's egg cells.

Biological damage from radiation is measured in rads, a quantity of energy absorbed per unit of body tissue. For humans the lethal dose is about 600 rads in a day. Exposure to 100 to 200 rads per day may cause nausea, vomiting, and fatigue. The effects vary from person to person, depending on body weight and general health. Under normal conditions the radiation in a spacecraft cabin is lower than first anticipated. During the Skylab's longest mission of 84 days, total radiation received was less than 8 rads. NASA sets a limit of 75 rads per year whole body dosage and a career limit of 400 rads. Astronauts carry dosimeters to monitor their exposure; instruments in the spacecraft cabin also monitor the radiation level.

Solar Proton Storms

Large solar flares may produce cosmic ray proton storms. The radiation intensity from these events occasionally reaches levels lethal to humans in space. It is particularly hazardous in a polar orbit inside the magnetosphere because

the Earth's magnetic field deflects the particles toward the north and south pole. During a proton event an astronaut could be exposed to more radiation in half an hour than NASA standards allow for a year. For the most energetic of these events, even the cabin walls of the Space Shuttle would not be sufficient shielding.

A solar proton storm which lasted longer than a week in August 1972 was intense enough to have killed an astronaut if one had been on an EVA outside the spacecraft in polar orbit. On August 4 the proton flux as measured by unmanned satellites translated to over 100 rads per hour for about 8 hours. Exposed to such a high dose, the astronaut would have been in severe pain with diarrhea and constant vomiting. He probably would have lived 4 to 6 days in that condition. Exposure to smaller dosages inside the cabin might not have killed the astronauts; they would just wish they were dead. Vomiting and diarrhea, leading to dehydration and emaciation, and the destruction of blood cells would have lead to death for some of them within a month.

Solar activity was discussed in Chapter 4. It is highly variable and not completely understood. Scientists have only a rudimentary knowledge of the causes of solar proton events, and forecasting their occurrence has only limited accuracy. Given that a flare has occurred, however, the forecaster can determine its intensity and can state with some reliability whether or not high energy protons have been blown into space. If they have, the forecaster can issue a warning to the astronauts. They would then have from 20 minutes to perhaps 3 hours to take cover in the best shielded part of the spacecraft or to return home. Reentry and landing at a particular point on Earth is possible only from a certain starting point in orbit, however, and may not be feasible as an emergency procedure. The inhabitants of a space station would have to "ride out" the storm. The space station design should include a heavily shielded compartment, a "storm cellar," for that eventuality.

Low Level Radiation

We have a pretty good understanding of the effects of high radiation dosage on people based on studies of the atomic bomb explosions in Japan during World War II. The effects on the body of continuous exposure to low radiation levels such as galactic cosmic rays are not well understood. We on Earth are exposed to low level radiation from cosmic rays entering the atmosphere, radioactive rocks and gases, and dental and medical x-rays. We often hear statistics such as "exposure to such radiation will lead to two deaths from cancer per 100,000 people in 50 years." The question is who are those two and might they have died from something else in those 50 years. Certainly driving an automobile, smoking, and a dozen other human activities are more hazardous than low level radiation. But here the discussion gets emotional rather than analytical. People can limit many of their hazardous activities if they want to. Radiation is frightening to many people because it cannot be seen and it is difficult for the average person to limit radiation exposure.

The normal level of intensity of galactic cosmic rays is rather constant, but researchers differ widely in their estimates of the hazard. One source estimates that continuous exposure to galactic cosmic rays for a year would exceed the safe dosage by some 60 times. Another says there is little danger, that the total annual dose would be from 6 to 20 rads. The main reason for this disparity is that researchers disagree as to the biological effect of protons. Estimates of their damage range from one to ten times the damage done by a similar dose of x-rays. While it is possible to accurately estimate the number and intensity of proton encounters, there is wide disagreement as to how to convert that to rads. We do know that for short trips the dosage is not excessive. The highest total dose received by an Apollo crew on a trip to the Moon was a little over 1 rad.

The trapped particles are also a serious hazard to people in space, but the Van Allen belts are well mapped and generally avoidable.

One interesting effect of cosmic rays is the occurrence of light flashes in the eyes, first reported by Buzz Aldrin on the Apollo 11 flight to the Moon. Other astronauts have also reported seeing flashes of light with their eyes closed. The most obvious explanation of this phenomenon is that cosmic rays penetrate the eye and deposit in the retina, sending a signal down the optic nerve which the brain interprets as a flash of light. However, a variety of shapes were observed such as streaks, commas, and diffuse clouds. These are difficult to explain.

To summarize, people in space are exposed to higher levels of radiation than people on Earth even if the Sun is quiet. The short duration of Space Shuttle flights keeps the exposure to tolerable levels. The long term effects on any particular individual cannot be predicted. This question will become more demanding of an answer as people live for longer periods in the space station, on the Moon without an atmosphere, and on Mars with only a thin atmosphere.

Gravity and Weightlessness

A person on Earth, along with everything else, experiences a constant acceleration due to gravity of 32 feet per second per second, called one g. This means that any unsupported object would fall toward the center of Earth with an ever increasing speed, just as a car increases speed when the driver presses down on the accelerator. A car speeding up uniformly from a stop to 88 feet per second (60 miles per hour) in, say, 44 seconds, accelerates at the rate of 2 feet per second per second. Similarly, an unsupported object, accelerating at one g, would be falling at a speed of 32 feet per second after 1 second, 64 feet per second after 2 seconds, 96 feet per second after 3 seconds, and so on.

The one g acceleration of gravity is always with us on Earth. There is no way to ''turn off'' gravity. We are born, live, and die with it, and the human body is designed and conditioned to operate in a one g environment.

The term ''g force'' or ''a force of 3 g'' is somewhat misleading because g is not a force. Rather it is the acceleration due to the force of gravity. However, in common usage, ''a force of 3 g'' means any acceleration that gives a sensation of weighing three times more than normal. It makes no difference whether the acceleration is due to gravity or due to a rocket engine. The sensation is the same and the effect on the body is the same. We will use the term ''g force'' in that context.

When going into space people experience dramatic changes in g forces. First, while the engines are running and accelerating the spacecraft, they experience more than one g of gravity. Then when the engines shut down and the spacecraft is in free fall, they are weightless. Finally, when the rocket motors are retrofired to return to Earth, they experience an acceleration again and its accompanying feeling of weight.

High g

Let us first examine the effects of a greater than normal g force on the body. Experience in high speed jet aircraft and experiments in a centrifuge and on a rocket-powered sled in the 1950s provided a good idea of the tolerance of the human body to higher than normal g forces. The record was set by Col. John Stapp when he decelerated at 35 g on a rocket sled at White Sands, New Mexico, in 1954.

While the general outer body structure is relatively rigid, the fluids within are free to move. Internal organs in the chest and abdomen are not rigidly fixed in place and can also move. Human bodies are well adapted to function in one g. Flexing muscles in the legs forces blood upward in the veins against normal gravity, helping the heart to keep the blood circulating. One-way valves in the veins also help prevent the blood from pooling in the lower body. At normal one g the internal organs hold their proper position.

Problems occur if a person is sitting or standing erect and an acceleration greater than normal one g acts lengthwise, head to feet. Leg muscles cannot supply enough force to prevent blood from leaving the head and pooling in the lower part of the body. Lack of blood in the brain causes dizziness and possible blackout. You can feel this sensation briefly when an elevator starts suddenly upward or when a roller coaster reaches the bottom of a curve. However, Col. Stapp in his rocket sled showed that very high g can be tolerated if the acceleration is directed front to back, perpendicular to the chest. The key factor in how much a body can withstand is the direction of the acceleration.

In the early manned flights into space, each astronaut had a contour seat specially fitted to his form. During launch into orbit he was lying back in the seat facing forward. During reentry he rode backward, again with the acceleration directed front to back, perpendicular to his chest. This allowed him to withstand over 8 g without blacking out.

The Space Shuttle is designed to operate at lower accelerations. During launch the engines are throttled so that the acceleration reaches a maximum of only 3 g twice during the rise to orbit, once just before the solid rockets burn out and separate, and a second time for about 5 minutes just before the external tank empties and drops away. This is for the safety of the spacecraft as well as the comfort of the crew. For comparison, 3 g is less than may be experienced on some carnival rides. The crew sits up in seats like riding in an airliner and the Shuttle accelerates nose first so the g forces are front to back. Just after liftoff, the Shuttle has greater acceleration than the Saturn boosters that carried men to the Moon. However, the Saturn attained much higher acceleration as the first stage rocket burned out.

During reentry Shuttle crews encounter 1.5 g. Because the Orbiter enters the atmosphere bottom side first, the force on the crew acts lengthwise as they sit upright in their seats. After several days or more in weightlessness the body could be especially susceptible to pooling of blood and blackout. Therefore, crew members wear antigravity suits during reentry. An antigravity suit looks like a pair of pants with inflatable bladders. As the g force increases, the bladders are inflated and apply pressure to the lower part of the body forcing blood toward the upper body and brain.

Weightlessness

Many of the problems a human body confronts while in space are related to what is commonly called weightlessness or microgravity or the absence of gravity or zero g (Figure 9.7). None of these terms are precisely correct. The force of gravity does decrease with distance from Earth. However, even at orbital altitude a spacecraft is not beyond Earth's gravity. It could not remain in orbit if gravity were zero. (Recall Newton's first law of motion: an object moves in a curved path only if some force deviates it from a straight line path. In the case of an orbiting spacecraft, gravity is the force.) At 300 miles g is still about 9 meters per second per second, nearly the same as it is on Earth. So the terms ''zero g'' and ''microgravity'' are somewhat misleading, although they do communicate the intended meaning.

As discussed in Chapter 3, an object in orbit is in free fall, falling toward Earth, but with sufficient horizontal velocity that it never strikes Earth and therefore remains in orbit. On Earth, the supporting upward force from the chair we sit on or the floor we stand on prevents us from falling downward. It is this force that gives us the sensation we

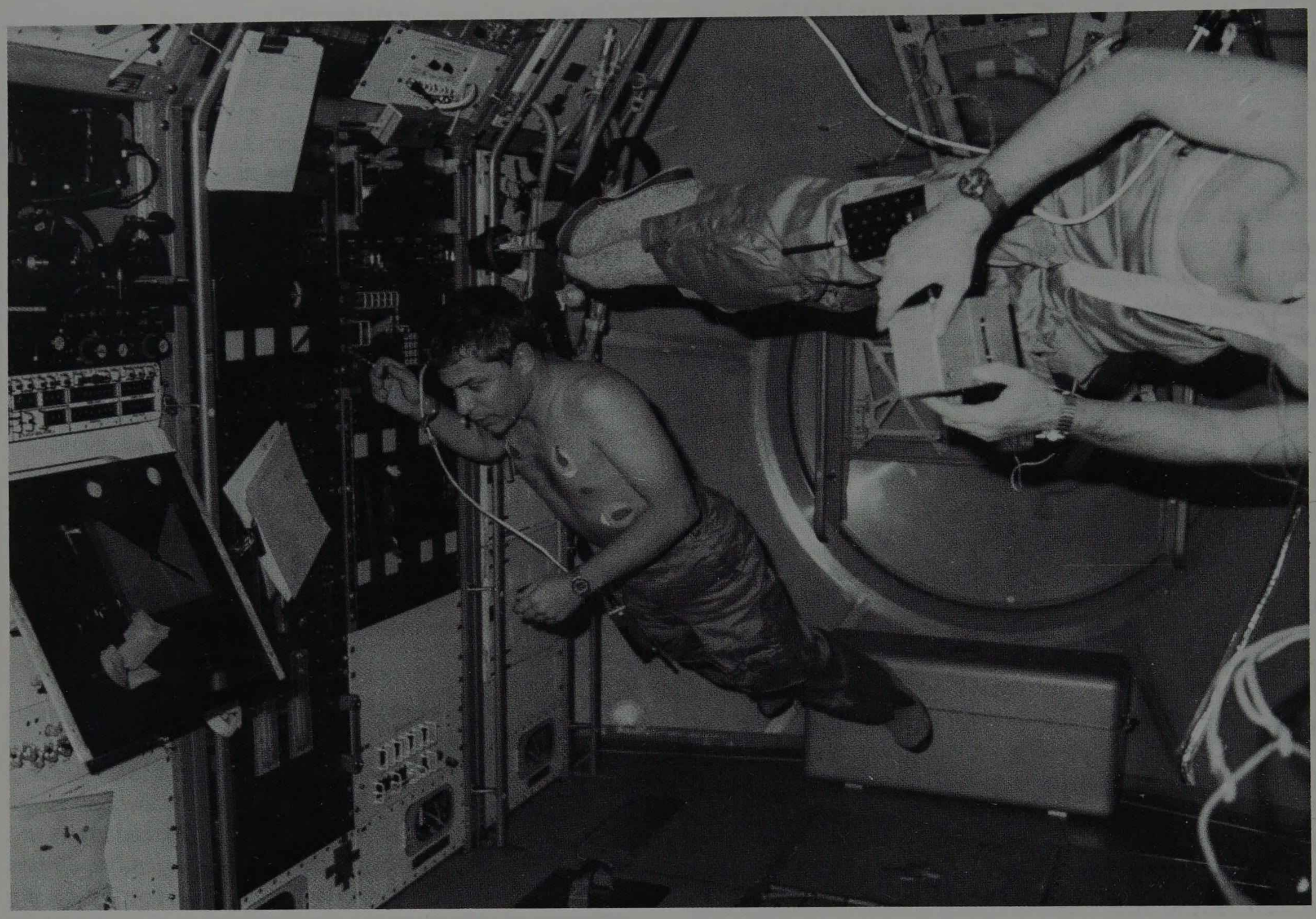


Figure 9.7 "Weightless" astronauts working in Spacelab aboard Orbiter *Columbia*. In a normal relaxed position, knees bend slightly, head raises or tilts back, shoulders hunch up, and arms float upward. It requires some effort to bend at the waist or to hold arms down to waist level. *Courtesy of NASA*.

call "weight." But in free fall in orbit, the floor does not provide any support. It and the entire spacecraft is falling the same as the crew is. Because there is no upward supporting force as there was on Earth we feel "weightless."

As described earlier, the problems of high g forces on the human body are well understood and taken into account in the design of the spacecraft and in its mission profile. In contrast, the problems with zero g, weightlessness, are not yet solved.

Under zero g, these are some of the effects on a human body:

a. Fluid shift from the lower part of the body to the upper. Lower body muscle structure is such that, under normal gravity, blood is forced upward to keep it from pooling in legs. Even in zero g these muscles continue to force blood and other body fluids upward.

b. Cardiovascular deconditioning and red blood cell loss. The heart does not have to work so hard to move weightless blood through the arteries and veins. Total quantity of body fluids is reduced, including blood.

c. Muscular deconditioning. Muscles don't have to work at normal levels so they begin to atrophy. It takes days or weeks to recover, depending on the length of time the person was weightless and how much exercising was done during the flight.

d. Calcium loss from bones. The loss continues throughout the entire flight. The longer the flight, the more calcium is lost.

e. Space adaptation syndrome. Space sickness lasts a day or two, affecting about half the people who go into space.

When the spacecraft reaches orbit and the engines stop, the vehicle and its contents are weightless, in free fall. At first there is a great feeling of euphoria, an absence of force on the body, freely floating about in the cabin.

After a short time, body fluids begin to shift. Muscles in

the lower limbs that work against gravity on Earth, pushing blood upward in the body, continue to work. Blood vessels in the legs are soon emptied because of the ''absence of gravity.'' Other fluids from the surrounding tissue flow into them. The upper body becomes somewhat swollen as the blood and other fluids move in that direction. The face becomes swollen in appearance as the normally loose flesh fills with fluid and ''floats'' on the cheekbones. Wrinkles and double chins disappear and eyes appear smaller. At the same time, the lower body, having lost the fluid, becomes thinner. Waist measurements decrease by an inch or two. Feet and legs become noticeably smaller; boots and pants may not fit as well. Astronauts called this ''bird legs'' and ''wasp waist.''

All this is accompanied by head congestion, a full stuffy head, throbbing in the neck, and perhaps a severe headache. The sensation is similar to that of hanging upside down on a gym bar.

Meanwhile, the body misinterprets what is happening. Sensors in the upper body indicate excess fluid and the kidneys begin action to eliminate it in the form of urine. One or two quarts of fluid and the dissolved salt are released this way in the first few days. The individual does not feel thirsty and does not replace the lost fluid by drinking water. After two or three days the cardiovascular circulatory system settles down to a more normal operation but with a smaller volume of blood. Prior to reentry on the last day of the flight astronauts take salt tablets and drink about a quart of water to begin the process of renewing the blood volume to its normal Earth level.

Most of the symptoms described above disappear in about three days, either by the body self-adjusting its functions or by the mental attitude of the individual simply ''getting used to it.''

Space Adaptation Syndrome

About half the people who have ventured into space have reported becoming sick on the first or second day of the flight. Earliest onset was during the first hour. The symptoms are similar to motion sickness, being seasick or airsick. Vomiting has been reported by 42 percent, headache by 37 percent, malaise by 30 percent, fatigue by 23 percent, and loss of appetite by 37 percent. The symptoms subside after two or three days and do not recur on that flight. Apparently the body adapts to whatever causes it.

This illness is not the same as motion sickness. All the early astronauts had been test pilots and were not susceptible to becoming airsick. Yet many of them suffered from space sickness. Research doctors fear they may not have accurate reports, since some astronauts may not want to admit to throwing up. Tests on Earth do not identify those who may be susceptible. It becomes apparent only when they reach orbit. Those individuals who get sick on one flight will likely get sick if they make another flight. Conversely, those who do not get sick on one flight probably will not on another. The common motion sickness drugs such as dramamine do not work against space sickness.

Space sickness is the subject of considerable research effort. Because the symptoms are similar to motion sickness it is thought that the cause lies in the vestibular apparatus, that organ in the inner ear that gives us a sense of balance. It provides information to the brain on accelerations and rotations. A person on Earth can tell up from down and estimate direction and speed of motion all from visual observation. While weightless in space, however, information sent from the eyes and from the vestibular apparatus may conflict. One may indicate you are upside down while the other says you are tumbling.

The relationship between vomiting and the vestibular apparatus has been shown by experiment. Monkeys and people who have defective vestibular apparatuses or have had them removed cannot be made to vomit when subjected to unusual acceleration or rotation.

One NASA researcher, Dr. Patricia Cowings, has equipped a laboratory with motion equipment designed to make people sick. One of the symptoms described to her by astronauts is that they have the feeling they are standing upside down. This is related to the shift of fluids to the upper part of the body. Dr. Cowings believes that biofeedback may help solve the space sickness problems. The subjects in her experiments learn to control their own heart rate, blood flow to their hands, facial pallor, and perspiration. This type of training may enable astronauts to control their space sickness symptoms as well.

Exercise

A regular regimen of exercise as part of the astronaut's daily routine is required to keep the heart and muscles in condition. A stationary bicycle was used on the Skylab space station. The treadmill shown in Figures 9.8 and 9.9 uses shoulder straps to keep the person in contact with the machine. Spring type exercise devices also work in weightlessness, but weight lifting is useless! Even with a vigorous exercise program, however, calcium loss continues and muscles do not remain as strong as they would on Earth. Depending on the length of the flight, it may take days or even weeks to recover after returning to Earth. It has been reported that after their record-setting eight month stay in space in 1984, Russian cosmonauts were not even able to stand up for several days. The human body may be the limiting factor in further exploration of space, particularly on such missions as a yearlong flight to Mars. It may be necessary to produce an ''artificial gravity'' by rotating the space ship—more about that in Chapter 11.

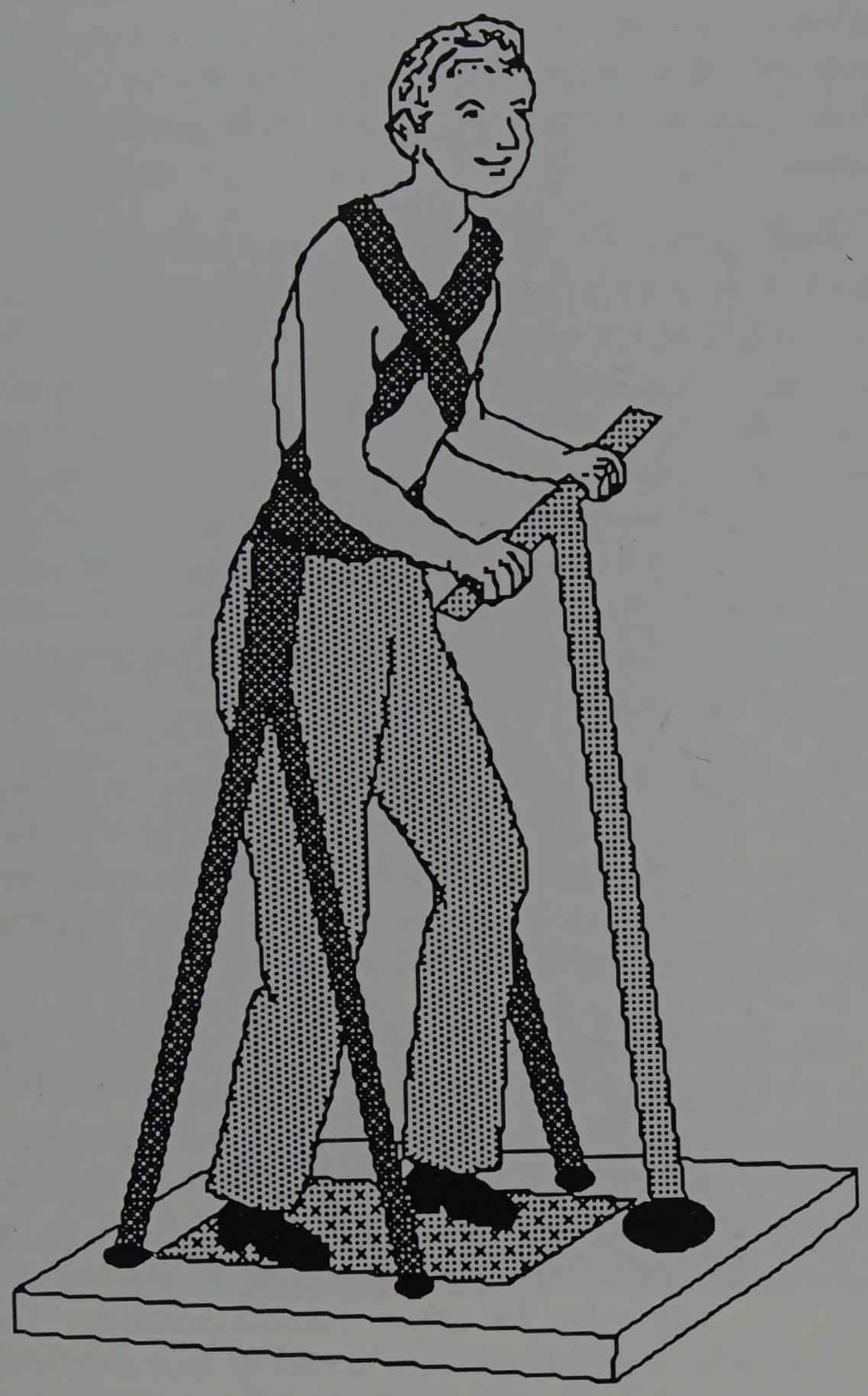


Figure 9.8 Exercise treadmill.



Figure 9.9 Astronaut Fred Hauck exercises on the treadmill. Straps are needed to keep the weightless astronaut in contact with the machine. *Courtesy of NASA.*

Adaptation to Long Duration Spaceflight

Up to now, astronauts have been a homogeneous bunch. The missions required a corps of tough test pilots, who could live with danger for a week or two cramped together in a small space. They were well screened in advance.

Now plans call for a changing crew composition, less homogeneous, less screened. In the future, space travel will be for everyone. Missions are more routine. As a consequence there is a growing interest in the psychological aspects of spaceflight. *Ergonomics* is the study of human factors.

Motivation is high at first, but during long duration flights, irritation sets in and small annoyances become big ones. Personal hygiene, use of the toilet, and lack of privacy become irritants. Astronauts also become less efficient in their work after a few months and cannot concentrate as well. Problems arise with attention span and with performing cognitive tasks. On Earth during long winters in the far northern countries, it has been noted that irritability increases and a higher suicide rate is seen. Submarine studies also bear out this human reaction to long confinement. There is a decrement in morale and mood, accompanied by higher stress, after the first 10 days. Things get better about a week before the final day of the mission when the end is in sight. People forget their petty grievances in the excitement over ending the mission.

Group cohesion is important. The Russians put crews in a small car and sent them on a 30 day trip around the Soviet Union to see how well they got along!

Crews are given training as to what to look out for in their co-workers, things which indicate they may "crack up." Certain changes in mood or changes in activity levels are some of the indicators. Psychological tests are available to determine profiles of candidates to predict their performance in long spaceflights.

During Skylab activities the astronauts sometimes complained of having too much to do and not enough time to relax and just look out the window at the Earth. One crew (Ed Gibson, Bill Pogue, and Gerald Carr) refused to do any work for a day. They just relaxed and did what they

pleased. In longer flights the Soviets have noted that comrades in a spacecraft tend to stick together, but get irritated with ground personnel in the command center. Interesting, varied tasks help relieve stress and boredom. Free time is important. Relaxation training may help relieve stress. From Soviet experience important factors are communciation with families, tapes of music of preference for each crew member, and just being alone once in a while.

One possible problem is the disruption of diurnal circadian rhythms. A spacecraft in low Earth orbit has 16 sunrises and sunsets a day. Fortunately humans are very adaptable. Only one-tenth of the variability in most psychological factors tested is accounted for by genes. Studies of adaptation show no significant difference between men and women. Edward Teller says women are smaller and smarter than men, so we should send more women.

The bottom line is that spaceflight is expensive and performance must be maximized. Getting the job done depends on people. Psychological factors become more important as the duration of the flight increases. NASA is becoming more interested in this problem but still has enough hardware problems to keep it occupied. Human factor problems have not been a top priority.

DISCUSSION QUESTIONS

1. A deep sea diver who experiences the bends on return to the surface is put into a pressure chamber. Why?
2. Name some of your favorite foods and tell how you would package them for eating in weightlessness.
3. Think of your daily habits of personal hygiene and cleanliness, such as combing hair, clipping fingernails, and dressing. What problems would have to be overcome while trying to do these things in weightlessness?
4. Newton's first law says that an object does not change its motion unless a force is applied. Why, then, does liquid float out of a cup and food float off a plate in an orbiting spacecraft?
5. Describe exercises that could be done in weightlessness.

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Chapter 10

Working in Space

The Space Shuttle has made it rather easy for people to get into orbit and to do various jobs there. A list of the many impressive things done by Shuttle astronauts includes:

1. Drop off satellites in orbit.
2. Recover and repair satellites.
3. Build large structures outside the Orbiter.
4. Measure the plasma environment around the Orbiter.
5. Manufacture perfect spheres and crystals.
6. Prepare pharmaceutical products by separating biological cells from one another.
7. Study effects of weightlessness on people, plants, and animals.
8. Experimentally refuel a simulated satellite.
9. Use radar and infrared to make high resolution images of the ground.
10. Measure solar and cosmic radiation.

Some of the work has direct commercial application, some helps develop new techniques for manufacturing and processing materials in space, and some is basic research for a better understanding of the world around us.

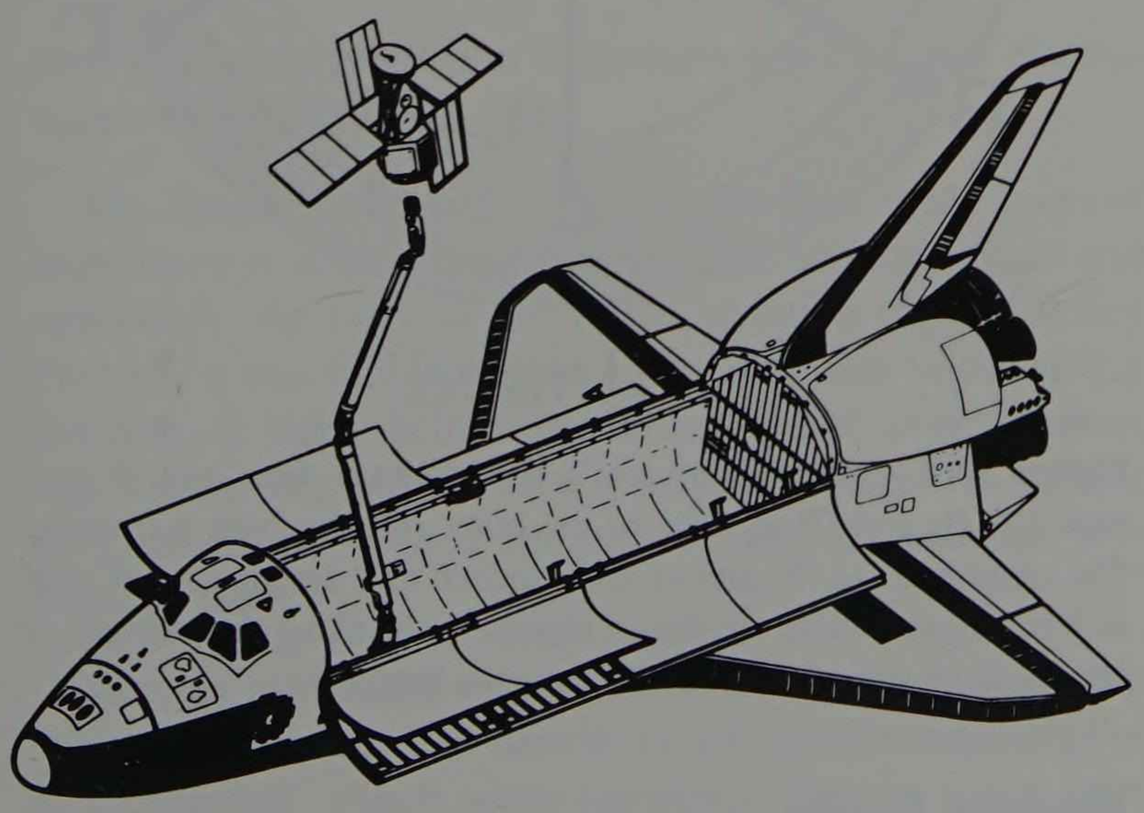


Figure 10.1 Remote manipulator arm. Fashioned after a human arm, it has a shoulder attached to the cargo bay, an elbow, a wrist, and a hand called the end effector. In this diagram it has just dropped off a satellite. *Courtesy of NASA.*

Remote Manipulator Arm

Much of the work aboard the Shuttle is done from inside the Orbiter cabin using the *remote manipulator arm*. This remarkable robot device, designed and built in Canada for the Orbiter, is powered by six electric motors. In many ways it resembles a human arm with a shoulder, elbow, wrist, and hand. In robotics terms, the hand is called an *end effector*. See Figures 10.1 to 10.3. When not in use, the arm is stowed against the side of the cargo bay. From a control panel on the upper deck of the cabin, an astronaut lifts it from its cradle and moves it to any desired position and location. Movement is controlled by a joystick, similar to those used for video games. A computer reads the joystick motion and translates it to motion in the arm. The operator

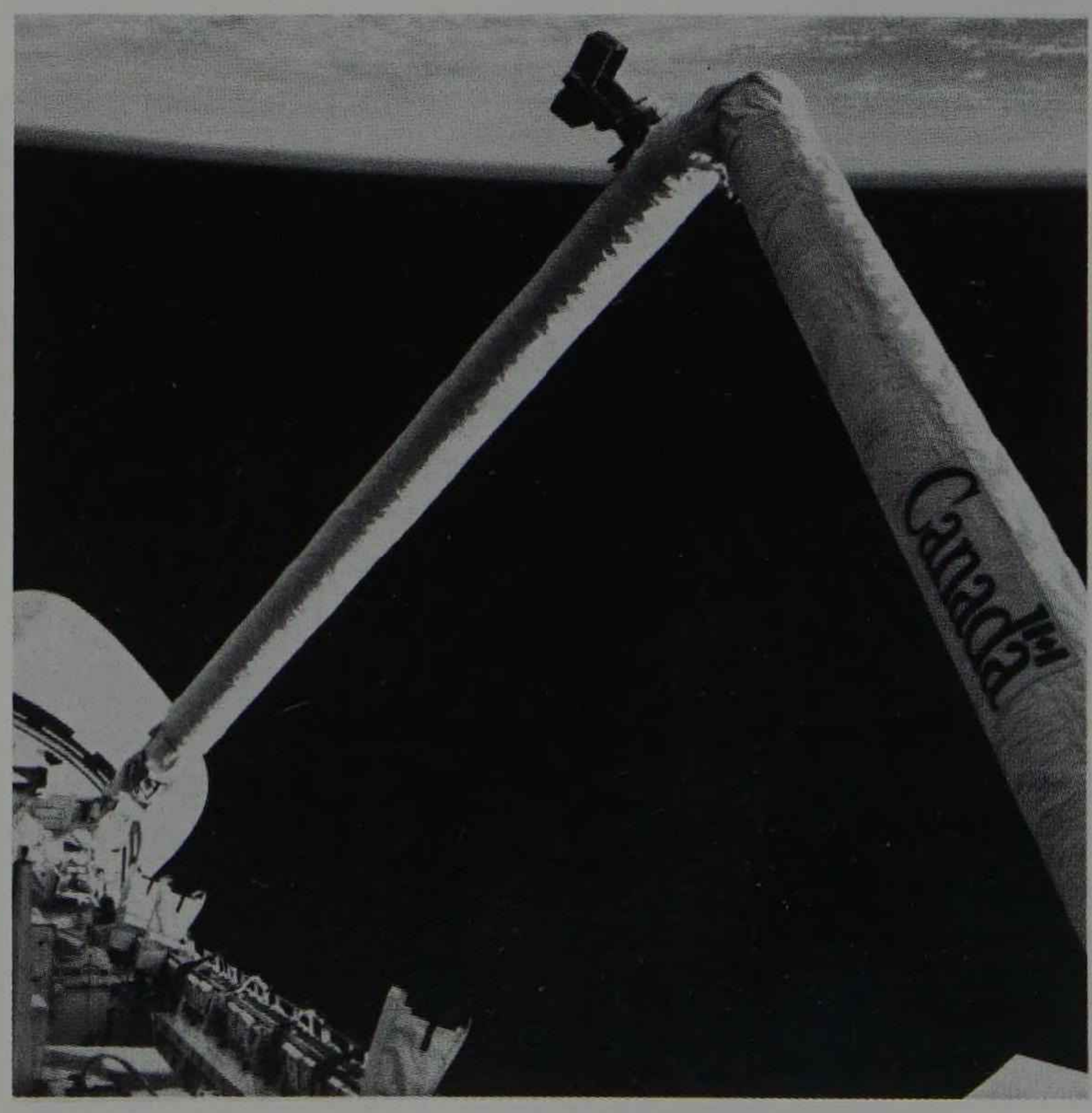


Figure 10.2 Remote manipulator arm as seen from the flight deck of the Orbiter. Notice the TV camera at the elbow. *Courtesy of NASA.*

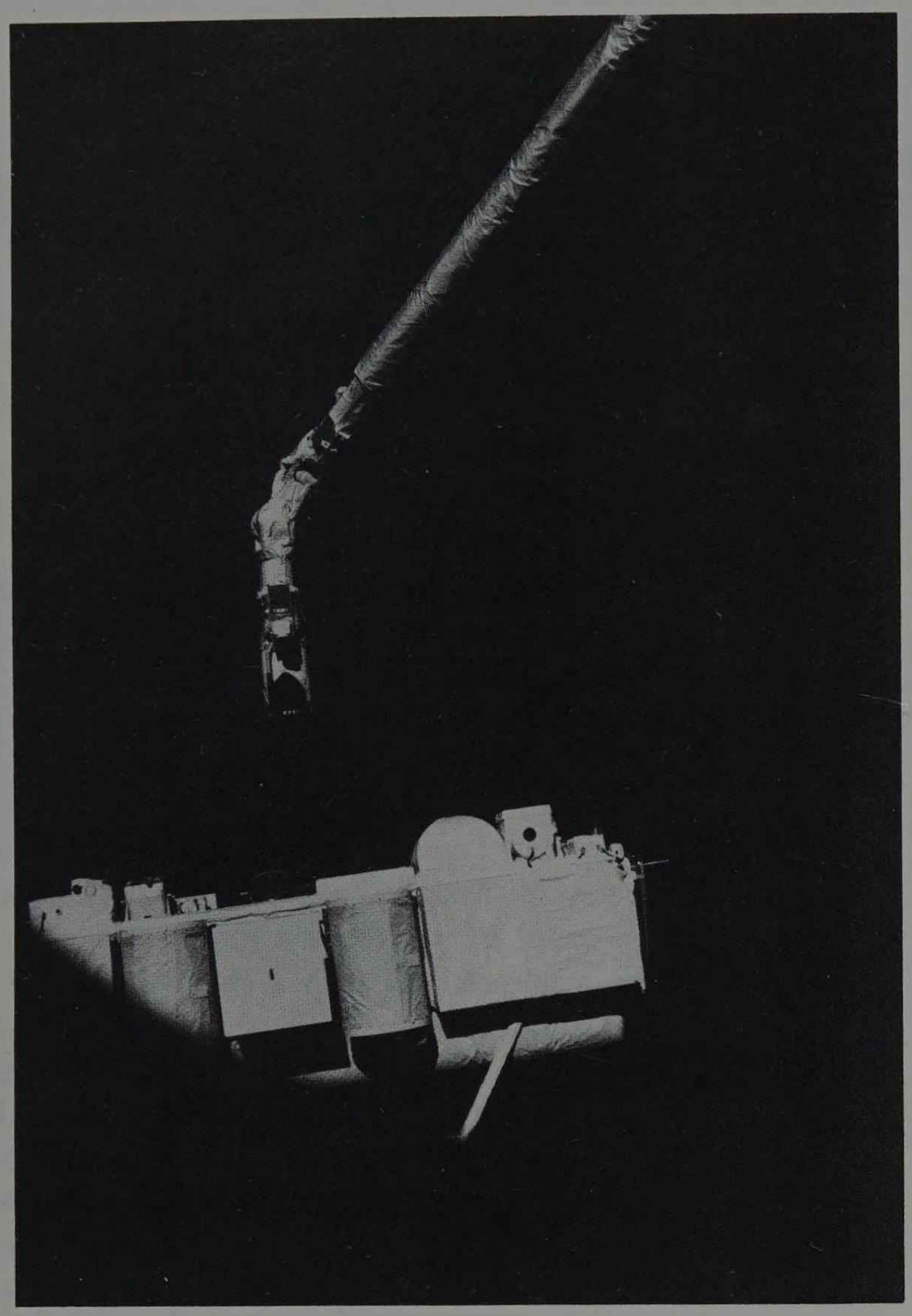


Figure 10.3 Manipulator arm moves in to grasp a small payload. The end effector is clearly seen; the grapple fixture on the payload is faintly visible. *Courtesy of NASA*.

can see what is happening through windows into the cargo bay and in the ceiling of the Orbiter, and by television monitors next to the control panel. TV cameras are mounted at the wrist and the elbow of the manipulator arm and can be focused and zoomed by the operator to give the best view.

The end effector does not have fingers, but uses an ingenious rotating wire arrangement to capture and hold a payload. See Figure 10.4. A mechanical finger is a complicated device with many joints; the wire device is simple by comparison and less likely to fail. Any payload to be manipulated by the arm must be equipped with a *grapple*, a rod-like protrusion. The end effector is slipped over the grapple and the wires tighten around it to make a firm connection. A platform with boot clamps can be attached to the end effector so an astronaut can ride the arm (Figure 10.5).

The robot arm works only in orbit. It cannot support its own weight on the ground, but in weightlessness it can manipulate any payload the Orbiter can carry.

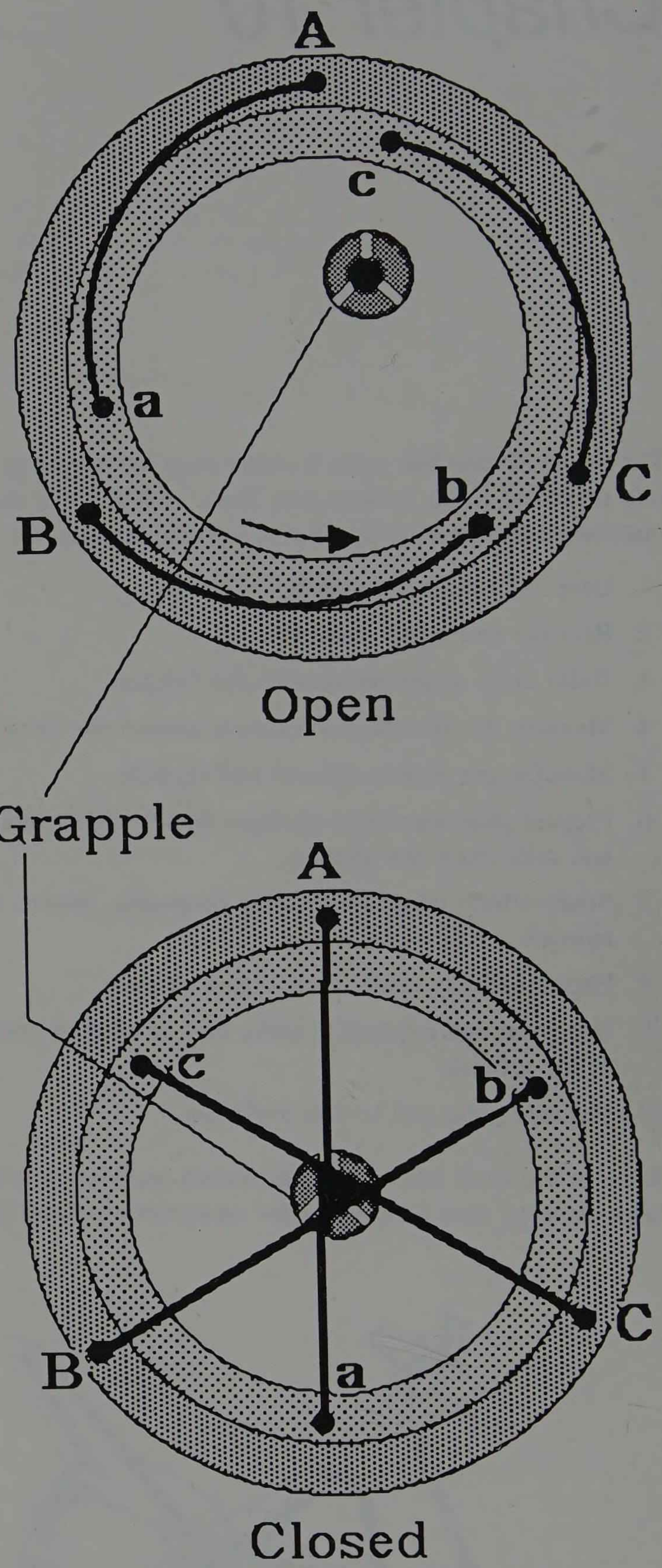


Figure 10.4 Manipulator arm's end effector. One end of each wire (A, B, and C) is fixed to the outer ring forming a triangle. The other ends (a, b, and c) are attached to a rotating inner ring; as it rotates the wires are drawn together, shrinking the triangle, to take hold of the grapple attached to the payload.

Space Suits

When work is to be done outside the cabin, in the cargo bay or away from the Orbiter, the astronaut wears a space suit equipped with a self-contained life support system. It also



Figure 10.5 Space suited astronaut rides the manipulator arm; foot restraints keep him from floating away. A just-released satellite is in the distance below his feet. *Courtesy of NASA.*

provides some protection from both particles and electromagnetic radiation.

The Shuttle space suit is the outgrowth of many years of experience in constructing suits for high altitude aircraft and spacecraft. As early as the 1930s, aviation pioneer Wiley Post had a suit molded in the shape of a man in the sitting position. It had a helmet something like a diver's helmet and was pressurized by the engine supercharger. In it, Post set cross-country speed and altitude records with his plywood airplane.

Mercury astronauts wore space suits as backup in case the cabin lost pressure. The suits were not pressurized except in an emergency, which never happened. Gemini space suits were designed specifically for working in empty space outside the cabin, called *extravehicular activity* (EVA). They were made in several layers to give greater flexibility than the Mercury suits. An inner bladder was made of nylon coated with neoprene rubber. Over that was a net woven of nylon and teflon strands which acted as a casing to keep the bladder from ballooning out, just as a bicycle tire acts as a casing over an inner tube. Flexibility was improved by making the outer casing slightly smaller than the inner bladder. In 1965, Ed White was the first American to leave a vehicle while in orbit. He was connected to the spacecraft's life support system by a 25 foot long umbilical cord. Cosmonaut Alexei Leonov had been the first human to "walk in space" just three months before.

Apollo space suits presented other design problems because they had to work on the surface of the Moon as well as in space. See Figure 10.6. The inner structure was similar to the Gemini suit, but the outer layers had to stand up to jagged rocks, the heat of the lunar day, meteoroids falling onto the Moon, and rough handling while climbing in and out of the lunar lander. The suit also had to be

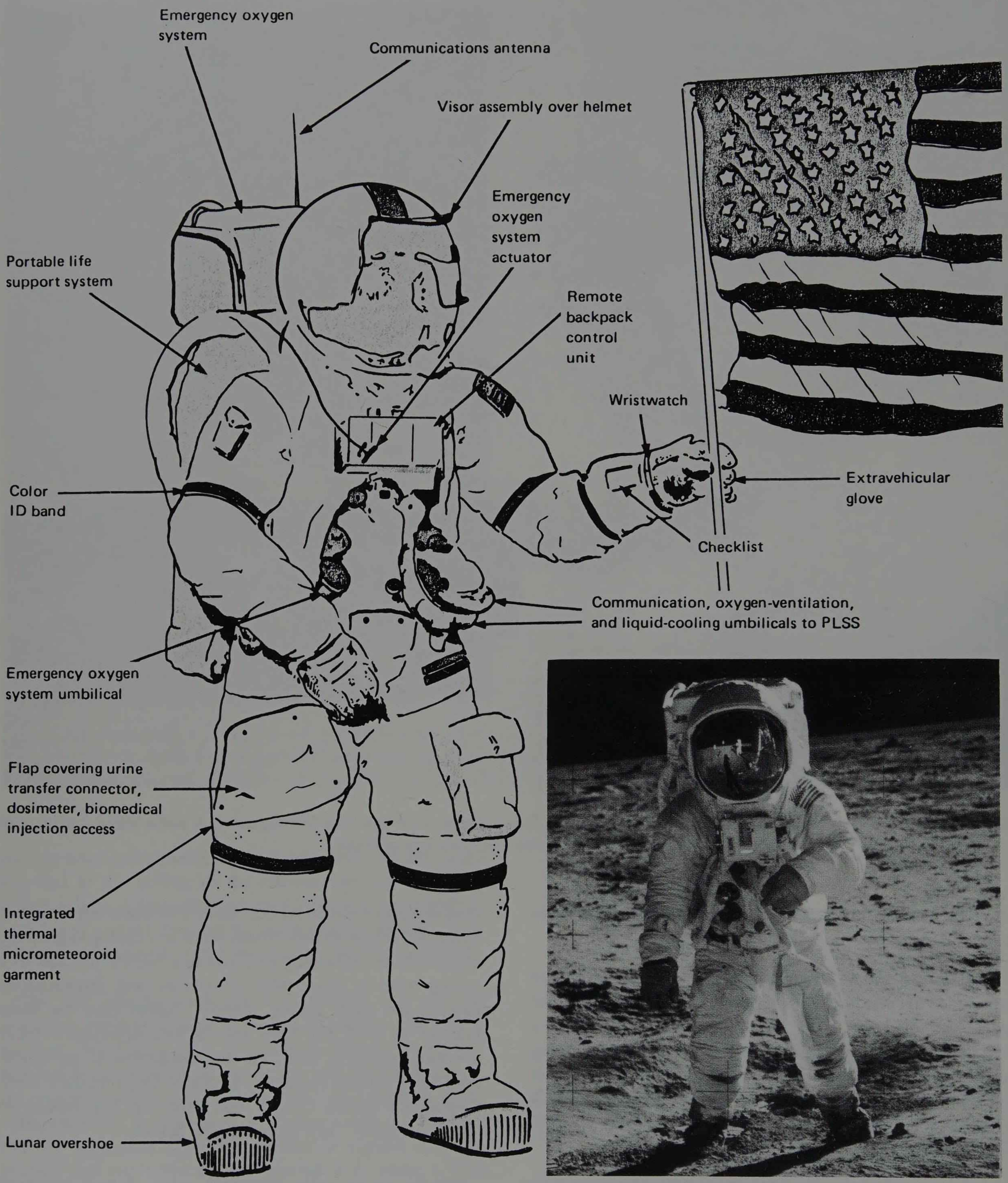


Figure 10.6 Apollo space suit. *Courtesy of NASA.*

flexible enough to allow stooping, bending, adjusting, instruments, and sitting on the lunar rover "dune buggy." Bellows-like joints at the knees, elbows, and waist gave greater freedom of movement. In earlier suits, when an astronaut wanted to bend an elbow, knee, or shoulder, that entire section of the suit had to compress, reducing the volume of the enclosure and increasing the air pressure inside. Fighting that increased pressure quickly tired the astronaut. Bellows joints do not increase the pressure. When they bend, the outer side of the bend expands while the inner side compresses and the volume remains constant.

Like the Gemini suit, the Apollo suit was made with an inner bladder of neoprene rubber enclosed in a casing to keep it from ballooning out. Multiple layers of thin plastic alternating with fiberglass, followed by several layers of mylar and teflon cloth provided the needed insulation and outer protection. Lunar boots fit over the space suit feet like overshoes. Backpacks carried communications and life support equipment. Each suit was custom made to fit its occupant at a cost of $400,000 each.

The Space Shuttle space suit is a direct descendent of the Apollo suit. It is easier to get into and has still more flexibility. In preparing for an EVA from the Orbiter, the astronaut first dons a urine-collection device designed for either men or women with a bag attached at the groin to hold up to a quart of urine. Next comes a suit of longjohns made of spandex mesh. Air can move freely around and through this undergarment, and tubes running through it carry water to keep the suit and its occupant at a comfortable temperature. Twenty-one ounces of drinking water is stored in a bag at the torso. A microphone and headphones are built into a tight fitting cap, the Snoopy Cap, and are attached to a radio transmitter-receiver for communicating with the cabin. Instruments for monitoring heart rate and respiration are built into the suit and connected to the radio.

The space suit itself (Figure 10.7) consists of a hard upper torso with an aluminum shell, a lower torso, gloves, helmet, and visor. All components are multilayered like the Apollo suit. The upper torso part of the space suit is mounted on the wall so a person can slip easily up into it. The astronaut puts on the lower half of the suit, then slips up into the upper torso and aligns the many connections between the two parts. The two halves lock together with metal rings to make an airtight seal. Helmet and gloves are then sealed in place, also with metal rings. A visor snaps over the helmet to provide protection from solar ultraviolet and from micrometeoroids.

The suits are not custom made for each astronaut as in previous manned space programs. Each component comes in several sizes and all are interchangeable so any astronaut, male or female, can be properly fitted.

A built-in backpack contains two oxygen tanks; a fan to keep the air circulating; a small canister of lithium hydroxide and charcoal to remove carbon dioxide and other gases; cooling water and a pump to circulate it through the suit; a unit to cool the water and remove water vapor; and batteries for power. Sufficient oxygen is carried in the main tank for seven hours; a 30 minute reserve tank provides for an emergency. The batteries will power the suit for seven hours also.

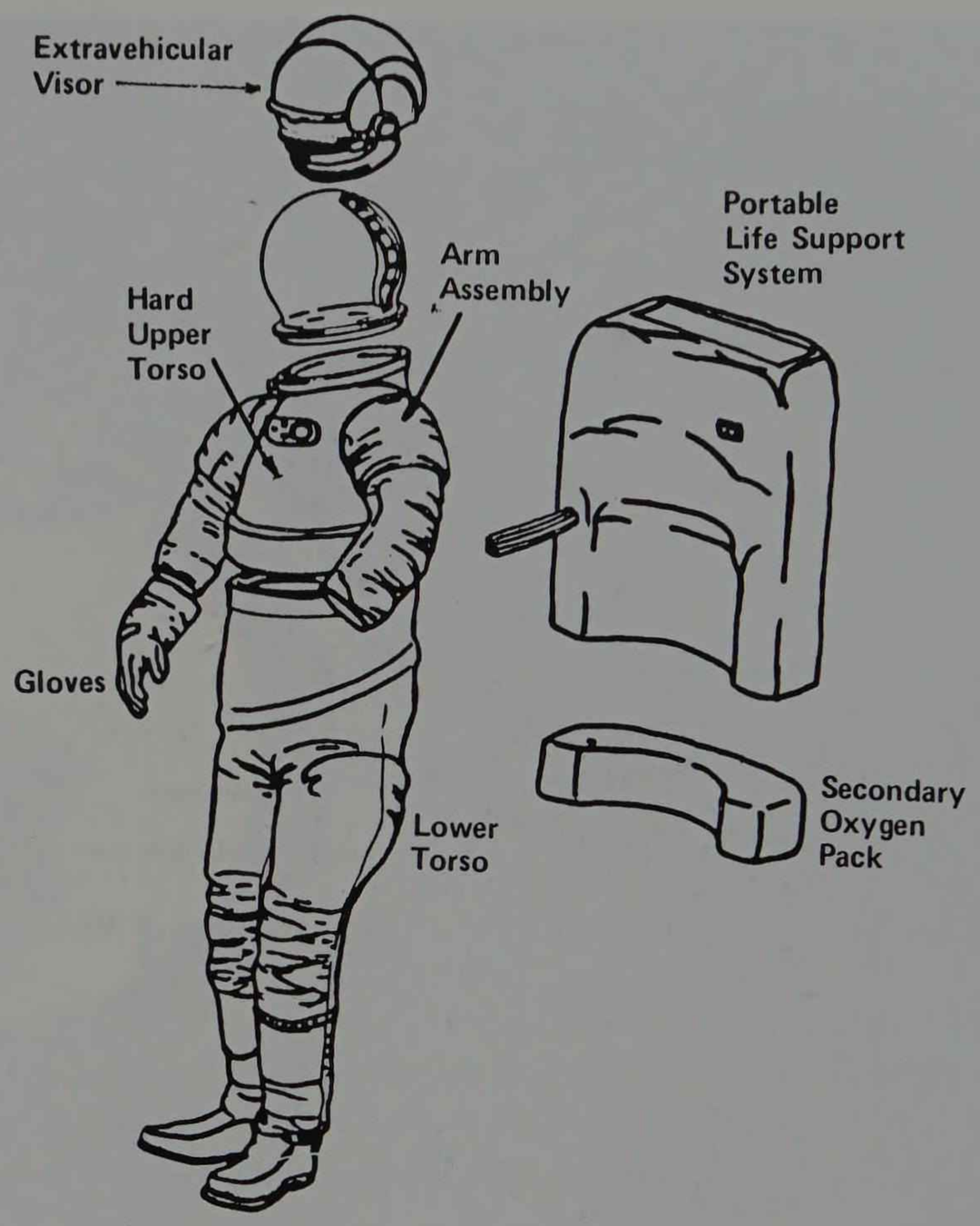


Figure 10.7 Space Shuttle space suit. *Courtesy of NASA.*

A control panel is attached to the hard chest part of the suit. The suit itself notifies its occupant of a malfunction, by sounding a tone in the headphones and flashing a light on the control panel. Pressure is kept at 4.1 psi, compared to 14.7 psi in the Orbiter cabin. The potential problem of decompression sickness, the bends, was discussed in Chapter 9.

Through the Airlock

Of course, astronauts cannot just open the cabin door and step out. Leaving the cabin is done through an airlock, a drum-shaped compartment 63 inches in diameter and 7 feet tall. See Figure 10.8. It may be mounted in the Orbiter in one of several places shown in Figure 10.9, depending on what is being carried in the cargo bay. The astronaut enters the compartment, dons the space suit, and attaches a tool kit and flashlight. After sealing the inner hatch, the air is pumped out. The outer hatch is then opened for exit into the payload bay, Figure 10.10.

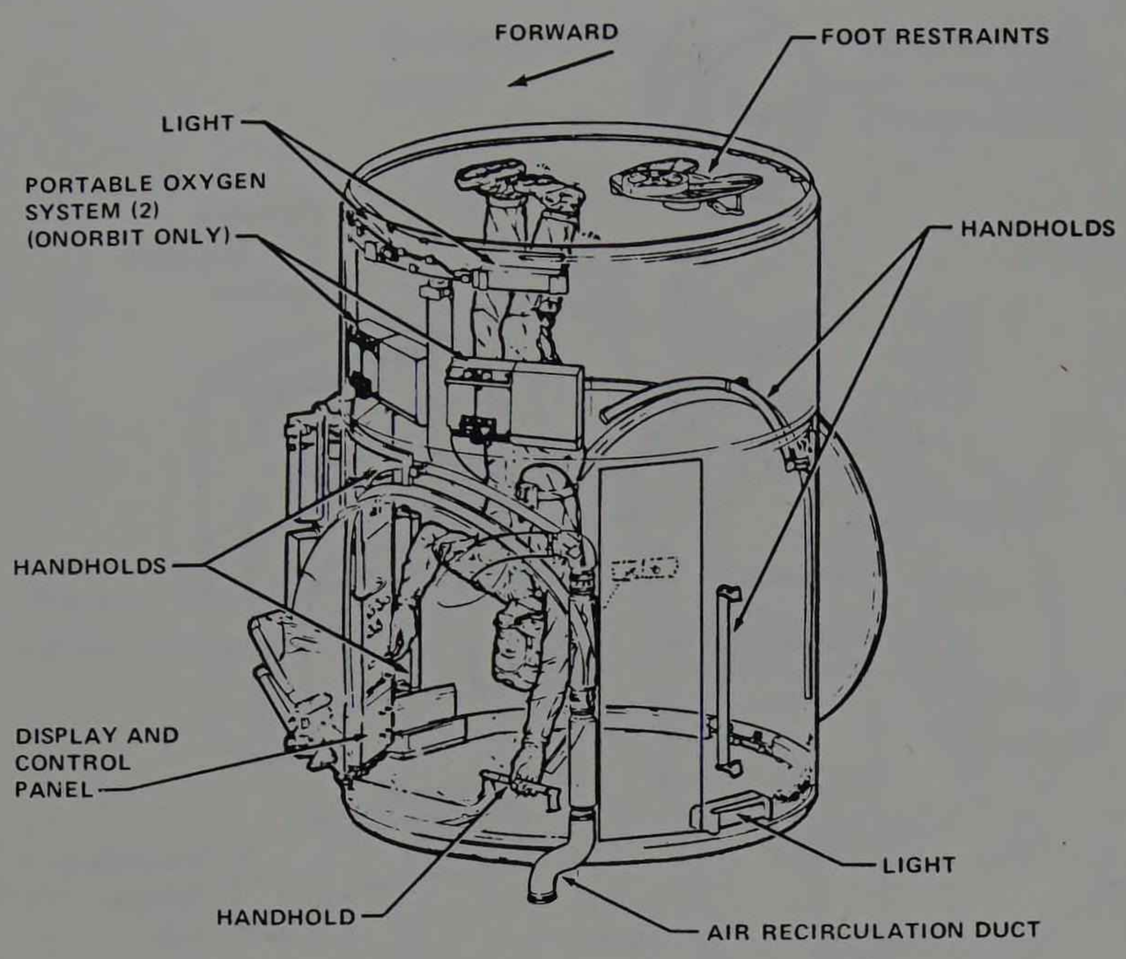


Figure 10.8 Space Shuttle Orbiter airlock. *Courtesy of NASA.*

Hand rails are conveniently located along the full length of the cargo bay near the door hinges and in several other places. Long wires run the full length of the cargo bay just above the hand rails on each side. A tether attached to the space suit and clipped to these wires keeps the astronaut from floating away, yet allows freedom of movement throughout the area. Perhaps you have tethered your dog that way, using a long wire in the back yard with the leash looped around it so the dog can run over a wide area but cannot run away.

Simple jobs become difficult when weightless. For example, turning a screwdriver is nearly impossible. When force is applied, the screw remains firmly anchored while the astronaut rotates. (Remember Newton's third law.) Foot restraints are located at strategic spots in the cabin and in the cargo bay, and they can be easily moved to other locations if needed. An astronaut is firmly planted in one spot by slipping both boots into the restraint. Working with hand tools is much easier when the feet stay in one place. Velcro is used abundantly to keep things from drifting off. Small objects can be tethered to straps on the wrist so they cannot float away.

Manned Maneuvering Unit

When there is work to be done beyond the reach of an astronaut in the payload bay, the manned maneuvering unit (MMU) converts him into the world's smallest completely self-contained spacecraft. Figure 10.11 shows Bruce McCandless on the first untethered spacewalk in February 1984. He and his partner Bob Stewart flew more than 300 feet from the Orbiter and returned several times. On one return McCandless flew around to the nose of the Orbiter, looked in, and asked if they wanted the windows washed.

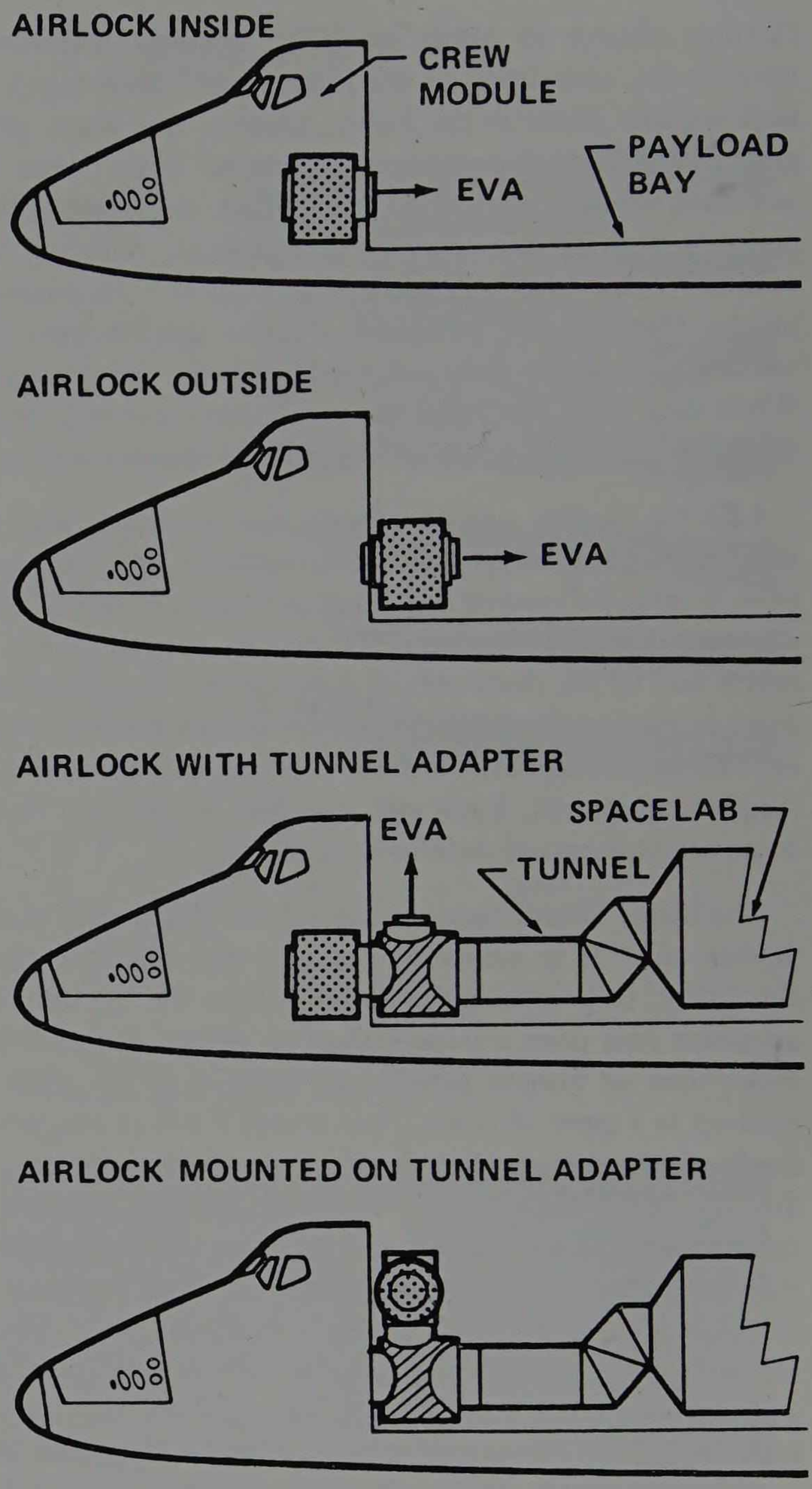


Figure 10.9 Mounting positions for the Orbiter's airlock. *Courtesy of NASA.*

Since those first flights, the MMU has been used to capture and repair satellites.

The MMU is stowed in the payload bay against the front wall. An astronaut (in a space suit, of course) simply backs up into it, closes two latches, and flies off.

Mounted on the MMU are 24 thrusters which produce 1.6 pounds of thrust each. Nitrogen is used for propellant. Supply tanks mounted on the back carry enough propellant for about six hours and can be refilled from the Orbiter's nitrogen supply. Flight controls are located on the ends of the armrests. At the left hand is the "throttle" and "brake" which control straight line motion: left or right, forward or backward, up or down. At the right hand is a joystick to control attitude: up and down for pitch, left and right for yaw, and rotation for roll. If the astronaut wants to stay in

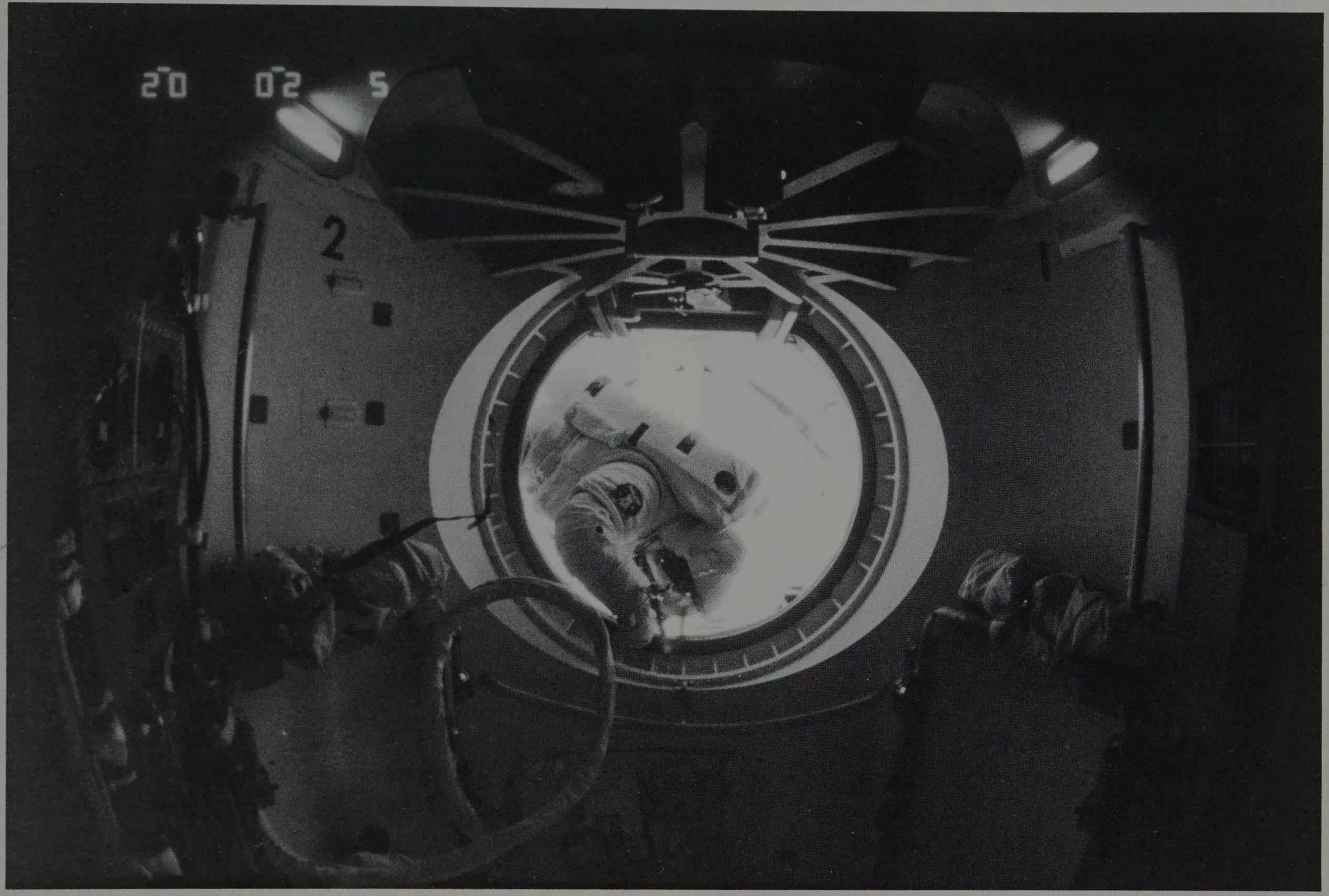


Figure 10.10 Astronaut leaves the airlock to go outside into the cargo bay. *Courtesy of NASA.*

a particular attitude, the MMU can be put on "autopilot," freeing both hands for other tasks.

There are actually two redundant sets of controls and propulsion systems operating at all times. The thrusters work as two sets of twelve, operating independently, yet together. If thrusters or controls on one set should fail, that set can be shut down and the other can bring the astronaut back home to the Orbiter.

Normal flight speed is from 0.3 to 1.0 mile per hour with respect to the Shuttle (in addition to orbital speed of 17,500 miles per hour with respect to Earth, of course).

To help the astronaut monitor what is happening, a tone is heard in the headphones anytime a thruster fires. Also, a fiber-optic cable connects the MMU to the space suit control panel so the nitrogen supply and battery condition can be monitored. MMU silver-zinc batteries are interchangeable with those that power the space suit and can be recharged in the Orbiter.

Care and Feeding of Satellites

One of the most immediate and obvious jobs to be done in space is to launch, recover, repair, and maintain satellites. The Space Shuttle acts as a first stage booster taking satellites to low Earth orbit. Some satellites remain there to do their jobs; others, such as communications satellites, must be fired to higher orbits by an attached rocket engine. Certain satellites may be recovered and either brought back to Earth for maintenance or repaired by astronauts in orbit. The Space Telescope described in Chapter 6 is a prime example of the Shuttle's ability to launch, repair, and maintain satellites while in orbit. The telescope was designed with this capability in mind.

Let us discuss this subject by way of several examples.

Satellite Launches

Figure 10.12 shows a satellite inside a protective cradle in the Orbiter's cargo bay. The clamshell doors are kept closed to shield it from the Sun until launch time. The spacecraft rests on a turntable and just prior to launch, a motor starts

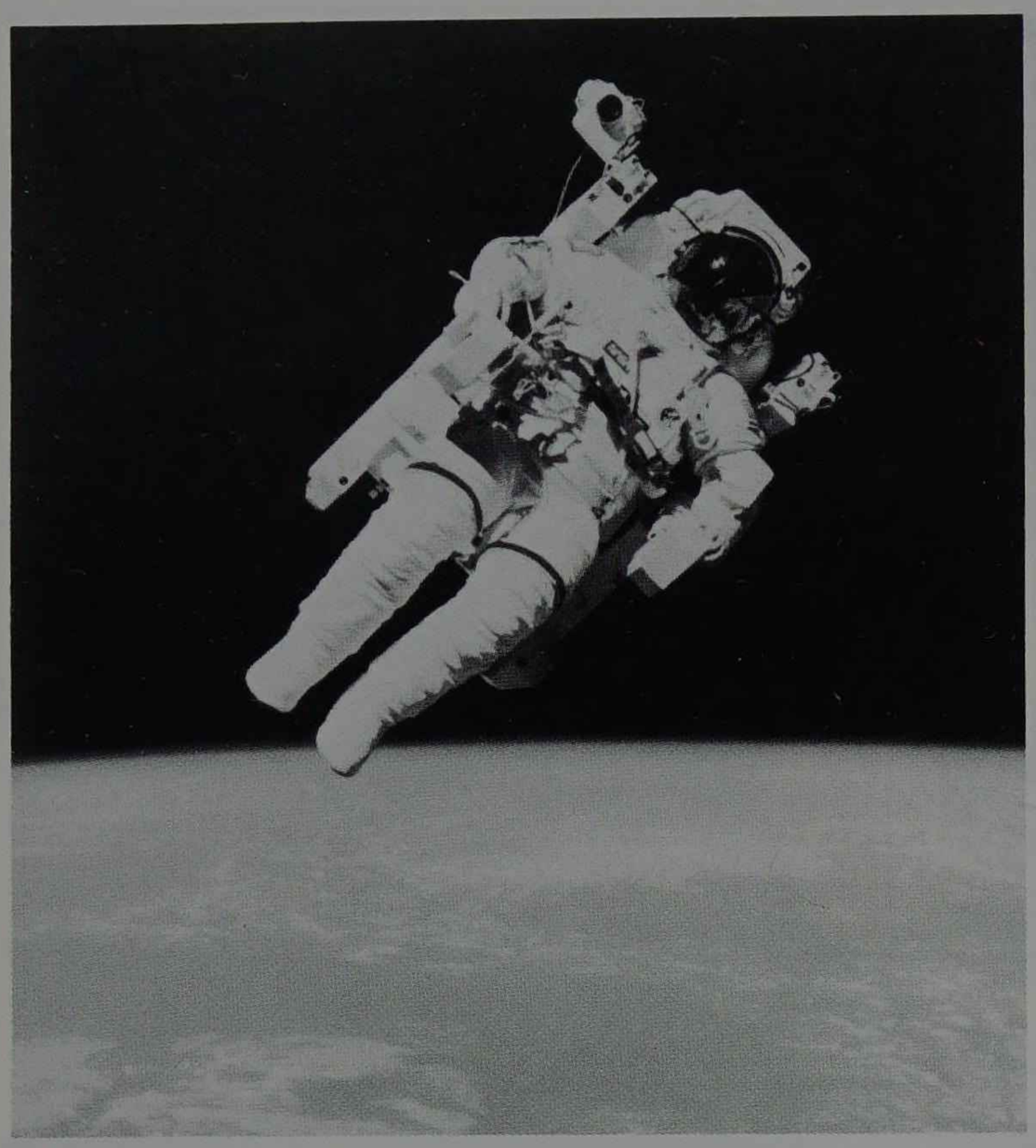


Figure 10.11 Bruce McCandless in the manned maneuvering unit, the first man to fly untethered in space. *Courtesy of NASA.*

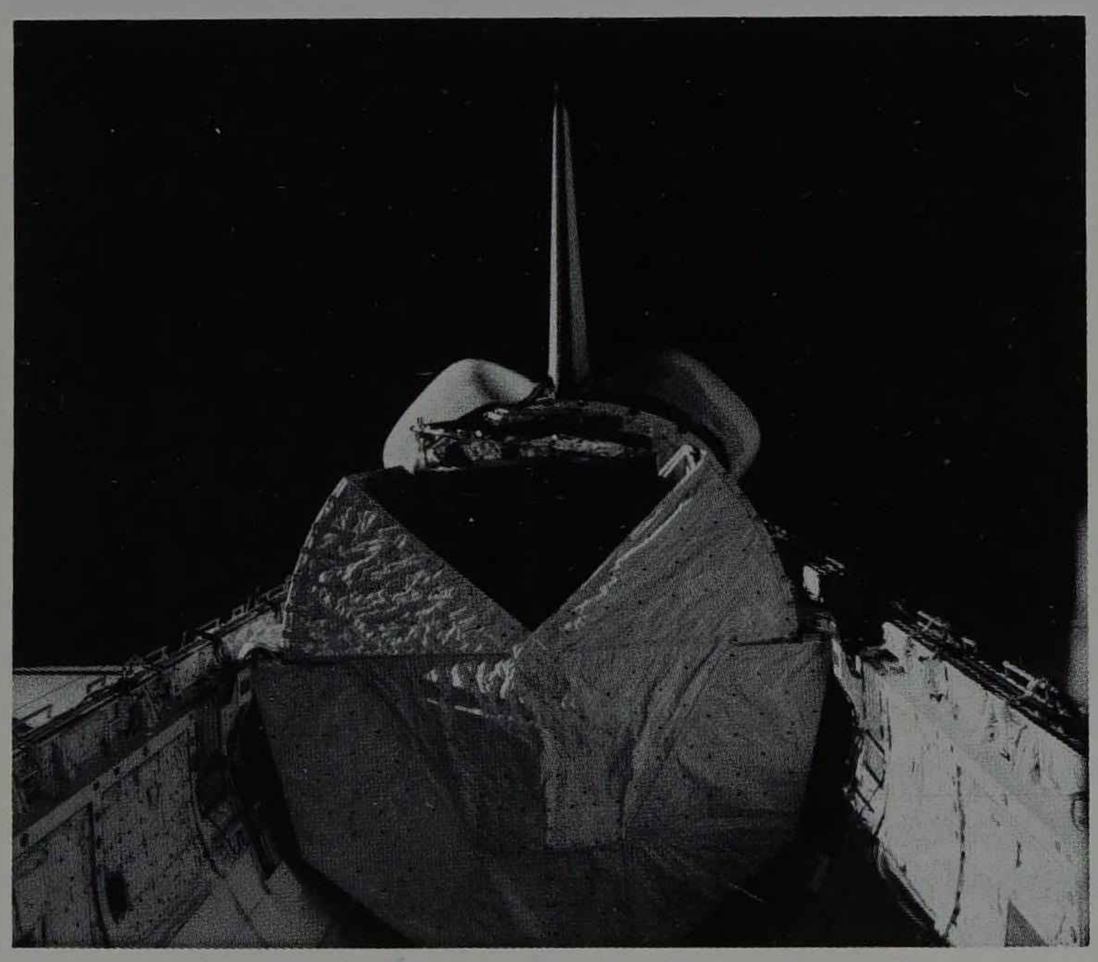


Figure 10.12 Satellite Business Systems spacecraft rests in its cradle in the cargo bay of the Orbiter *Columbia*. White insulated clamshell doors cover the satellite to protect it from both the cold and the excessive heat from the Sun until it is ready for launch. *Courtesy of NASA.*

the turntable and satellite rotating. Spinning the satellite serves two purposes. First, heat from the sun is more evenly distributed over the entire surface. Intense solar heating on one side can damage the satellite. Second, a spinning object remains oriented in the same direction in space. Consider how a top or gyroscope remains upright while spinning and topples over as the rotation slows.

When the satellite is rotating at about 50 revolutions per minute, springs eject it out of the cradle into space (Figure 10.13). Their slight difference in speed causes the Orbiter and the satellite to slowly drift apart. In 45 minutes they will be separated by 20 to 30 miles. The Shuttle's maximum altitude is about 600 miles. If a satellite is to be sent to a higher orbit, an attached solid booster rocket, called a payload assist module (PAM), is fired by a command from the ground at the proper time (Figure 10.14). The PAM transfers it from the Shuttle's orbit to an elliptical orbit with apogee at the desired altitude. When it reaches the desired altitude, an apogee motor in the spacecraft fires to circularize the orbit.

Retrieving Satellites

Communications satellites are not designed to be repaired while in geosynchronous orbit because the Space Shuttle cannot reach that altitude. In February 1984, two communications satellites, Westar VI and Palapa B-2, had been dropped off in orbit, but their booster engines failed to carry them to geosynchronous altitude and they remained in low orbits, useless for communications satellites. On a Shuttle flight in November 1984, two more communications satellites were deployed and then Westar VI and Palapa B-2 were recovered and returned to Earth for repair. See Figure 10.15. A number of new untested procedures had to be devised.

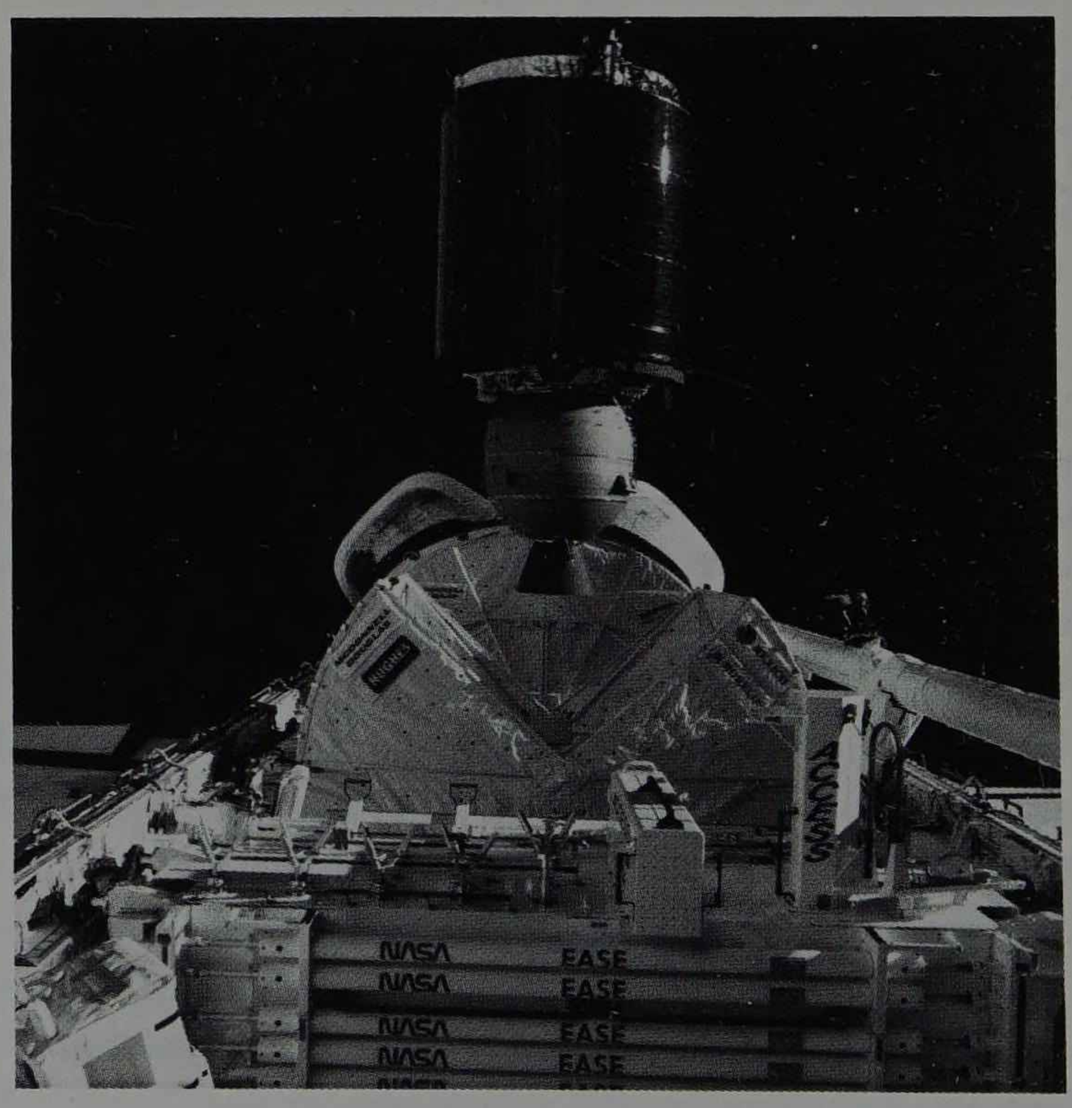


Figure 10.13 Mexico's communications satellite, Morelos-B, being deployed from the cargo bay of the Orbiter. Rocket attached to the satellite will boost it to geosynchronous altitude. *Courtesy of NASA.*



Figure 10.14 The payload assist module booster rocket carries a communications satellite to geosynchronous orbit. *Courtesy of McDonnell Douglas.*

Astronaut Joe Allen flew the MMU to Palapa and inserted a device called a "stinger" into the nozzle of the apogee kick motor. Attached to the satellite by the stinger, Allen fired his MMU thrusters to stop its rotation. He then backed away so the remote manipulator arm could take hold of the stinger and move it into the cargo bay. The next step would have been to attach a bracket to the top of the satellite for the manipulator arm to grab onto and set it into a cradle for the trip back to Earth. However, the bracket would not fit, so Allen held the satellite for a complete trip around the Earth while another astronaut, Dale Gardner, prepared it for berthing. The two together then pulled the satellite into its cradle. The satellites weigh over a thousand pounds on Earth. Although they are weightless in orbit, some force must be exerted to make them move into position (Newton's laws again).

Discovery caught up with Westar the following day. Gardner and Allen traded jobs and followed the same procedures to capture it and berth it in the cargo bay.

Insurance companies had paid out about $180 million for the lost satellites. By paying NASA about $10 million to bring them back to Earth, they hoped to refurbish and relaunch them, recouping up to $40 million of their settlement.

Solar Max Repair

One of the most exciting ventures undertaken by the Space Shuttle was the recovery, repair, and release of the Solar Maximum Mission satellite. Solar Max had been in orbit doing its job monitoring the Sun for about eight months when its attitude controls and one of its instruments, a coronagraph polarimeter, failed. It remained in orbit, disabled and spinning.

In April 1984, the Orbiter *Challenger* made a rendezvous with Solar Max in orbit at about 290 miles, approached within 200 feet, and "parked." Astronaut George Nelson donned an MMU and flew over to the rotating satellite. He approached one end where a trunion pin was protruding and, facing the pin, rolled the MMU at the same rate as the satellite was spinning. With both Solar Max and Nelson/MMU rotating at the same speed, there was no relative motion between them and he could reach out and grab on. But the device that Nelson carried to attach to the satellite wouldn't lock because an insulation fastener was in the way.

The plan had been to capture the satellite and fire the MMU thrusters until the rotation stopped so *Challenger*'s manipulator arm could take hold. When he could not connect to the pin, Nelson tried to stop the rotation by bumping the extended solar panels. But his efforts only caused Solar Max to tumble erratically and he had to give up.

During the night, commands from the ground to Solar Max reduced the tumbling enough so that the following day *Challenger* could capture the satellite with the manipulator arm, bring it into the cargo bay, and lock it into a repair cradle. There, Nelson and James van Hoften replaced the faulty attitude control module and an electronics box for the coronagraph polarimeter. Solar Max was then released back into space and *Challenger* went home.

The original cost of Solar Max was $235 million. The cost of repair, including part of the launch costs, was about $55 million, a savings of $180 million over the price of a new satellite.

Syncom IV-3 Repair

Syncom IV-3 is another satellite that failed to reach geosynchronous orbit when the booster rocket engines would not fire on command from the ground. It, too, was stuck in a low orbit. In August 1985, the Shuttle *Discovery* rendezvoused with the disabled Syncom. Astronaut James van Hoften rode the manipulator arm to a position where he could attach a handle to it and pull it down to astronaut Bill Fisher. While Fisher held it steady (Figure 10.16), van Hoften attached a grapple to the satellite. The manipulator arm then took over the chore of holding it in place while the two astronauts repaired the trouble. First they shorted across some of the wiring and attached a new electronics box to bypass the defective part. Next they connected a battery power supply and sent a command to unfold the radio antenna. They also placed a cover and temperature sensor over the nozzle of the perigee-kick

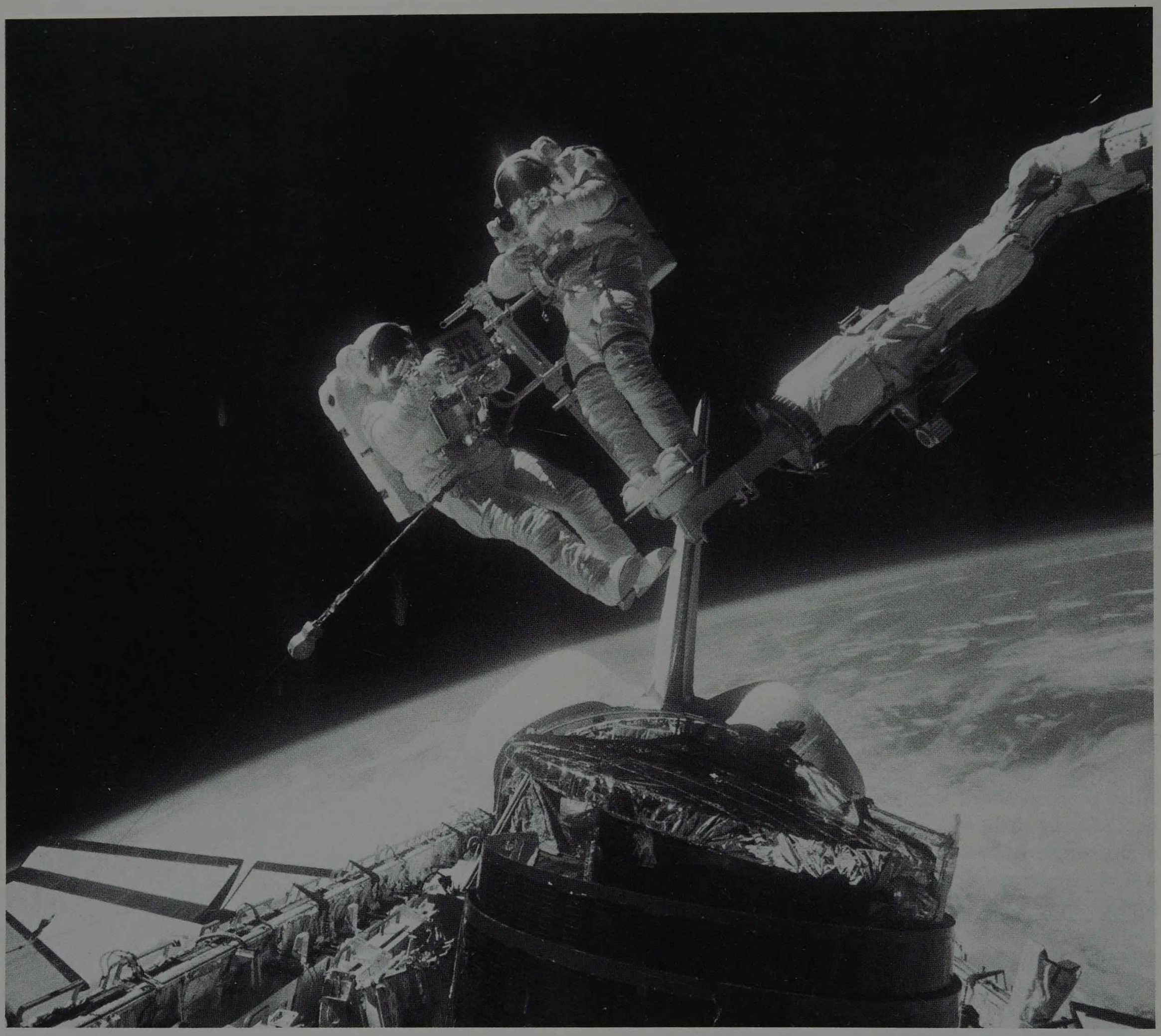


Figure 10.15 Astronauts Gardner and Allen display a "For Sale" sign for the two disabled satellites they recovered from orbit. The two satellites were brought back to Earth for repair and re-launch. *Courtesy of NASA.*

motor to help stabilize the temperature of the solid rocket propellant (Figure 10.17). Finally, van Hoften stood on the manipulator arm and, using a handle he had attached, started the satellite rotating at three revolutions per minute and shoved it off (Figure 10.18) to drift slowly away from the Orbiter. A two month warmup period was planned before it would be safe to ignite the solid propellant.

Construction of Large Structures

Large structures, such as solar power satellites (discussed in Chapter 5) and the space station (to be covered in Chapter 11), cannot be boosted into orbit completely assembled. It will be necessary to build them in space.

Developing elements of a structure which fit together easily, tinker toy fashion, while weightless required several years of engineering and experimentation. Astronauts wearing space suits in a tank of water to simulate weightlessness tried working with various struts, tubes, beams, and joints until they had two designs which seemed to work well. Pieces lock together using only one simple tool, the astronaut's hands.

The designs were then tested in space during a flight of the Shuttle *Atlantis* in November and December 1985. Two

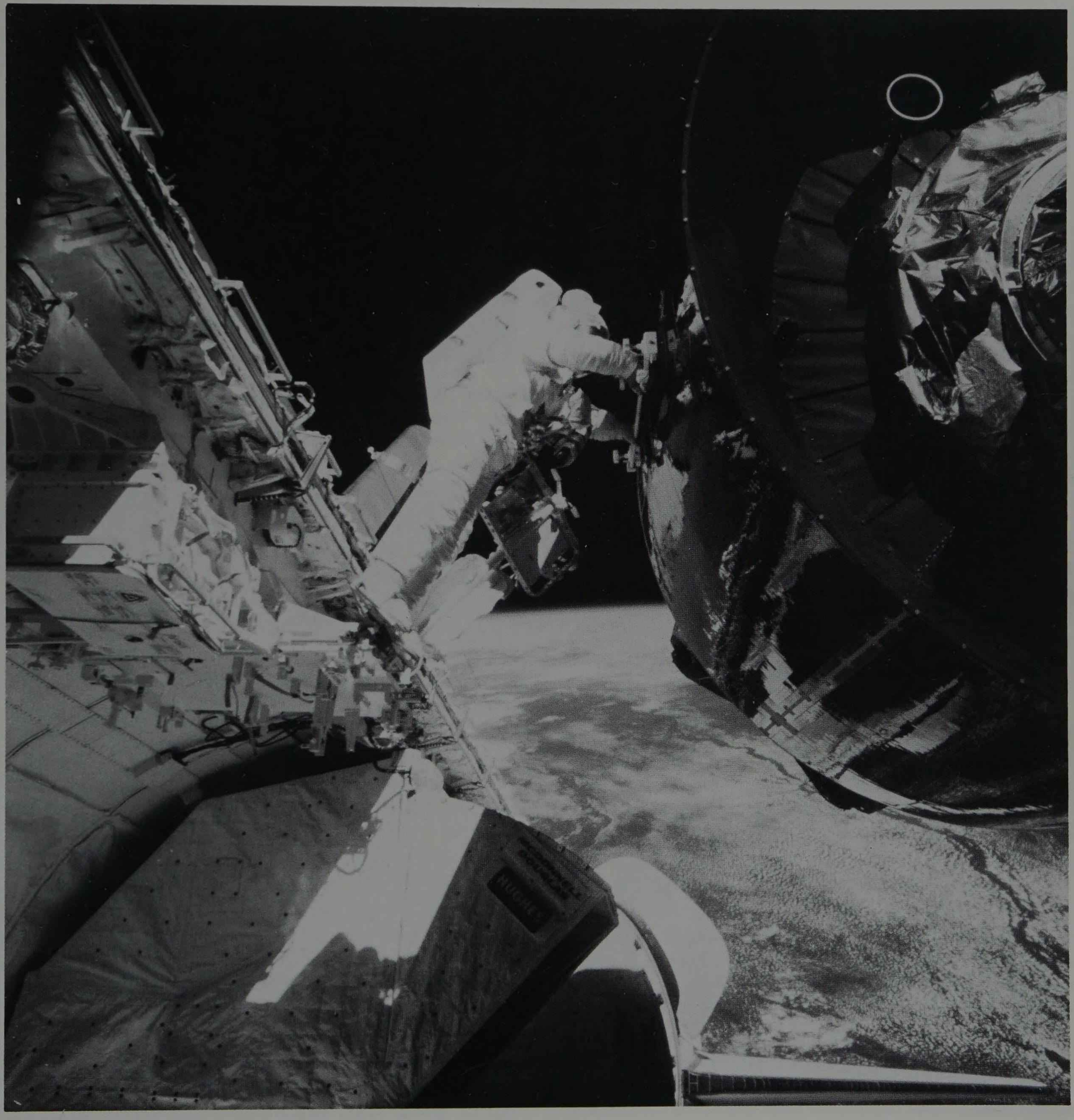


Figure 10.16 Astronaut Fisher holds Syncom in place while van Hoften, out of the picture on the other side of the satellite, attaches a grapple for the manipulator arm to grab onto. *Courtesy of NASA.*

structures were erected, a towerlike truss called Access and a tetrahedron called Ease.

With their boots clamped into foot restraints, astronauts Woody Spring and Jerry Ross assembled pieces of the three sided truss into 4.5 foot sections using a rotating jig on the floor of the cargo bay. One side of a section was assembled, then the jig was rotated and another side built, then rotated again and the third side finished. As each section was completed, it was pushed up the jig and another section assembled beneath it. Using 93 struts and 33 joints, the astronauts built ten sections, a total of 45 feet, the height of a four story building, and tore it down in an hour and 25 minutes.

Astronaut Spring, riding the manipulator arm, picked up

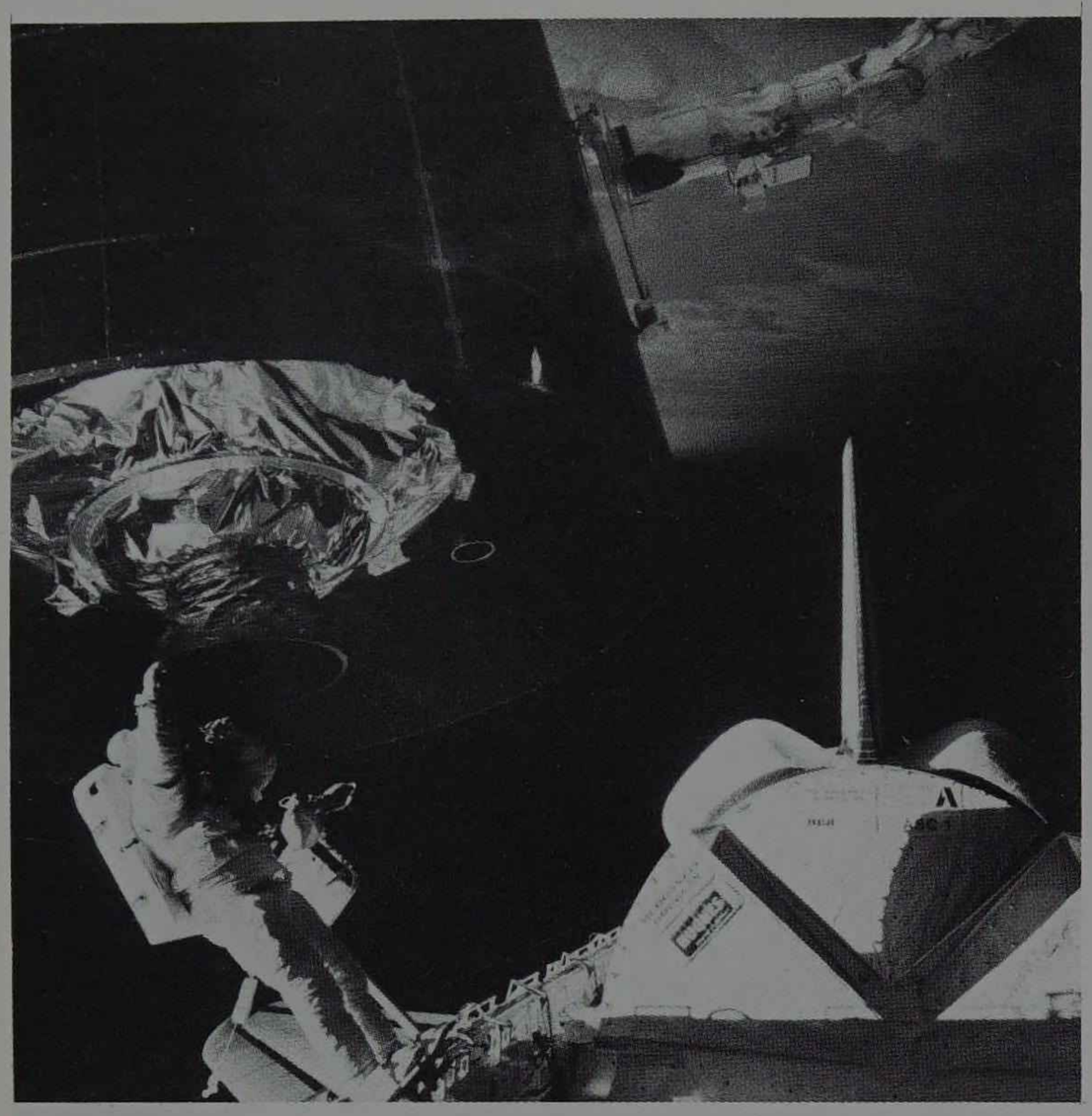


Figure 10.17 Astronaut inspects the nozzle of Syncom's perigee kick motor. The satellite had been floating in orbit for four and a half months. A cover was placed over the nozzle to help warm up the solid propellent before firing it to geosynchronous orbit. *Courtesy of NASA.*

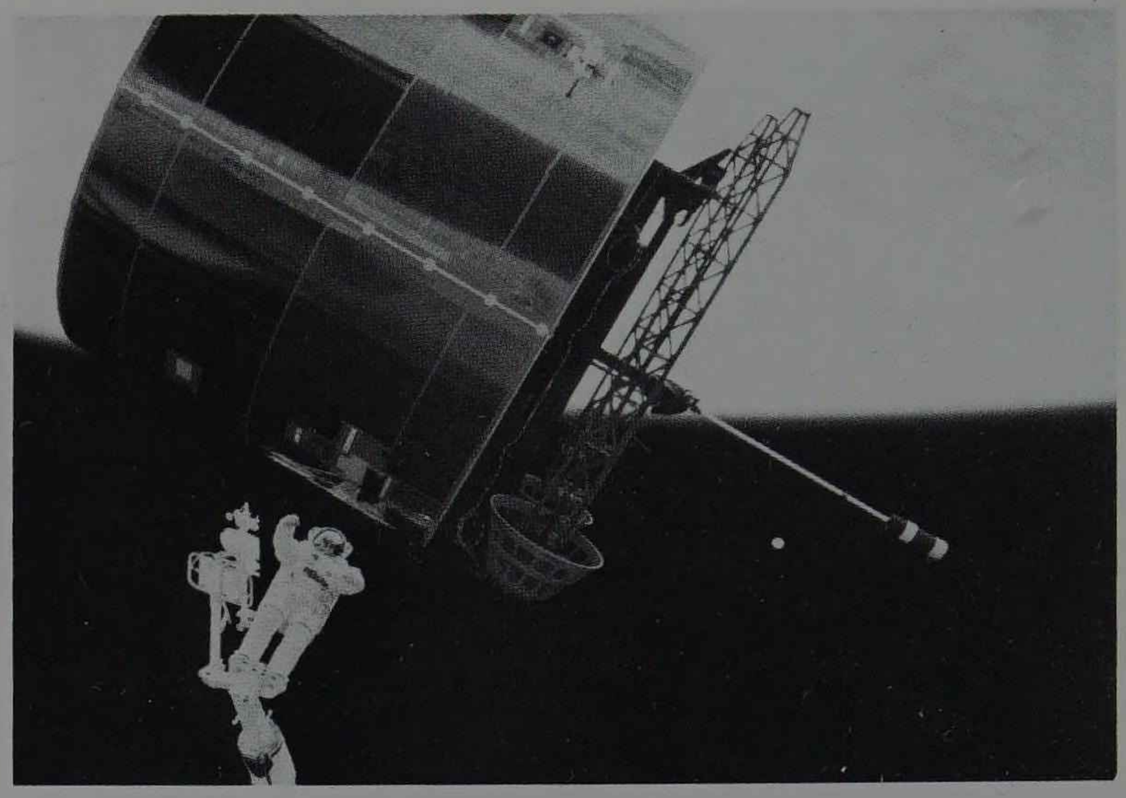


Figure 10.18 Van Hoften manually started Syncom rotating at about three revolutions per minute, then shoved it off away from the Orbiter. The Moon is seen below the satellite's antenna. *Courtesy of NASA.*

the tower by one end and moved it in several directions to see how easily it could be maneuvered and repositioned as might be done when building a space station. Figure 10.19 shows some of the action. He found it easy to point the structure at some point on Earth and keep it in that position. He also found it easy to hold it at its center and spin it without undue stress on the manipulator arm. Later he removed and replaced some struts in the truss to simulate repairing a damaged part (Figure 10.20); that too was not a difficult task. Finally, he ran a cable along the inside of the tower and then removed it to see how difficult a job it is in weightlessness.

Looking something like a pyramid, a tetrahedron has four triangular sides. (A pyramid has four triangular sides and a square base.) The astronauts built the Ease tetrahedron while floating freely without foot restraints, connected to the Orbiter only by a tether. See Figure 10.21. The entire structure consists of six beams, each 12 feet long, connected together with only four joints.

Trying to maintain a fixed position in space while rotating the 12 foot sections into place and snapping the corners together proved to be more difficult than building the Access tower. On Earth the beams weigh 60 pounds and, even though weightless in orbit, they resist the force applied to move them (Newton, again). It was particularly tiring on the hands and wrists. The time needed to build the tetrahedron decreased with practice, of course. The first time took Spring 12 minutes; the last time required only 9 minutes. At one point he disconnected the structure from the Orbiter to see how well it could be moved into various positions and found it to be more difficult to maneuver than the tower.

Manufacturing

The low gravity environment of an orbiting vehicle offers possibilities for carrying on manufacturing processes that are more difficult and less efficient than on Earth. For example, very large pure crystals have been grown on Skylab and on Shuttle flights which would have been impossible to grow under normal Earth gravity. Gravity causes the crystal to sag and become malformed. In addition, impurities from the container can become part of its structure. A large percentage of the silicon crystals grown for computer chips must be thrown out because of imperfections. Gallium arsenide chips are faster and more powerful than silicon chips, but are even more difficult to manufacture. In weightlessness, crystals can be processed without a container eliminating the impurity problem and can be grown much larger with a near perfect molecular structure. In spite of the high cost of transportation to and from space, it may be profitable to manufacture such crystals in orbit.

Manufacturing high quality alloys is another possible commercial venture in space. An alloy is a mixture of two or more different metals to produce a material with different characteristics than any of its components. For example, titanium steel is a material of exceptional strength even at high temperatures. Some aluminum alloys are as strong as steel but weigh much less. When mixing an alloy in Earth gravity, the more dense metal tends to sink to the bottom



Figure 10.19 Astronaut Ross examines the tower-like truss, named Access, which he and Astronaut Spring just constructed in the cargo bay of the Orbiter *Atlantis*. The white framework inside the lower part of the tower is a jig used to assist in the construction. *Courtesy of NASA.*

before the mix cools and hardens, producing a nonuniform material. That separation would not happen in the microgravity of an orbiting spacecraft. Materials of unprecedented purity and uniformity could be prepared by allowing the mix to float in a vacuum without a container until it hardens.

Electrophoresis

One of the manufacturing processes that has been tested for commercial use in space is electrophoresis. Electrophoresis is a method of separating materials from one another while they are immersed in a liquid or gel. Every substance has an



Figure 10.20 Spring simulates a repair job on the truss. The Gulf of Mexico is below. *Courtesy of NASA.*

inherent electrical charge because its molecules are made up of atoms which contain negatively charged electrons and positively charged protons. Since the particles carry a charge, they can be made to move through the fluid by applying an electric field. Negatively charged particles migrate toward the positive side of the electric field. The speed at which the particles move in the fluid depends on their mass and charge, and on the strength of the electric field.

In one type of electrophoretic machine, substances to be separated are injected into a fluid flowing continuously downward through the chamber. See Figure 10.22. An electric field is applied perpendicular to the flow. As the various substances move downward with the flow, they split into several particle streams, migrating across the flow at various rates in the electric field. The substances are collected at outlets at the bottom of the chamber.

The most important application of electrophoresis is in the separation of medically useful biological substances, such as enzymes and hormones. For example, insulin is produced by beta cells in the pancreas. Beta cells can be a source of natural insulin if they can be separated from the pancreatic cells. Pure natural insulin is used for research and treatment of diabetes. Similarly, kidney cells produce an enzyme, urokinase, which can help in the treatment of blood clots, phlebitis, and strokes. Pituitary cells produce a growth hormone. The problem comes in separating the pure hormones, enzymes, cells, and other proteins from one another.

Electrophoresis works on Earth, but two problems occur, both due to gravity. First, if the biological materials are much more dense than the moving fluid, the injected stream collapses under gravity around the inlet and the purity of the separation is reduced. If they are diluted to a lower density, the purity is improved, but the quantity that can be separated in a given time is reduced.

There is a second gravity problem. If the temperature of the moving fluid is not uniform throughout, the cooler parts, being more dense, will sink due to gravity while the warmer parts rise, producing convection currents. This phenomenon can be observed when looking into a pot of water on a stove. The water at the bottom of the pot is hotter because it is in contact with the burner while the top surface of the water is cooler. Convection currents can be easily observed. In an electrophoretic machine, convection cells disrupt the moving streams, reducing their purity. Using a smaller chamber slows the convection currents, but also reduces the output of the separated substances.

In a weightless environment these problems disappear. High volume, high density samples can be injected into large volume chambers and large quantities of pure substances can be produced. Two experiments were flown in the Apollo-Soyuz project in 1975, one a continuous flow system from Germany and the other a static flow system by NASA. A mixture of horse, rabbit, and human blood cells were successfully separated into the three constituents. McDonnell Douglas Corporation built electrophoretic machines which were operated by astronauts on five Shuttle missions from 1982 to 1985. The results were remarkably successful. On one of the flights the unit separated more than 700 times the material with four times the purity than was achieved in a similar machine on Earth. McDonnell Douglas has plans to fly a larger, completely automated production unit in the cargo bay of the Shuttle. The unit will have 24 times the capacity of the experimental units previously flown.

Plans have been developed for an electrophoretic factory in space, either manned or unmanned, for operation in the 1990s. An unmanned factory would be visited four times a year by astronauts to bring up fresh materials for processing, return the separated materials back to Earth, and perform any necessary repairs and maintenance on the equipment. A manned version could be operated aboard the space station in the mid-1990s. Cost effectiveness would be greatly improved because the machine would have to be launched only once and would operate continuously while in orbit.

Spacelab

Major scientific research is done in the Spacelab, Figure 10.23. The European Space Agency developed the laboratory module which fits into the Shuttle cargo bay and connects to the cabin through the airlock hatch. This

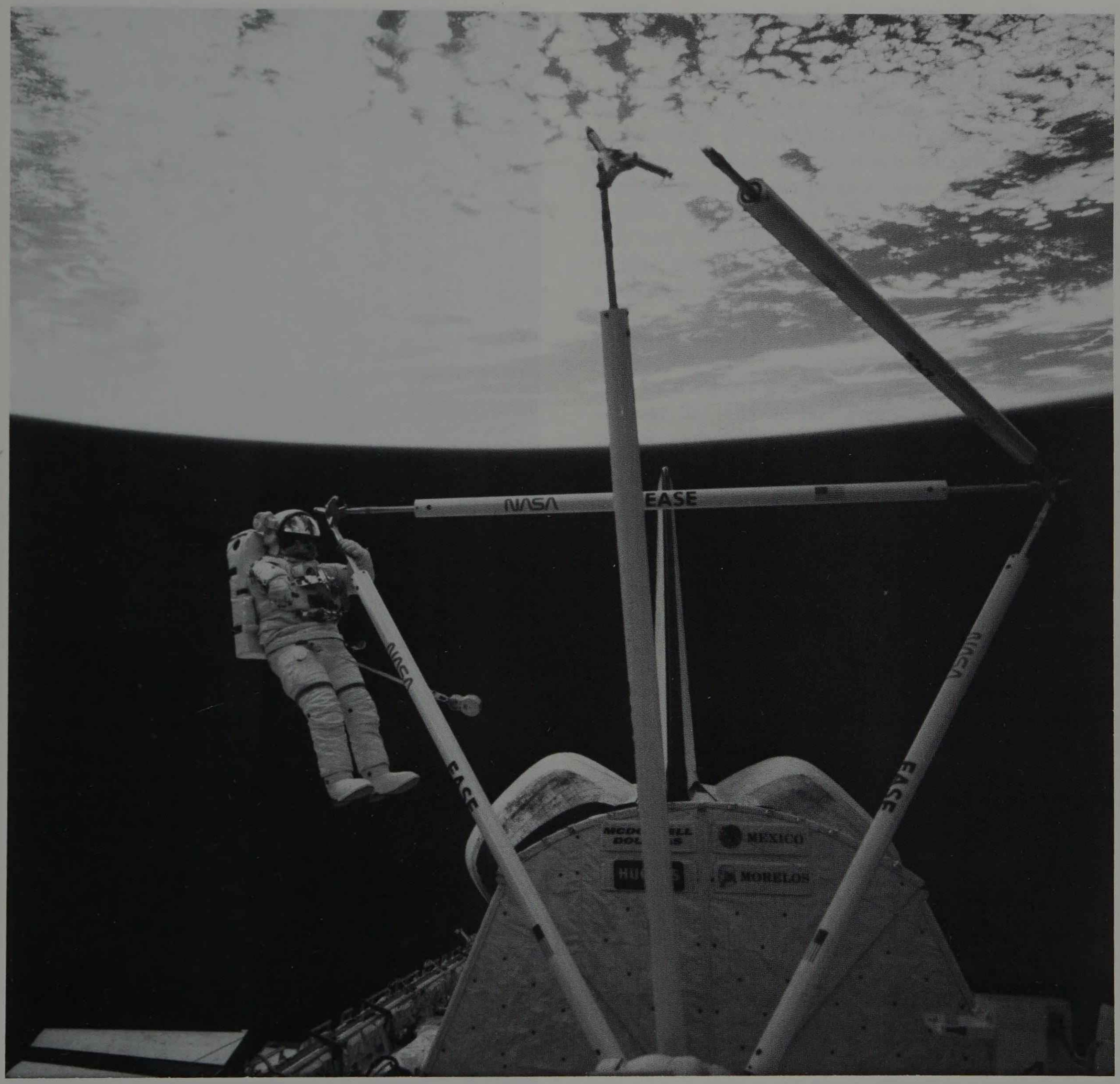


Figure 10.21 Ross floats freely while constructing the Ease tetrahedron. *Courtesy of NASA.*

configuration can be seen in Figure 10.9. Experiments can be placed either in the Spacelab or outside on pallets and operated from inside. Scientist-astronauts from European countries and the United States work together in a shirt-sleeve environment. Hundreds of experiments have been carried on four Spacelab flights in biological sciences, materials processing, Earth sensing, astronomy, solar physics, and a variety of other areas. The scientists have voice, data, and television communications with experts and advisors on the ground so their work can be discussed as the experiments progress. If a problem comes up or if a new idea rises from the results, modifications to the experiment can be made.

Many of the experiments depend on weightlessness and require a very smooth ride without bumps or jolts. Crystal growth, for example, can be disrupted by motions of the Orbiter. One method of avoiding and disturbing motions is to let the Orbiter drift free in orbit with either the nose or tail pointed down toward Earth. This attitude is called gravity

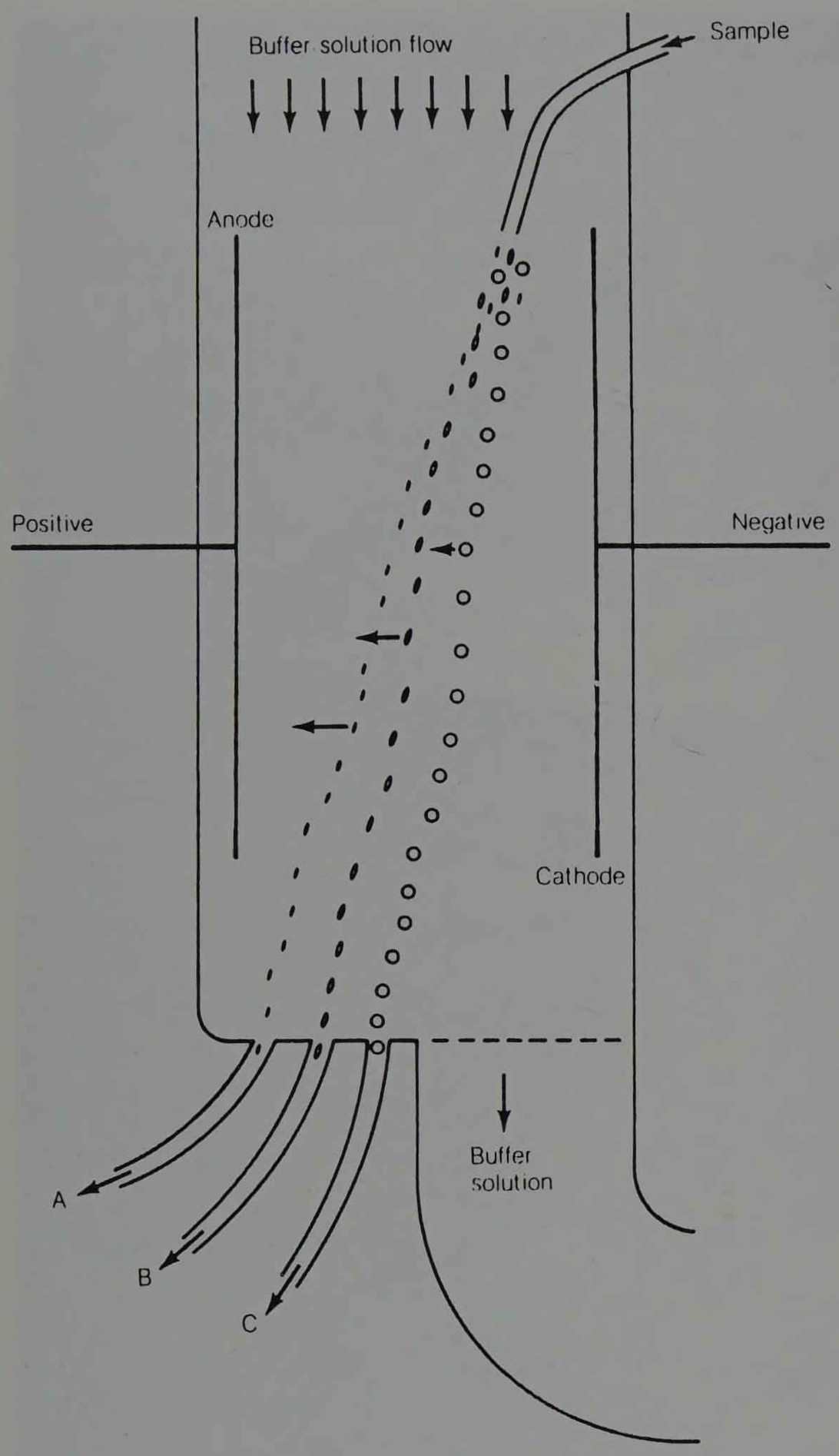


Figure 10.22 Electrophoresis. *Courtesy of NASA.*

gradient stabilization. Gravity acting on the long dimension of the Orbiter keeps it oriented in that position without firing the thrusters. See Figure 10.24.

Science Experiments

A radar was carried aboard two Shuttle flights to make images of selected locations on Earth. A spectacular result was the discovery of dry river channels buried under the sands of the Sahara Desert. Radar waves can penetrate dry soil, but reflect from water droplets in wet ground. In effect, they see through the sand. Radar waves reflect differently from various surfaces. Interfaces between dissimilar kinds of rock, diverse types of vegetation, and paved surfaces, for example, all produce a different radar image. The travel time of the signal is measured so the distance to objects in the picture can be mapped. Also,

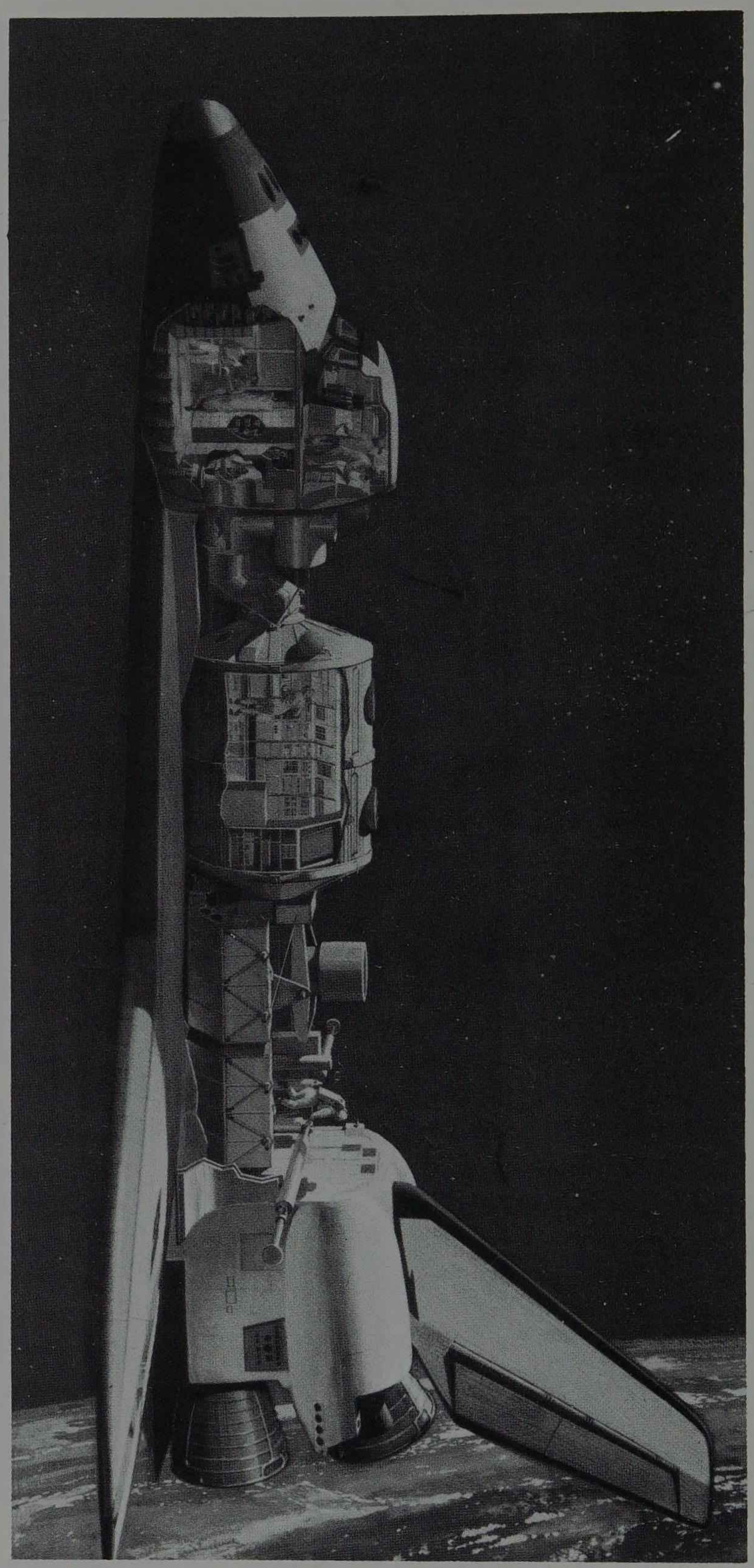


Figure 10.23 Artist's concept of Spacelab in the cargo bay of the Orbiter. Scientists work inside the pressurized laboratory in a "shirtsleeve environment"; some of the instruments, located just to the rear, are tended by a space suited astronaut. A tunnel connects Spacelab with the Orbiter cabin and the airlock for exit to space is seen attached to the top of the tunnel. (Refer back to Figure 10.10.) The Orbiter is in "gravity gradient" attitude. *Courtesy of NASA.*

because the antenna points at an angle to the ground, vertical objects have a three-dimensional look in the picture. Anthropologists have recommended further use of



Shuttle in gravity gradient attitude and 57° orbit plane

Figure 10.24 Shuttle in gravity gradient attitude. *Courtesy of NASA.*

radar imaging to search for ancient cities buried under sand and debris.

Numerous small experiments have been carried on Shuttle missions. Only a few will be mentioned here.

A colony of 3,300 honey bees in a 9 inch cube was carried on a six day mission to see if they would go about their usual bee-business in weightlessness. They did. They built a normal honeycomb of hexagonal cells and the queen laid 35 eggs. That experiment had been devised by a Tennessee high school student.

In another insect experiment, flies, moths, and bees were observed while weightless. Moths flew around in the chamber rather well, bees let themselves tumble without flapping their wings, and flies spent most of the time walking on the walls of the chamber.

Sunflower seeds were carried in sealed plant containers with measured amounts of soil and water. On Earth, gravity pulls water down into the soil. Under weightlessness the water collects around the seed and drowns it. Previous experiments have failed because of this problem. The quantity of water in the soil may determine whether a seed will germinate or not.

Plants produce a substance called *lignin* which gives them structural strength to stand up against gravity. Although lignin is vital to the plants, commercially it is a relatively useless material which interferes with paper manufacturing. Seedlings have been carried on Shuttle missions to see how they grow while weightless, particularly how much lignin they produce. Better understanding of lignin production may help in more efficient utilization of wood products.

Floating algae, *phytoplankton,* in the oceans are a basic food for fish. Find the phytoplankton and you find the fish. In a Shuttle experiment, light reflected from the eastern sides of the Atlantic and Pacific Oceans was directed through a telescope to a diffraction grating which broke the light into its spectrum of colors (wavelengths). Chlorophyll in phytoplankton absorbs certain blue wavelengths and reflects certain green wavelengths. If the bright green wavelength was present while blue was absent, a concentration of phytoplankton and, therefore, fish was probably at that location. Routine methods for leading commercial fishermen to good fishing spots could come from these experiments.

At any given time, about 2,000 thunderstorms are occurring, most of them in the tropics. On two flights, nighttime lightning strokes were photographed through a diffraction grating which spread the light into its spectrum of component wavelengths. From these spectrograms the temperature, pressure, types of molecules, electron density, and amount of ionization in the lightning stroke can be calculated. Daytime lightning was detected by a device which created an audible pulse and recorded it on a cassette recorder, while a 16 millimeter camera simultaneously photographed the clouds. This information may lead to a better understanding of the development of severe storms.

Contamination by Spacecraft

All spacecraft create a contaminated ''atmosphere'' which travels with them in orbit. This was first noticed in the Mercury flights. John Glenn and others reported ''fireflies'' following the capsule. Windows clouded over on Mercury, Gemini, and Apollo vehicles. The density of the induced atmosphere around Skylab was nearly 10,000 times greater than the normal space environment. This type of contamination has many sources:

a. Outgassing of molecules from the body of the vehicle when it is in the vacuum of space

b. Small leaks of fluids and gases from spacecraft systems

c. Exhaust gases from rocket engines and maneuvering thrusters

d. Deterioration of paints and other coatings due to ultraviolet radiation from the Sun

e. Leakage of air from the cabin

f. Water and urine dumped overboard

g. Gases from the waste management systems

This contamination follows along with the spacecraft because those molecules of gas are in the same orbit as the vehicle and, perhaps, because of the gravitational attraction between the molecules and the vehicle. As a result of this contamination several problems arise. The surfaces of windows and optical equipment such as lenses and mirrors become fogged. Deposits on solar panels reduce their electric power output. Deposits on radiators and the outer surface of the vehicle affect their heat absorbing and radiating properties. At certain angles, sunlight scatters off this induced atmosphere causing a glare and making it difficult for sensitive optical instruments to work properly.

Besides gaseous contamination, an Orbiter produces ''light pollution''. It glows as it moves through the oxygen of the thin atmosphere at 200 miles. The phenomenon is not completely understood, but it may have to do with the electrical and magnetic fields produced by the motion of the Orbiter. The oxygen probably becomes ionized, then emits a glow as it recombines into atomic oxygen.

DISCUSSION QUESTIONS

1. If objects are weightless in the payload bay, what is the advantage of using the manipulator arm to move them around?
2. What kinds of jobs can robots do better than people? What jobs can people do better?
3. What limits the length of time an astronaut can work outside the cabin on an EVA?
4. Why does the pilot warn the crew when the thrusters are about to be fired to change the attitude of the Orbiter in space?
5. Does it make any difference which way the Orbiter is oriented when a satellite is released into orbit?

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Chapter 11

Space Stations

In his State of the Union Message of January 5, 1984, President Reagan directed NASA to develop a permanently manned *space station* and to do it within a decade. The purpose is for peaceful economic and scientific gain and for quantum leaps in research and technology. When Americans moved westward in the nineteenth century the government provided land to settlers, incentives for building railroads, and military protection. In modern terms, the government provided or encouraged the development of an *infrastructure* to allow the westward expansion of the country. Development of air transportation also required a government sponsored infrastructure consisting of airports, flight control centers, radar sites, weather stations, and communications systems. Now once again the United States is developing an infrastructure for expansion into the new frontier of space. A transportation system and a permanently manned space station are the first steps.

The United States had a space station in the 1970s called Skylab. See Figure 11.1 and Chapter 1. Skylab was constructed from the large fuel tank of a Saturn rocket, the type that had been used to carry men to the Moon. It weighed 100 tons, the equivalent of seven Greyhound buses, the heaviest object put into orbit until the Space Shuttle Orbiter which weighs 80 tons plus up to 32 tons payload. Skylab was occupied by three crews of three men, the first for a month, the second for two months, and the third for three months.

The Soviet Union has far greater experience with living in space than has the United States. The Soyuz space stations have been a continuous presence for many years. The Mir space station has been permanently occupied since its launch in 1986 (Figure 11.2).

What will the United States space station of the 1990s look like? Perhaps the best known concept for a large space station is the "big wheel" that appeared in the movie *2001: A Space Odyssey*. Such a structure was first presented to the public by Wernher von Braun in an article in *Colliers* magazine, April 30, 1954. See Figure 11.3.

But our 1990s space station will look and function quite differently. Many different designs have been proposed. See Figures 11.4, 11.5 in the color pages, and 11.6.

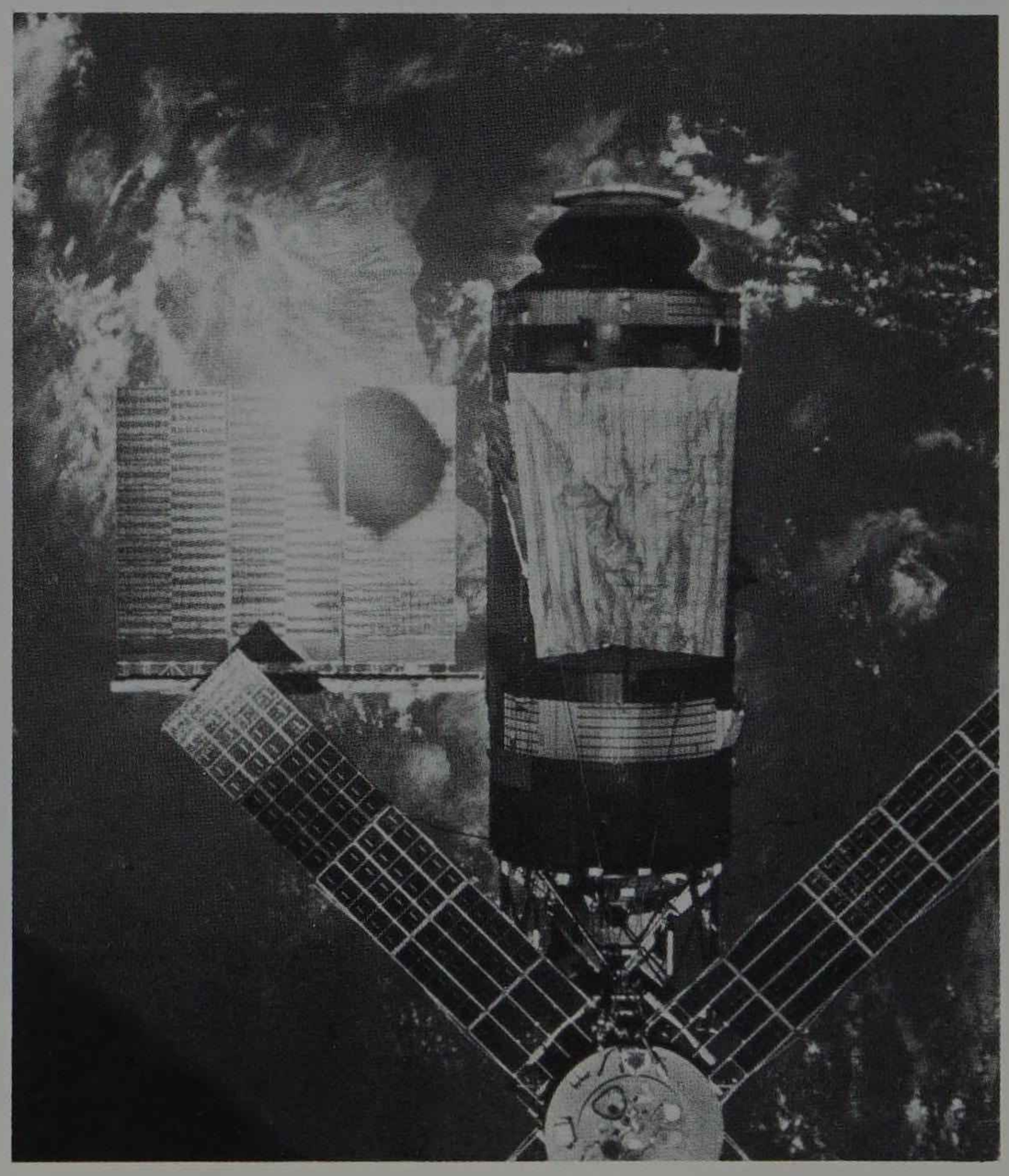


Figure 11.1 Skylab Space Station, photographed by the last crew to work there as they departed for Earth. The shadow of the Apollo command module can be seen on the solar array. *Courtesy of NASA.*

Basically they all have one or more long spars or arms, with a number of things attached: living quarters, workshops, laboratories, solar collectors to produce electricity, radiators to dissipate heat, platforms (pallets) for experiments and manufacturing, communications antennas, and docking ports. The design is deliberately made flexible to allow variation and modification, assuring its usefulness well into the twenty-first century.

Why a Space Station?

Many of the scientific research tasks now being done by satellites will be done better aboard a permanently manned

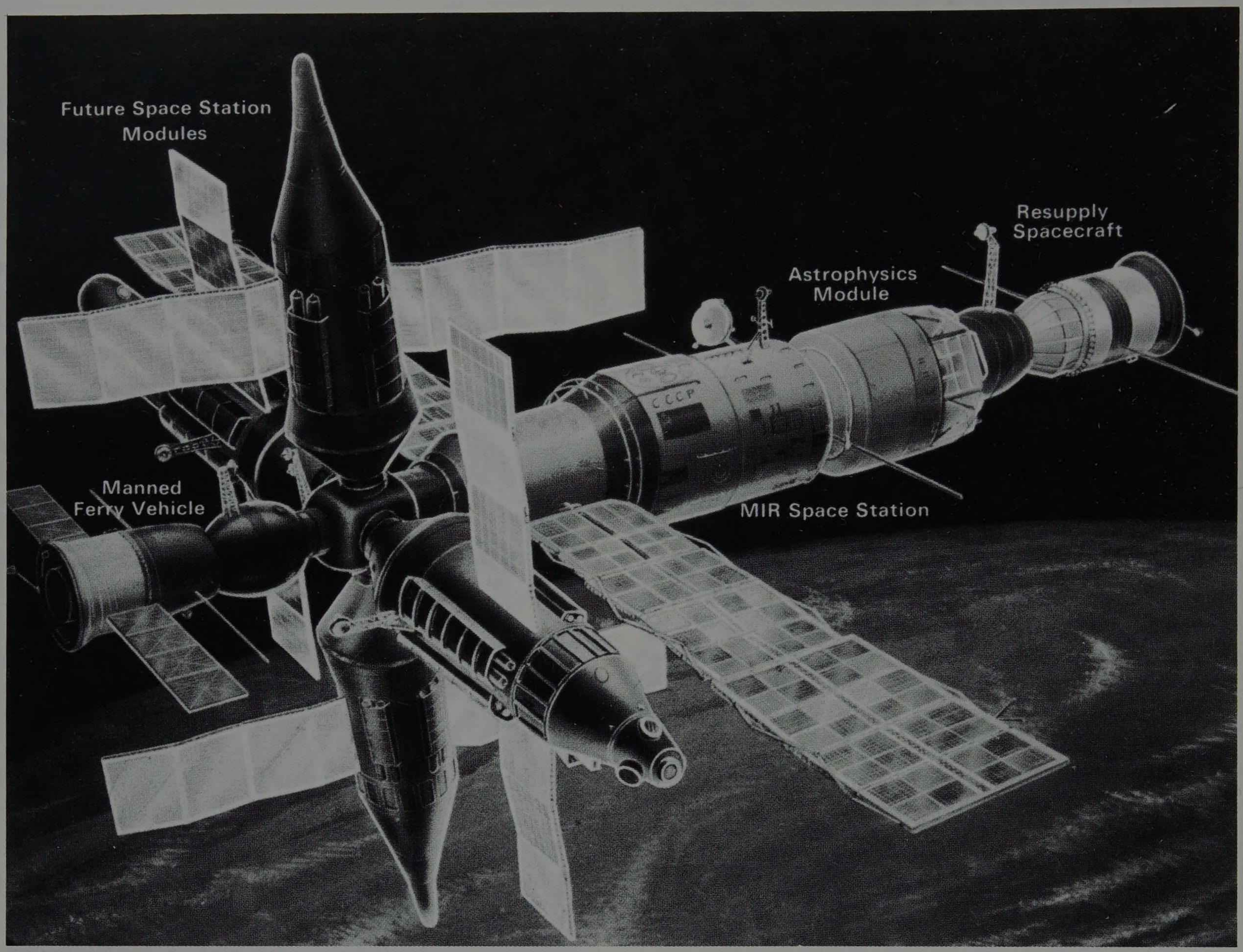


Figure 11.2 Soviet Mir space station. Six docking ports enable a ferry craft, resupply vehicle, and four other modules to be attached and detached as desired. Crew members have individual cabins. *Courtesy of U.S. Space Command.*

space station. We will see advances in astronomy, earth resources, and solar and space physics from our national laboratory in space. Cost savings are a factor, too. Presently, unmanned satellites must be proven 100 percent perfect before launches because if something goes wrong in orbit, that is the end of it. Ground testing to certify the equipment ready for space is expensive and time consuming. Such perfection is not so necessary if the equipment is aboard a space station with someone tending it. Also, now if the results of experiments and measurements suggest a new or modified approach to the experiment, a new satellite has to be designed, tested, and launched. In the future, people tending experiments on or near the space station can modify the experiment and test, repair, or replace the equipment. Spacelab, carried in the Orbiter's cargo bay, gives a hint of this. Radio, television, and data link interactions between the on-board scientist and the scientists on Earth have already proved fruitful in many ways.

Manufacturing in space has been done experimentally, electrophoresis for example (see Chapter 10). But Shuttle missions are limited to a week or so. To be commercially profitable, manufacturing must be a continuous operation; idle machinery makes no profit. Experiments and manufacturing aboard a space station could go on indefinitely.

However, each time a Shuttle docks, the clunk will shake the whole station. Therefore, free flying platforms nearby, but not attached, will carry machinery and experiments that must be free of vibrations, protected from contamination, or precisely pointed. Two of them can be seen in the upper right in Figure 11.5 in the color pages. Machinery could be *teleoperated*, that is, a video camera would send a view to a person in the space station who would operate the machine remotely using robot hands and arms. In advanced robotics, any move of the operator's hands and arms would be reproduced exactly by the machine. An astronaut in an MMU could take care of

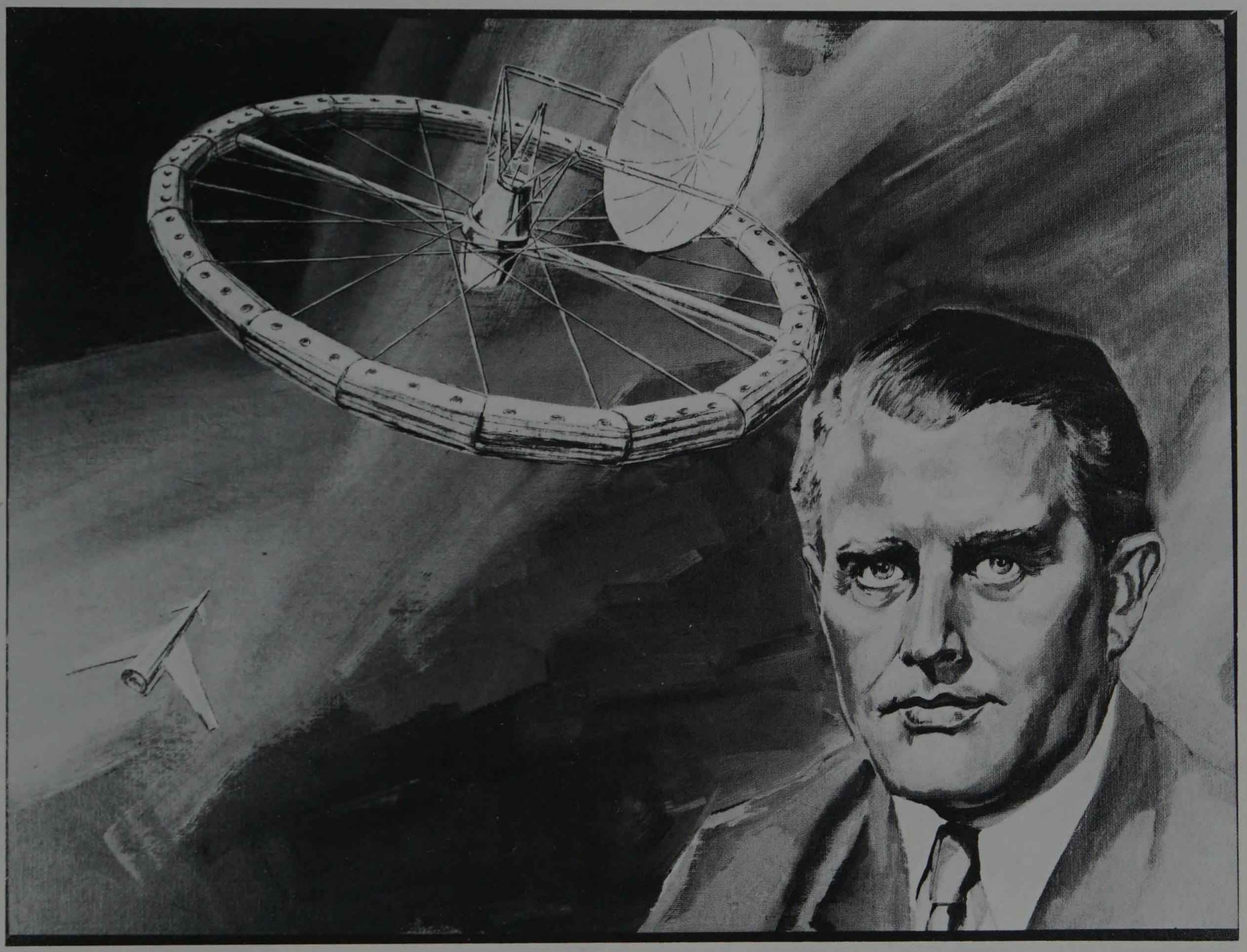


Figure 11.3 Wernher von Braun and his conceptual space station. *Courtesy of David Christensen.*

repair, maintenance, or adjustments, or even propel the platform back to the space station.

Using orbital maneuvering vehicles (OMV), satellites and perhaps people will be carried to and from higher orbit, particularly geosynchronous orbit. The OMV will be able to return satellites to the space station when necessary for repair and maintenance. It, too, would be remotely controlled from the space station.

Plans for the space telescope include such support. An OMV could boost the telescope to higher orbits as needed to maintain pointing accuracy. If it transported the telescope to an orbit higher than can be reached by the Shuttle, boosts would not be required as often. An OMV could also bring the telescope back to the station for routine maintenance and overhaul. Doing these jobs in a ''drydock'' at the station would save the expense and possible damage to the instrument inherent in bringing it back to Earth. Because the OMV will use hydrogen-oxygen fuel, the contamination problem will be alleviated.

A novel way to return a satellite from higher to lower orbit is by using atmospheric drag, Figure 11.7. Retrorockets are fired to reduce the energy of the satellite and transfer it from a high circular orbit (e.g., geosynchronous) to an elliptical orbit with perigee in Earth's upper atmosphere. There the frictional air drag further reduces the energy of the satellite so it does not return to so high an apogee. After several orbits, when apogee is lowered to the altitude of the space station, the satellite's orbit is again circularized and the two rendezvous. This maneuver, called *aerobraking*, reduces the amount of fuel required to transfer from a higher energy orbit to a lower energy orbit. The technique is under study and has not been widely used as yet.

Design and Construction

The initial configuration of the space station is shown in Figure 11.4. At first, plans call for one long keel truss with two radiators, several lab and habitat modules, and four

solar panels providing 75 kilowatts of power. Later expansion adds more trusses perpendicular to the keel truss creating a window-shaped structure with additional modules and a large antenna attached (see Figure 11.5 in the color pages). Also, two concentrating solar collector power units are attached at the ends of the keel to increase the available power to 125 kilowatts. These are clearly seen in the end view, Figure 11.6. The drag from additional solar panels would cause the station's orbit to decay quickly. Therefore, concentrating collectors, which produce more electricity with a smaller area, are used as the station expands.

This model space station is designed to accommodate six to eight crew members: engineers, scientists, technicians, and others. The Space Shuttle and unmanned cargo ships will haul the sections and modules into orbit.

Much of the space station will consist of prefabricated modules designed to fit into the cargo bay of the Orbiter or the cargo ship. Larger framework sections will be constructed in space, some automatically and some by astronauts in space suits and MMUs. An advanced remote manipulator arm, actually two arms, will assist in the assembly and will be used subsequently in many space station activities. It is visible near the center of Figure 11.4.

The Space Station will be in a circular orbit at about 250 miles. Thrusters will be attached for adjusting its orbit and attitude. Hydrazine fueled thrusters are well developed for the Space Shuttle, but small, low thrust hydrogen-oxygen rocket thrusters are technologically feasible and may be developed by the time the space station is being assembled.

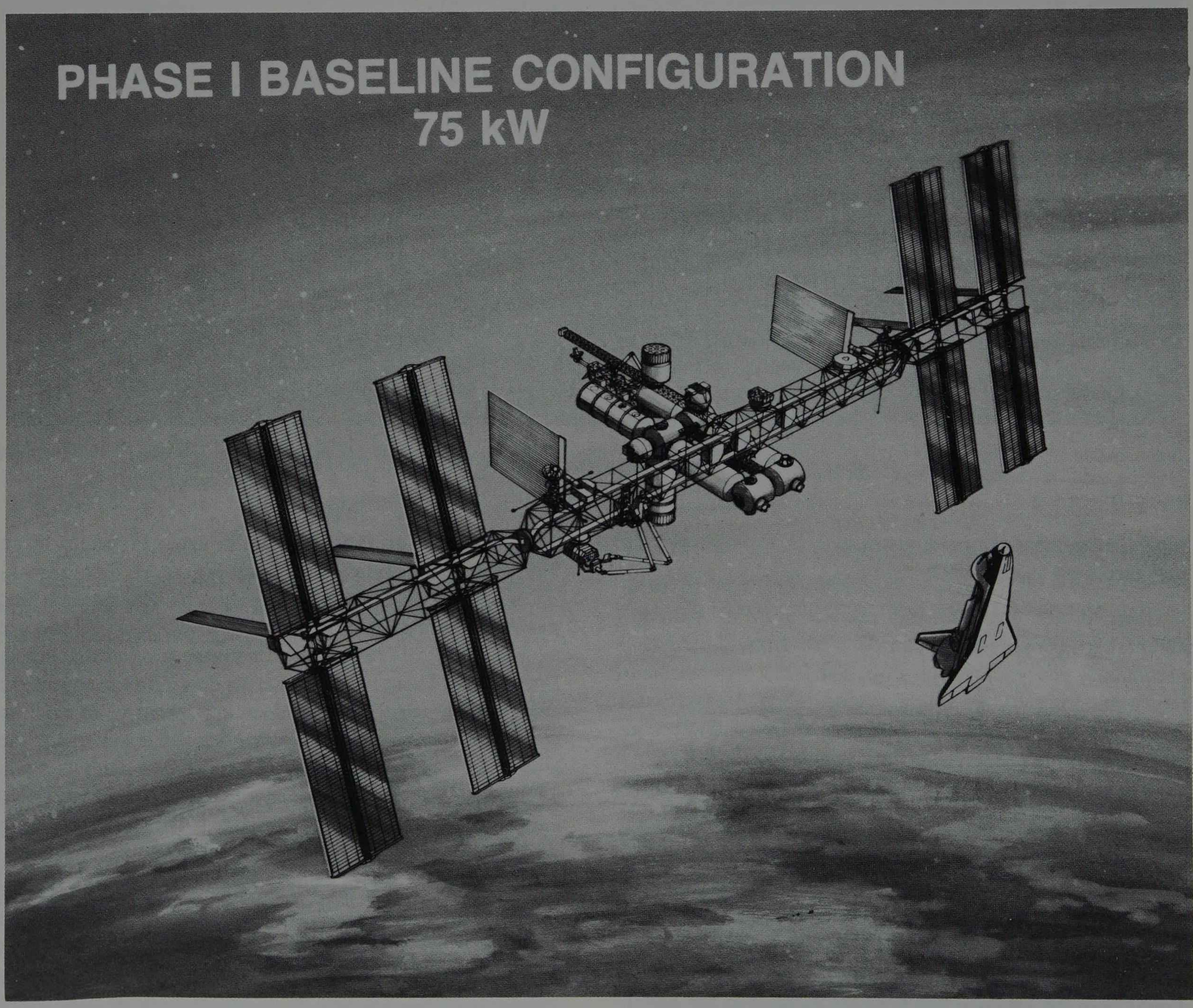


Figure 11.4 Space station concept, initial configuration. Four large solar arrays power the station with 75 kilowatts of electricity. Cylindrical sections near the center are habitats and workshops. A radiator juts out on either side of the center for removing heat. Remote manipulator arms can be seen just left of center. *Courtesy of McDonnell Douglas.*

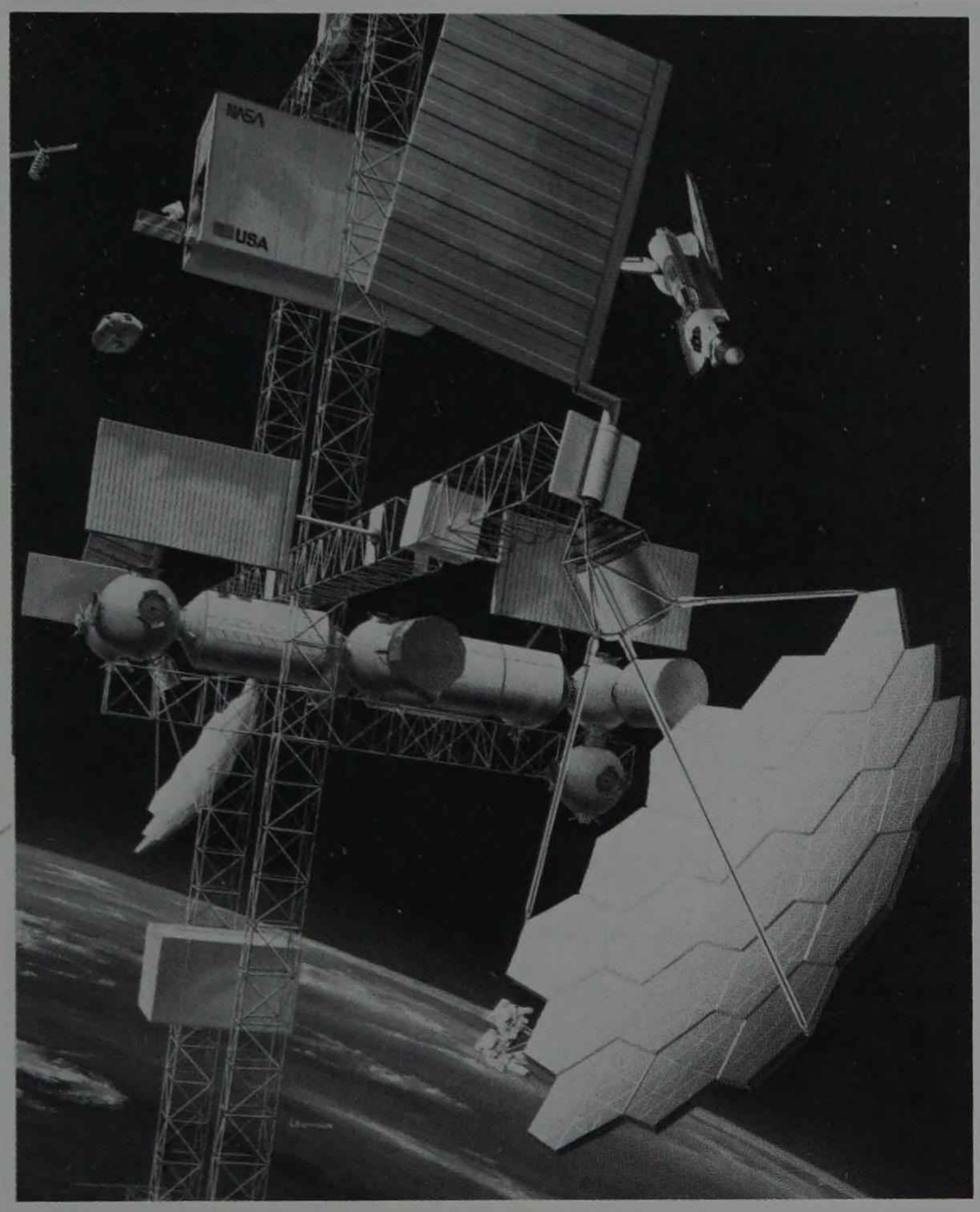


Figure 11.6 End view of the expanded space station. Two astronauts work on the concentrating reflector which focuses solar energy into the electric power generator. The reflector, made up of a number of hexagonal mirrors, may be as large as 64 feet in diameter. Two free flying platforms are seen at the upper left. A box-like satellite repair shed is at the top. *Courtesy of Harris Corporation; artist J. Harrelson.*



Figure 11.7 Aerobraking the orbital transfer vehicle. As the vehicle skims the top of the atmosphere, the kinetic energy of motion of the satellite is converted to heat energy which is absorbed by the blunt end heat shield. With less kinetic energy, apogee is lowered and the orbit becomes less eccentric. *Courtesy of Eagle Engineering; artist Pat Rawlings.*

Life Support

It will be necessary to perfect an economical means of recycling water and air in the space station. The Space Shuttle now carries all necessities for its relatively short flights. Water is manufactured by the fuel cells; hydrogen and oxygen supplies are brought along to power them. Electricity for the space station, however, will come from solar energy, not fuel cells, so that source of fresh water will not be available. In the Shuttle, excess humidity, carbon dioxide, and other noxious gases are removed from the air, while oxygen and nitrogen are added as needed from tanks carried aboard. For a continuously operating space station it may be less expensive in the long run to install machinery to recycle air and water rather than replenish the supplies every few weeks. A NASA study group in 1977 examined this question in some detail. The scientific principles involved are well known, but the technology to do it reliably is not perfected.

What happens to a closed and sealed atmosphere after a few years? For periods of weeks or months, we have the experience of Skylab and nuclear submarines to draw on. But for longer times, research is just getting underway. Toxic chemicals tend to build up in a closed environment and must be carefully monitored. For example, nickel has been detected in fuel cell water. Excessive intake could be a problem for astronauts.

Beyond recycling air and water, the science and technology of recycling solid waste is even less well understood. It will probably not be feasible on the space station, but will be a necessity for very long term ventures such as large colonies in space or on other celestial bodies. We will look at this subject again later in this chapter.

Bus Service to Orbit

Once the station is completed and occupied, Shuttle flights will carry fresh supplies and crews to the station and return crews and trash to Earth about every three months. The Orbiter will be the bus, the delivery truck, and the garbage scow. The Shuttle is an integral and essential part of the space station operation.

A new very different sort of bus is also under development, the aerospace plane, X-30, seen in Figure 11.8. It will be a single-stage-to-orbit passenger and light cargo craft, taking off horizontally from a runway, flying into

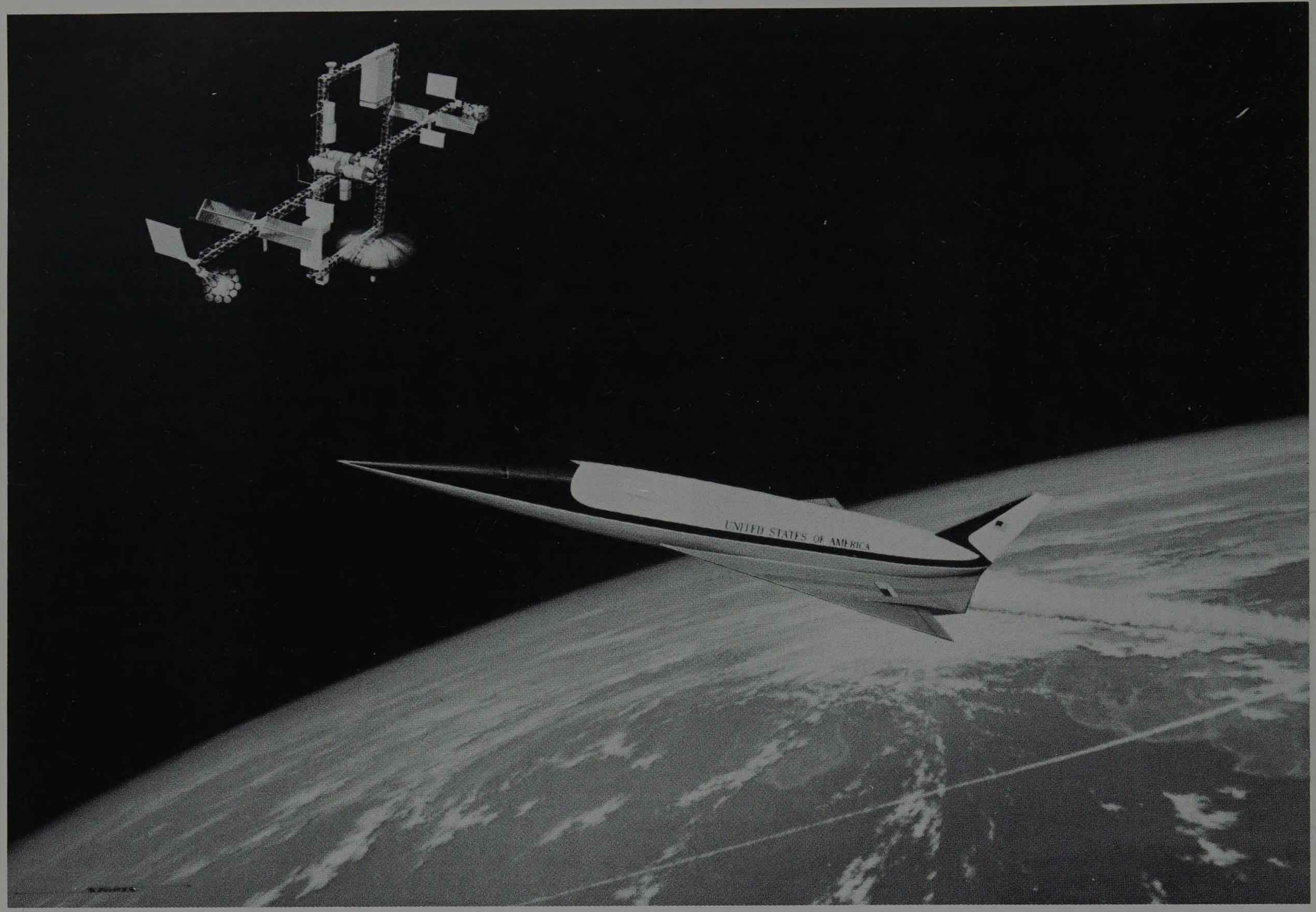


Figure 11.8 Aerospace plane, X-30. This vehicle, under development, will take off horizontally like a jet airliner, fly into orbit, and return to Earth to land on a runway. It will not require booster rockets. *Courtesy of NASA; artist Stan H. Stokes.*

orbit, and returning to land like a standard airplane. The propulsion system is radically different. The design calls for a supersonic ramjet (scramjet); no booster rockets will be needed. As pointed out in Chapter 2, Figure 2.7, a ramjet will not work from a dead stop; it must be moving at high speed to ram air into the intake. That is accomplished by operating as an air-breathing turbojet to mach 3 or 4, then switching to ram jet operation to mach 5 or 6, finally operating as a scramjet to speeds above mach 12 to perhaps mach 25. Propellants are liquid hydrogen and atmospheric oxygen. Such an engine has never been built. Present jet engines are designed to avoid supersonic flow in the combustion chamber because it is difficult to keep a flame burning in supersonic flow and because the engines cannot withstand the heat and pressure associated with a supersonic shock wave. New structural materials with greater strength and lower weight are being developed for the X-30. Engineers feel confident that they can solve the problems and build a working engine, perhaps a complete plane, in the 1990s.

This same plane could be used as an airliner; flights between any two points on Earth at mach 12 would take less than two hours. For this reason the aerospace plane is sometimes referred to as the Orient Express.

City-Sized Space Stations

The big wheel habitat of Wernher von Braun and Arthur Clarke may become a reality in the far future. NASA study groups in 1975 and 1977 did serious research into large space colonies and much of the material in this section comes from their work. Although NASA's greatest effort in the following decade was the Space Shuttle, some research on space colonies has continued and many questions have been answered; at least as many other questions have been raised.

Imagine 10,000 people riding in the rim of a rotating wheel a mile in diameter (Figure 11.9). The rim would be a tube, like the tire on an automobile wheel, with the occupants on the inside. We live on the surface of Earth; living in the wheel would be as if Earth were turned inside out and the atmosphere and people were put on the inside. Figures 11.10 and 11.11 are artists' conceptions of what the interior might look like.



Figure 11.9 One-mile diameter ''big wheel'' space colony. Ten thousand people live inside the rim of the wheel. The round object above the wheel is a mirror which reflects sunlight into the colony. The long ''rod'' at the lower left extends to a manufacturing facility separated from the main colony for safety. *Courtesy of NASA.*

To get funding necessary to build and support a large colony in space there ought to be some economic payoff. Certainly it would be part of the infrastructure necessary for further exploration of the solar system. But colonists could not expect a continuous flow of supplies to come from Earth unless they offered something in return. What is in space to entice governments to build a colony and send people to live there? The space station of the 1990s has many useful and profitable jobs to do. That is part of the answer, but not enough to support 10,000 people.

What else is there? One major industry of a space colony could be exploitation of the Moon's natural resources to manufacture very large satellites, such as solar power satellites. In Chapter 5 we discussed satellites in geosynchronous orbit which harvest sunlight and beam it to an energy hungry Earth in the form of microwaves. The enormous cost of transporting the materials and construction crews from Earth for such a huge structure dampened the initial enthusiasm for energy satellites. To ship cargo to geosynchronous orbit requires an acceleration, called *delta-V (ΔV)*, to nearly 7 miles per second from the surface of the Earth. Now suppose ore from the Moon is sent to a space colony where it is processed and fabricated into such satellites. These large structures could be transferred to geosynchronous orbit, completely built, by a ΔV of only 2.9 miles per second. As you will remember from Chapter 3, the amount of fuel consumed depends on how much you must accelerate the vehicle. The saving in fuel costs occurs because lunar gravity is only one-sixth Earth gravity and the Moon has no atmosphere.

Using lunar materials, the colony could be the site for construction of large space vehicles, ''star ships,'' for long duration flights to the outer solar system and beyond. The cost of an interplanetary vehicle to carry people on an expedition to Mars, for example, is greatly reduced if it originates from a space colony. The spaceship is built and stocked with supplies at the colony. Crews come aboard, check it out, and blast off. Escape velocity from Earth is about 7.5 miles per second, from the Moon it is only 1.5 miles per second, and from an orbiting colony it would be even less. Both mining the Moon and human exploration of Mars are discussed in the next chapter.

The initial processing plant, solar power equipment, and construction crew would have to come from Earth, but the habitat itself would be built with a supply of lunar ore. When the habitat and manufacturing facility were completed, other projects, such as the two described above, could be undertaken. Building additional new colonies is another logical step. Of course, the initial investment is high. An industrial plant in space and a mining camp on the Moon would not be cheap. Once in place, however, they could become profit-making ventures.

Location

Where would you locate such a city in space? Low Earth orbit is not the best choice for several reasons. In the first place, some of each orbit is spent in darkness, and the colony will depend on a continuous supply of solar energy. Second, the Van Allen belts must be avoided. If the colony's industry is to operate in conjunction with a lunar mining colony, then a location near the Moon may be advantageous.

There are points in space where the gravitational attractions of Earth and Moon combine in such a way that an object placed at that point will just stay there. These places are called *libration points* or *Lagrangian points* after Joseph Lagrange the French mathematician who discovered them theoretically. The L point locations are shown in Figure 11.12.

L1 is located between the Earth and the Moon while L2 lies beyond the Moon; L3 lies between Earth and the Sun. These three points are unstable. If displaced perpendicular

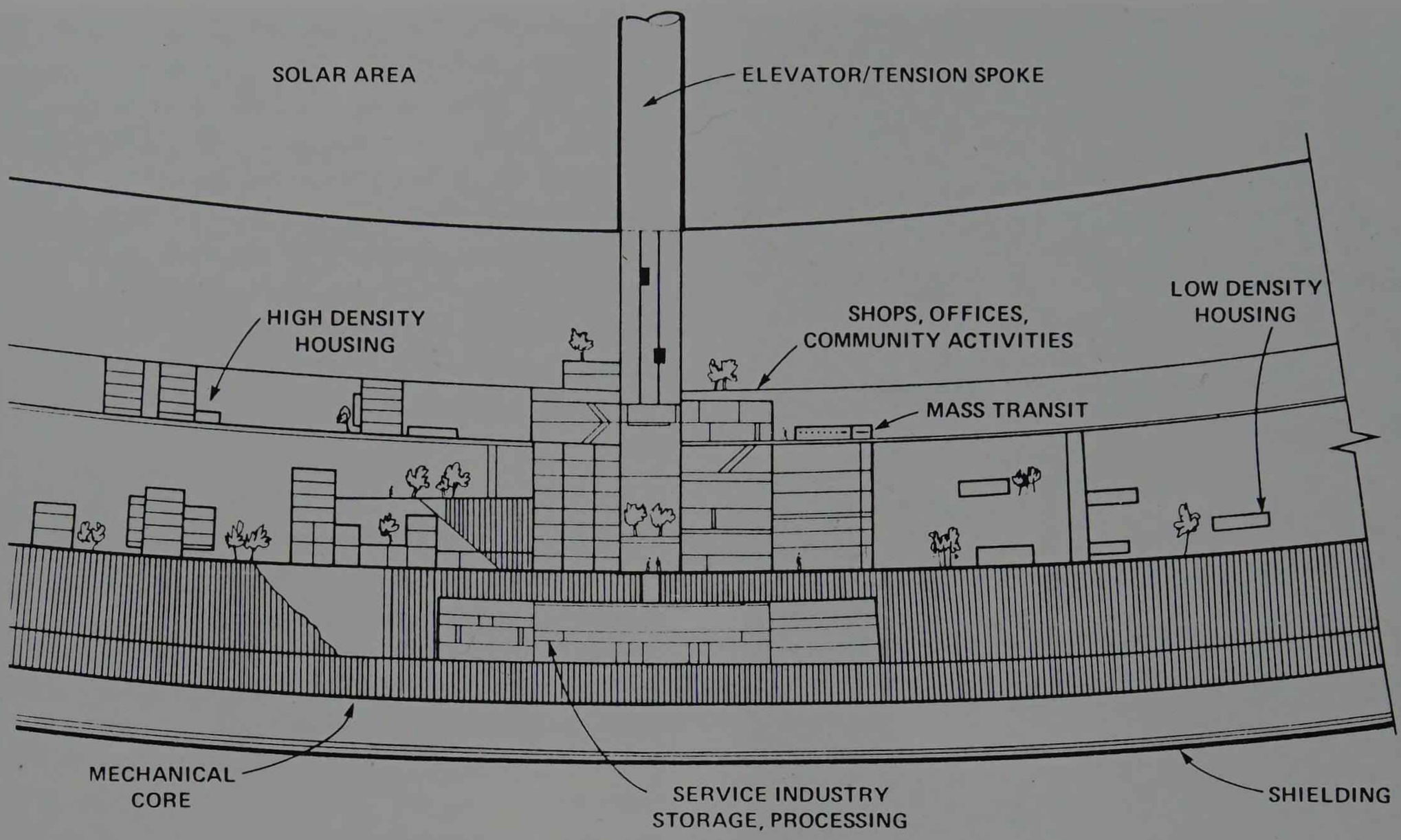


Figure 11.10 Partial cross section of the interior of the ''big wheel'' space colony. *Courtesy of NASA.*

to the Earth-Moon line, the space station would return to position. However, if displaced away from Earth or Moon, it would continue to drift away. Two stable points lie in the orbit of the Moon, 60 degrees ahead of and 60 degrees behind the Moon. Each point is at the corner of an equilateral triangle with the Earth and the Moon at the other two corners. Placed at one of these points, the station would remain with no expenditure of energy. The point leading the Moon in its orbit is called L4 and the one trailing the Moon is L5. To say ''an object will just stay there'' is misleading. It is really in the Moon's orbit, circling Earth with the same period as the Moon, about 27.5 days, but its position relative to Earth and Moon is fixed.

Actually, the space station would not remain at exactly the same spot. When we include the influence of the Sun's gravity, we find that the station would make a slow ''halo'' orbit. But a colony at one of these points would remain essentially fixed in the Moon's sky like a geosynchronous satellite remains in the same spot over the Earth. Let us select L5 as our colony's location.

Energy

Because the space colony is in direct sunlight, solar energy would be continuously available for smelters, mills, and fabrication factories as well as for light and agriculture inside the colony. Solar energy falling on Earth averages about 25 watts per square foot; the maximum with the Sun directly overhead is about 70 watts per square foot. In space, without an intervening atmosphere, a continuous 130 watts falls on a square foot surface. The only limit to the amount of energy available to the colony is the size of the array of solar cells or concentrating mirrors.

Materials

To build the L5 habitat, excluding the mandatory protective shield, will require an estimated 200,000 tons of materials (Earth weight). The proportions of the primary elements are shown in the center pie diagram of Figure 11.13. The main structure would be made chiefly of aluminum. That plus atmospheric oxygen and soil constitutes most of the mass of the habitat. Analysis of lunar soil brought back by Apollo 16 shows it to be composed of mostly oxygen, silicon, and aluminum. See the right pie diagram in Figure 11.13. This is not too surprising. Those three are the most common elements in Earth's crust, too, although the Moon has a higher percentage of aluminum, at least at the Apollo 16 site. These materials, then, would come from the Moon. Because of the Moon's lower gravity, it is much easier to lift mass to L5 from the Moon than it is from Earth. Only hydrogen to make water; nitrogen to dilute the atmospheric oxygen; carbon for plants, animals, and humans; initial structures; and machinery would have to be brought up from Earth. As seen in the left pie diagrams of Figure 11.13, these amount to a small percentage of the total mass of the habitat.

Artificial Gravity

As pointed out in Chapter 9, weightlessness even for a few days has adverse effects on the human body. Permanent

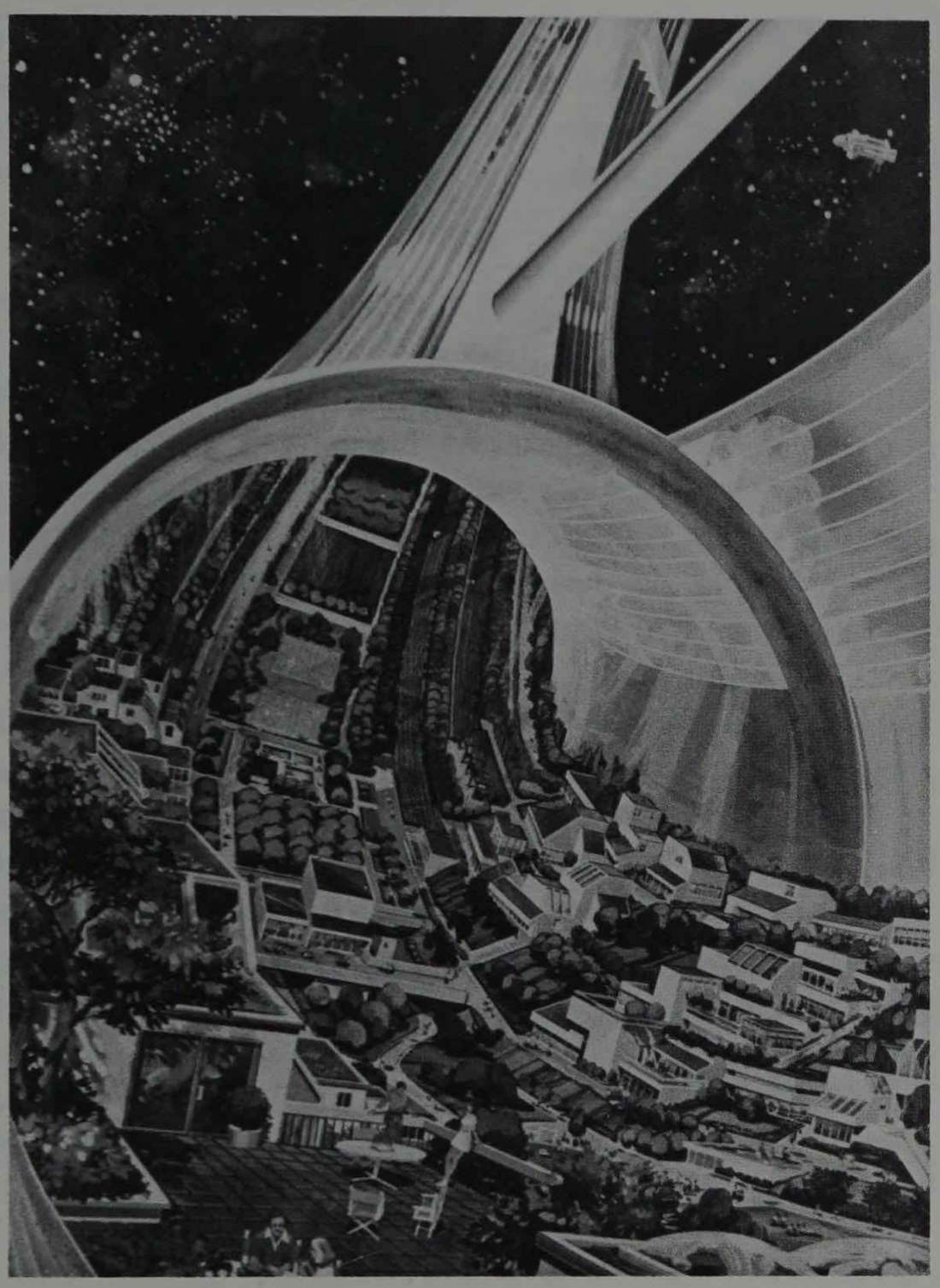


Figure 11.11 Artist's concept of the interior of the "big-wheel" space colony. *Courtesy of NASA.*

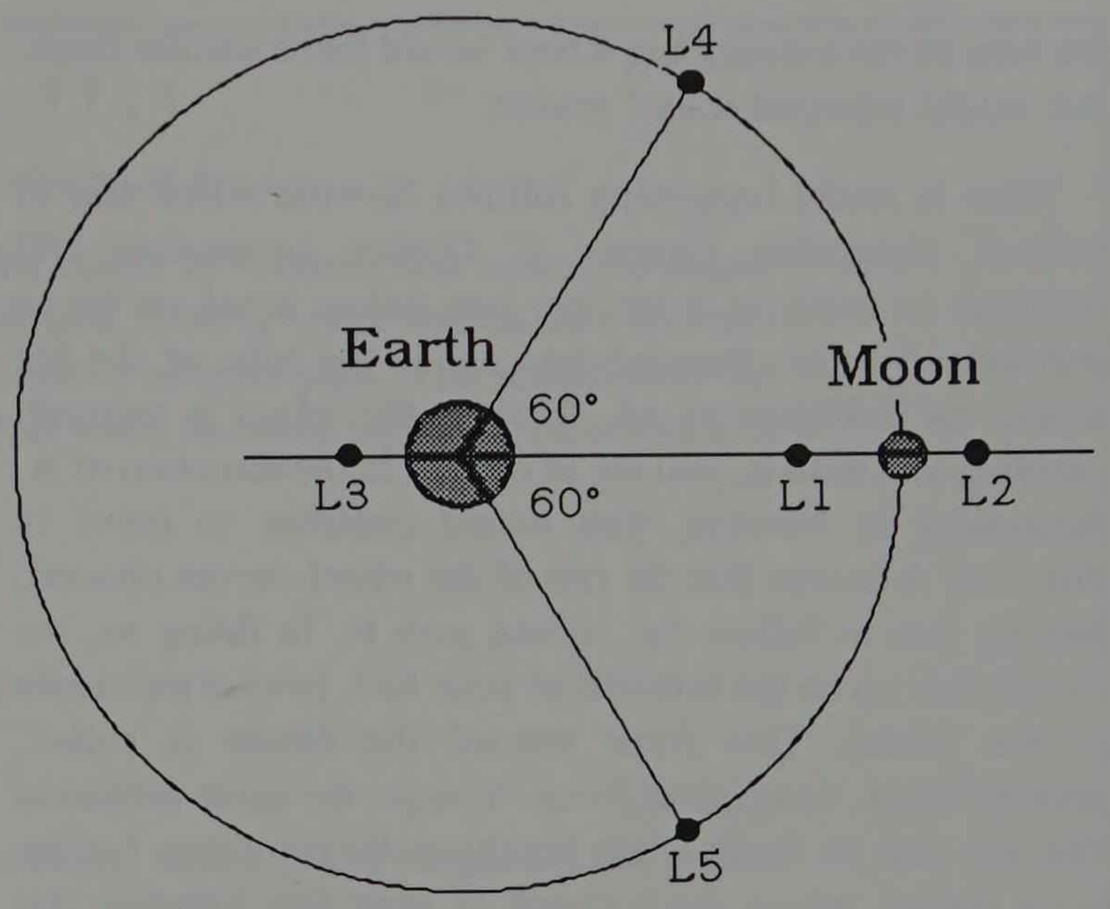


Figure 11.12 Libration points in the Earth-Moon system.

weightlessness may destroy a body, so a large colony in space must have some way of producing an artificial gravity. Rotating a big wheel space colony does just that. When you go around a corner in your car you can feel a force pushing you toward the outside of the turn. On a revolving carnival ride you get the same sensation; you need to hold on to keep from being thrown off. Objects in

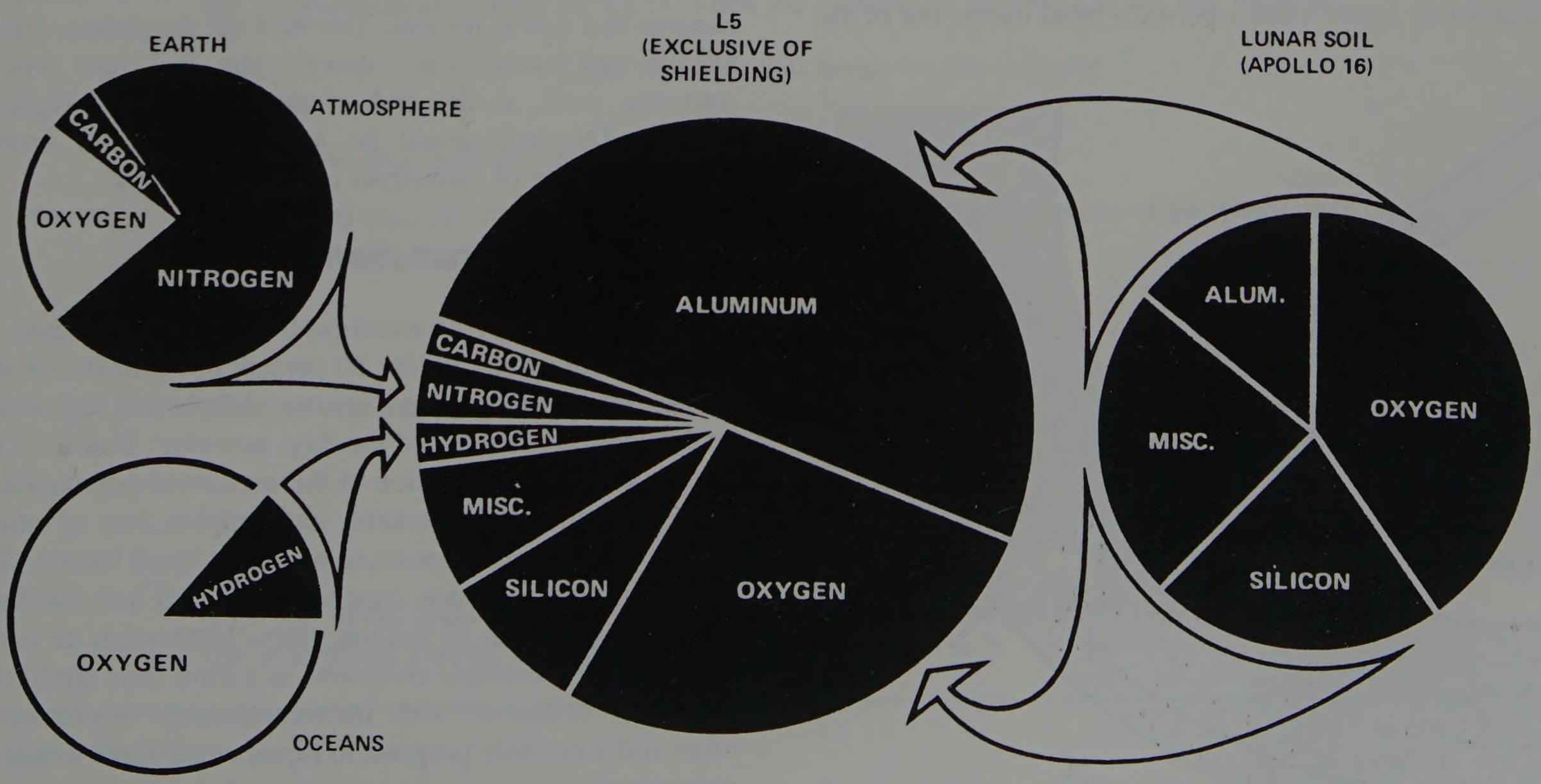


Figure 11.13 Sources of materials required for construction of the L5 habitat. Center diagram shows proportion of various elements needed; left and right diagrams show what could be supplied from the Moon and from Earth. Shielding can be the slag and waste materials from processing lunar ore. *Courtesy of NASA.*

the tube of the rotating big wheel would feel a similar force, but would interpret it as ''gravity.''

What is really happening follows Newton's first law of motion; remember Chapter 2. Objects in motion will continue to move in a straight line unless acted on by an unbalanced force. Imagine you are in the tube of the big wheel, as in Figure 11.14. Because the wheel is rotating, carrying you with it, you are in motion in the direction of A. According to Newton, you would continue to move in direction A except that the rim of the wheel curves upward, forcing you to follow the curved path B. In doing so, the rim pushes up on the bottoms of your feet, toward the center of the wheel. This force toward the center is called, appropriately, *centripetal force*. You get the same sensation that you feel on Earth when gravity pulls you down but the floor pushes up on the bottoms of your feet keeping you from falling through. Centripetal force becomes an artificial gravity. In the rim of the rotating wheel, heads point in toward the central hub while feet point out. ''Down'' is away from the hub.

The amount of artificial gravity, that is, centripetal force, depends on how large the wheel is and how fast it is turning. A one mile diameter wheel rotating at one revolution per minute produces an artificial gravity at the rim approximately equal to Earth gravity. See MATHBOX 11.1 for the mathematics involved. It is possible to obtain any g force desired by changing the radius or the speed of rotation.

Living in a rotating vehicle can cause motion sickness. The problem arises when a person's head moves out of the plane of rotation of the vehicle. Physiologists have found that most people can adapt to rotation rates up to four revolutions per minute. To be conservative, most space colony designs limit the rotation rate to one revolution per minute.

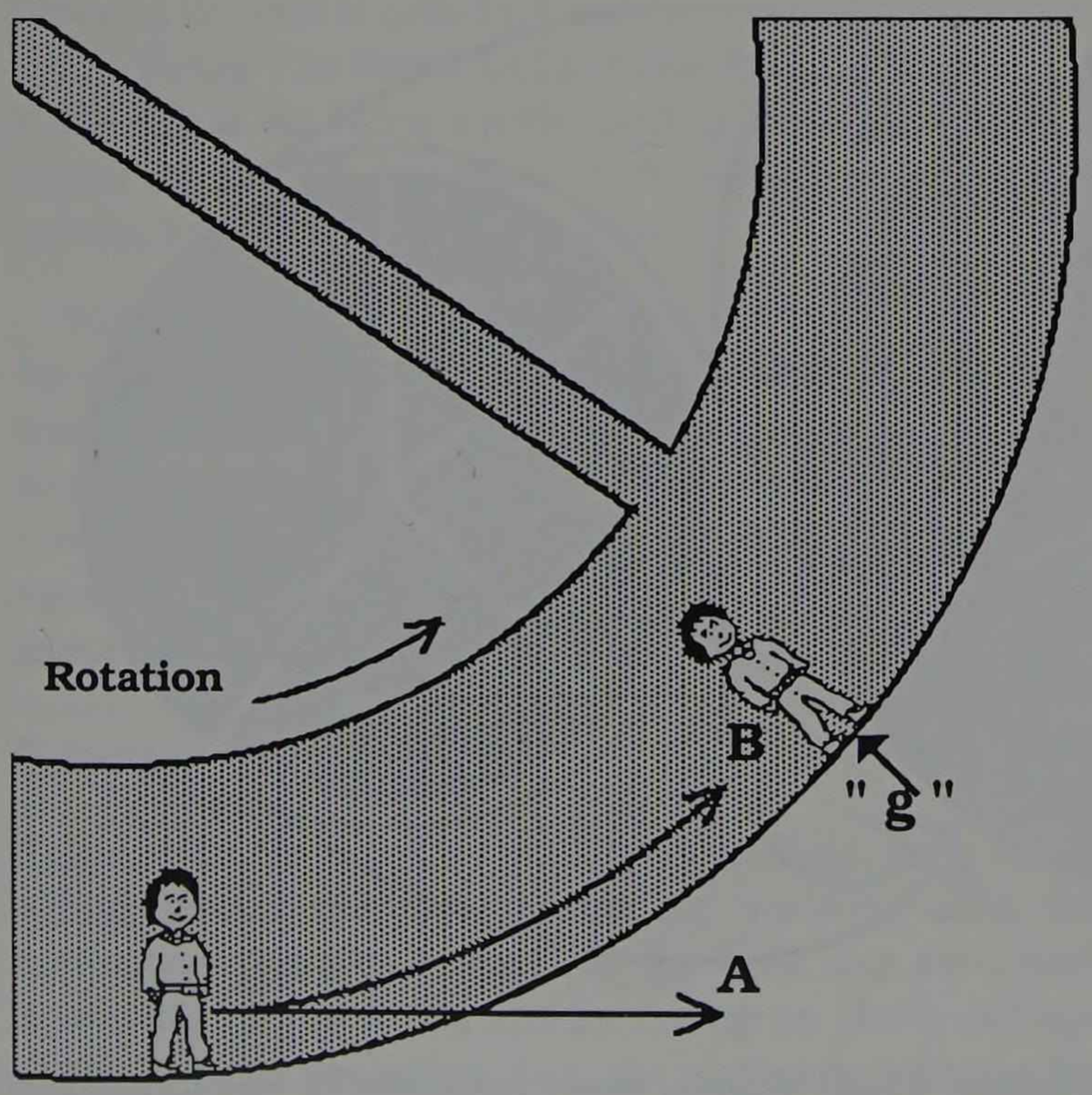


Figure 11.14 Rotation of wheel to produce artificial gravity.

The open question is: how much gravity, or rather, how little gravity can the human body tolerate permanently? Although Soviet cosmonauts have spent as much as a year at a time in weightlessness, no one as yet has a conclusive answer to that question. But the answer is crucial to the design of the L5 habitat. For economy and ease of construction, it would be desirable to keep gravity as low as tolerable. One g in the living area means that the buildings would weigh the same as they do on Earth and would have to be built to same specifications as if they were on the surface of Earth. The habitat shell, in turn, would have to be built to support that weight. If humans could live at one-half g then everything would weigh only half its Earth weight, allowing the shell and buildings to be built with less structural strength. This would greatly reduce the mass of material that must be shipped out to build the colony. One of the experiments to be carried out on the space station of the 1990s will be an artificial gravity lab which can be rotated at various speeds to find out how much gravity humans require to stay in good physical condition.

Visitors to the colony would dock their spacecraft at a port on the hub shown in Figure 11.15, enter through an airlock, and take an elevator in one of the spokes out to the rim of the wheel. The hub is an interesting place, because there the g force is zero, that is, weightlessness. Try to imagine that ride to the rim. You start out weightless, but as the elevator carries you ''down'' you feel your weight returning until, at the end of the ride, your weight is normal. The hub would be a good recreation center. Imagine a game of basketball in weightlessness!

Meteoroid and Radiation Protection

Possible collisions with meteoroids must be considered. A big wheel colony could lose 60 percent of its air in one day through a hole one yard in diameter. A hole that size would be discovered and patched quickly, however. Based on the density and size distribution of the meteoroid population in the Earth-Moon environment, catastrophic loss of atmosphere in a collision appears to be only a small hazard. The probability of a collision creating a one yard hole has been calculated at one in 10 million years. Meteoroids do occur in clusters and multiple collisions in a short time are likely. Certainly, collisions with micrometeoroids would occur often and a monthly program to repair small leaks would be necessary.

A more serious aspect of the meteoroid problem is the explosion overpressure caused by an impact. Even a small (one gram) meteoroid would create a pressure wave of

MATHBOX 11.1

Artificial Gravity

Centripetal force is the force directed toward the center of rotation that makes an object move in a circular path. If you stand in the rim of a rotating space station you feel this force on the bottoms of your feet, pushing you into a circular path. The sensation is the same as the force of gravity produces on your feet when standing on Earth, therefore it is called artificial gravity.

The formula for centripetal force is

$$F_c = \frac{mv^2}{r}$$

where m is the mass of the object, v is its velocity, and r is the radius of the circle. Remember Newton's second law

$$F = ma$$

which relates the acceleration of an object to the applied force. Compare the two equations above and note that the acceleration due to centripetal force must be

$$a_c = v^2/r$$

Solving for v we get

$$v = \sqrt{a_c r}$$

Our rotating big wheel space colony is one mile (5,280 feet) in diameter; the radius, r, is 2,640 feet. If we desire one g artificial gravity, a_c must be 32 feet per second per second, the acceleration of gravity on Earth. Then the velocity of an object at the rim must be

$$v = \sqrt{2640 \times 32} = 290 \text{ ft/sec} = 198 \text{ miles/hr}$$

That is less than half the speed of a jet airliner.

Next, let us calculate the period of rotation. First find the circumference of the wheel, that is, the distance travelled in one rotation.

$$5280 \text{ feet} \times \pi = 16{,}600 \text{ feet}$$

Next, divide that distance by the speed.

$$\frac{16{,}600 \text{ feet}}{290 \text{ ft/sec}} = 57 \text{ seconds}$$

So a big wheel space colony one mile in diameter rotating once every minute will have one g artificial gravity at its rim.

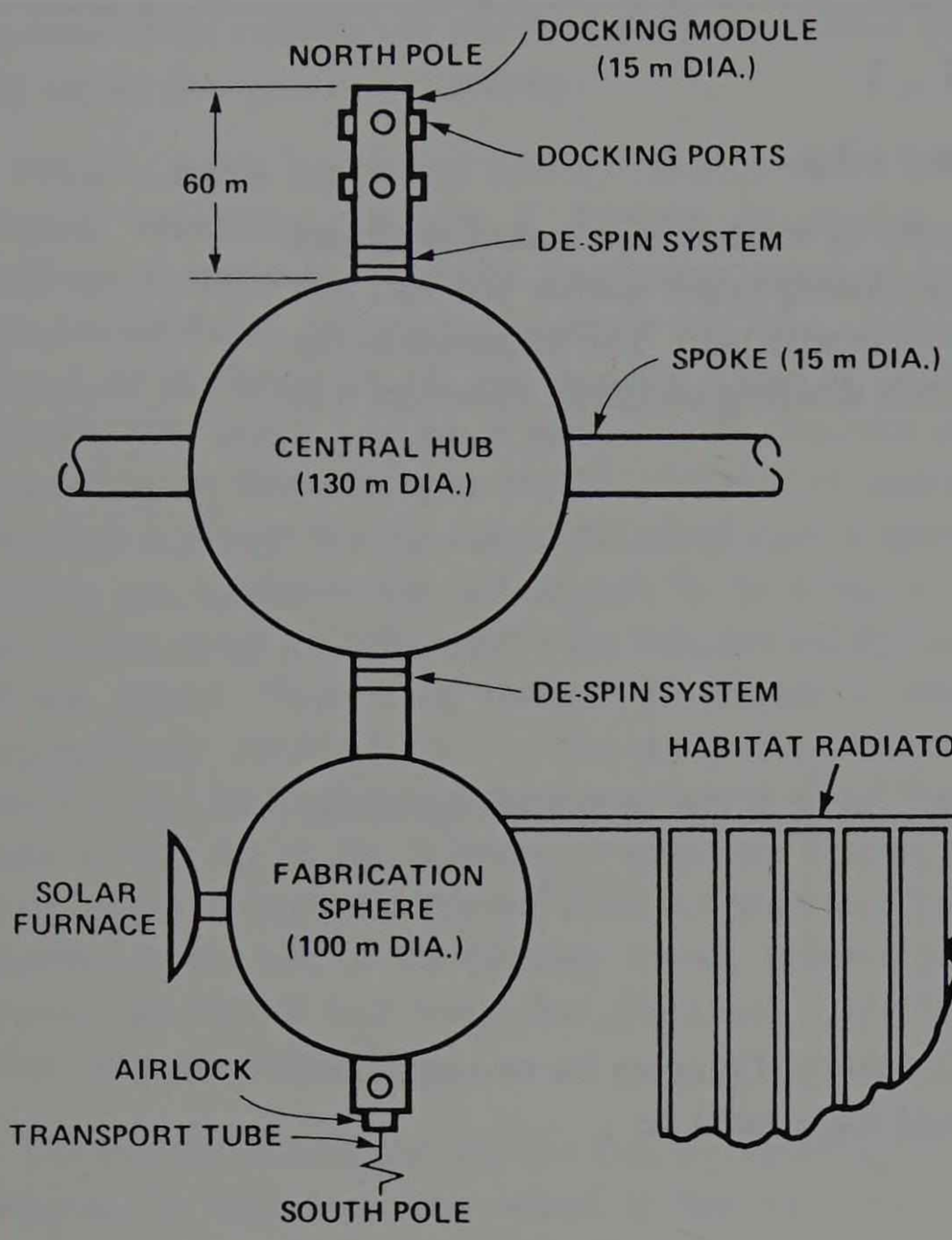


Figure 11.15 Hub configuration. The de-spin system keeps the docking ports, fabrication sphere (manufacturing plant), and radiator from rotating with the main part of the habitat. Elevators in the spokes carry passengers and materials to the living areas in the rim. *Courtesy of NASA.*

killing force for a distance of about 7 feet from the point of impact. A meteoroid shield or bumper separated from the main shell of the space station would provide protection from such pressure waves.

Protection from cosmic rays and solar protons would also be needed. Solar flares of sufficient magnitude to cause a serious radiation sickness problem occur during the high part of every 11-year solar cycle. We on Earth are protected from particle radiation by Earth's magnetic field. Similarly, a magnetic field around the space station would deflect the high energy particles away. However, building a machine to produce a magnetic field of sufficient strength to protect a mile diameter space station is beyond present technology.

A massive shield could provide protection from both high energy particles and meteoroids, but would not hold together if rotated at one revolution per minute. It would have to be non-rotating, not attached to the rest of the space station. However, a shield placed between the Sun and the habitat to block solar particles would also block the needed sunlight. One proposed design calls for a mirror on the opposite side of the big wheel, not connected to it, reflecting sunlight into the colony. The mirror can be seen in Figure 11.9. This design would allow a massive shield to be located on the sunward side. Ten million tons of mass would be required. The slag from the industrial processing of the lunar soil would provide part, but not all of it.

Life Support

The life support question rises again as it does for any inhabited spacecraft. The design of the habitat is greatly dependent on solutions to the problems of life support: air, food, water, and protection from radiation. In Chapter 9 we discussed creating a comfortable and healthy environment in the Space Shuttle. All the supplies needed for the relatively short mission times are carried along, oxygen and nitrogen are added to the atmosphere as needed, carbon dioxide is removed by canisters of lithium hydroxide, excess water is dumped overboard, and the wastes are returned back to Earth. Now, however, we must design a city which will be completely self-sufficient, independent of Earth. Continually shipping supplies to L5 from Earth is out of the question; it would be much too expensive. The life support system must be a closed loop, everything recycled.

Atmosphere

Can a person live in an atmosphere different from normal Earth atmosphere for long time periods? Space Shuttle carries a normal Earth atmosphere, 21 percent oxygen and 79 percent nitrogen. Most previous manned spacecraft had pure oxygen atmospheres. The long term effect of a pure oxygen atmosphere on people, plants, and animals is unknown. Pure oxygen also increases the fire hazard. Until more definitive research is done, the oxygen should be diluted with some inert gas such as nitrogen. Oxygen would come from lunar ore, but the initial supply of nitrogen would have to come from Earth. Helium has been suggested as an inert dilutent instead of nitrogen because it is not as dense. There would be less mass to bring from Earth, and the rotating habitat would have less weight to support. But helium gives a strange Donald Duck-like quality to voices.

Sea level pressure is 14.7 psi, but some people, plants, and animals live their entire lives at altitudes where atmospheric pressure is only two-thirds that at sea level. Pressure in Skylab was only 5 psi, one-third normal. It would be advantageous to equip a space colony with an atmosphere at lower pressure to reduce the strain on the shell of the habitat, thus requiring less structural strength. One difficulty is that sound does not travel as far in a gas at low pressure. Skylab astronauts said that a loud speaking voice carried only about 15 feet.

For transportation, no cars would be allowed, only an electric railway or moving sidewalks, roller skates, and bicycles. According to plans, it would be only a little more than 3 miles around the entire colony, and the elevator shafts through the central hub would act as shortcuts to the other side. By using nonpolluting transportation, the air

would only have to be cleansed of dust, excess water vapor, carbon dioxide, and other gases. Plant photosynthesis becomes a primary factor in closing the atmosphere loop, but will not do the complete job. Cold plates and coils will condense the water vapor into droplets to remove it from the air, making it available for reuse.

Food and Water

Although much is understood about human nutritional needs, there is no certainty that all the necessary nutrients have been identified. An important question is whether loss of bone calcium, loss of fluids, muscle deterioration, and other effects of living and working in space can be compensated for by diet adjustments. Proper diet is not only necessary for good health, it is also a factor in psychological well being.

Initial food supplies will be brought from Earth, but farming and raising livestock will begin as soon as they can be established. Plant agriculture is practical and beneficial for two reasons: food and oxygen. While animals inhale oxygen and exhale carbon dioxide, plants intake carbon dioxide and release oxygen. That is a great oversimplification, but is basically true. Photosynthesis is the chemical and metabolic process by which plants use water from the ground and carbon dioxide from the air with sunlight as an energy source to manufacture carbohydrates. Oxygen is released as a by-product. In fact, the original atmosphere of Earth probably contained carbon dioxide and water vapor, but no oxygen. According to the geological fossil record, plants inhabited Earth before animals did. It wasn't until plants came along that oxygen began to build up in the atmosphere and make higher forms of animal life possible.

The large variety of foods available on Earth may be impractical to produce in the colony simply for lack of space. Meats are a good example. What kind of livestock should be raised? Cattle for beef? Hogs for pork? People have different preferences. Hogs, chickens, and turkeys have been suggested because they can consume table scraps and noncellulose plant wastes. Turkeys are particularly efficient in protein production. However, these choices may not be the best because their main diet, e.g., corn, could also be eaten by humans. Energy is lost when the animal converts the food to meat and it may be more energy efficient for humans to eat the food directly.

Ruminant animals would be an excellent choice in a closed environment because they can digest cellulose plant wastes inedible for humans. Cellulose parts of plants include the structural parts, roots, husks, and hulls. Cows are ruminants and yield both dairy products and meat. A beef steer grows to about 900 pounds in 16 months. Dairy products are a particularly important source of nutrition because of the high calcium content, and dairy cows convert food to milk with greater efficiency than they convert food to meat.

Small animals such as goats, rabbits, ducks, and geese may be good choices. They reproduce frequently, mature rapidly, and would only have to be fed during their short rapid growth period, then slaughtered for their meat. Rabbits reach 7.5 pounds in about four months. Table scraps and by-products from vegetable production would provide the bulk of their diet. Goat milk and duck eggs would add variety to the human diet, also.

Aquatic food production is another likely possibility and has been carried on in some parts of Earth for many centuries. Animal and human waste is effective fertilizer for aquatic production. In the Orient, human waste is often dumped directly into lakes or ponds for cultivating water plants and fish. Fish can be harvested in a year weighing in at about 4.5 pounds.

Weather in the habitat would be under complete control. In the agricultural areas, a measured amount of precipitation with sunlight, temperature, humidity, and carbon dioxide content kept higher than normal promotes rapid growth and maturation of crops. Agricultural and animal production can be highly efficient in a small area if diseases are eliminated or at least kept under careful control. Under these controlled conditions, it has been calculated that sufficient food could be produced on only 151 acres with lunar soil. See the artist's conception of an agricultural area in Figure 11.16. A

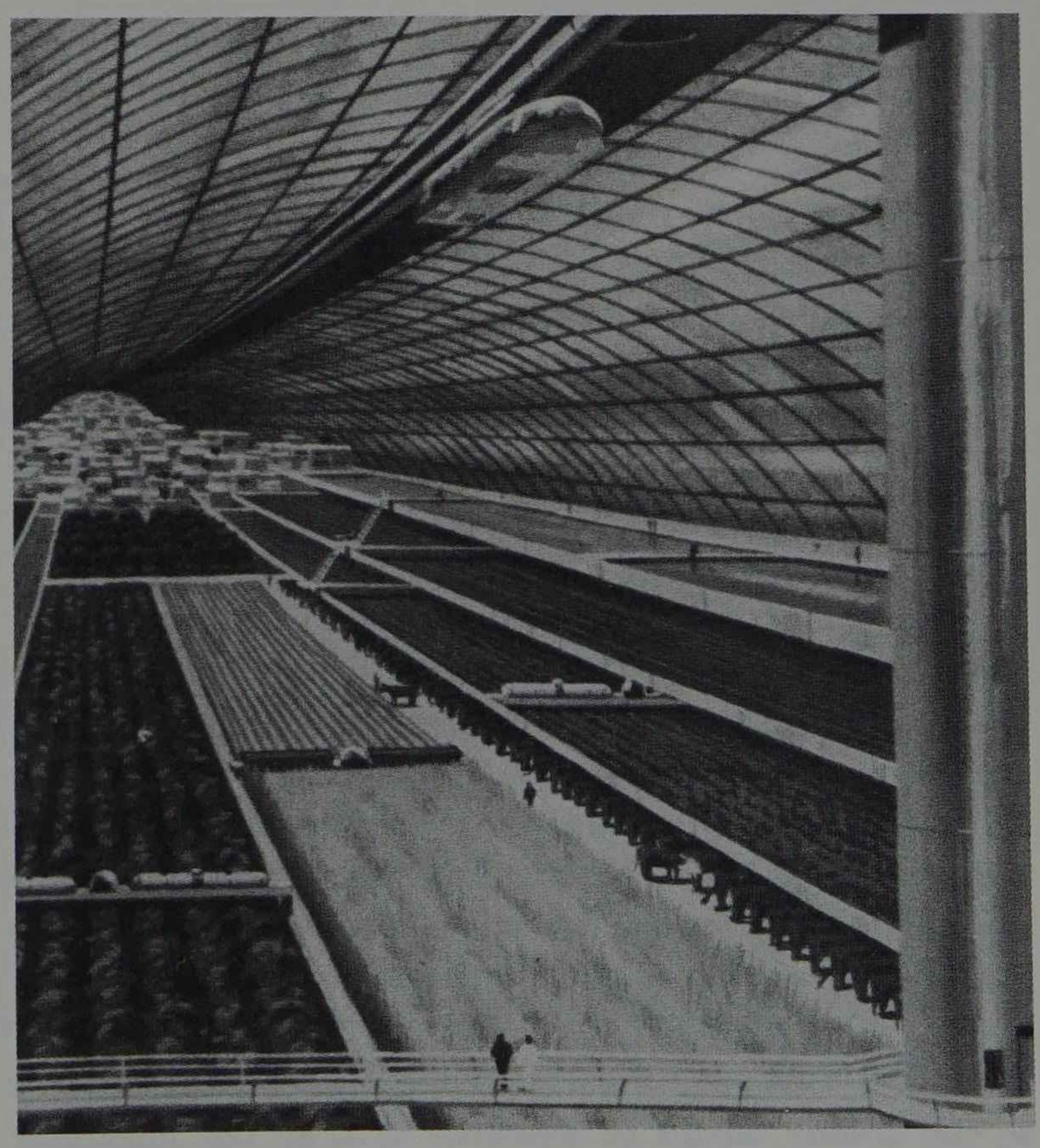


Figure 11.16 Artist's view of agricultural area in the L5 space colony. Compare with Figure 11.17, a diagram of the area. A residential section is in the background. *Courtesy of NASA.*

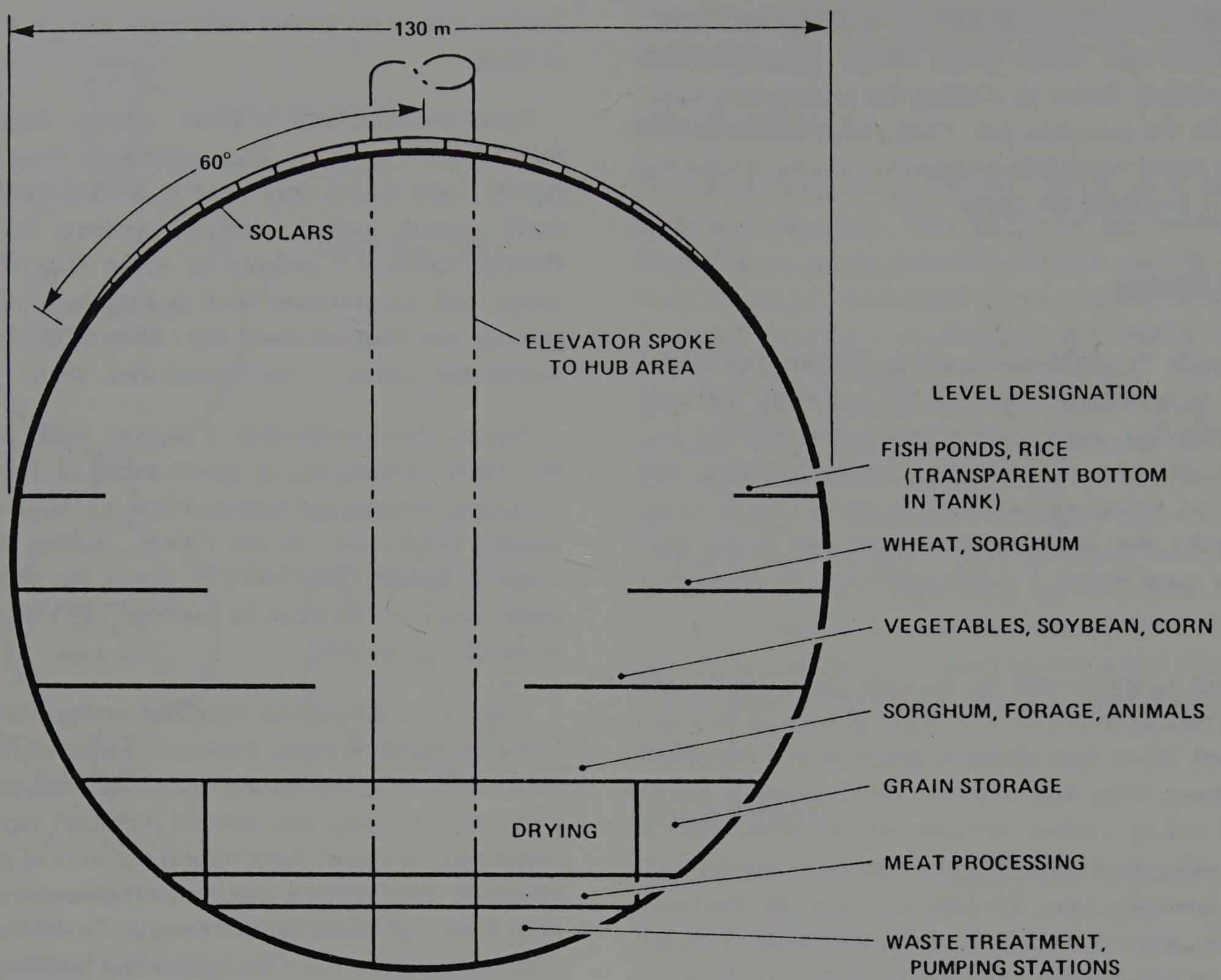


Figure 11.17 Cross section of agricultural area in the L5 habitat. *Courtesy of NASA.*

tiered arrangement yields more usable growing area in a smaller space (Figure 11.17). Water cascades down from the aquaculture ponds on the top tier to irrigate the lower tiers and ends up at the bottom for the livestock.

The colony would be divided into six sections, three for living and three for agriculture, alternating around the cycle. See Figure 11.18. Each section can be isolated from the others, and by placing the crops and livestock into three separate areas, crops can be started at various times to assure a continuous supply. Alternating and blending residential and agricultural areas would also create a more pleasant living environment for the inhabitants. For example, fruit trees might not be restricted to the agricultural areas, but grown instead throughout the residential areas for their beauty as well as their fruit.

Careful screening of everything and everybody brought to the colony would be essential to keep out infectious diseases and parasites. Infrared sensing technology from the Landsat satellites could be used in the agricultural areas to monitor the health of crops. If disease should occur in one

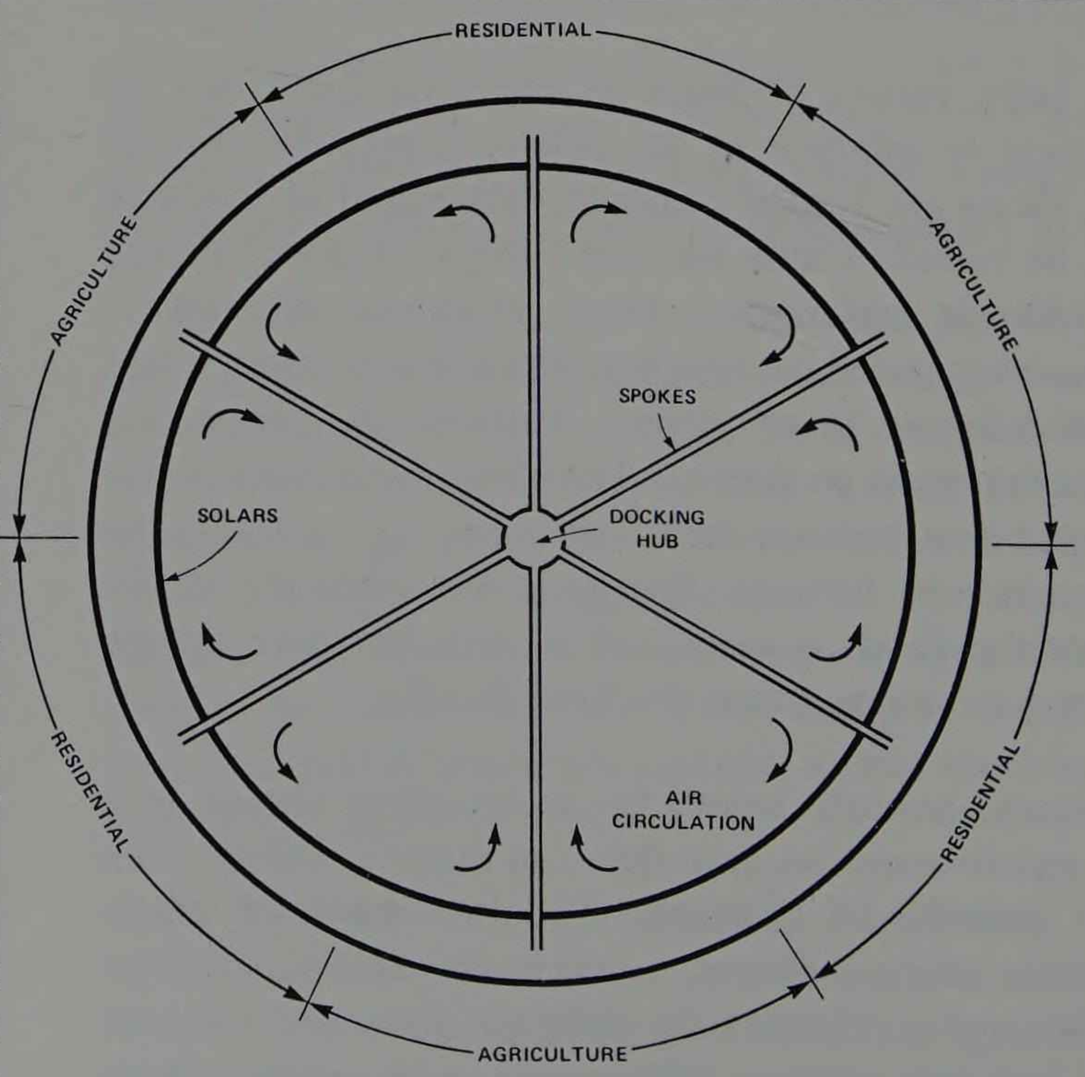


Figure 11.18 Distribution of residential and agricultural areas in the L5 habitat. *Courtesy of NASA.*

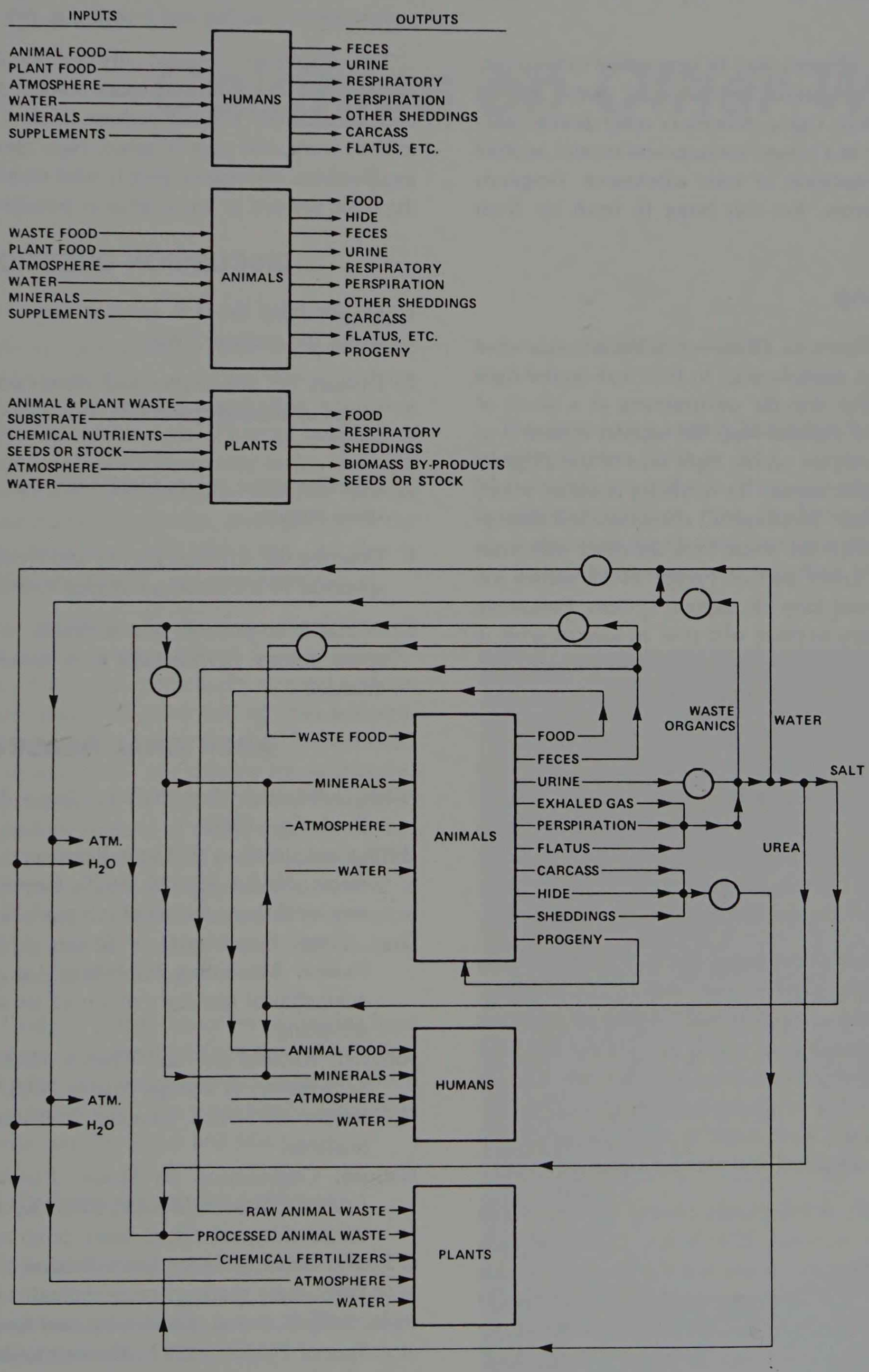


Figure 11.19 Closed loop life support system. The problem is as complex as the diagram appears. *Courtesy of NASA.*

area, it could be isolated and hopefully the other two would not be affected.

Common human ailments may be impossible to keep out. Immunization and quarantine are the usual tactics against the spread of infection. Using chlorine or other disinfectants to control microbes in a closed environment creates another problem, the accumulation of toxic substances. Hospitals have similar problems, but can bring in fresh air from outside.

Closing the Loop

The upper part of Figure 11.19 shows on the left side what humans, plants, and animals need to live, and on the right side what they output into the environment as a result of living. The object of a closed loop life support system is to assure that all the outputs on the right side of the diagram are converted to usable inputs. If everything is not recycled, waste will accumulate. Mechanical, chemical, and biological methods to convert the waste back the other way must be perfected. The lower part of Figure 11.19 shows the complexity of a closed loop life support system. Following the arrows from place to place will give an idea of what is involved. Circles represent chemical and mechanical devices which recycle the waste into usable substances.

Notice that the biological activity partially closes the system. For example, the respiratory output of animals and humans is partially carbon dioxide, which is the atmosphere input to plants. The respiratory output of plants includes oxygen which is the atmosphere input to humans. Plants are food for animals and humans; animals are food for humans. Human and animal feces make fertilizer for plant growth.

Chemical and mechanical means for converting outputs to inputs have been devised for some of the waste products, but not all. For example, animals and humans output water in respiration and perspiration which are recoverable from the air mechanically. Purifying urine into drinking water is easy, although there is a psychological barrier to its acceptance by many people. Wash water is also easy to reclaim and purify using mechanical and chemical processes.

The great difficulty in completely closing the loop is that *everything* must be recycled. If it is not, there will be a gradual buildup of unusable waste and a decrease of usable materials in the system. Just imagine the accumulation of fingernail clippings of 10,000 people! Some of the waste may be toxic, causing additional problems. If the toxic substance is not removed by the recycling process, then it will accumulate, its concentration increasing with each pass through the cycle.

The most complete experiment yet devised is underway in Arizona. People will attempt to live in a completely closed environment for a year or more. Careful monitoring will enable the research scientists to determine how the environment is acting and reacting at any time.

This chapter has covered only one possible configuration and location for an orbiting space colony. Many others have been considered. You can perhaps think of alternative ways to live, work, and play in space. New ideas come from the imaginations of creative people who understand enough of the basic science to know what is possible.

DISCUSSION QUESTIONS

1. Do you think the U.S. space station of the 1990s will be worth the expense? Why?
2. Discuss the advantages and disadvantages of manned versus unmanned spacecraft. What jobs are best done by each?
3. Describe some recreational activities in a nonrotating space station.
4. Describe the artificial gravity and living conditions in a spherical or a cylindrical shaped rotating space colony.
5. Would it be possible and desirable to require a sterile space colony environment as a means of eliminating disease?

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Chapter 12

Colonies on Other Worlds

Each form of life on planet Earth finds an appropriate environmental niche into which it settles down, perhaps moving with the seasons, perhaps suspending animation during harsh times. One of the signs of human intelligence is that, rather than search out a hospitable niche, we have learned to survive in any environment by building habitats to maintain a comfortable temperature and bringing in the necessities of life: fresh air, food, and water. All that is needed is raw materials, energy, and intelligence.

There are many places on Earth where people cannot survive without a habitat to protect them from an inhospitable environment. Antarctica, perpetually covered with ice and snow, provides plenty of water and air, but temperatures are above freezing only during the short summer and little or no plant or animal life is available for sustenance. The side of a mountain may be hospitable and inviting in summer, with abundant streams of clean water, fresh air, warm sunshine, plants and animals for nourishment—all the necessities of life. But it may be impossible to survive in that same spot in winter, when temperatures drop below freezing even during the day, plants wither and die, and streams freeze up and stop flowing.

Just as people living in Antarctica or on mountains have done, the first colonists on other bodies of the Solar System will need to build habitats to enclose environments in which they can survive comfortably. The most likely candidates for human habitation are the Moon and Mars.

Permanent Colonies on the Moon

Why live on the Moon? See Figure 12.1. It is difficult to think of a more hostile environment. Only 12 humans have ever set foot on the Moon, all of them American astronauts. In Figure 12.2 one of them takes a sample of Moon rock to bring back to Earth. The first and most obvious drawback is the lack of air to breathe. The Moon has no atmosphere. Colonists would have to live in sealed and pressurized astrodomes or semiburied habitats and would have to wear space suits while outside. Second, without an atmosphere there is no protection from ultraviolet, x-rays, cosmic rays, solar particles, and meteoroids. Third, there are no easily utilized resources; all food and other supplies would have to be brought from Earth. Finally, no water has been found on the Moon.

This description sounds like space itself, and the Moon appears to have little to offer. Living conditions on the Moon would be similar to living on a space station with two important differences. First, the Moon has natural gravity, about one-sixth the force of Earth gravity, and second, there are plentiful raw materials, including soil and useful ores.



Figure 12.1 The Moon rotates on its axis in the same time as it takes to make one complete orbit around the Earth. Therefore, the same side of the Moon always faces Earth. The features may appear in different places, however, because we view it from different angles as it moves across the sky.

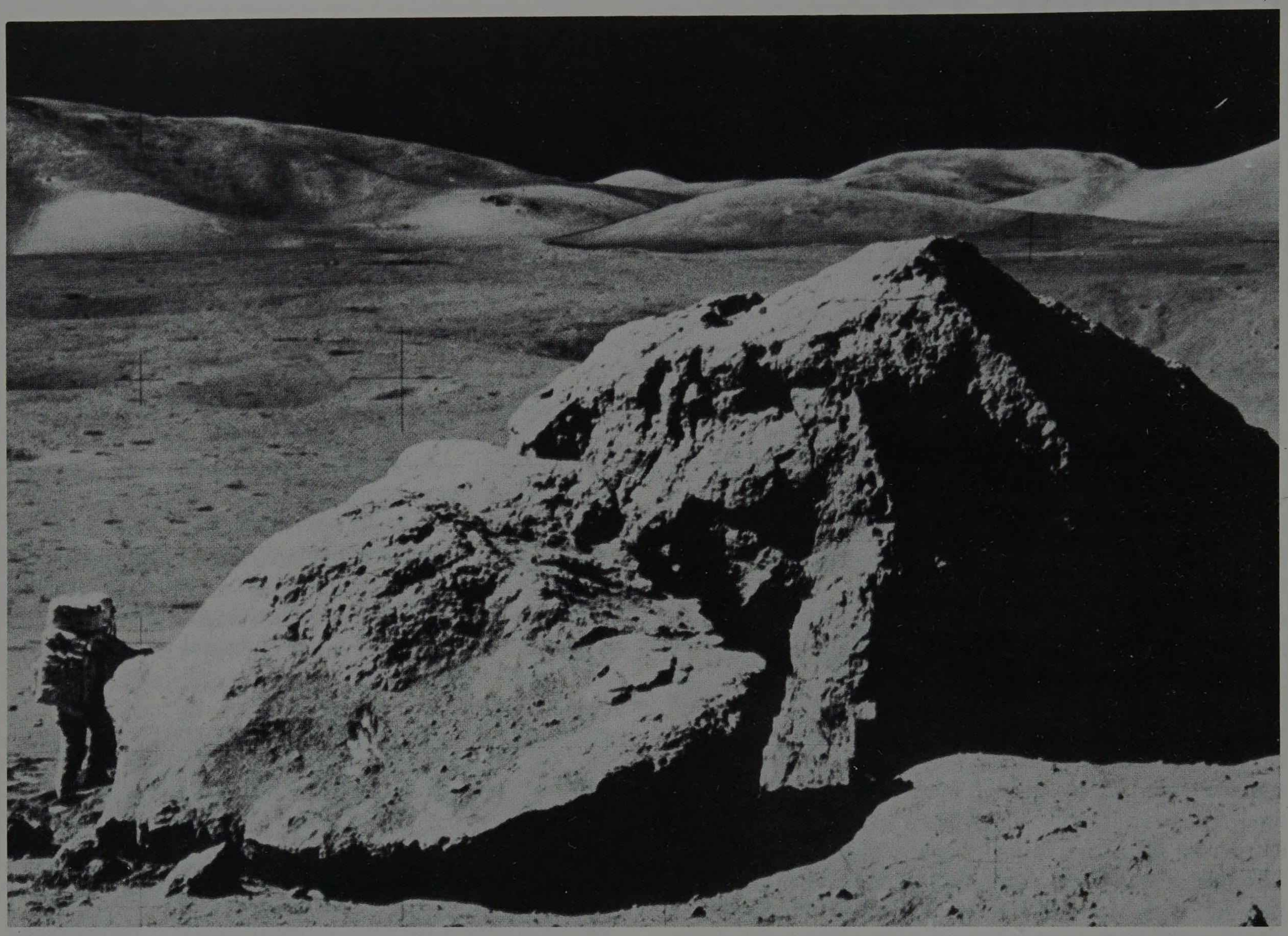


Figure 12.2 Apollo 17 astronaut-geologist Harrison Schmitt studies the rocks of the Taurus-Littrow Valley of the Moon. *Courtesy of NASA.*

So, why colonize the Moon? Two reasons come to the forefront: mining and science, particularly astronomy.

Moon's Natural Resources

If it were cheap and easy to go to the Moon, colonists would have done so long ago. The Moon is an enormous source of valuable raw materials. Chemical analyses of lunar rocks and soil returned to Earth by Apollo astronauts show them to be rich in aluminum, titanium, iron, calcium, and silicon. Pure iron is found everywhere as a fine powder from the bombardment of the Moon by meteoroids during the past eons. It can be simply separated by a magnet as soil passes by on a conveyor belt. Aluminum and titanium are found in ores not commonly refined on Earth, so new methods of extraction would have to be developed. Silicon is just what is needed for photovoltaic solar cells.

Over 40 percent of the surface soil mass is oxygen compounded with other elements. Oxygen for a colony's atmosphere and for rocket propellant would be easy to extract from surface soil by simply heating it. At least three-fourths of the takeoff weight of most launch vehicles is propellant. If lunar mining and processing could supply the oxygen for rocket engines plying *cislunar space* (Earth-Moon space), much less mass would have to be lifted from Earth. Hydrogen is scarce on the Moon, however. Its original supply escaped the low lunar gravity long ago, and solar wind protons are the source of the very small amount of hydrogen now found in the soil (recall that protons are nucleii of hydrogen atoms). For rockets burning hydrogen and oxygen, hydrogen is only one-seventh of the mass of the propellants, oxygen is six-sevenths.

No water has been found, not even in chemical combination in the rocks and soils, but there is a possibility that water lies deeper in the crust or perhaps in sheltered areas in the polar regions. The Moon's axis is not tipped as Earth's axis is, so some deep polar craters and crevices may never see sunlight and temperatures may never rise higher than 40 Fahrenheit degrees above absolute zero. Not only water, but carbon dioxide, methane, and other gases may be found

frozen there. Those regions are not visible from Earth and none of the spacecraft that studied the Moon looked into them. There is also some possibility that water lies deep in the crust in liquid form, since the interior of the Moon is warmer than the surface. If a plentiful supply could be located, some could be electrolyzed to provide needed hydrogen for fuel. On the other hand, if water is not found, hydrogen fuel brought from Earth and burned with lunar oxygen produces an exhaust of pure water.

Mining the Moon's Oxygen

Figure 12.3 in the color pages is an artist's concept of a lunar mining colony. Lunar soil is scooped up (red end-loaders) and ground up (red structure to left), oxygen is extracted and liquified (yellow buildings), and piped to the yellow storage tanks. Waste tailings are carried away by a conveyor system. A rocket takes off in the background carrying several tanks of oxygen to a rendezvous point in lunar orbit. The habitat for a dozen technicians is just right of the communications antennas, covered by a mound of soil. The power lines come from a nuclear generator beyond the horizon.

Figure 12.4 shows a cargo vessel hauling liquid oxygen from the Moon to a "filling station" in low Earth orbit. The oxygen tanker is equipped with an inflatable heat shield for aerobraking in Earth's upper atmosphere. Therefore it does not have to carry as much fuel as would be needed if the orbital change were done by rockets alone.

Automatic robotic mining machinery could be operated from inside the habitat so people would not be exposed to the harsh environment outside. In fact, it has been suggested that a completely automated mining operation could be controlled remotely from Earth and only a small maintenance crew would have to be sustained on the Moon.

Plenty of solar energy is available for processing ores to extract the oxygen. Just spread out an array of photovoltaic cells and tap in. However, the Moon rotates on its axis once a month resulting in a two week day and a two week night. Another source of energy would be needed during the long

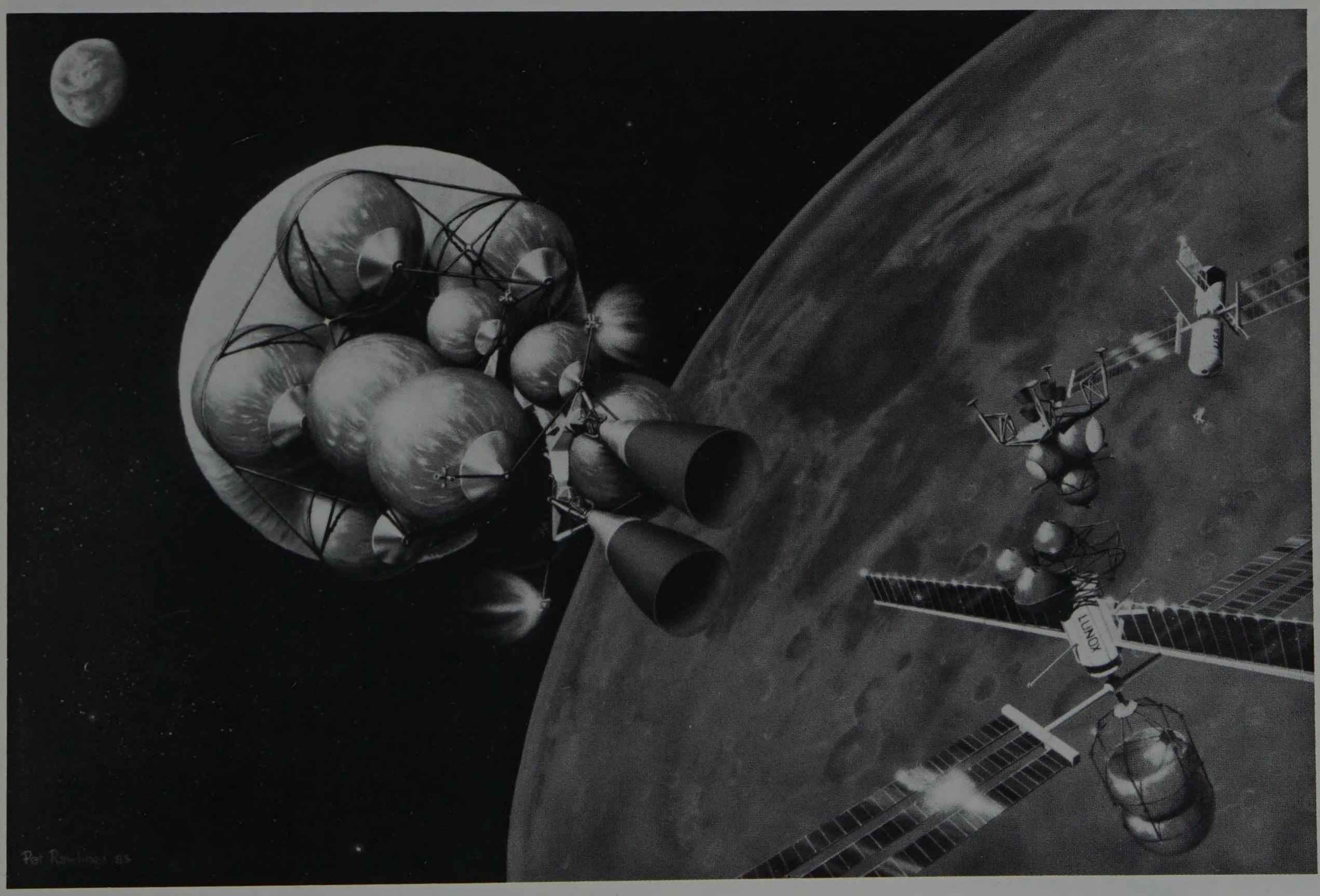


Figure 12.4 Ferry vehicle transports liquid oxygen manufactured on the Moon to low Earth orbit. Spherical tanks are assembled at the facility in the lower right; the rocket engines and heat shield are attached. The ferry heads for Earth (upper left), the heat shield inflates to several times its illustrated size, and the vehicle aerobrakes in the atmosphere to reduce the fuel required for orbital transfer. On the return trip the ferry brings a supply of liquid hydrogen from Earth. In the upper right is a lunar space station; a lunar lander has just arrived with more oxygen from the surface. *Courtesy of Eagle Engineering; artist Pat Rawlings.*

dark night. There are several possibilities. First, orbiting mirrors could concentrate and reflect sunlight onto the collectors like miniature suns. With four of them equally spaced in lunar orbit, one would always be in the right position throughout the two week night. Second, some of the electricity produced during the day could be stored by spinning up massive flywheels to high speed using electric motors. After dark, the flywheel could be connected to a generator to generate electricity. In fact, the motor could be designed to act as the generator. Finally, the brute force method, bring in a nuclear power generator from Earth.

The Mass Driver

Instead of processing the ore on the Moon, an alternative is to ship it elsewhere, to a space colony which is in continuous sunlight, as we discussed in the last chapter. Material can be lifted from the Moon to space with only 5 percent of the work needed to lift material from Earth to space. Instead of using chemical rockets to haul the ore from the Moon to the L5 space station, an electrically powered launcher on the surface can accelerate the ore to escape velocity. Such a launcher, called a *mass driver,* has been designed and tested on Earth at MIT and at Princeton. The principle of a mass driver is simple. Put the ore into a bucket, then accelerate the bucket and its cargo to escape velocity, stop the bucket and let the ore go flying off into space. We could not use such a device to launch objects off Earth. Escape velocity from the Earth's surface is about 7 miles per second. Atmospheric friction would quickly slow the object, converting its kinetic energy of motion to heat, and destroy it. However, a mass driver is entirely practical on the Moon, because the lunar escape velocity is only about 1.5 miles per second and there is no atmosphere. Figure 12.5 is an artist's concept of a mass driver in operation on the Moon.

One approach to accelerating the ore uses the attraction and repulsion of magnets. When an electric current flows through a coil, it becomes an electromagnet with a north pole and a south pole. If another magnet is brought near, with its north pole pointing toward the north pole of the coil or its south pole pointing toward the south pole of the coil, the two will repel one another. However, if a north pole and a south pole are facing one another, they will attract each other.

A container fitted with superconducting magnets is inserted into a tube and a coil is energized just ahead of the bucket to attract it and accelerate it forward. Just as the container reaches it, the coil is turned off and the next coil a little farther down the track is turned on to accelerate it

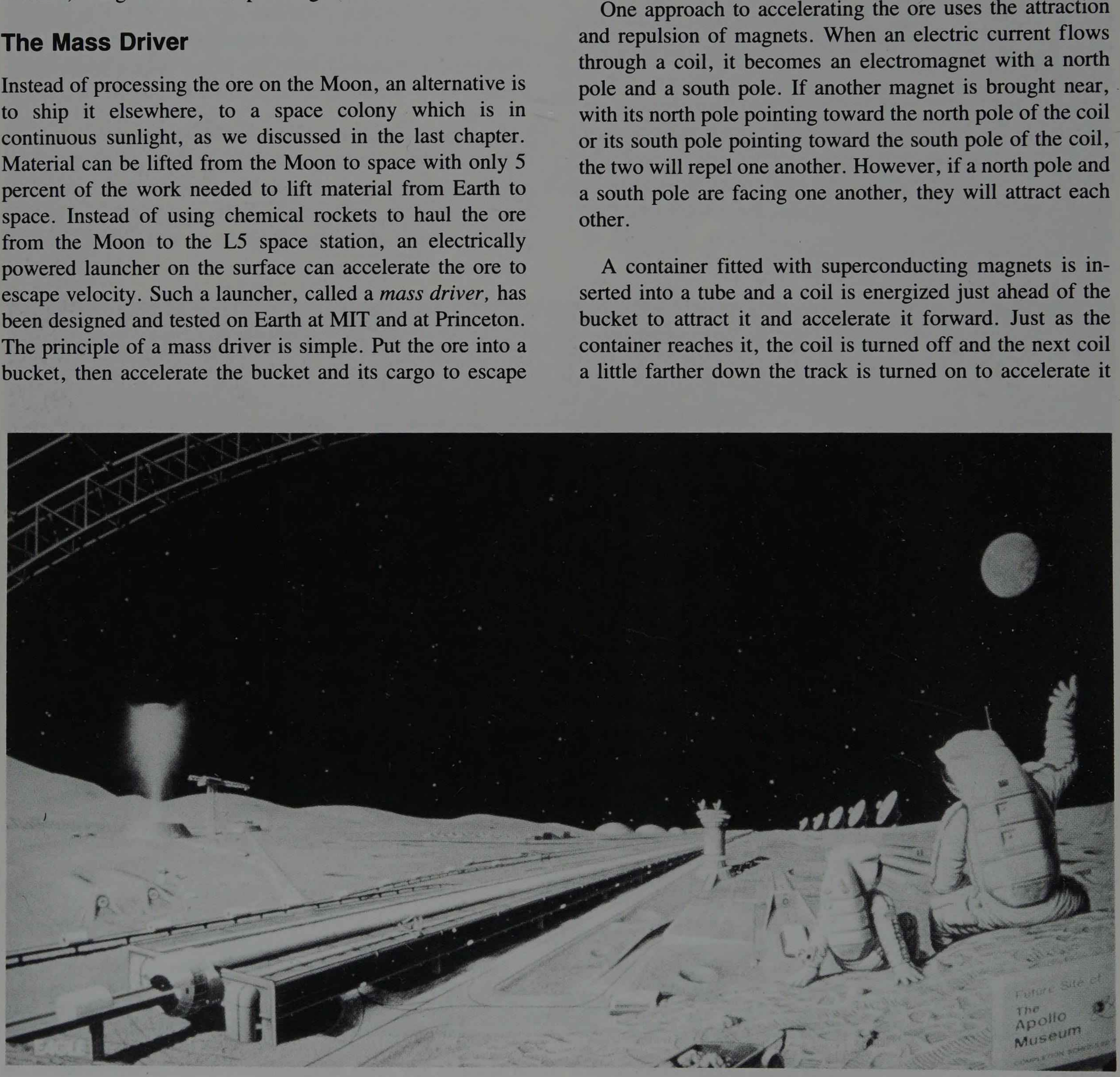


Figure 12.5 Advanced lunar base equipped with a mass driver which accelerates ore to escape velocity and sends it to a collection site at L2. Ore buckets enter the driver at the near end and, after releasing their load at the far end, return for another load on the track behind the mass driver. In the right foreground an astronaut sits with his son at the future site of the Apollo Museum. © *Lunar and Planetary Institute; artist Pat Rawlings, Eagle Engineering.*

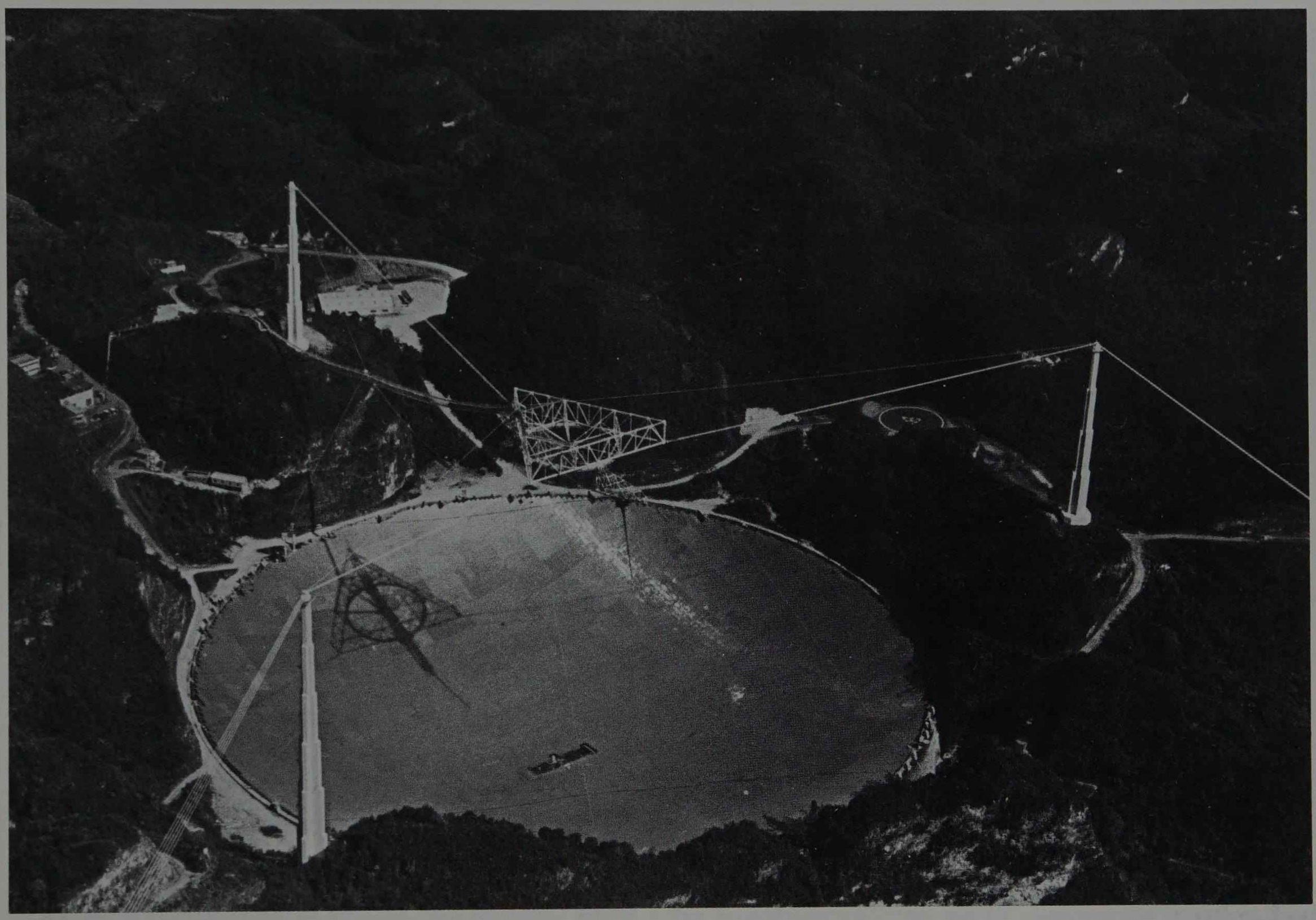


Figure 12.6 The world's largest radio-radar telescope antenna hangs in a natural bowl in the mountains of Puerto Rico. The 1000 foot dish, made of nearly forty thousand 3 by 6 foot perforated aluminum panels, is precisely spherical in shape to an accuracy of less than an eighth of an inch over the 20 acre surface. The triangular-shaped 600 ton platform, suspended 435 feet above the big reflector, supports the antenna feed horns and lines. The telescope either receives natural signals from space or connects to a transmitter to act as a radar. The antenna feeds can be moved to study various parts of the sky in a wide range of wavelengths. *Courtesy of Arecibo Observatory.*

further. Passing through coil after coil, the loaded container is accelerated to escape velocity.

In one design about 25 pounds (Earth weight) of lunar soil is *sintered* (heated and compressed) to form a cylindrical slug about 18 inches long and 4.5 inches in diameter. The slug, firmly attached in its container, enters the mass driver where it accelerates at 1,000 g to escape velocity, 1.5 miles per second, in the first thousand feet. It then moves through guide rails for a distance of 6,500 feet to damp out any sideways motion. At that point the slug is released and the container is suddenly decelerated by two magnetic loops and deflected sideways away from the ore. The slug of ore, now separated from the bucket, continues on it way into orbit, while the container is directed onto a return track back to the loading point for another run.

The slug continues on its escape trajectory toward a catching device located at L2. (Refer back to Figure 11.12.) Although the processing and manufacturing plant may be located at L5, it does not seem advisable to launch the ore directly toward the colony. The best location for the mass driver would be on the front side of the Moon, near the equator, so the slug would follow a half-orbit to L2, similar to a Hohmann transfer orbit. The actual trajectory is more complicated because of the balance between Earth gravity and Moon gravity in that part of space. The velocity of the ore slugs must be very exact as they leave the mass driver; otherwise they would scatter over a wide region of space near L2. Two additional "trim stations" are located downrange from the launcher to precisely adjust the final velocity.

At L2 a device is positioned to catch the slugs as they arrive. Several designs have been suggested, from a metal mesh net to a 10 mile wide piece of styrofoam. There are two main problems to overcome. First, there is sure to be some scatter in the arriving pieces of ore, and, second, the catcher would be accelerated backward from the impacts of the ore slugs. Solutions have been suggested, but both of these problems are difficult to deal with.

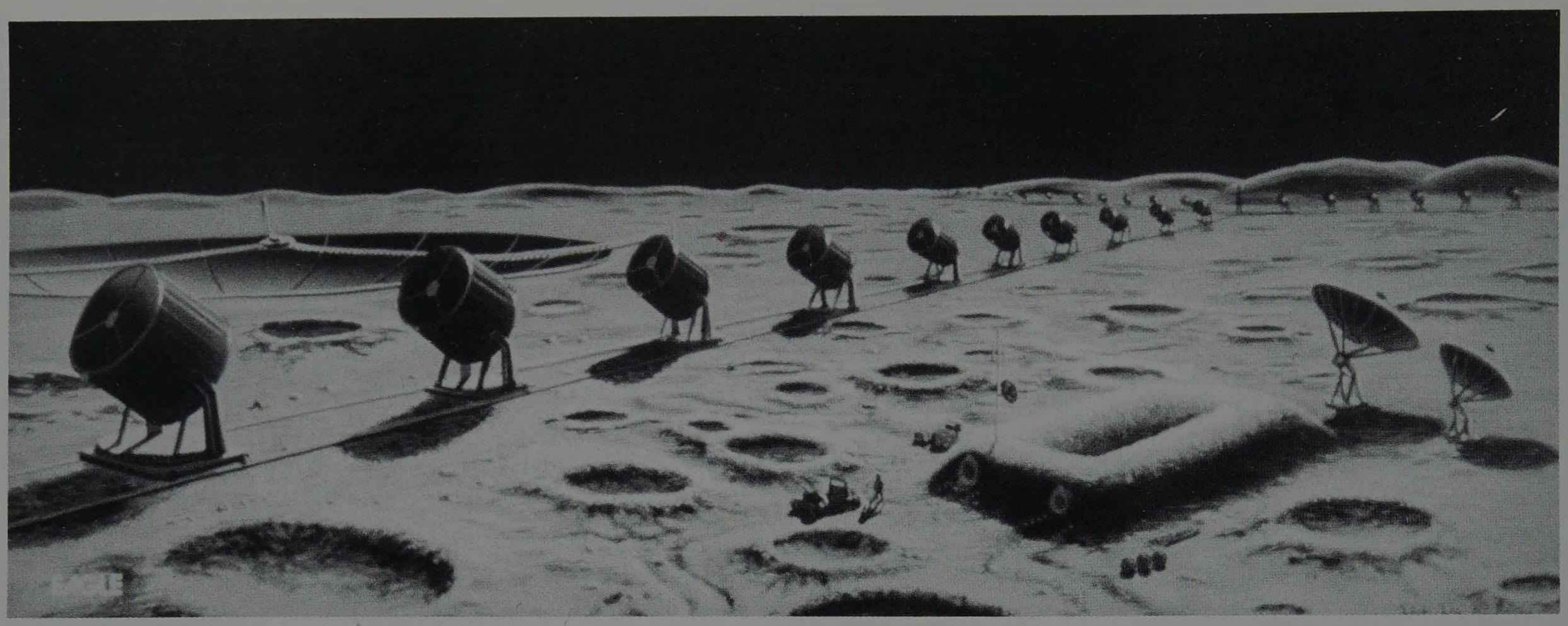


Figure 12.7 Astronomical observing site on the back side of the Moon. Two rows of optical telescopes at right angles to each other form an interferometer, used by astronomers for very high resolution imaging. At the left rear, a radio telescope antenna hangs in a crater. The covered habitat is in the foreground. Communications antennas point at a relay satellite; since the observatory is out of sight of the Earth, communications must be relayed. © *Eagle Aerospace, Inc.; artist Pat Rawlings.*

A space tug would haul an accumulated stock of the slugs to the L5 colony for processing. While the L5 habitat is under construction, raw ore would be sent; the waste slag from ore processing would be used for the L5 shield. Later, preliminary separation could be done on the Moon so only the aluminum, oxygen, and titanium-bearing minerals are shipped out.

Operating at full capacity, this design of a mass driver would launch 10 ore slugs per second, a total delivery of 600,000 tons a year to L2.

Astronomy on the Moon

Astronomy from a lunar base has tremendous advantages. Optical telescopes on the Moon would be unhampered by atmospheric refraction, pollution, and city lights. Low gravity and the slow rotation of the Moon would allow construction of large telescopes and simplify the construction of a telescope mount. Radio telescopes located on the far side of the Moon, pointing away from Earth, would not suffer interference from man-made radio noise. A lunar crater would be a perfect natural bowl-shaped depression in which to build a large dish antenna like the one at Arecibo, Puerto Rico (Figure 12.6). Telescopes designed for observing other parts of the electromagnetic spectrum such as infrared, ultraviolet, or x-ray, would be unimpeded by atmospheric absorption. Over a billion dollars was spent on the Hubble Space Telescope, an indication of the value astronomers place on an observing site in space. Figure 12.7 shows an array of optical telescopes forming an interferometer and a radio telescope built into a lunar crater.

Luna City

Figure 12.8 is an artist's concept of what a lunar colony may look like while under construction.

The prefabricated buildings, similar in design to space station modules, are set into trenches with several feet of lunar soil heaped over the top for shielding from solar and cosmic radiation and from meteorites. The soil also insulates the structures from extreme temperature variations during the two week lunar day and two week lunar night. Buildings are interconnected by hallway-like tunnels; all doors are airtight so if one section loses pressure it can be sealed off until the leak is repaired. A deeper ''storm cellar'' module is buried beneath the main habitats to provide protection during solar proton storms.

Most of the machinery for the mining camp could be automated and operated remotely from Earth, requiring perhaps as few as 10 maintenance people on site. Luna City could grow and might even become self-sustaining. With additional processing and manufacturing equipment, lunar materials could be used to build and expand a permanent city. Construction would be simpler than on Earth because of the low gravity.

Once established, Luna City could engage in interplanetary commerce, selling its products to space stations and serving as a way station for spacecraft leaving the vicinity of the Earth. As was pointed out before, it is much less costly in energy to launch supplies from the Moon with its one-sixth g than it is to launch from Earth. Only small rocket engines and a short fuel burn were needed to launch Apollo's LEM from the Moon. Only small shuttle craft

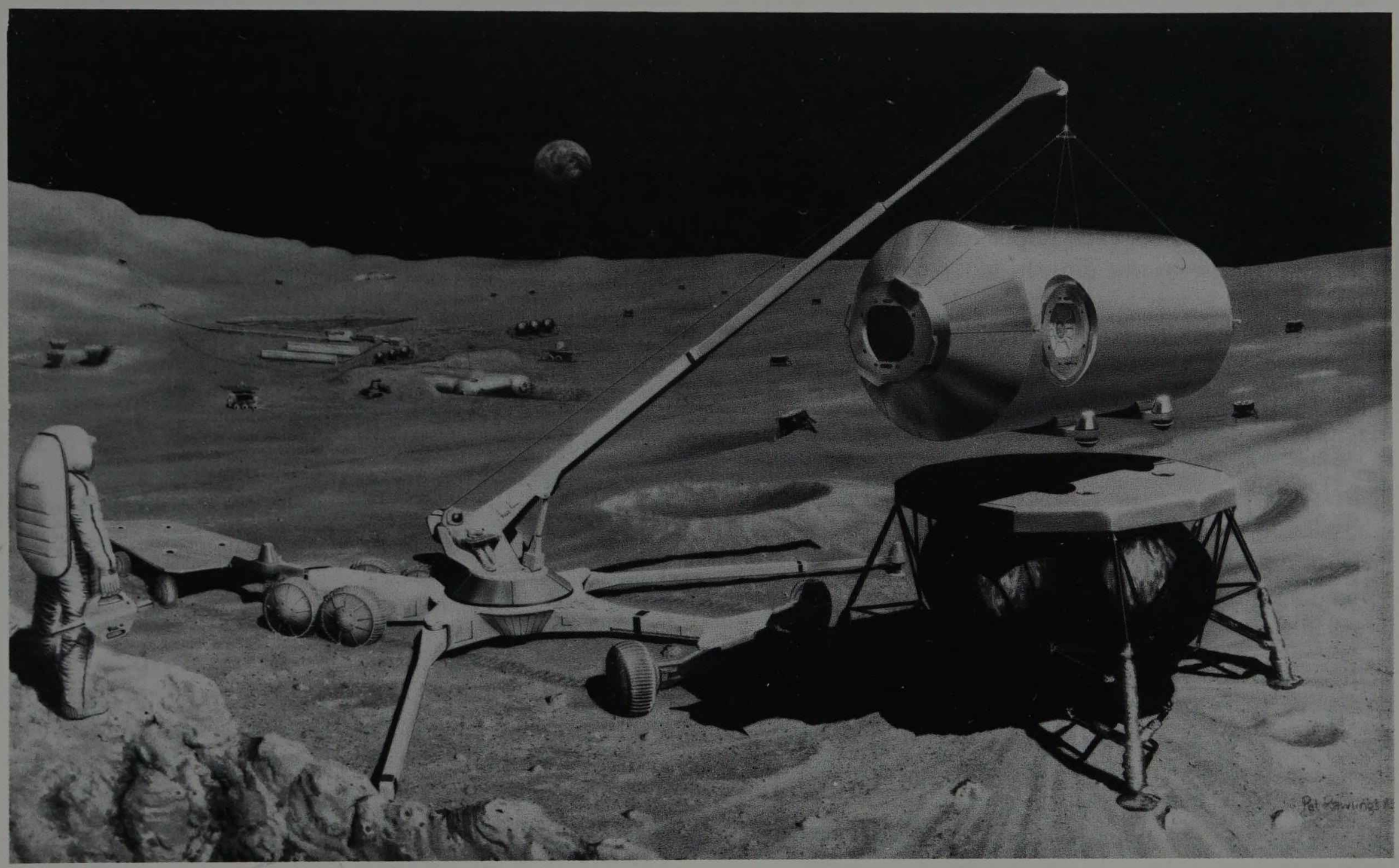


Figure 12.8 Unloading a habitat module just delivered to the lunar base. The flimsy looking crane can do the job easily because the module weighs only one-sixth its Earth weight. Other modules, delivered by other landers scattered around the scene, are already in place in trenches at the base in the background. The assembled habitat is then heaped over with lunar soil for protection and insulation. Earth hangs low in the sky. *Courtesy of Eagle Engineering; artist Pat Rawlings.*

would be needed to deliver fresh supplies and oxygen propellant to customers parked in orbit around the Moon before they proceed to the farther reaches of the solar system. A possible cislunar infrastructure is shown in Figure 12.9. Each part has been discussed separately in this and the previous chapter; this diagram brings it all together.

Not everyone agrees that the Moon will become a permanent home to a large group of colonists. Other ideas are discussed in the additional readings listed at the end of this chapter. A lunar outpost will undoubtedly be established early in the twenty-first century, but how far it will expand is the question.

Mars, the Red Planet

Mars as a place to live has been an appealing notion for centuries. Science fiction writers from Edgar Rice Burroughs to Ray Bradbury and many others have described the native Martians or human settlers who became "Martians" when they colonized the red planet.

As early as 1659, markings were seen on the surface of Mars and the observers could estimate the period of rotation of the planet by watching the markings. In 1877 Schiaparelli reported seeing linear markings which he said were like the fine threads of a spider web and called them "canali," an Italian word for lines or grooves.

In the 1890s, astronomer Percival Lowell built an observatory in Flagstaff, Arizona, where he devoted much time and effort to observing Mars. His observing site was better than most and he was in possession of a fine instrument. Much of the time the image of the planet was blurry and shimmering, even when looking through the clear desert sky. Sometimes the image would clear and become quite sharp and detailed.

Lowell, too, saw the markings which had been observed by Schiaparelli, but he saw much more. He saw seasonal changes in the markings and in the polar caps. The markings seemed to widen and become darker in the spring and summer. At the same time the polar caps retreated in the summer and advanced in the winter. Lowell mistakenly interpreted these seasonal variations as being due to vegetation along canals which he thought had been constructed by Martians to carry water from the polar caps to their agricultural land in the warmer equatorial regions. He was

convinced that intelligent beings inhabited the red planet, struggling to keep their civilization going as their planet was cooling and drying up.

Later Earth-based observations using more advanced telescopes equipped with spectrographs and other equipment told a different story. Mariner spacecraft were launched from Earth for close inspection of Mars. Mariners 4, 6, and 7 flew by for closeup looks during 1964 and 1969. Mariner 9 was injected into orbit around Mars in 1971. Then, in 1975, two spacecraft called Viking were sent. The Viking landers settled softly onto the surface of Mars, sniffed the air, tested the soil, searched for signs of life, photographed the surroundings, and sent the findings back to Earth (Figure 12.10). They found no canals, no vegetation, no Martians. In fact, Mars is almost as inhospitable as the Moon. Almost. Several differences make it a more appealing place, a potential site for human communities. Two of the most important are water and an atmosphere.

Because it is 1.5 times farther from the Sun, its year is 687 Earth-days long, 1.88 Earth-years (recall Kepler's third law?). A day on Mars is 24.6 hours long, just 37 minutes longer than Earth's day; so the Martian year is 669 Mars-days long. The tilt of its axis is 25 degrees, compared to Earth's 23.5 degrees. So Mars has seasons, but because of the long year, each season is about twice as long as on Earth; see Table 12.1. By comparison, Earth seasons last about 90 days. Also, the eccentricity of its orbit is 0.093, greater than Earth's 0.017. At perihelion it is 26 million miles closer to the Sun than it is at aphelion. Mars is at perihelion during the southern hemisphere summer so that season is shorter and warmer than the northern hemisphere summer. Recall Kepler's second law?.

The diameter of Mars is about 4,000 miles, half that of Earth, and its mass is only 0.1 that of Earth. Therefore, its gravity is much lower, about 0.4 g on the surface. Escape velocity from the surface of Mars is 3 miles per second compared to nearly 7 miles per second from Earth.

Mars has two tiny moons. Phobos is potato shaped, about 6 by 8 miles in size, and therefore has a very low surface gravity, only 0.001 g. It orbits 5,600 miles from the planet in about 7.6 hours. Deimos is even smaller, about 3.5 by 4.5 miles, and its surface gravity is 0.0005 g. It is about 14,000 miles from Mars and completes an orbit in 30.3 hours. These two moons could be reconstructed into way stations for space ships travelling between Earth and Mars.

TABLE 12.1 Length of Martian Seasons

Season		Length	
Northern Hemisphere	Southern Hemisphere	Earth Days	Mars Days
spring	autumn	199	194
summer	winter	183	178
autumn	spring	147	143
winter	summer	158	154
		687	669

Martian Landscapes

Except for the lack of vegetation, the Martian landscape is strangely Earth-like. Viking lander pictures of the rocks, soil, and sand dunes have a familiar look about them, giving the impression that they were taken in a barren desert on Earth. Figure 12.11 shows the scenery surrounding Viking; you would almost expect to see a camel walk by. Soil analysis at the Viking lander sites detected the presence of many of the same minerals as found on Earth. Many of the iron-bearing rocks are oxidized to a red color like iron-bearing rocks on Earth. Over time, erosion has cut away sand and dust-sized grains, and wind has distributed them over the planet. For centuries Mars has been called ''the red planet''; it really is red.

The southern hemisphere is covered by old, eroded impact craters much like the Moon, but the northern hemisphere shows evidence of geological activity including volcanoes, lava flows, canyons, and what appear to be dry river valleys and glacier deposits. This geological activity along with wind erosion has obliterated most of the craters. The largest of the dormant, perhaps extinct, volcanoes is Olympus Mons, measuring 15 miles high, 325 miles across at its base, and sporting a 40 mile wide caldera crater at the top. It is the largest volcano discovered in the Solar System so far.

A huge canyonland, Valles Marineris, stretches along the Martian equator nearly 3,000 miles, about the distance across the United States from New York to California. Parts of it have walls which appear to have been deeply eroded by running water. It is up to 150 miles wide and 4 miles deep. The Grand Canyon of Arizona would fit into one of the side tributaries.

Martian Atmosphere

Mars has an atmosphere, very thin by Earth standards, equal in density to Earth's atmosphere at about 20 miles altitude. Pressure at 20 miles is only 10 millibars, 0.15 pound per square inch, one-hundredth what it is at sea level on Earth. Furthermore, the Martian atmosphere is 95 percent carbon dioxide. The other 5 percent consists of nitrogen and argon, with traces of oxygen, water vapor, and other gases. Humans could not survive outside space suits or pressurized habitats. Notice, however, that the constituents are the same as Earth's atmosphere, just in vastly different proportions.

The atmosphere contains so little ozone that ultraviolet radiation reaches the surface of Mars with full intensity. Because of the distance from the Sun, the ultraviolet is

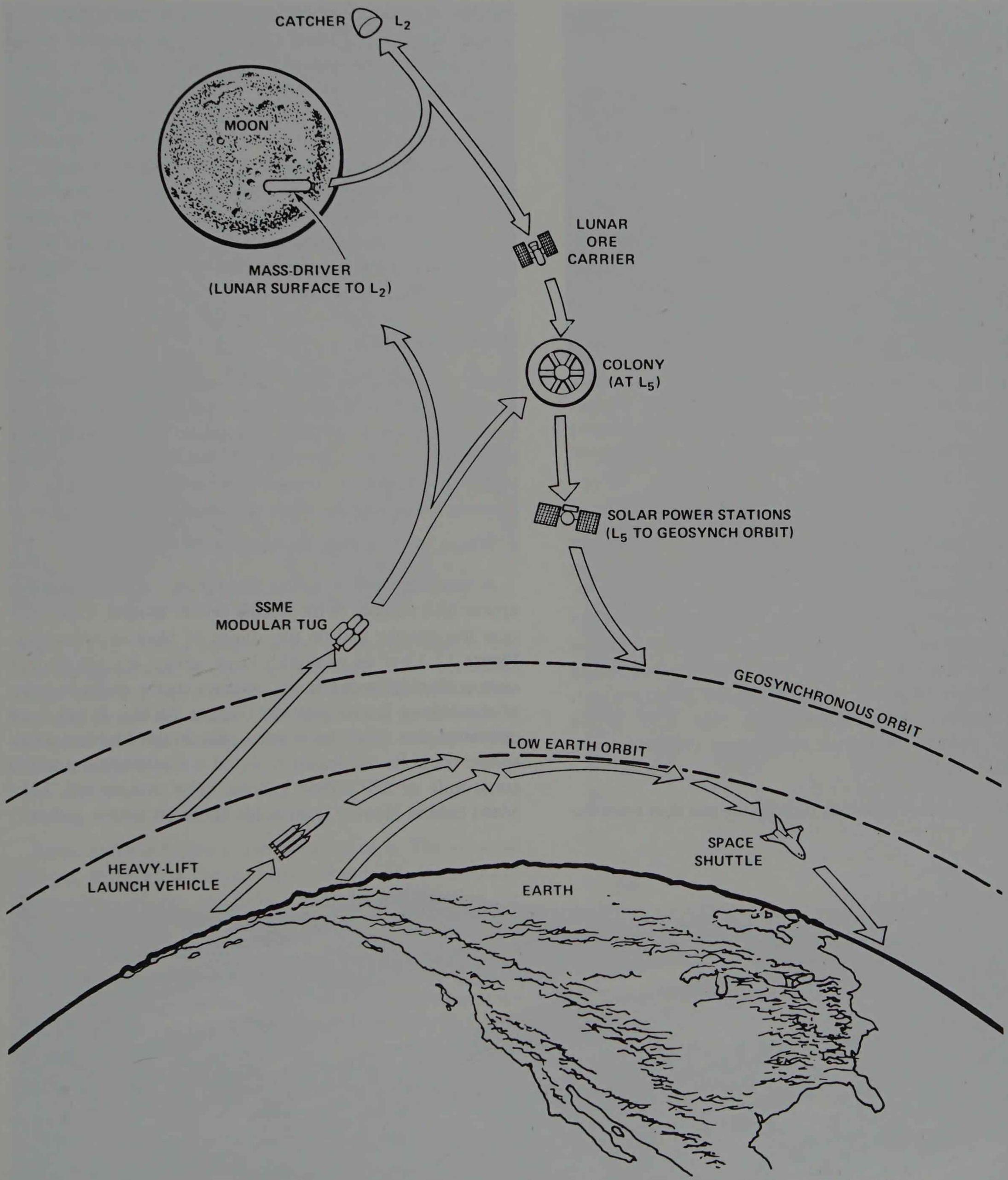


Figure 12.9 Cislunar infrastructure. (An SSME modular tug is a cargo vessel assembled from Space Shuttle main engines.) *Courtesy of NASA.*

much less intense than it is at Earth's distance. Nonetheless, it is sufficient to be hazardous to unprotected human beings.

Thin as it is, the atmosphere provides some protection from meteoroids. Although there are many large craters, Viking lander pictures show no small craters. Smaller meteoroids burn up as they fall through the atmosphere.

At the landing sites, light southwest winds blew in the early morning and light easterly winds blew in the after-

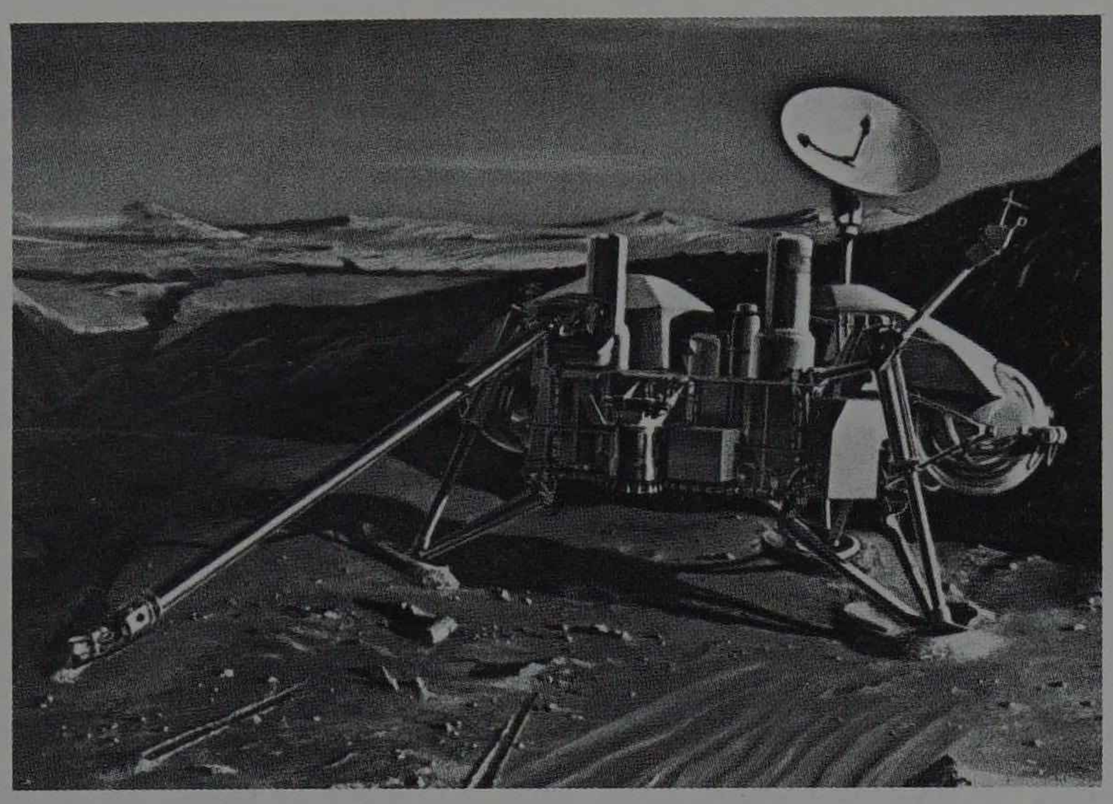


Figure 12.10 Viking lander. A long mechanical arm with a scoop for sampling Martian soil reaches out to the left. Weather instruments are on the boom extending up to the right. Imaging equipment is in the center, and the communications antenna points toward Earth. *Courtesy of NASA.*

noon. Maximum recorded wind speed was 15 miles per hour. Afternoon temperatures were typically −25 °F; at night temperatures regularly dropped to near −120 °F. Because of its greater distance from the Sun, Mars receives only 43 percent as much solar energy as Earth, and, because of its thin atmosphere, the little solar heat absorbed during the day is lost to space at night. In the polar regions, summer daytime temperatures reach only −95 °F. In equatorial regions, the highest temperature recorded was a comfortable 80 °F.

Dust storms occur as winds pick up the red dust from the surface. A major storm may encompass the entire planet for several weeks. The energy contained in the wind is not great, however, because of the low density of the air. Dust storms seem to occur mostly during the southern hemisphere summer when Mars is at perihelion, closest to the Sun, and receiving maximum solar radiation. It is possible that some of the features observed by Lowell were due to the red dust settling out onto the dark bedrock at some time and then being blown off the rocks during a storm. Very fine dust remains suspended in the air for long periods of time causing the sky to appear pink rather than the blue we are accustomed to on Earth.

Water on Mars

Water is present on Mars in substantial quantities. The Mariner and Viking images show geological features that look like river beds on Earth that appear to have been made by running water (Figure 12.12). But there is no running water on Mars now; temperatures are too cold and the pressure is too low for water to remain in the liquid state.

Where, then, did all the water go?

A small amount is in the atmosphere. Clouds and fog appear on a number of the Viking orbiter images, especially near the equator and on the slopes of Martian volcanoes. Figure 12.13 is an example. Frost, either dry ice (frozen carbon dioxide) or water ice, appears on the rocks in some of the Viking lander pictures (Figure 12.14). It has been estimated that if all the water vapor in the Martian atmosphere could be condensed to liquid it would amount to 0.2 cubic mile or 220 billion gallons. (For comparison, Lake Mead behind Hoover Dam holds about 10 billion gallons.)



Figure 12.11 The scene at the Viking I lander site looks strangely Earth-like. The structure at the right is part of the spacecraft. *Courtesy of NASA.*

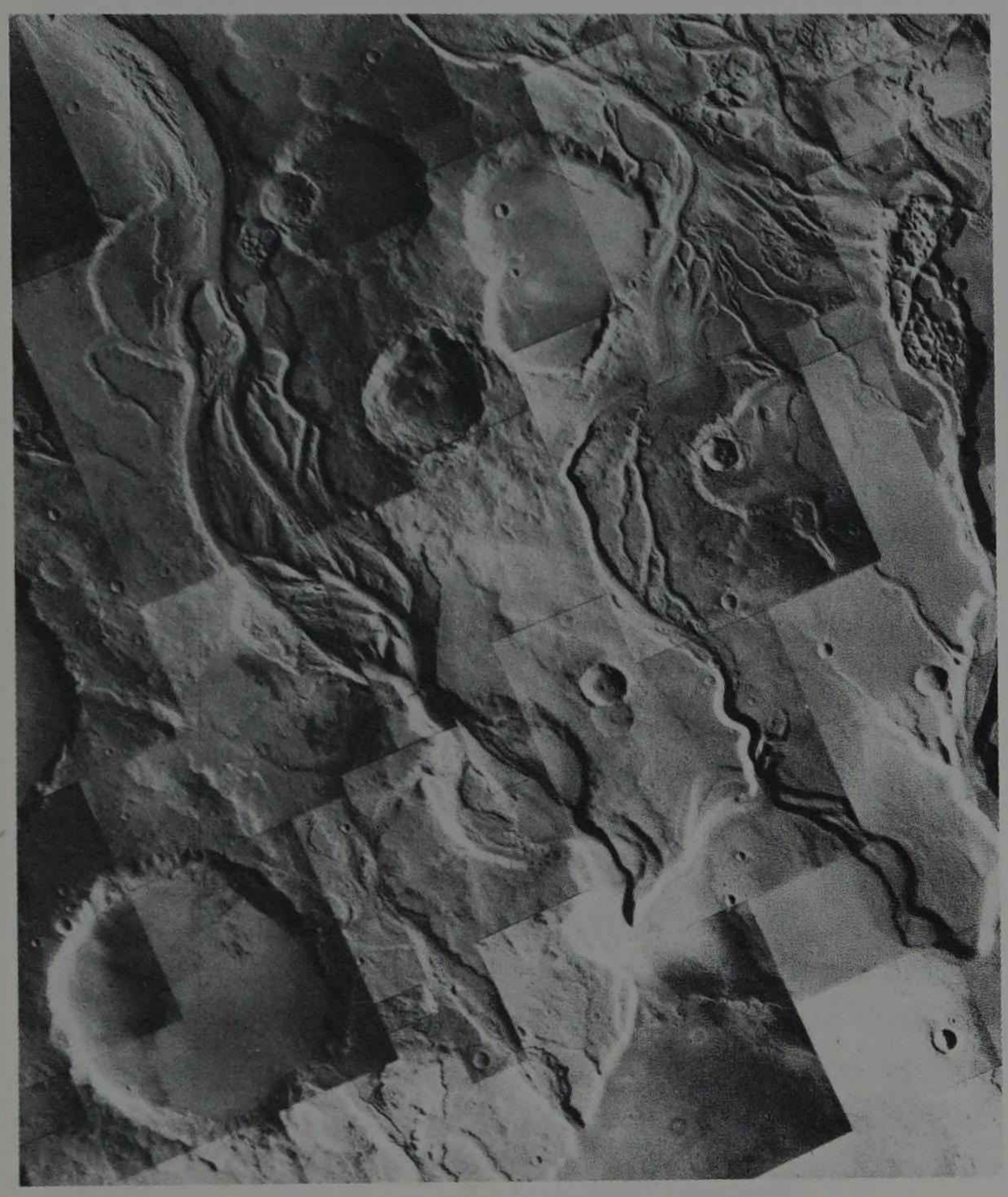


Figure 12.12 Viking orbiter picture of Martian features that have the appearance of dried up river beds. They cut across craters, indicating that water flowed on Mars after meteor bombardment formed the craters. This picture is a composite of a number of individual small photos taken by the Viking orbiter. *Courtesy of NASA.*

Some water is frozen in the polar ice caps. The seasonal changes observed in the ice caps are probably the result of a deposition of dry ice from the atmosphere during the severely cold polar winter season and the sublimation (evaporation) of the dry ice during the following spring. However, the ice caps do not disappear completely during the summer season, indicating that the residual is probably water ice mixed with Martian soil. Figure 12.15 is a Viking picture of the north polar region in midsummer when the carbon dioxide dry ice has sublimated, leaving the water ice exposed.

The water vapor content of the atmosphere varies widely from season to season, indicating that water is also stored in the ground in the form of permafrost, permanently frozen soil and ground water. Permafrost is found on Earth in the northern parts of Alaska, Greenland, Canada, Scandinavia, and Siberia. In the equatorial regions of Mars it is probable that the top 3 feet or so of soil has been completely dehydrated. If permafrost water is present there, it is deep in the ground. Because the interior of the planet is warmer than the surface, liquid water may be found at greater depths, perhaps a mile down. If so, it could be tapped like groundwater is tapped on Earth, by drilling wells.



Figure 12.13 Early morning fog on Mars. The fog seems to form in the canyons and dissipate by midday. A few craters can be seen on the plateaus to the right and left of center. *Courtesy of NASA.*

Colonies on Mars

In spite of its harsh environment, Mars has the basic ingredients necessary to support a self-sufficient colony of humans. It is the most Earth-like of all the planets.

Should we go? It is technically feasible and would require no major breakthroughs in technology. Breakthroughs in

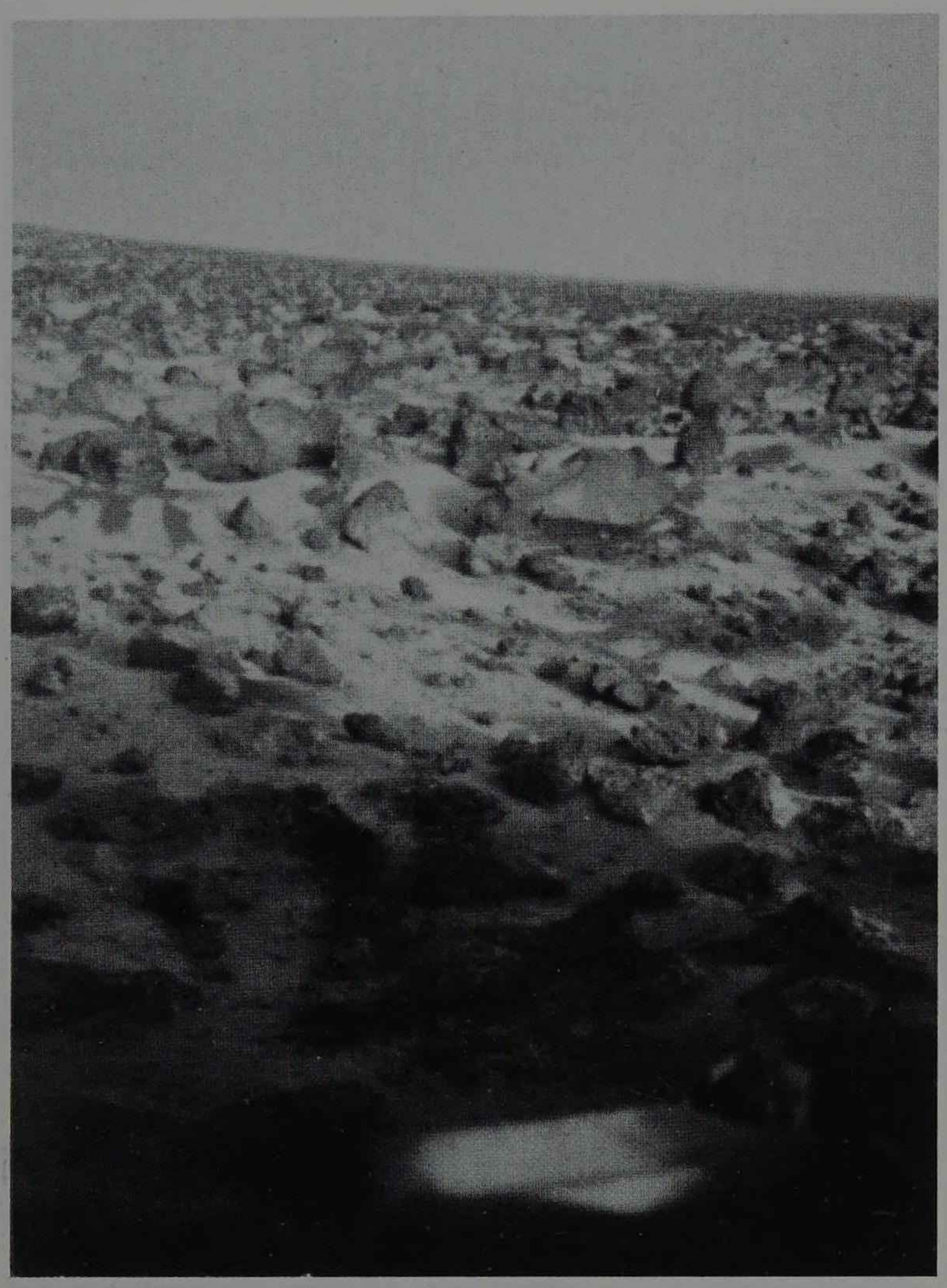


Figure 12.14 Frost on the ground and rocks at the Viking 2 lander site. *Courtesy of NASA.*

"exotic" propulsion systems, nuclear fusion, and bioengineering would make it easier, but it is entirely possible to do the job with our present technology. Indeed, the research and development concomitant with a commitment to a Mars mission would undoubtedly lead to major advances in those areas.

Interest and enthusiasm for establishing a colony on Mars has been steadily increasing. A particularly active group of students and teachers, dubbed the Mars Underground, held a Case for Mars conference at the University of Colorado at Boulder in 1981. Since then the group has joined with the Planetary Society in forming a Mars Institute to promote studies and research for Mars exploitation. Two more Case for Mars conferences have been held in Boulder, attracting more and more serious scientists and engineers. Studies related to the transportation systems, construction in orbit and on Mars, use of Mars resources, and human factors have been done and are continuing. Even influential political figures are beginning to lend support. The Soviet Union is seriously planning several flights to Mars and a cooperative mission between the United States and the Soviets has been suggested as a means to get the two nations working together on something of positive value to the human species.

It seems probable that a human settlement on Mars will become a reality within the next 50 years. Indeed, it has been suggested that the first Martians are probably alive on Earth today! Ultimately we may have self-sufficient cities on Mars where people live normally as they do on Earth, going about their business of growing food, manufacturing



Figure 12.15 North polar region of Mars. Carbon dioxide dry ice has sublimated during the northern hemisphere summer exposing the water ice and the step-like layers in the cliffs at the edge of the ice cap. The ice must be quite thin; patches of bare ground can be seen at the top left. *Courtesy of NASA.*



Figure 12.16 Artist's concept of a Mars base. Partially buried habitat is at the center, greenhouses to the right, and mine tunnels to the left rear. The vertical structure near the tunnel entrances is a well drilling rig. A "wagon train" vehicle made in segments climbs the hill in the foreground while a rocket lifts off at the right rear of the scene. Dish antennas on the mesa are for off-planet communications; the mast antenna is for communicating with roving exploration vehicles. Because Mars has an atmosphere, a very thin one, remotely piloted aircraft with very large wings can be used for transportation and exploration. In the lower right a geologist examines a newly discovered fossil. *Courtesy of Eagle Engineering; artist Pat Rawlings.*

products, doing scientific research, and enjoying themselves while doing it.

The First Settlement

The first problem that comes to mind is, of course, the atmosphere. It would be a major accomplishment if we could modify the Martian atmosphere so it could support our human needs. *Terraforming* refers to the process of modifying a planet to make it more Earth-like so humans can live a normal existence. It will be discussed later in this chapter. The first colonists, however, will have to live in closed, sealed habitats as they would on a space station or lunar colony. Work outside the habitat will be done in space suits. Figure 12.16 shows an artist's concept of a Mars base.

The first habitat modules and supplies of food, air, and water will be imported along with machinery for mining ore, extracting usable minerals, and fabricating construction materials. Continuing dependence on Earth for fresh supplies would be far too expensive, though, so eventually colonists will have to learn to live off the land as our ancestors did when they migrated to new territory. In the case of Mars, the land is barren, but the technology to make it productive is available.

Buildings constructed on permafrost and heated on the inside could have structural problems if the permafrost melts beneath the building. On Earth, such buildings are built on piers above the ground, insulated from the ground. But on Mars it is necessary to protect the inhabitants from solar and galactic cosmic rays. As on the Moon, the solution is to dig a trench, put a habitat module in it, and cover it with several feet of soil. Storm cellars will be needed, also. After ore is dug from the mines, the tunnels can be sealed off and used as habitats.

Power for the colony could come from solar cells, concentrating solar electric generators, or nuclear power plants. Because Mars is one-and-a-half times farther from the Sun than Earth is, solar energy is only 43 percent as intense as it is at Earth. Therefore, arrays of solar cells will have to be twice the size of arrays near Earth to produce the same amount of electricity. Nuclear power generators could be installed in the polar ice cap to generate electricity and their waste heat could melt the ice to provide water for the colony in a warmer climate near the equator. Then Mars might finally have its canals.

Interplanetary Transportation

Shipping all that machinery, materials, and supplies directly from the surface of the Earth would be enormously expensive in energy, especially if cargo and crew are sent together in a fast transfer orbit. Several ideas have been explored. One calls for shipping cargo and fuel in smaller batches first to a space station in low Earth orbit. There the pieces would be assembled into a larger unmanned cargo vessel and sent ahead to Mars via a Hohmann transfer, the least-energy transfer, requiring nearly a year transit time. See Figure 12.17 in the color pages. At Mars it would be injected into a low orbit to wait the arrival of the smaller passenger craft coming by a faster, high energy route, taking about five months. The interplanetary passenger ship would rendezvous with the cargo ship and materials would be taken to the surface in small batches. Aerobraking in the Martian atmosphere reduces the fuel requirements for retrorockets to inject the spacecraft into orbit around Mars.

The Hohmann transfer requires a minimum of fuel but takes a longer time. The slow route is all right for cargo, but not for people, for two reasons: 1) the weight of a year's supply of food, air, and water that must be lifted from Earth and 2) the physiological and psychological effects of a yearlong trip on the human body. On the other hand, a fast trip requires more fuel at both ends, to accelerate the craft to higher speed at departure and to slow it on arrival. Although the mass of the life support supplies is less for a quick trip, the mass of the fuel is greater. An optimum must be determined.

The crew must be able to function in Martian gravity immediately upon arrival. Since even a voyage of a few months may incapacitate crew members, a rotating vehicle to produce artificial gravity may be essential to keep the crew in good physical shape. The effects of long term weightlessness and exposure to cosmic radiation are still undetermined.

Another important advantage to separating the cargo from the crew is that the cargo would be in place in orbit around Mars before the crew leaves Earth, giving greater assurance of a successful mission.

If a lunar colony is established first, it could provide the oxygen for the trip and some of the necessities for establishing the Mars base at a lower cost than supplying them from Earth.

1999 Trajectories

Every two years Earth and Mars are properly aligned in their orbits for a voyage. Because Earth is traveling faster in its smaller orbit closer to the Sun, it overtakes and passes Mars every 780 days. When that happens, Mars and Earth are lined up on the same side of the Sun, a position called *opposition* by astronomers, and minimum energy voyages can be made.

Three of many possible trajectories to Mars during the 1999 opposition are shown in Figure 12.18. Figure 12.18a is a fly-by without a landing, a 1 year flight. A complicated mission taking the spacecraft past Venus on the way to Mars is shown in Figure 12.18b. The gravity of Venus accelerates the spacecraft so it "cracks the whip" around that planet

MARS FLYBY FOR 1999 OPPOSITION
ONE YEAR MISSION

1 EARTH DEPARTURE, APRIL 2, 1999
2 MARS PASSAGE, AUGUST 8, 1999
3 EARTH ARRIVAL, APRIL 2, 2000

OUTBOUND VENUS SWINGBY 1999 OPPOSITION

1 EARTH DEPARTURE, JAN. 26, 1998
2 VENUS PASSAGE, JULY 9, 1998
3 MARS ARRIVAL, JAN. 16, 1999
4 MARS DEPARTURE, MARCH 17, 1999
5 EARTH ARRIVAL, NOV. 18, 1999

CONJUNCTION CLASS MISSION 1999 OPPOSITION

1 EARTH DEPARTURE, DEC. 17, 1998
2 MARS ARRIVAL, SEP. 28, 1999
3 MARS DEPARTURE, JAN. 25, 2001
4 EARTH ARRIVAL, SEP. 2, 2001

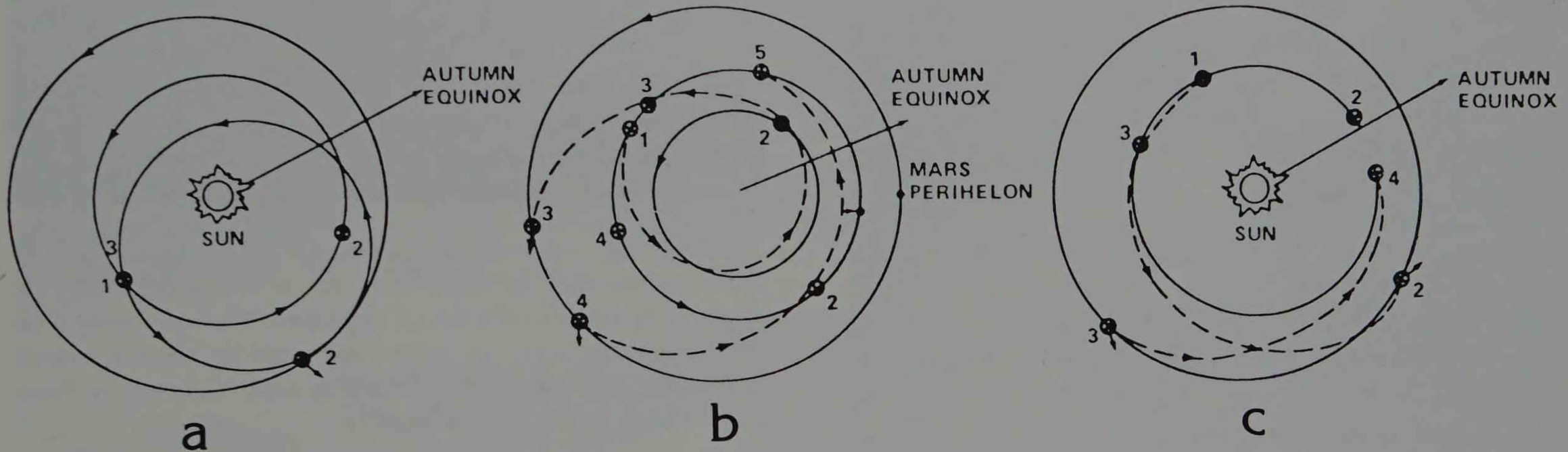


Figure 12.18 Three possible trajectories to Mars during the 1999 opposition. Follow the numbers in sequence in each figure. (**a**) is a fly-by without landing, a transfer orbit with a period of exactly 1 year; the spacecraft returns to meet Earth at the same point as at departure. The trajectory shown in (**b**) includes a fly-by of Venus. The spacecraft picks up enough energy in its fall toward Venus to whip past that planet and head out for Mars; a greater payload can be carried with less take-off energy. This mission takes 1 year and 10 months, including a 2 month stopover on Mars. (**c**) shows a 9 month outbound transfer orbit, 16 months on the planet, and about 7 months to return. *Courtesy of NASA.*

and heads for Mars. Less energy is required for a larger payload, including provisions and vehicles for a 2 month stay on Mars, but the trip takes more time; total mission time is 22 months. A 16 month stay on Mars is included in the mission shown in Figure 12.18c. It uses Hohmann transfers to Mars at the 1999 conjunction and back to Earth at the 2001 conjunction. Mission time is more than 2 years and 8 months.

Eventually a "bus" service could be established between Earth and Mars by placing large rotating spacecraft into an orbit around the Sun that intersects the orbits of the two planets. For example, see Figure 12.18a. These buses would continuously cycle in that orbit, eliminating the need for accelerating and decelerating the large vehicle at each end of the trip. Passengers bound for Mars leave Earth in a passenger craft, perhaps the X-30, with a first stop at the space station in low Earth orbit. From there they ride a small shuttle craft to a rendezvous with one of the cycling ships already equipped with an atmosphere and provisions supplied from the Moon or Mars. The refueled shuttle craft is hangared in the bus for use at the other end of the trip. At Mars the shuttle craft takes the passengers from the cycling bus orbit to a space station in low Mars orbit (Figure 12.19). A Mars lander carries the passenger to the surface (Figure 12.20).

Once the bus line is established, no fuel would be required to keep the buses running in their orbit. Power would be needed only for the life support equipment. Shuttle craft fuel requirements would be comparatively small. Travel time will be from five to seven months depending on which transfer orbit is used.

Unmanned Exploration

We know very little about the Martian soil and no suggestions for its exploitation can be made until further unmanned exploration reveals its composition. The same is true of Martian water. We are confident that it is there somewhere, but, except for the ice caps, we do not know exactly where the water is located or in what form.

The Soviet Union has a firm commitment to Mars exploration. Launch windows occur about every two years and the Soviets seem to have plans for each window through the 1990s. The first mission (launch July 1988, arrive April 1989) studies Mars from orbit as well as its tiny moon Phobos. Because Phobos has such low gravity and no atmosphere, the spacecraft will rendezvous as if it were a space station and examine it from as close as 150 feet. Images with half an inch resolution are possible. One experiment blasts it with a laser beam and analyzes the gas

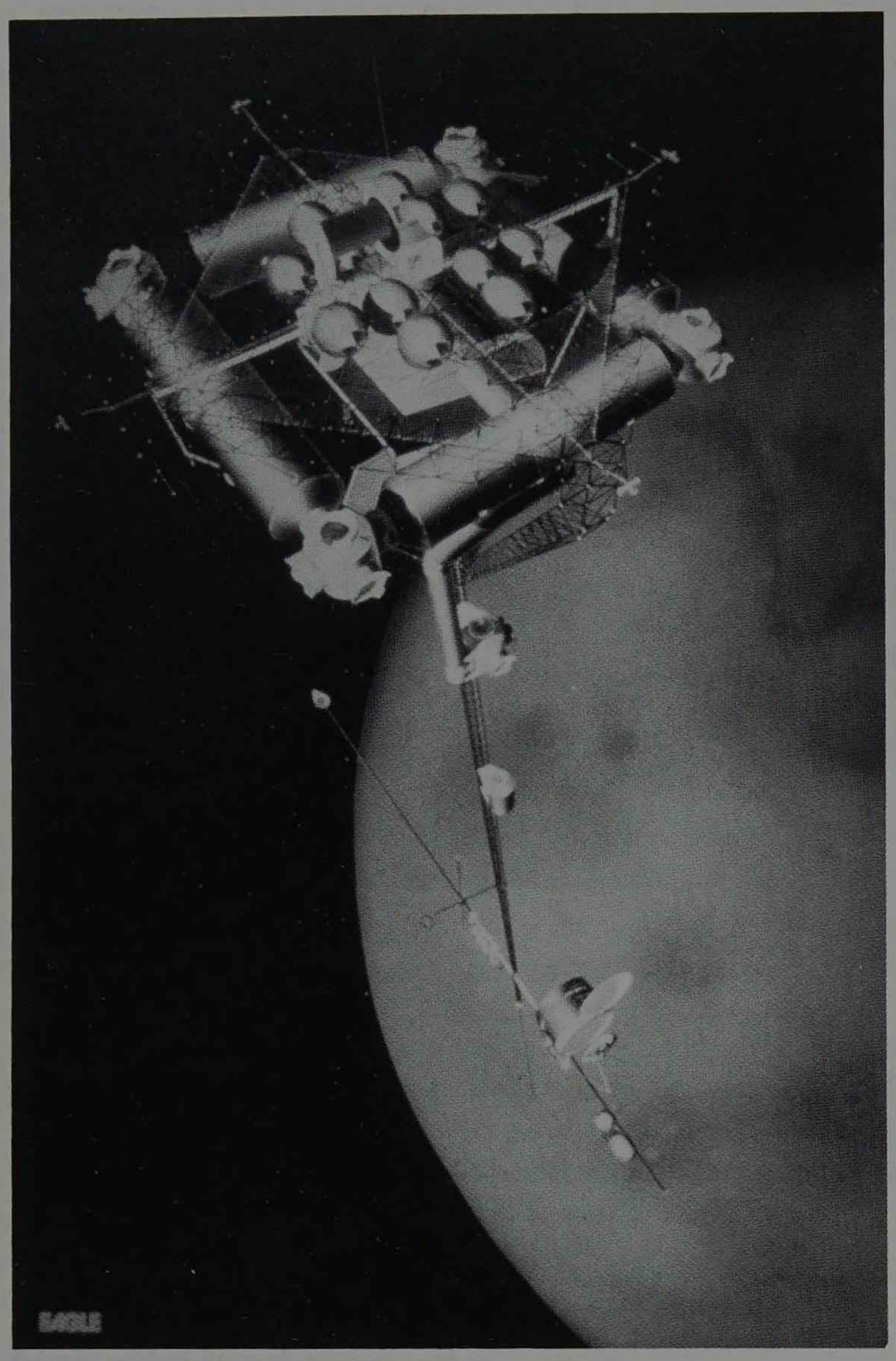


Figure 12.19 A spaceport in low Mars orbit for refueling ships on their way to and from the planet. Docking and hangar facilities and "motel" habitats are part of the port. *Courtesy of Eagle Engineering; artist Mark Dowman.*

to determine its composition. Later an instrumented lander is placed on Phobos. Other experiments study the atmosphere, ionosphere, and magnetosphere of Mars.

In the 1994 window a Soviet spacecraft will be launched to Mars where it will drop French designed balloons to study the planet's surface and atmosphere. Instruments are attached to a 300 foot long rope hung below two balloons. The upper one is a closed balloon inflated with 200,000 to 300,000 cubic feet of helium. The lower one operates something like a hot air balloon. It is made of a material which readily absorbs solar energy and is open and filled with Martian atmosphere. When the Sun shines on it during the daytime, the solar balloon heats up and rises into the atmosphere, drifting with the wind. After sunset, as the solar balloon cools, it slowly sinks until the instrument package reaches the ground. There it parks for the night to make measurements of soil conductivity and other things. The helium balloon remains inflated and bouyant at all times to keep the solar balloon off the ground. Next day

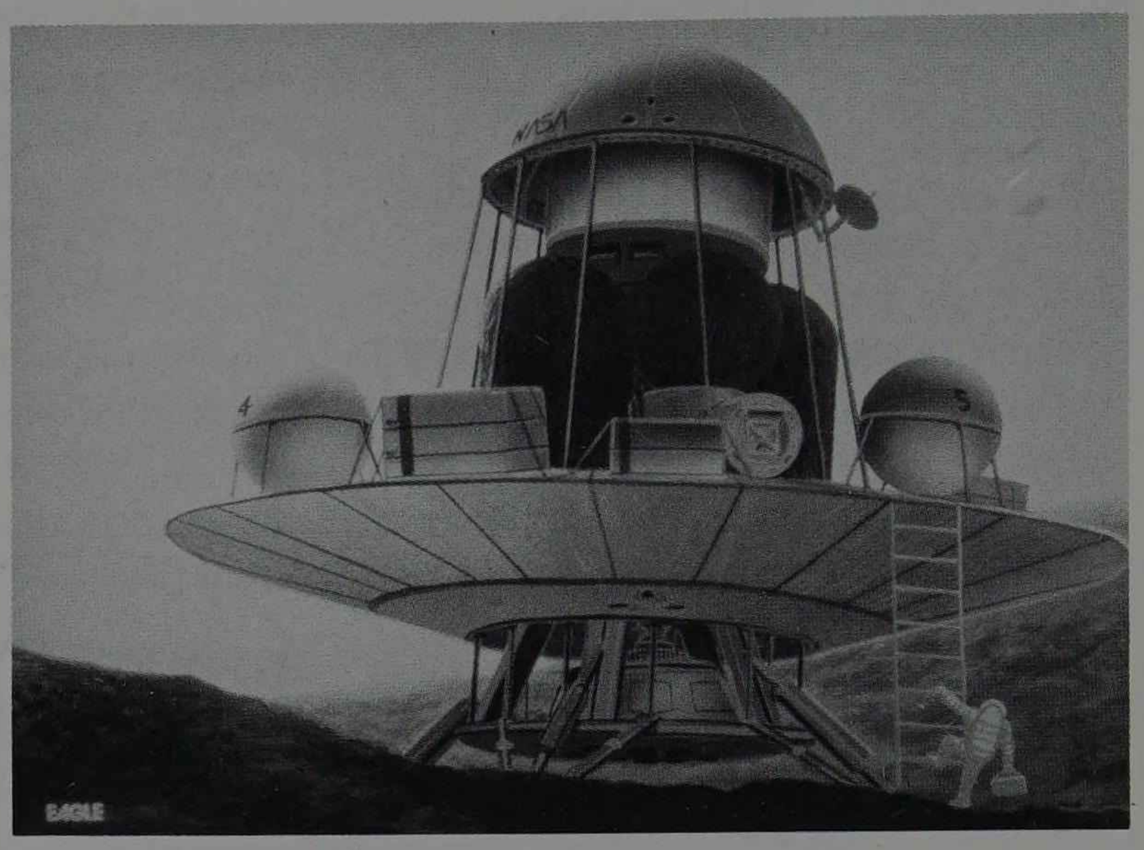


Figure 12.20 Aerobraking Mars shuttle vehicle lands vertically using retrorockets. Because Mars has a thin atmosphere, the aerobraking system must have a large area. This one opens wide for reentry and folds up against the sides to make a smooth streamlined vehicle for launch back to orbit. *Courtesy of Eagle Engineering; artist Pat Rawlings.*

when the Sun comes up the solar balloon heats up again to carry the experiment to a new location. A camera package is attached for making close up images of the ground. The balloons may be accompanied by a small robot rover and penetrating devices to be fired into the ground to make measurements. Prior to the balloon mission the Soviets plan to send a radar mapper to study the surface terrain and search for water from orbit. A larger Mars rover and sample return mission is planned by the Soviets for 1996 or 1998.

In 1992, the United States Mars Observer will carry experiments into orbit around Mars to study the climate and the composition of the surface, and especially to search for the missing water. It will also produce very high resolution images using scanners similar to Landsat or weather satellites (recall Chapter 6).

NASA may send an unmanned robot roving vehicle in the 1998 window to drive around Mars for a year, picking up samples, drilling into the ground in search of permafrost, photographing the landscape, and doing numerous other experiments. The samples would be transferred to a capsule and returned to the space station under quarantine for analysis of their chemical composition, a search for fossils, and age dating. The window for returning to Earth opens in January 2001.

Figure 12.21 shows one design of a Mars rover, a segmented vehicle consisting of three sections each with its own pair of wheels, coupled together with swiveling pivots. It is equipped with stereo cameras in the midsection so controllers on Earth can examine the surroundings in 3-D. A rover which can traverse rocky terrain pitted with



Figure 12.21 Mars sample return mission. The lander in the background brings the rover in the foreground to the surface while the mother ship remains in orbit. The three-segmented rover wanders about the planet for a year studying the terrain and picking up samples of the soil and rock. The samples are then transferred to a small rocket attached to the lander which takes them to a rendezvous with the mother ship for return to Earth. *Courtesy of NASA/JPL.*

craters and avoid stream channels and steep cliffs without a driver must be a smart robot. Round trip communication time between Earth and Mars is anywhere from 8 to 25 minutes (at the speed of light) depending on their relative positions in their orbits. By the time controllers on Earth saw a problem ahead and sent a message to turn back, the rover could be a pile of scrap at the bottom of a canyon. The machine can climb over obstacles up to 5 feet high and climb a 35 percent grade, but it must be smart enough to recognize terrain it cannot handle. Of course, it would move very slowly, less than a mile a day, and could be instructed to move only a few feet and stop for further instructions after controllers get a new stereo picture to examine.

Some engineers think that the Soviet-French balloons have a better chance of success. They can travel farther more safely in a short time, picking up ten or more samples and dropping them at one spot with a radio beacon. The rover would then land at the beacon to pick up the rock collection and return it to Earth. The complex part is steering the balloons to desired locations.

Terraforming

Someday human Martians may stand by the side of a flowing stream, gaze at the blue sky above and the flowers below, and think how much it reminds them of pictures they have seen of Earth. We have been discussing building comfortable human habitats in colonies on other worlds. Is it possible to change an entire world into an Earth-like human habitat? Technically, yes, but it requires time, centuries perhaps.

Earth is warm and comfortable primarily because of its distance from the Sun and because of the composition of its atmosphere. The Moon is the same distance from the Sun, but, without an atmosphere, it is cold, dry, and bombarded with lethal radiation. Mars, farther from the Sun and with only a thin atmosphere, is also cold and bleak. On the other side, Venus, closer to the Sun and with a dense carbon dioxide atmosphere, is a 700 °F inferno.

The air blanket around Earth is transparent to the visible wavelengths of sunlight, the region of the spectrum which contains most of the solar energy. Visible light can penetrate almost undiminished through the air to warm the ground. On the other hand, heat from the Earth does not readily escape back to space because water vapor and carbon dioxide, both minor constituents of the atmosphere, strongly absorb the infrared wavelengths emitted by the warm ground. You are probably aware that deserts cool rapidly after sunset because the absence of water vapor in the air allows the heat to escape. Similarly on a clear, cloudless night, the temperature drops quickly for the same reason. Thus, these trace gases in the atmosphere act as a blanket, keeping the heat in.

To make Mars more like Earth, then, the first step is to increase the density of the atmosphere and change its composition. Oxygen is needed by humans, but that may be difficult to find and it will not help warm the planet. So let us begin with water vapor and carbon dioxide, two gases which absorb infrared radiation and hold in the heat. Both are found on Mars, although the quantity of each is uncertain. We can begin by melting the ice caps. Orbiting mirrors can concentrate solar energy into the polar regions. White ice reflects most of the sunlight, so a coating of dark material should be spread over the ice first to absorb rather than reflect the energy. Where do we get the dark material? Phobos and Deimos are both made of dark carbonaceous matter and mass drivers can easily propel the stuff off the moons onto the planet. In fact, the gravity on Phobos is so low that a big league baseball pitcher could throw an object into orbit. These moons probably contain water also, which would evaporate and aid in building the Martian atmosphere.

The carbon dioxide dry ice evaporates first, at a temperature of −108 °F. As the carbon dioxide content of the atmosphere increases, the heat loss to space decreases and the planet gradually warms, releasing still more carbon dioxide. How much it warms depends on how much carbon dioxide we can release, a largely unknown quantity at this time. Because Mars is farther from the Sun, an atmosphere twice as dense as Earth's would be needed to bring the average temperature above freezing. Melting the water from the ice caps and permafrost is the second step. Water vapor in the air will contribute a great deal to the blanket.

Next we need oxygen. As the atmospheric density increases and the temperature rises, we introduce primitive life, beginning with lichens and cyano-bacteria (blue-green algae) which photosynthesize carbon dioxide from the air and nitrogen from the soil, building their own mass, releasing oxygen and breaking rock down into fertile soil. Later, grasses, shrubs, trees, and food crops can be introduced to speed up the process. Slowly the oxygen content increases until the atmosphere is breathable by insects, then by birds and mammals.

This biological creation of a breathable atmosphere has happened before. The sequence of events described above is similar to the evolution of Earth's atmosphere. How long would it take on Mars? Thousands of years, probably, but in that time the Martians may tire of living in closed habitats and space suits and will find some shortcuts.

Several possible shortcuts are already known. Chlorofluorocarbons are the gases used in refrigerators and spray cans and are being accused of destroying Earth's ozone layer. They also absorb different wavelengths of infrared than carbon dioxide does. One way to rid the Earth of them and to speed up the terraforming of Mars may be to introduce them into the Martian atmosphere at a very early stage. They would contribute to the temperature rise and, after a few hundred years or so, would have broken up and dissipated. Genetic engineering of a particular life form suited to the harsh Martian climate could begin the oxygenation process at an earlier stage.

Other planets and moons could perhaps be terraformed also, but with more difficulty than Mars. For a planet with plenty of oxygen but no water, hydrogen could be imported by tanker from Saturn. Or a water-bearing asteroid could be steered on a collision course. It would vaporize on impact yielding, at least temporarily, a water vapor atmosphere.

On to the Stars

Human travel beyond the Solar System is not at all feasible with our present science and technology. The distances involved are enormous (See Figure 12.22.) The next nearest star after the Sun, Alpha Centauri, is four light years away. That is, light traveling at 186,000 miles per second takes four years to travel that distance. The speed of light is a cosmic speed limit; nothing can travel faster. However, strange things begin to happen as one accelerates to high speeds. In particular, time slows down for the high speed object relative to its surroundings. In his theory of relativity, Einstein postulated that this strange thing would occur and experiments have shown it to be true. It is not in the realm of science fiction; it really happens. If some of the more "exotic" propulsion systems could be made to work to accelerate spaceships to speeds approaching the speed of light, then it may be possible to send humans on interstellar flights. For example, accelerating to 90 percent of the speed of light during the first half of the trip, then turning around and decelerating for the last half, would take about nine



Figure 12.22 On to the stars—the belt and sword of Orion. The bright star in the lower right is 815 light years away. By comparison, the star nearest to Earth is about 4 light years away.

Earth-years to make the round trip to Alpha Centauri. But on the spaceship only a few months would pass. The crew would return from the trip a few months older while everyone on Earth would have aged nine years. A round trip to the next large galaxy, in the constellation Andromeda, would require 40 or 50 years ship time, depending on how fast it accelerated and decelerated. But five million years would pass on Earth. Not many of their friends and relatives would be around to greet the crew when they returned! Perhaps in a century or two, the capability to travel at near light speed will be commonplace. But now, in the last part of the twentieth century, there is no propulsion system capable of accelerating to that speed.

Even if we had a spaceship travelling near the speed of light, we have no idea in which direction to head to find a habitable planet, or whether planets even exist around other stars. Stars appear to us as just points of light in the sky. At this time even the largest telescopes cannot magnify the image large enough to see the disk of a star as we can see the disk of the Sun. Further, it is not possible with present equipment to determine if a distant star has a planet in orbit around it. Planets only reflect starlight and are so dim that they are lost in the glaring brilliance of the star.

Looking for planets around other stars is especially difficult from Earth because the atmosphere scatters starlight, increasing the glare around a star's image. The Hubble Space Telescope, when put into orbit above the atmosphere, has the resolution necessary to offer some hope for success in this search. Attempts have been made to infer the presence of large planets around stars by looking for nonuniform motion of those stars. If such a star has a large planet, then both it and the planet will orbit around their common center of mass, and the irregular motion should be observable. Several such searches have thus far been inconclusive. Indirect evidence of other planetary systems has come from the Infrared Astronomical Satellite which has shown the presence of cool dust clouds around several stars. These observations are consistent with the theory that planetary systems form when a star is born from a collapsing cloud of gas and dust. Most of the gas goes into the star while some of the remaining dust condenses into planets.

Even if we find a planet around another star, we do not now have the means of determining whether it is habitable by human beings. To be habitable, the planet should have surface gravity similar to Earth gravity. Less than Earth gravity may be satisfactory, but much more than one g would be difficult to adapt to. A breathable atmosphere and suitable temperatures would certainly be desirable although we could build comfortable habitats and go out only when necessary. Water and oxygen are the two essentials, because it would be difficult if not impossible for Earth to provide continuing support to an extraterrestrial colony of human beings.

Any native inhabitants would, we hope, be friendly. If intelligent, they would have to be willing to accept our colonists. If not intelligent, they must not be hostile. If only microbes, they must not cause incurable disease.

People who are headed for the stars must be equipped with the best total education possible. Everyone will have to work. A group of colonists should include not only specialist scientists, engineers, and test pilots, but people with a broad knowledge of the humanities, the arts, and the sciences. Colonizing the Moon and Mars will provide experience as to the endurance of the human body and mind. We are, first of all, human and we must take our humanity with us. However, one curmudgeon said that we will probably take the two worst possible things into space: germs and management.

DISCUSSION QUESTIONS

1. Why does Earth have an atmosphere, while Mars has only a thin one and the Moon has none?
2. Compare and contrast a colony on Mars, a settlement on the Moon, and the bases in Antarctica.
3. How would you select the first group of settlers? What

skills? What ratio of women to men? What age groups? What health standards? Any mental health screening?

4. If you were going to Mars, what one personal item would you take with you besides the basic necessities of life? Why?
5. How would you govern a permanent settlement on Mars? Should it become an independent state? At what point in time?
6. How could you terraform Venus?

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Chapter 13

Life in the Universe

Do living beings exist elsewhere in the universe? The answer is either "yes" or "no," and either one of them would be bewildering. How should we look for other life? Is the probability of finding it so low that searching would be a waste of time?

There are several ways to search: by going and looking, or by remote sensing. We have sent astronauts and robot spacecraft to look throughout the Solar System. Astronauts have brought rocks and soil back from the Moon for examination; robot laboratories have tested the soil of Mars. So far, nothing living has been found anywhere off Earth.

Space travel is expensive and time consuming. It took almost a year for the Viking spacecraft to reach Mars. The fastest spacecraft, Voyager, launched in 1977 took 1 1/2 years to reach Jupiter, over 2 years to reach Saturn, 9 years to Uranus, and 12 to Neptune. At that speed, Voyager would take some 50,000 years to reach the next nearest star. Exploration of the Solar System may be practical in a lifetime, but until faster spacecraft are developed, an alternative method must be found to look beyond.

We have also looked for signs of life on the other planets of the Solar System by remote sensing. We examine the electromagnetic energy coming from them, determine their temperatures, analyze the composition of their atmospheres, and try to deduce whether living organisms could possibly endure. By listening intensely to the radio frequencies, we search for signals which would proclaim an intelligent source. That type of search is, of course, limited to intelligent extraterrestrials who have discovered radio communications. None have been found, as yet.

Both deliberately and unintentionally we have been signalling our presence to the universe. We have attached messages in the form of audio and video recordings onto several spacecraft. Daily we send radio, radar, and semi-intelligent television signals which could be detected by sensitive receivers many light years away. If some intelligent, hopefully friendly, aliens pick them up, they will learn about Earth and its inhabitants.

The Chemistry of Life

Before we can search for life elsewhere, we need to define what it is we are looking for and to understand how it manages to flourish on Earth.

What do all living things have in common? First, they all have the ability to reproduce, to replicate themselves cell by cell. Instructions for reproducing a cell are contained in the *DNA molecule* which is an integral part of each cell. The DNA splits lengthwise, unzips, so to speak, each half joining with other atoms and molecules until two identical DNA replicas are made. Each builds a duplicate cell. And so the growth of new cells and replacement of old dying cells continue.

Second, living organisms take in nourishment and release waste materials; they interact with their environment. On Earth, animals inhale oxygen and exhale carbon dioxide. They eat food and eliminate gas and solid waste. Plants perform basically the same process as animals. But, additionally, during daylight hours, plants take in carbon dioxide from the air and nutrient-laden water from the soil to manufacture carbohydrates. During this process, they return more oxygen back to the air than they consume.

Earth life is carbon-based. That is, all living organisms are composed of long chain molecules made up of carbon, oxygen, hydrogen, and other elements. It is not essential that life be carbon-based, but the chemical characteristics of carbon make it the most likely building block. Carbon atoms combine with each other and with other elements in a multitude of ways to form large complex molecules which remain stable at Earth temperatures. In contrast, silicon, sometimes proposed as a element base for alien life, cannot form long-chain, stable molecules. These tend to fall apart into useless fragments.

Atoms of elements bind together through the electrical force of attraction to form molecules. The nucleus of an atom carries a positive electrical charge and is surrounded by an electron cloud bearing an equal but negative charge. Thus, an atom is electrically neutral. If some of the negative charge is missing, however, the atom becomes a *positive ion;* if an excess of negative charge is present, the atom

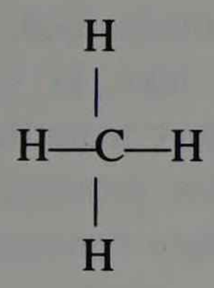
becomes a *negative ion*. Because particles bearing opposite electrical charges attract one another, positive and negative ions move toward each other and bind together to form ionic compounds. For example, a positive sodium ion and a negative chlorine ion bind together to form the compound of sodium chloride, common table salt.

Ions of sodium are devoid of one electron. They therefore carry a single positive charge and are said to have a valence of $+1$. The *valence* indicates how many and what kind of excess charges the ion carries. Oxygen has a valence of -2 while hydrogen has a valence of $+1$. Thus, two hydrogen ions will bind with one oxygen ion to form a molecule of water. Salt molecules and water molecules are the ''end of the line''; they are the largest molecules that can be formed from those elements. Carbon is rather unique, however, in that it has a valence of -4 or $+4$ and can combine with other carbon ions as well as with ions of other elements to form very large molecules. Molecules built on carbon are called *organic* molecules and their study is called organic chemistry.

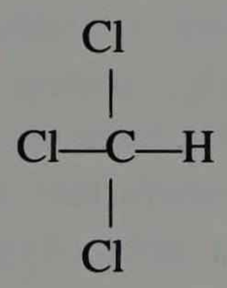
Molecules of water and salt may be represented by diagrams as follows:

H-O-H Na-Cl

H stands for hydrogen, O for oxygen, Na for sodium and Cl for chlorine. These diagrams, called structural formulas, show how the atoms are ''hooked together''. Some simple organic molecules are represented as follows:

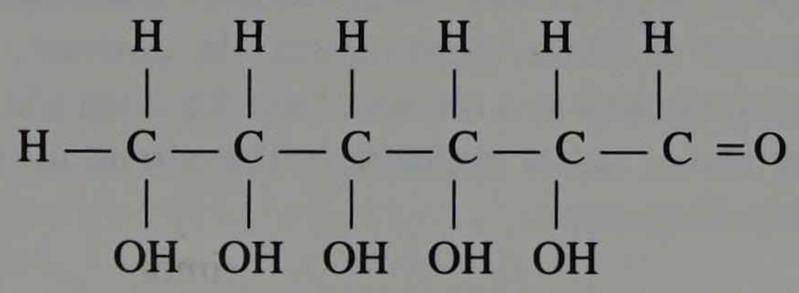


methane



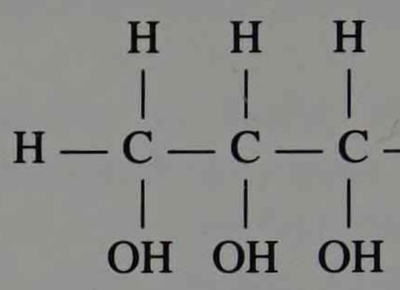
chloroform

These two compounds involve only one carbon atom each, but carbon atoms can join with other carbon atoms also. A carbohydrate, a simple sugar, looks like this:

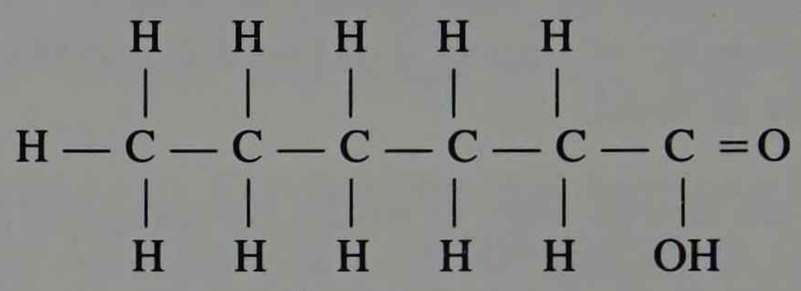


OH is the hydroxyl radical; it consists of the union of an oxygen atom, valence -2, and a hydrogen atom, valence $+1$. Thus the hydroxyl radical, taken as a unit, has a valence of -1. The double line connecting the O to the C indicates oxygen's valence of -2. A simple sugar, then, is a chain of six carbon atoms combined with hydrogen atoms, hydroxyl radicals, and an oxygen. More complex carbohydrates are formed by linking together simple sugar molecules.

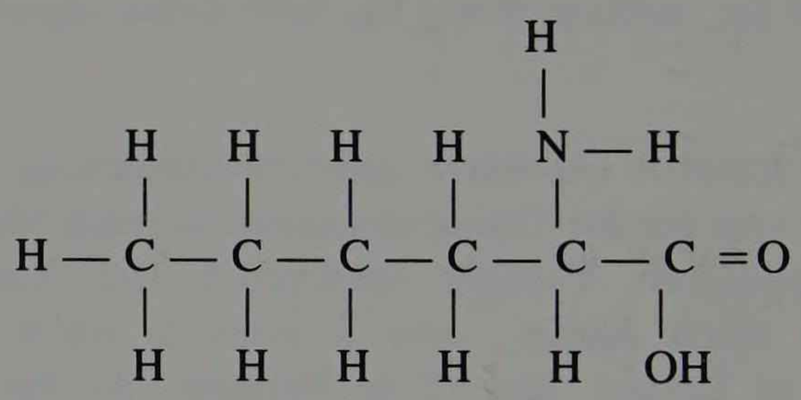
A glycerine molecule is similar, but starts with a chain of three carbons and contains no oxygen:



Simple fatty acids are structured like this:



and simple amino acids are structured:



N stands for nitrogen, and the combination of N and two H is an amino group. The combination of a C, an O, and a hydroxyl is a carboxyl group. Complex fats and proteins are made of these simpler molecules linked together into long chains.

The significance of this discussion is that all life on Earth, all life that we know about, is composed of these organic molecules. Every plant, every animal that has ever been studied, from simple bacteria to complex human beings, all are made of carbohydrates, fats, and proteins. There is, of course, a limit to the length of a molecular chain that can be constructed in this way. Temperature is a factor. In the optimum environment provided by typical Earth temperatures, some organic molecules consist of hundreds of atoms.

Organic molecules are easily manufactured. At the University of Chicago in the early 1950s, Harold Urey, a recipient of the Nobel Prize in Chemistry, and Stanley Miller, a graduate student, mixed together methane (natural gas), ammonia, water vapor, and hydrogen, and ran an electric spark through the chamber. After several days, a brown coating of amino acids and other organic compounds

was found on the inside. The experiment is easy to perform; it is now done in undergraduate biology labs. But the conditions they created are also found commonly in natural environments. The gas mixture is thought to be similar to the original atmosphere of the Earth. Similar atmospheres are found on Jupiter, Saturn, and Titan. Electric sparks, lightning, were observed by Voyager as it passed by Jupiter. Further, the experiment succeeds if ultraviolet light is used instead of electric sparks, and ultraviolet is found in both sunlight and starlight.

Organic molecules were discovered in interstellar dust clouds by radio telescopes and have been found in meteorites. Although these organic molecules are not from living things, they do show that organic chemistry takes place in other parts of the Galaxy as well as on Earth, and they support the idea that if life exists elsewhere, its chemistry is most likely carbon based.

The presence of organic molecules on a planet does not necessarily mean that living organisms are present, however. The step from molecules to a living organism is a giant one, not at all well understood and impossible to duplicate in the laboratory. Even the simplest bacteria is a marvelously complex living machine which has never been made from simpler molecules in a laboratory.

Life on Earth

Earth is certainly a beautiful place: green plants, blue oxygen-nitrogen atmosphere, colorful birds and flowers, oceans of water and ice. There is none other like it, at least not in our Solar System.

What set of circumstances allows life to flourish on Earth? Earth was not always as it is today. Its original environment was conducive to the development of primitive living things which, in turn, altered the environment of Earth. If a planet is to support life as we know it, its atmosphere must contain the elements found in organic molecules: carbon, oxygen, nitrogen, and hydrogen. Earth's original atmosphere was mostly hydrogen, methane (CH_4), sulfur oxides, ammonia (NH_3), and water vapor—gases which were expelled from the interior of the planet through volcanic vents. The essential elements were there, but they needed to be ordered and combined into the stuff of life. There was little or no free oxygen. That came much later, as a waste product from the first organisms living on Earth. In fact, free oxygen would have been lethal to early life forms.

The importance of liquid water to life as we understand it cannot be overemphasized. In a liquid, molecules are mobile and can meet and join together into cells, and cells can join together into colonies. Equally important, water absorbs ultraviolet radiation which can disintegrate organic molecules. Earth's oceans provide protection from solar UV allowing complex molecules to form and remain stable. The early atmosphere, without oxygen, afforded no such protection. Later when oxygen molecules were released into the atmosphere, they were split into atoms by the UV, and then recombined into the three-atom-molecules of ozone. Ozone is a strong absorber of UV and provides the needed shield for living things to survive out of water on dry land.

Probably the most important circumstance conducive to nurturing life was Earth's location just the proper distance from the Sun so that its temperature was just right for liquid water to exist. Recent study indicates that the zone around a star which has a satisfactory temperature may be very narrow. A little farther from the Sun, a little colder, and Earth would have been frozen in the grips of a perpetual ice age. A little closer to the Sun, a little warmer, and the water would have remained a vapor, perhaps even escaped Earth's gravity and drifted off into space.

Temperature also determines the length of a molecular chain that can be constructed from the basic sugar, fatty acid, and amino acid molecules. At typical Earth temperatures these organic molecules may consist of hundreds of atoms. At higher temperatures they simply fall apart. Pasteurizing milk or boiling water destroys bacteria because the heat breaks up their molecules. Other planets may not have such an appropriate temperature.

The Drake Equation

Frank Drake of Cornell University has been asking questions about life in the universe since the 1950s. At one point he organized his thinking by setting the unknowns into an equation to calculate the number of advanced civilizations in our Milky Way Galaxy that would be capable of communicating with us. The equation and some estimated answers to the question are shown in MATHBOX 13.1. Let us examine the ideas Drake incorporated into his equation.

Many astronomers think that the creation of planets and moons always accompanies the birth of a star, that they all form simultaneously out of the same cloud of dust and gas. Since there are about 100 billion stars in our Galaxy, there may be that many planetary systems. It seems like there should be many places for living creatures to thrive, but other factors interfere. About half the stars have companions, two or three more stars in orbit around a common center of mass. Planets in such star systems would undergo extremes of temperatures as they moved around in the star group. About a quarter of the stars are very old, born when the Galaxy was just forming out of the primordial hydrogen. They could have no planets because no heavy elements existed at that time for the creation of planets. That still leaves 25 billion candidate stars to consider.

On Earth simple forms of life date back about 3 billion years. It has taken that long for life forms to evolve to their present state of intelligence. At 5.5 billion years of age, our

MATHBOX 13.1

The Drake Equation

Drake's equation calculates N, the number of advanced civilizations now existing in our Galaxy which would be capable of transmitting and receiving radio signals.

$$N = R * P * E * L * I * C * T$$

R is the number of stars formed per year in the Galaxy. There are about 100 billion stars in the Galaxy. Therefore, since the Galaxy is about 10 billion years old, the average rate of production of stars during the lifetime of the Galaxy would be about 10 per year. They may not be forming at that rate now, however.

P is the fraction of stars that have planets. If all stars have planets, then P equals 1.0; if one in ten have planets, P is 0.1.

E is the number of planets per star that have suitable conditions to support life. Judging from our Solar System, the only one we know anything about, E could be about five.

L is the fraction of those planets on which life actually does develop. L equals 1.0 if life develops inevitably in any suitable environment. If life is a very fragile and unlikely occurrence, then L would be very small.

I is the fraction of those life forms that develop intelligence.

C is the fraction of intelligent species which become technically developed and discover radio communications; and

T is the time in years that a technically developed civilization manages to survive.

Values for these last three factors are even more speculative. Any numbers could be used depending on your viewpoint. There is no scientific basis or experience for making a choice.

To find how many advanced civilizations exist in the Galaxy, multiply all these factors together.

Let us, then, use the following optimistic values: R = 10; P = 1; E = 5; L = 1; I = 0.1 (1 in 10); C = 1; and T = 5,000 years. Multiplying these together gives N = 25,000. Twenty-five thousand intelligent civilizations! But if we take more conservative numbers of, say, L = 0.1 (1 in 10), C = 0.2 (1 in 5) and T = 100 years, then N is only 1: us.

To consider the possibility of any type of life, intelligent or not, including bacteria, algae, or other primitive forms, then we omit I and C from the equation. T becomes the time that any kind of life form manages to survive. On Earth, simple forms of life date back about 3 billion years. Using the conservative numbers from the previous example and 3 billion years for T gives an N of 15 billion places where life now exists in the galaxy.

The value of Drake's equation lies not so much in the answer you get for N; you can get any result you want depending on your point of view. The importance of the equation is that it provides a starting point for considering the factors involved in the search for life in the universe.

Sun is about halfway through its lifetime. But many stars burn at a furious rate and live only a few million years. Life may not have sufficient time to develop on their planets.

Our Solar System has nine planets and about 50 moons. Most of these objects are too cold, too hot, too small, or too something else to support living organisms. We know life exists only on one, our Earth. Other environments, however, may be hospitable to primitive life forms: Mars, Titan, the seas of Europa, or the atmosphere of Jupiter. Some scientists believe that given a suitable environment, it is inevitable that life will develop. Others believe life to be a very fragile and unlikely occurrence.

No one knows how intelligence arises. However, in our Solar System, only Earth has the proper environment for supporting life forms of sufficient complexity to be called intelligent. Presumably, if a species is intelligent, it will discover the natural laws of the universe and become technologically capable. However, a species could be intelligent and yet not be able to build radio transmitters. We consider dolphins intelligent and attempt to communicate with them, but they could not communicate across interstellar space.

How long an intelligent species can survive is the next question. Humans have survived plague, pestilence, climate changes, and probably meteoroid impacts. Can we survive our own technology in the form of nuclear weapons, environmental destruction, and pollution? Perhaps technical civilizations promptly destroy themselves within a hundred years or so after discovering nuclear power. But perhaps those species that develop technologically are also smart enough to figure out how to survive for millions of years.

Scientists are strongly divided on the question. Some would say that we humans are indeed the only intelligent beings in the Galaxy. Others believe that life is a natural part of the physics and chemistry of the universe and that the Galaxy must be teeming with life. If we search and find another advanced civilization, it will be perhaps the most important discovery ever made. On the other hand, if we come to the realization that we are alone, that too will be a most profound conclusion.

The search for life thus far has taken several forms: on-site experiments on Mars, transmitting a radio message, sending videodisks on spacecraft, and listening for intelligent radio signals.

The Mars Experiments

Influenced by Percival Lowell's observations of Mars at the beginning of this century, many people were convinced that Martians truly lived. Notions of what a Martian would look like led to many descriptions and drawings. If Mars had low gravity then its inhabitants would probably have long, spindly legs. A thin atmosphere meant large lung capacity. Sound would not propagate well in a thin atmosphere so large ears were needed. And because the planet was so dry, a long nose was needed to filter out the dust.

In 1976, two Viking spacecraft carried robot laboratories to the surface of Mars to search for something that could be considered alive. They landed during the northern hemisphere summer, one at 23° north latitude, the other at 48° north, on opposite sides of the planet. A mechanical arm (Figure 13.1) scooped up Martian soil (Figure 13.2) and did various tests to see if it contained living organisms.

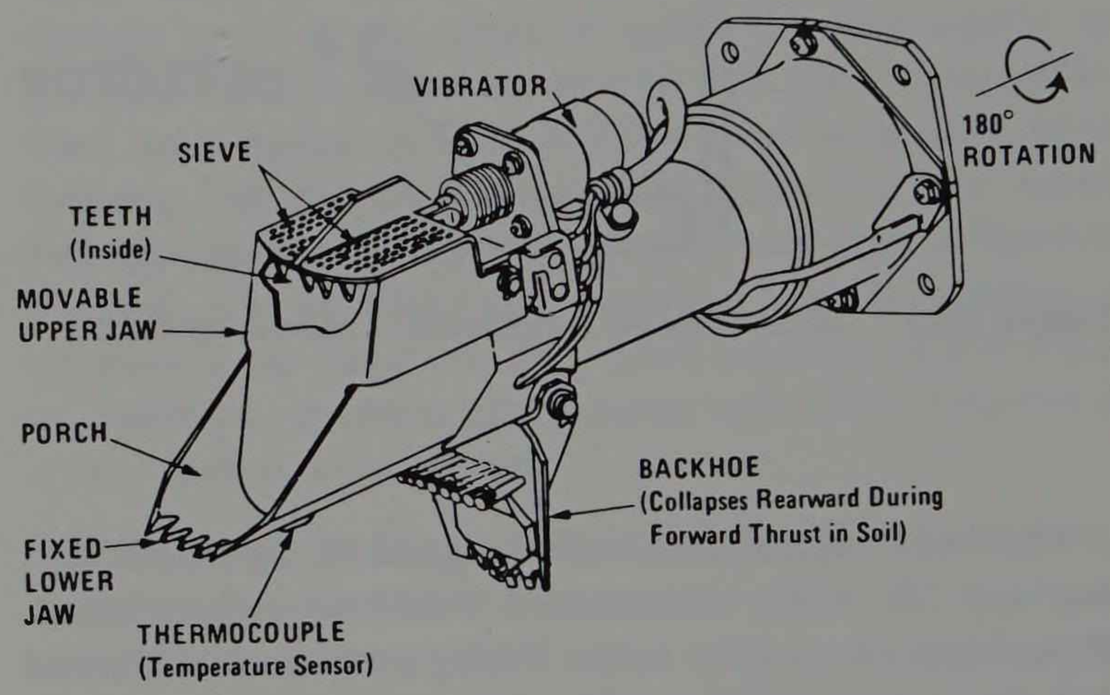


Figure 13.1 Viking scoop for sampling Martian soil. The upper jaw opens and the scoop, on the end of a mechanical arm, digs into the soil. With the upper jaw closed, the scoop is moved to the instrument, rotated upside down, and soil is sifted into the instrument's intake. A backhoe on the bottom enables the scoop to dig deeper into the soil. *Courtesy of NASA.*

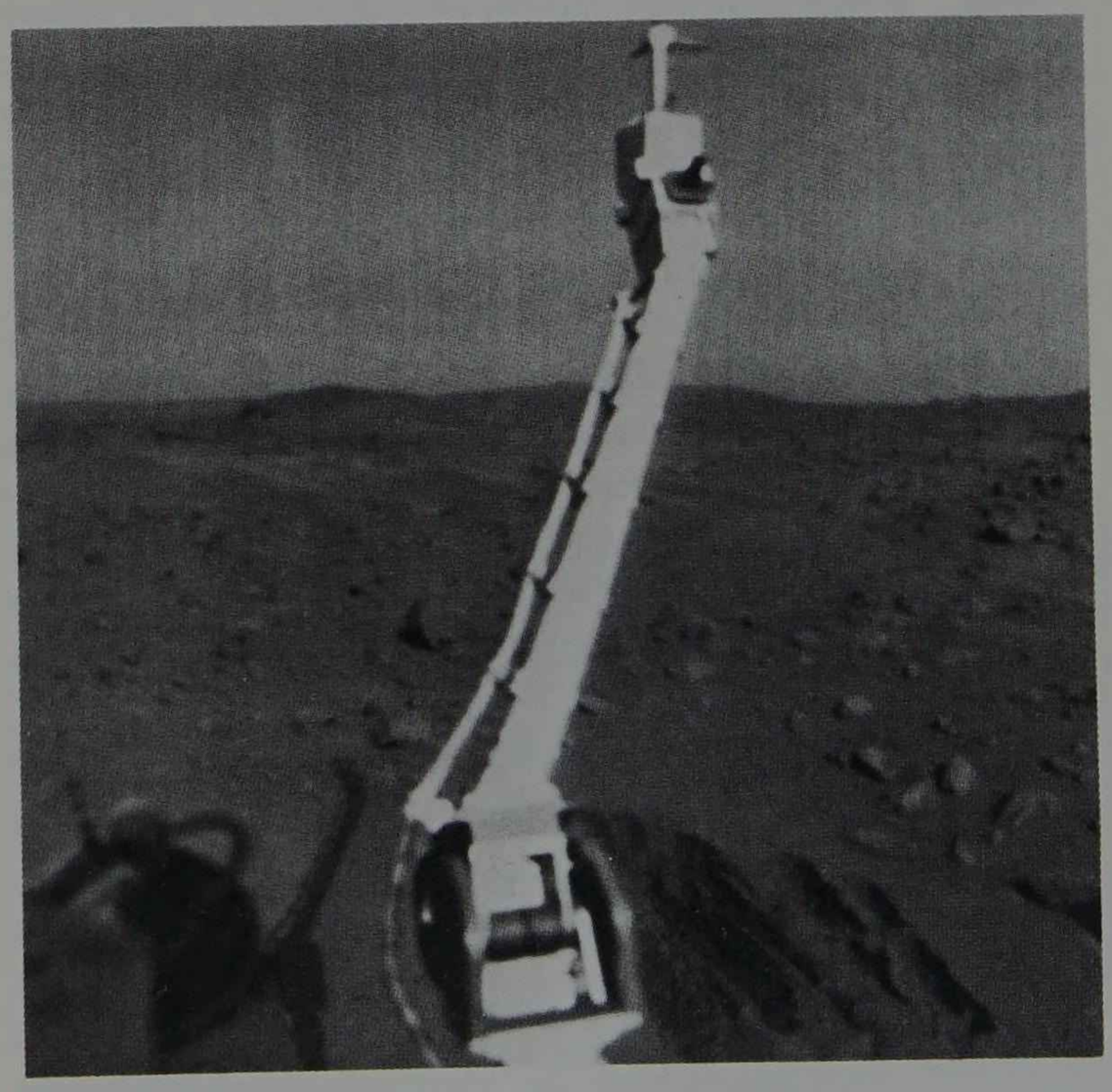


Figure 13.2 Trenches dug into the Martian soil. The boom at the center holds weather-observing sensors. Trenches to the right of the boom are up to 12 inches deep. The boom's shadow can be seen just to the left. *Courtesy of NASA.*

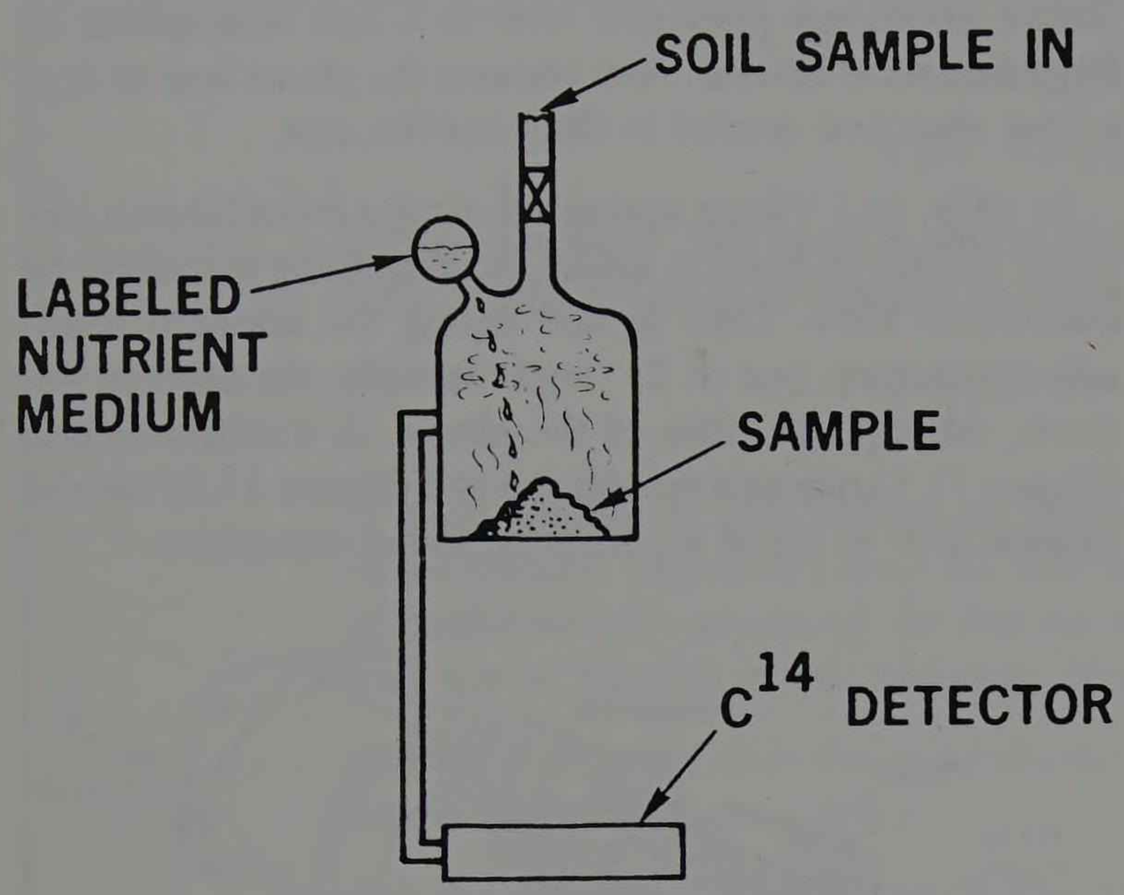


Figure 13.3 Labeled release experiment. *Courtesy of NASA.*

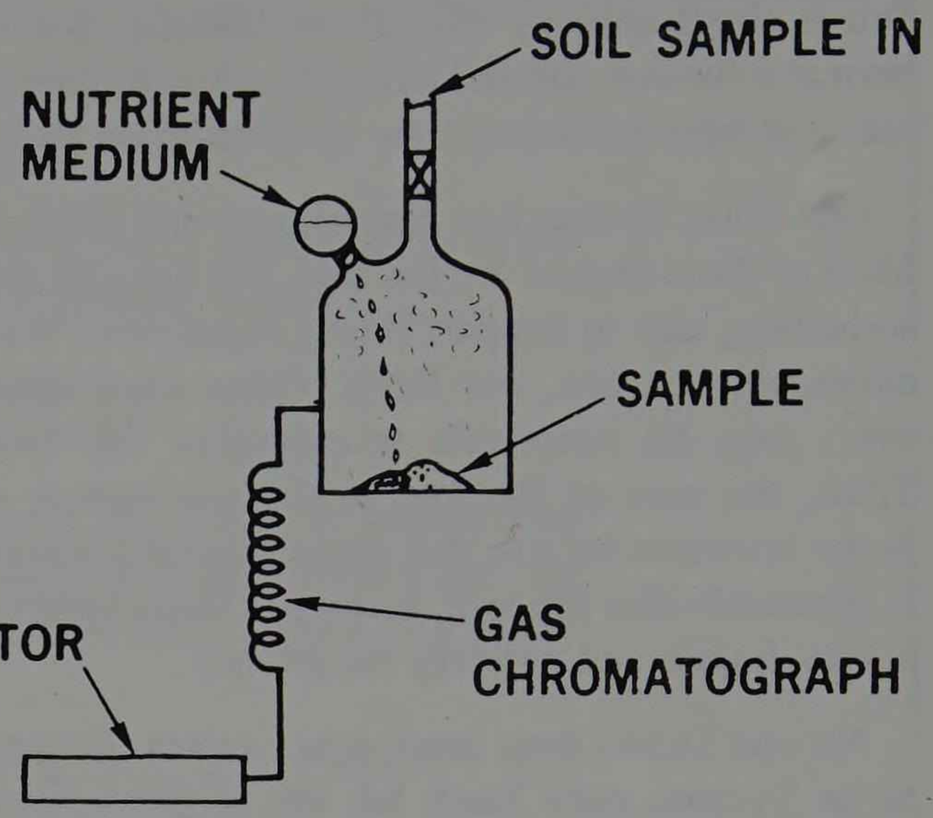


Figure 13.4 Gas exchange experiment. *Courtesy of NASA.*

The Mars experiments were designed on the assumption that any life forms encountered would be carbon based. Experiments done prior to the Viking missions had showed that organic chemistry could take place in Martian conditions simulated in Earth laboratories. Reactions were observed, some of them almost violent reactions, but the results were ambiguous, inconclusive, and could be explained as simple chemical reactions.

In the *labeled release experiment* (Figure 13.3) a nutrient "soup" which contained radioactive carbon-14 was mixed with Martian soil. The idea was that if living organisms were in the soil they would eat the soup and exhale or excrete gases made up of molecules which included the carbon-14. Sensors would then look for the radioactive carbon. A large quantity of carbon-14, more than expected, was released. The problem was that the reaction rose to a high level almost immediately, then stopped and did not start again when more soup was added. If the gases were biologically produced, they should have continued to increase as the organisms metabolized, grew, and reproduced. The observed results seemed to indicate that the reaction was chemical rather than biological. Something in the soil with a high oxygen content, perhaps a peroxide, fizzed and bubbled up when the soup was added. Whatever produced the reaction was used up at the first introduction of the moist nutrient and therefore when more was added, nothing happened. To be sure that any positive result was not simply a chemical reaction, other samples of soil were used as controls. They were first heated to temperatures up to 320 °F, then mixed with the soup, and the results were compared with the unheated soil. The heated samples showed less activity, indicating that the reaction may be biological. Heat destroys microorganisms so heated samples would show less action.

The second experiment, the *gas exchange experiment* (Figure 13.4), looked for signs of respiration. The chamber was filled with an inert gas that does not react chemically or biologically, then the soil and nutrient were introduced. If anything was exhaling carbon dioxide, nitrogen, oxygen, or other gases, it could be detected. At first, only a small amount of nutrient was injected into the chamber just to increase the humidity without saturating the soil. Carbon dioxide and oxygen were released immediately and rapidly, then ceased abruptly. Martian soil is probably full of carbon dioxide absorbed from the atmosphere and the moisture drove it out in this experiment. The production of oxygen is more difficult to understand, but was probably a chemical reaction like that seen in the labeled release experiment. Later, enough nutrient was added to saturate the soil and the mixture was allowed to incubate for nearly seven months. Frequent measurements were made, but nothing further of significance happened.

The *pyrolytic release experiment* (Figure 13.5) searched for photosynthesis, the biological activity of Earth plants. Soil was sealed in a chamber along with a simulated Martian atmosphere of carbon dioxide and carbon monoxide that contained carbon-14. Artificial light illuminated the chamber for five days. The gas was then removed and the soil sample was baked at high temperature to break any organic molecules that formed. If the radioactive gas had been consumed, the molecule fragments released by the baking would contain carbon-14. Some was detected in the experiment, but it may have been simply absorbed by the soil rather than metabolized by living organisms.

The Viking television pictures were, of course, examined in minute detail for any sign of life. Although the desert landscape would have been a perfect backdrop for a camel or a prospector with his mule, no hint of life, large or small, was seen (unless Martians are shaped like rocks and sit very quietly).

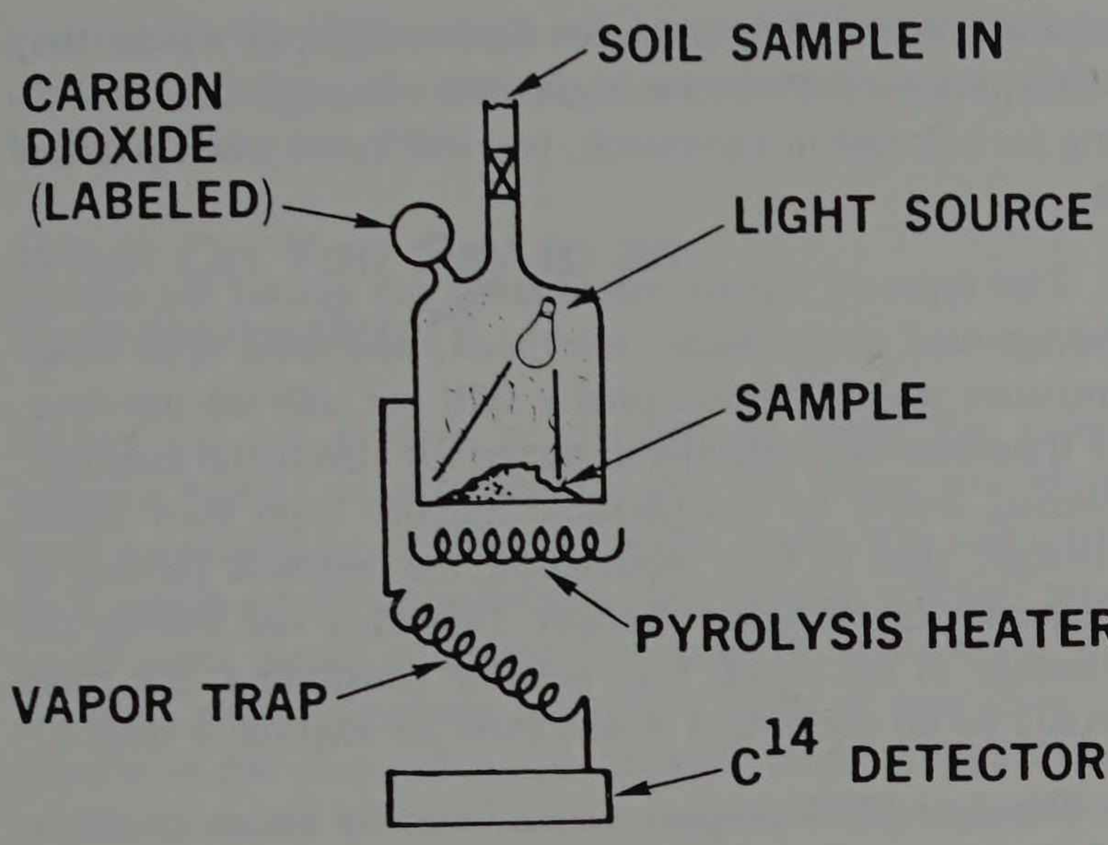


Figure 13.5 Pyrolytic release experiment. *Courtesy of NASA.*

Also, a mass spectrometer analyzed soil samples to determine what molecules were present. Absolutely no organic molecules were found at either site. The apparatus was sensitive enough to detect organic molecules in concentrations as low as a few parts per billion. It was thought that the apparatus would detect at least a few organic molecules, some from meteoroids if nothing else. It is now thought that, because of the thin atmosphere, the solar ultraviolet waves reach the ground with enough intensity to destroy all exposed organic molecules.

In summary, the experiments all showed some very different chemical reactions taking place, different from any observed on Earth or with lunar soil, but none could definitely be associated with biological activity. This does not say that there is nothing living on Mars; it only says that there was no firm indication in the results at these two locations. There may be more favorable environments elsewhere, perhaps in deep canyons, at the polar caps, or deep in the soil. Scientists designed the experiments based on what they knew about life on Earth. Perhaps there are living organisms on Mars, but they just didn't like the soup we sent. Their metabolism may be quite different from Earth organisms. Possibly there was once life on Mars, but it became completely extinct as the atmosphere dwindled, water dried up, and the climate changed. Our first crew to land on Mars should include a paleontologist to search for fossils!

Search for Extraterrestrial Intelligence (SETI)

To look for living organisms in general, we must either go there and look, or we must infer their presence from their biological activity, or their organic chemistry. But to search for intelligent creatures, we have alternate methods. An advanced civilization will almost certainly discover the electromagnetic spectrum and the ways to produce electromagnetic waves: light, radio, infrared, and so on. In doing so, they give themselves away. The waves, travelling at the speed of light, spread throughout the Galaxy to be intercepted by anyone with a sensitive enough detector and the patience to search carefully and thoroughly.

Earthlings have been generating radio waves since the early 1900s, radar pulses since World War II, and television since the 1940s. The earliest radio broadcasts were weak and did not penetrate the ionosphere into space. However, for at least 60 years those broadcasts have been travelling through space at the speed of light. The first signals to penetrate the ionosphere are now 60 light years from Earth. They have passed at least 3,000 stars. Has anyone been listening out there? Does anyone know we are here? Perhaps someone on a planet 60 light years from us has just received one of those old programs and is sending a response in our direction. Sixty years from now it will reach us. Two way communications across interstellar distances is a very slow process indeed.

But perhaps there are civilizations that have been transmitting radio waves for a longer time. If we do receive a transmission from a planet, say, a thousand light years away, they certainly will not be as backward as we are. Their message would have originated while we were still in the Dark Ages. In those intervening thousand years they may have progressed to something beyond radio or television, something we have not yet discovered and cannot imagine. Maybe they are no longer listening.

It would seem easy enough to conduct a search of the heavens for intelligent signals, but it is not as simple as it first appears. Where do we point our antenna? Where do we tune the dial? What kind of signal do we look for? The electromagnetic spectrum is a gigantic place. For example, the FM radio band (Figure 13.6) covers 20 megahertz, from 88 to 108 megahertz on the dial. (A *hertz* is one oscillation per second, and *mega* means million.) There are 20 million individual frequencies in the FM band alone. Each televi-

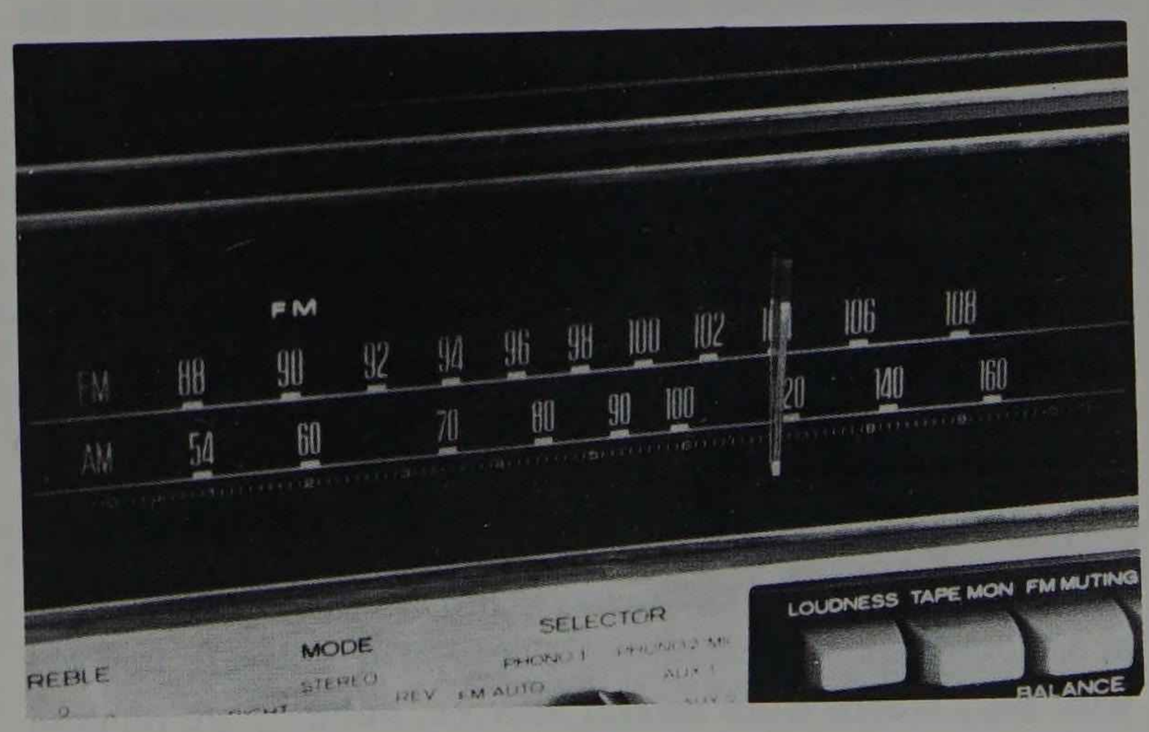


Figure 13.6 FM radio band from 88 to 108 megahertz. The AM radio band is between 540 and 1600 kilohertz.

sion channel has a bandwidth of 6 million hertz and there are 82 such channels in the television bands. In addition there are the police, fire, and emergency bands, the satellite communication bands, and the microwave bands. There are a total of 100 billion frequencies in the entire radio band. So, where do we begin?

We certainly do not want to start in the FM radio band. It would be difficult to pick up an extraterrestrial through the rock music. The television bands are out, too, for a similar reason. However, a number of frequency bands have been set aside as quiet bands by international agreement in which no human transmissions are made. They are used primarily by radio astronomers for scientific research. Their selection has been somewhat arbitrary, but one in particular is at the natural resonant frequency of the hydrogen atom, near 1,420 megahertz, a frequency used by radio telescopes to locate clouds of hydrogen gas in interstellar space. If intelligent extraterrestrials think like human scientists, they may think of the hydrogen resonance frequency as an interstellar hailing frequency. Radio astronomers everywhere would have sensitive equipment tuned to that band. If they wanted to make contact with other radio astronomers, it would be logical to transmit a signal on or near that frequency. But, perhaps those far superior extraterrestrials, if they exist, tried that thousands of years ago and gave up. Nonetheless, the hydrogen frequency appears to be a good place to start a search.

In fact, the entire microwave band from 1,000 megahertz to 10,000 megahertz is a good place to begin searching. In that frequency range cosmic background noise is low and Earth's atmosphere is most transparent. But, there are 9,000 million frequencies to examine in that band! We have narrowed the problem from 100 billion to 9 billion, still a sizeable problem.

Where do we look? There are at least 100 billion stars in our galaxy. How do we choose? Young stars may be a poor choice because it takes millions, perhaps billions of years for advanced life forms to evolve. Old stars from the origin of the universe would also be a poor choice because in the beginning the universe consisted of only hydrogen and helium. There were no heavy elements such as oxygen, nitrogen, iron, silicon, and all the others from which a planet could form. Best choice seems to be sun-like stars at the middle or toward the end of their life cycle. Even so, we cannot be sure which stars have planets. Even with careful observations, no planets around other stars have ever been confirmed.

What kind of signal do we look for? In Chapter 6, we noted that electromagnetic waves are emitted by everything at a temperature above absolute zero. The universe is filled with such waves from natural sources, but they are random and without pattern, like the "sizzling" noise you hear as you tune the FM radio between stations. If an extraterrestrial intelligent being produces electromagnetic waves, they will contain a pattern, a recognizable message. Like searching for a needle in a haystack, you will know when you find it.

Two types of signals would stand out against the cosmic background noise: radio, television, and radar type transmissions which unintentionally spill out into the universe, or transmissions specially designed for interstellar contacts. Signals would be recognizable initially from their signal strength, then by their modulation, the rhythmic shifting of frequency or changing strength. Decoding and finding the message in the signal may be time consuming, but there would be no doubt that it was from an intelligent source.

The first SETI project, Ozma, was by Frank Drake in 1960 using an 85-foot dish antenna at Green Bank, West Virginia. Drake spent 400 hours looking at two nearby sun-type stars in a 400,000 hertz band around 1,420 megahertz. Receiving equipment was not automated, so it was a tedious task to scan the possible frequencies.

Since then there have been over 30 attempts, some for only a few hours and some continuing year after year. The Soviets and a half dozen other countries have made serious efforts.

The most comprehensive SETI survey was begun in 1986 by Paul Horowitz of Harvard University. He had built a computerized receiver-signal processor which listens to 128,000 frequencies simultaneously and tested it at Arecibo in 1982, probing 250 stars in only 75 hours. The equipment was so successful that Peterson and Chen of Stanford University designed a signal analyzer that can handle 8.4 million channels at the same time. The search continues using the new analyzer and an 84-foot dish antenna in Massachusetts. The antenna is set at a specified height above the horizon and as the Earth rotates it scans a half-degree wide band around the sky. Next day the antenna is shifted upward slightly and allowed to scan another overlapping half-degree band in the next 24 hours. In seven months the northern hemisphere sky is scanned from horizon to pole.

Even with automated equipment and computerized analyzers the SETI investigators require years to scan the entire sky at all the desired frequencies. In the first 18 months the equipment processed 15,000 billion numbers. It automatically discarded all but about a million per month which needed further examination. These fell into four categories: noise, earthly radio interference, equipment malfunction, and others. Only three signals looked promising but, on searching that area of the sky many times over, the signals were not seen again.

Horowitz's search is sponsored by The Planetary Society and funded with private donations, including $100,000 from Stephen Spielberg. NASA also has a SETI program

planned for the 1990s which will use a 100-foot antenna to scan the entire sky at a number of wavelengths and to study individual sun-like stars.

What Do You Say to an Extraterrestrial?

During the last century people had no doubt that other celestial bodies were inhabited, that the Moon and Mars were populated by intelligent beings. Radio was unknown as a means of communications, but several scholars proposed other means of letting the extraterrestrials know we are here. Once suggested planting a forest of pine trees in Siberia in the shape of a right triangle large enough to be visible from the Moon. Another suggested draping a black cloth over a large white surface of Earth and moving it back and forth. From Mars it would seem to blink. Yet another said to dig a 20 mile wide trench in some geometric shape across a desert, fill it with kerosene, and ignite it.

Now radio is the obvious means of communication. But, what should we say? They would not understand any Earth language, may not have ten fingers on which to base a decimal counting system, and probably have a completely different biology. But, an advanced civilization would have one language in common with us. Mathematics and the sciences of chemistry, physics, and astronomy are universal.

A message intended to initiate communications with another world would be designed specifically so it could be easily decoded. A simple message might consist of the first ten *prime numbers*, 1, 2, 3, 5, 7, 11, 13, 17, 19, 23, transmitted in sequence using on-off pulses: one pulse, pause, two pulses, pause, three pulses, pause, *etc.*, to the

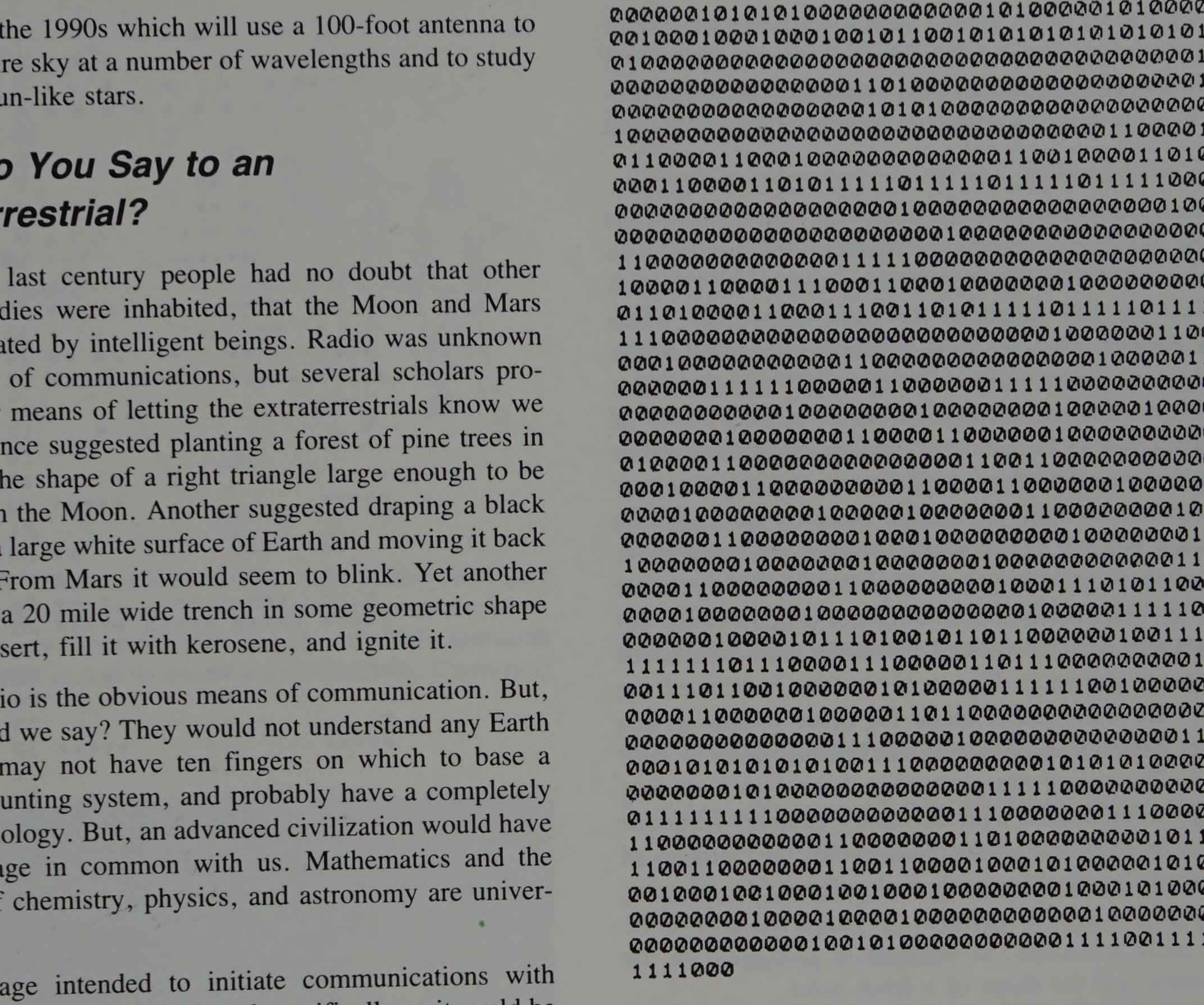


Figure 13.7 The Arecibo message.

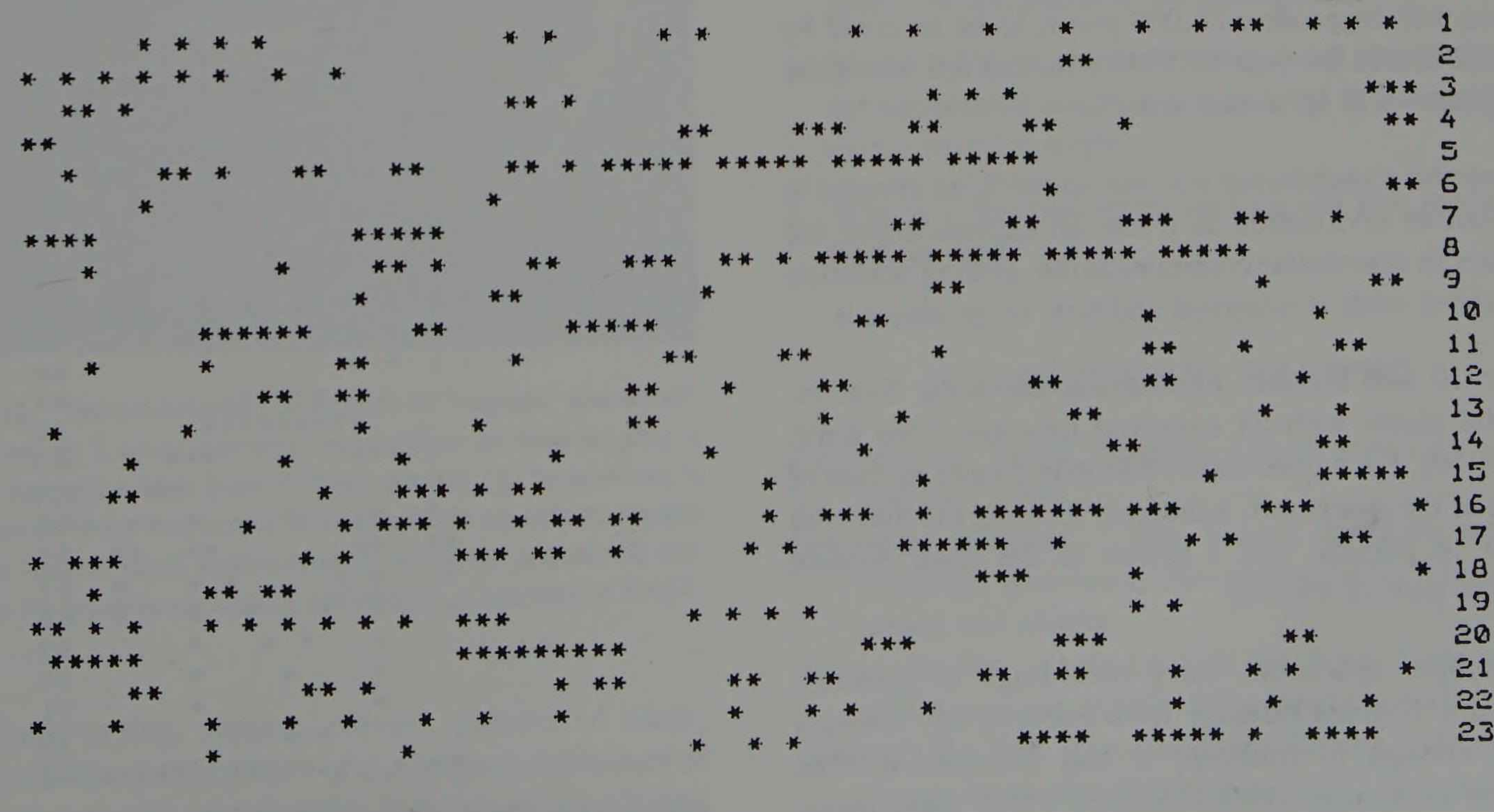


Figure 13.8 The Arecibo message incorrectly decoded.

end, long pause, begin again. Such a sequence would not occur randomly in a natural radio noise source, and would be immediately recognized by an extraterrestrial mathematician. It could serve as a beacon, in effect saying "We are here."

A much more complex message was transmitted from the radio telescope antenna at Arecibo, Puerto Rico, in November 1974. The antenna is hung over a bowl-shaped valley in the hill country, far from man-made noise sources. Shown in Figure 12.6, it has an area of 20 acres, more than all other radio telescopes put together. The message consisted of a series of on-off pulses, 1,679 of them, displayed in Figure 13.7, which, when arranged in the proper pattern, produces a picture. A smart extraterrestrial would know how to arrange them by noticing that 1,679 is the product of two prime numbers, 23 times 73. If they are arranged in 23 rows of 73 pulses each, they do not produce anything of obvious intelligence (Figure 13.8), but ordering them into 73 rows of 23 pulses each creates the pictogram as shown in Figure 13.9. (We have used the symbol * for ones and a blank for zeros so the pattern shows up more clearly.) Notice the human figure at lines 46 to 55. The top of the pictogram, lines 1 to 4 reading from right to left, starts with the binary numbers from one to ten, followed by the atomic numbers for the elements of life and formulas for the organic molecules of life, all using binary numbers. At the bottom is the shape and size of the Arecibo radio telescope. In between is a diagram of the Solar System and the shape of a DNA helix.

This message was transmitted toward M13, a great globular cluster of about half a million stars in the constellation Hercules some 24,000 light years away. If beings are intelligent enough to pick up the message, they may be intelligent enough to decode it. If they send an answer back, travel time will be another 24,000 years, to be received by our descendents in the year 49,974! Who can tell where the human species will be at that time.

The Arecibo transmission was not so much an attempt to contact another civilization as it was an exploration of the possibilities in interstellar communication, getting scientists to think about what is involved and how to go about it.

Pioneer 10 and Pioneer 11, leaving the Solar System, carry metal plates with an engraved message from Earth (Figure 13.10). Each plate shows a human couple in front of an outline of the spacecraft, a diagram locating the Sun with respect to 14 pulsars, and a sketch of the Solar System showing the path of Pioneer.

The Voyager spacecraft carry recordings of pictures, voices, and a diagram message from Earth to any creature intelligent enough to intercept it and translate it. The recording is something like a videodisc which plays music (Bach, Beethoven, Chuck Berry, primitive drums), sounds

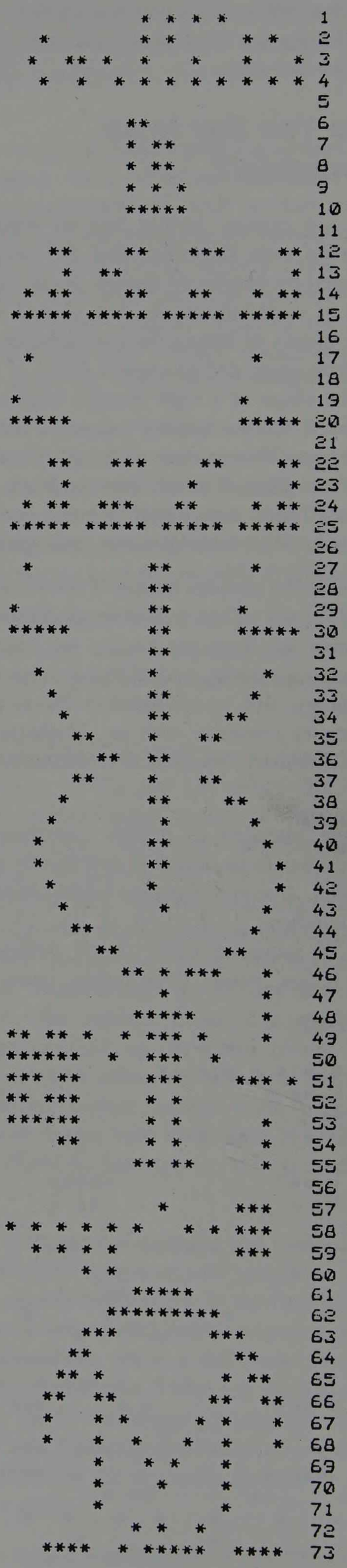


Figure 13.9 The Arecibo message correctly decoded.

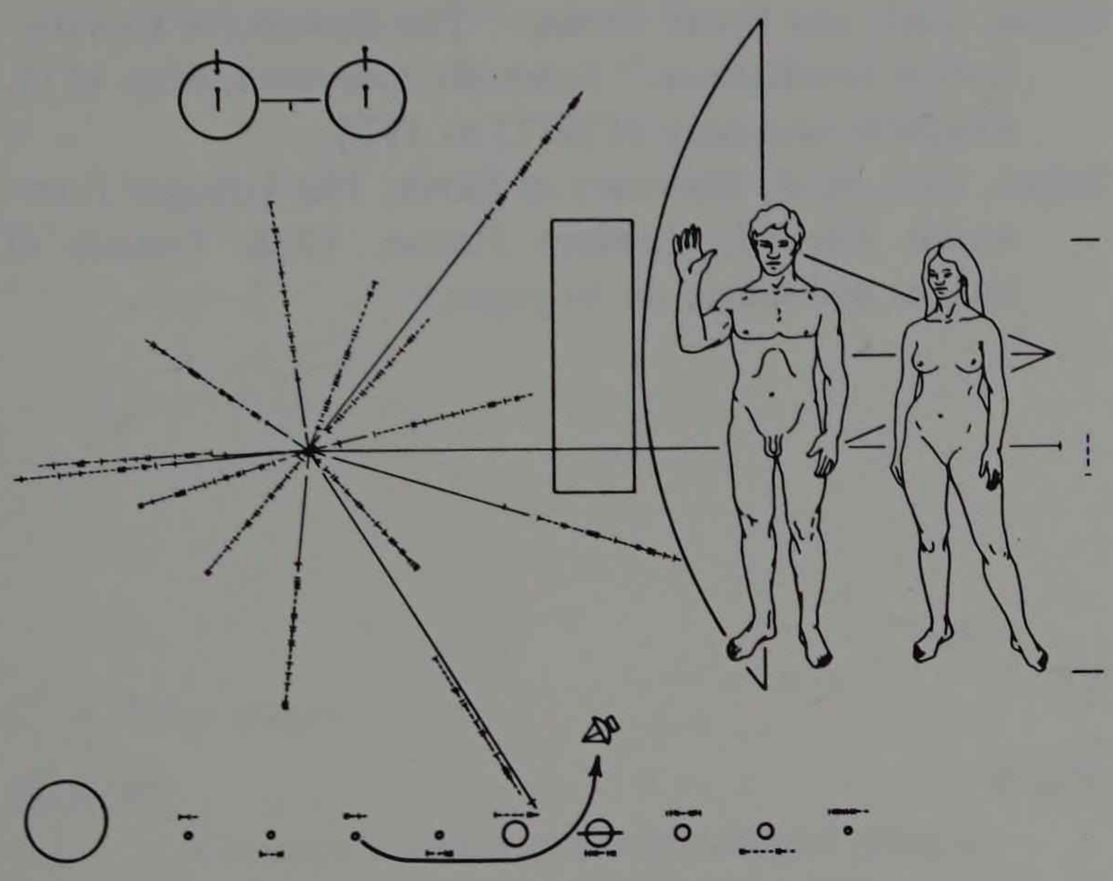


Figure 13.10 Plaque carried out of the Solar System on Pioneer 10 and 11 spacecraft. Short vertical lines and dashes are binary numbers. An extraterrestrial smart enough to catch the spacecraft should be smart enough to understand the numbers. *Courtesy of NASA.*

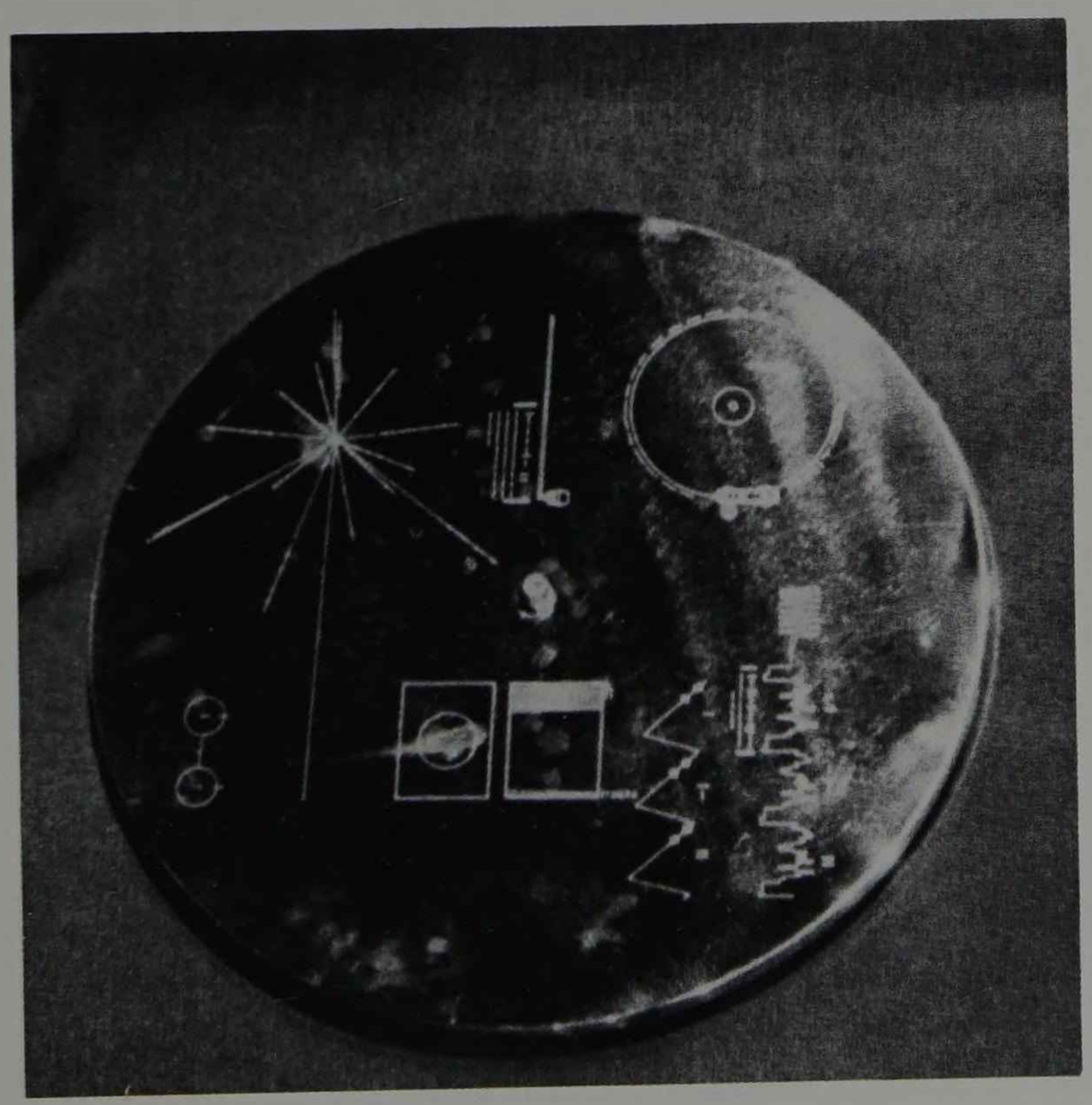


Figure 13.11 Record attached to outside of Voyager spacecraft. It is protected by a cover carrying instructions on how to play it along with the pulsar map from Pioneer 10 and 11. In addition, a small sample of pure uranium-238 is attached; an extraterrestrial will be able to determine approximately when the spacecraft was launched using radiometric dating techniques. *Courtesy of NASA.*

of Earth (baby crying, singing, waves), pictures of Earth, and for international acceptance of the project, the names of leaders of all countries of the world. Instructions for playing the record are on the cover (Figure 13.11) along with diagrams similar to those on Pioneer. If extraterrestrial space travelers catch Voyager and figure out how to make it run, their first response back to Earth will probably be, "Send more Bach!"

The final question: if we do get a message from a highly advanced extraterrestrial civilization, should we respond? If they are like us, but further advanced with the capability for interstellar travel, maybe it would be unwise to let them know of our presence. Human beings have spread over the entire Earth, the stronger oppressing the weaker as they migrated. Would the extraterrestrials have the same goal? If their population is growing exponentially, if they seek greener pastures, if their motivation is simply to conquer, then perhaps we should keep to ourselves. Perhaps they already know we are here, but do not want to have anything to do with us. More likely, if their society has survived technological advancement without self destruction, then they have probably learned to be peaceful and benevolent. We would learn much from such a society.

DISCUSSION QUESTIONS

1. What effect would the discovery of intelligent life elsewhere in the universe have on human society?
2. If intelligent beings were found on some other planet, in what ways would they be like humans? In what ways would they be different?
3. If we find anything living on Mars should we terraform the planet, even if it means death to the native organisms? What if the native life is only bacteria-like?
4. Make up a message to send to extraterrestrials different than the Pioneer, Voyager, and Arecibo messages. Be sure it is decipherable by nonhumans.
5. Watch a TV program with the sound turned down as an extraterrestrial might see it and try to interpret it as an extraterrestrial might.
6. Why is it true that when we look out into space we look back in time?

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Glossary

ABM Antiballistic missile, as in ABM weapon or ABM Treaty.

acceleration A change in velocity; a change in either the speed or direction of a moving object.

aerobraking A maneuver in which a spacecraft accomplishes an orbital change by dropping into the upper atmosphere of a planet to reduce its energy instead of firing retrorockets.

airlock An airtight chamber used to move between spaces of different pressure, from the Orbiter to the cargo bay, for example.

alpha particle The nucleus of a helium atom consisting of two protons and two neutrons.

amino acid One of the fundamental organic molecules which includes groups containing two atoms of hydrogen bonded to one atom of nitrogen; the structural unit of all proteins.

aphelion The point which is farthest from the Sun on an elliptical orbit around the Sun.

apogee The point which is farthest from Earth on an elliptical orbit around Earth.

apogee kick Firing rockets at apogee to decrease the eccentricity of the orbit, to make it more nearly circular.

apsides The two extreme ends of the major axis of an elliptical orbit; see also **line of apsides**.

asteroid A piece of rock, metal, or frozen gases in space, larger than a meteoroid but smaller than a planet.

atom The smallest particle of an element, composed of electrons, protons, and neutrons.

atrophy Waste away because of disuse.

attitude The orientation or position of a vehicle.

ballistic Referring to the path followed by a vehicle which is affected only by the forces of gravity and air friction.

bends See **decompression sickness.**

booster rocket A rocket used to provide large initial thrust for launch, usually dropped off after it has served its purpose.

burn Rocket engine firing.

cardiovascular deconditioning Weakening of the heart and blood vessels.

centripetal force The force required to keep an object moving in a curved path; it is directed toward the center of the curve.

chromosphere The lower atmosphere of the Sun.

circadian rhythm A natural periodicity in human activity or bodily function, such as the 24 hour sleep-wake cycle.

cislunar space Referring to the space between Earth and the Moon.

clevis A fitting with a U-shaped end.

combustion The chemical process in which a fuel oxidizes, that is, combines with oxygen, usually accompanied by heat and fire.

comet A ball of dust and frozen gas travelling in an orbit of high eccentricity arround the Sun; as it approaches the Sun, solar heat and the solar wind cause particles to evaporate, break off, and trail into space producing a visible tail.

convection The process by which heat is transferred in a fluid by the bulk motion of warmer fluid of lesser density rising in cooler surroundings of greater density.

core Referring to the Sun, the central region in which nuclear fusion is taking place.

corona The outermost part of the solar atmosphere which extends out into the Solar System past the Earth.

coronagraph A telescope designed for viewing the Sun's corona.

cosmic ray Nucleus of an atom travelling at very high speed through space. Protons coming from the Sun are called **solar cosmic rays** while heavier nuclei coming from outside the Solar System are called **galactic cosmic rays.**

cryogenic Involving very low temperatures.

decompression sickness Illness produced by a too rapid decrease in air pressure surrounding a body, causing bubbles of nitrogen in the blood to expand painfully.

dehydrate Remove the water from a substance, particularly for the preservation of food.

deorbit Fire a rocket engine to reduce the energy of a vehicle so it leaves orbit and returns to Earth.

directed energy weapon An antimissile weapon which uses an intense beam of electromagnetic energy, such as a laser beam, or of small particles, such as hydrogen

atoms, to burn through the shell of a missile or damage its electronics.

diurnal Referring to a daily occurrence.

DNA The organic molecule which is part of all living cells, containing the genetic "instructions" for the cell to reproduce.

docking Joining together two orbiting vehicles.

drag Frictional force which decelerates a vehicle, particularly atmospheric friction.

eccentricity A number which tells the elongation of an ellipse.

electromagnetic spectrum The range of wavelengths of electromagnetic waves including, in order of decreasing wavelength: radio, microwaves, infrared, light, ultraviolet, x-rays, and gamma rays.

electromagnetic waves The means of transmitting energy at the speed of light, produced by the oscillation or acceleration of electrically charged particles.

electron A small particle of matter carrying a negative electrical charge, one of the three constituent particles of an atom.

electrophoresis A process by which different materials suspended in a fluid are separated from one another by applying an electrical field.

element A basic substance consisting of only one kind of atom.

ELINT Electronic intelligence gathering.

ellipse A closed oval-shaped curve.

end effector Robotics term for a grasping device.

ephemeris A set of numbers which specify the location of a celestial body or satellite in space.

ergonomics The study of human factors in space operations.

escape velocity The velocity an object must have to escape the gravitational attraction of a planet (or other celestial body) and neither fall back nor enter an orbit around it.

ET The Space Shuttle's external tank.

EVA Extravehicular activity, working outside a spacecraft.

external tank Referring to the Space Shuttle, the propellant tank which carries liquid hydrogen and liquid oxygen for the Orbiter main engines.

filaments Referring to the Sun, dark streaks on the Sun which are actually **prominences,** masses of hot gas suspended in the atmosphere, which appear dark against the bright disk of the Sun.

flare A sudden, explosive emission of electromagnetic radiation in the solar chromosphere, sometimes accompanied by the ejection of high speed protons, called solar cosmic rays.

force A push or a pull which accelerates an object.

fossil fuels Coal, oil, and natural gas, the fuels formed from organisms which lived millions of years ago and became buried in sediments.

fuel A substance which burns in the presence of oxygen.

fuel cell A device which produces electricity by combining hydrogen and oxygen into water.

fusion A nuclear process by which smaller atomic nuclei fuse together to form larger nuclei, such as the fusion of hydrogen into helium.

g Symbol for the acceleration of gravity at the surface of the Earth.

galaxy A basic structure of the universe consisting of billions of stars, dust, and gas, held together by their mutual gravitational attraction, usually in a spherical, elliptical, or spiral shape.

gamma rays Electromagnetic waves with wavelength shorter than x-rays.

geostationary orbit See **geosynchronous orbit.**

geosynchronous orbit An orbit approximately 22,300 miles above the equator with a period of one day, the same as the rotational period of the Earth; a satellite in geosynchronous orbit appears to remain stationary in the sky as viewed from the Earth.

grain The segment of solid propellant enclosed in a rocket engine.

grapple A fixture attached to a satellite or other payload so the Space Shuttle remote manipulator arm can grasp it.

gravitation The natural force of attraction between any two objects.

Hohmann transfer Transfer orbit which requires the least amount of energy.

hydrogen-alpha (H-alpha) A particular wavelength of red light produced by glowing hydrogen gas; solar flares are readily seen by their H-alpha light.

hyperbola An open curve, not closed as an ellipse or circle.

hypergolic Referring to the spontaneous ignition of a fuel and oxidizer when they come into contact.

hypoxia Illness produced by lack of oxygen.

ICBM Intercontinental ballistic missile.

inclination Referring to an orbit, the angle between the Orbital plane and the plane of the Earth's equator measured at the point where a spacecraft crosses from the southern hemisphere to the northern hemisphere.

inertial upper stage (IUS) A rocket booster attached to a satellite carried in the cargo bay of the Space Shuttle orbiter to boost the satellite to a higher orbit. See also **payload assist module.**

infrared Electromagnetic waves with wavelengths in the range 1 to 1,000 micrometers, longer than light but shorter than radio waves.

infrastructure The basic facilities, installations, and equipment needed for an organization or a system to operate.

inhibitor A coating over the areas of a solid propellant grain which are not supposed to burn.

injector A mechanical device which forces or sprays fuel

and oxidizer into the rocket engine combustion chamber.

intelligence Referring to the military, gathering information about a potential adversary.

ion An atom or combination of atoms which carries an electrical charge due to the addition or removal of electrons.

ionize To produce an ion by adding or removing electrons from a neutral atom or combination of atoms.

ionosphere Region of a planet's atmosphere in which the atoms are ionized by solar x-ray and ultraviolet radiation.

irradiate Expose to radiation, particularly to destroy the bacteria in food to preserve it.

IUS See **inertial upper stage.**

kinetic energy The energy of a moving object.

kinetic energy weapon An antimissile weapon which fires a projectile at the missile to destroy it by collision.

Lagrangian points See **libration points.**

laser A device which produces an intense beam of electromagnetic waves of a single wavelength, most commonly light waves of a single color.

LEM See **LM.**

LEO Low Earth orbit.

libration points A location in space where the gravitational attraction of two or more celestial bodies add to zero, that is, a neutral point in the gravitational field; also called "Lagrangian point," after the mathematician who first investigated the phenomenon.

light Electromagnetic waves to which the human eye is sensitive, with wavelengths of approximately 0.5 micrometer.

light year A measure of interstellar distance; the distance light travels in a year, about 6 trillion miles.

lignin A substance produced by plants which helps give them their structural strength so they stand upright.

limb Referring to the Sun, the edge of the disk.

line of apsides Major axis of an elliptical orbit.

LM Lunar module, the part of the Apollo spacecraft that landed on the Moon.

LOX Liquid oxygen.

mach 1 The speed of sound. Similarly, **mach 2** is twice the speed of sound, and so on.

magnetosphere Region around a planet in which the planet's magnetic field is sufficiently strong to prevent or impede the solar wind particles from entering.

manned maneuvering unit Device equipped with thrusters which an astronaut in a space suit can attach to and fly freely, untethered away from the Orbiter.

mass Most simply, the amount of matter contained in an object. Mass varies with velocity, increasing significantly as it approaches the speed of light. More precisely, a measure of a body's resistance to acceleration.

mass driver An electrically powered device which accelerates projectiles to very high velocities.

MECO Main engine cutoff, referring to the Space Shuttle.

metabolism The chemical processes which take place in an organism to maintain life.

meteor Bright streak of light in the night sky produced by a meteoroid falling toward Earth and burning up from the heat of friction with the atmosphere.

meteorite A meteoroid which has survived the fall through the atmosphere and lands on the surface of the Earth.

meteoroid A piece of rock, metal, or frozen gas in space, varying in size from microscopic to asteroid size.

meter Metric unit of length equal to about a yard, 39.37 inches to be precise.

micrometeoroid A microscopically small meteoroid.

micrometer One-millionth of a meter, also called a micron.

microwaves Electromagnetic waves with wavelengths in the range 1 millimeter to 30 centimeters (1/25 inch to 1 foot).

missile An object that is fired or thrown at a target; a projectile.

MMU See **manned maneuvering unit.**

module A self-contained, standardized component of a spacecraft, space station, or habitat, designed for ease of assembly with other components.

muscular deconditioning Weakening of the muscle tissue due to lack of use while weightless.

NASA National Aeronautics and Space Administration.

neutron A small particle of matter with no electrical charge, one of the three constituent particles of an atom.

NORAD North American Aerospace Defense Command.

nozzle The exhaust duct of a rocket combustion chamber through which the combustion gases are accelerated to higher velocity.

OMS See **orbital maneuvering system.**

OMV See **orbital maneuvering vehicle.**

orbit Closed path followed by a satellite.

orbital injection Firing rocket engines to transfer a spacecraft from a ballistic trajectory into a closed orbit.

orbital maneuvering system A pair of rocket engines located in pods next to the tail of the Space Shuttle Orbiter, used for orbital insertion, changing orbit, and deorbiting.

orbital maneuvering vehicle A remotely operated spacecraft which delivers satellites from a space station to higher orbits and returns them for repair and maintenance.

orbital mechanics The science and mathematics of orbits.

Orbiter The Space Shuttle's rocket-powered aircraft and spacecraft.

organic Referring to a substance containing carbon as the basic atom of its molecular structure.

O-ring A rubberlike seal between segments of a solid rocket engine.

oxydizer A substance which provides oxygen to support the combustion of a fuel, including oxygen itself.

paleontologist A scientist who specializes in the study of fossils and ancient life forms.

PAM See **payload assist module.**

payload assist module (PAM) A solid rocket booster attached to a payload in the Shuttle Orbiter's cargo bay for the purpose of boosting the payload to a higher orbit. See also **inertial upper stage.**

perihelion The point which is closest to the Sun on an elliptical orbit around the Sun.

perigee The point which is closest to Earth on an elliptical orbit around Earth.

perigee kick Firing rockets at perigee to increase the eccentricity of the orbit.

period Referring to an orbit, the time required for a spacecraft to make one complete orbit as viewed from space.

photosphere The visible surface of the Sun.

photosynthesis The process by which plants convert carbon dioxide from the air, light from the Sun, and water from the Earth into carbohydrates with oxygen as a by-product.

photovoltaic cell A semiconductor device which converts light directly into electricity; called a solar cell when used in sunlight.

phytoplankton Tiny algae plants which float in the ocean; the basic organism of the oceanic food chain.

pitch Up and down rotational motion of the nose and tail of an aircraft or spacecraft. See also **roll** and **yaw.**

pixel Contraction of "picture element," one bit of an image.

plage On the Sun, a bright region of hot gas in the chromosphere.

plasma A gas composed of a mixture of neutral and ionized atoms.

polarimeter An instrument for measuring the polarization of light waves.

prime number A number which is evenly divisible only by itself and one.

progressive burn The burn of a solid propellent grain in which the thrust increases with time.

prominence Referring to the Sun, a cloud of hot gas in the solar atmosphere appearing bright when seen on the edge of the disk against the dark background of space, and appearing as a dark filament when seen against the bright surface of the Sun.

propellants The fuels and oxidizers burned in rocket engines to produce thrust.

proton A small particle of matter carrying a positive electrical charge, one of the three constituent particles of an atom.

proton event Referring to the Sun, an outburst of high energy protons during a flare which reach the vicinity of the Earth.

rad A unit of absorption of radiation in a living organism; 600 rads in a day would be a lethal dose for most humans.

radar A device which transmits a microwave pulse, receives the returned pulse which is reflected from an object, and calculates the distance and direction to the object.

radiation The transfer of energy from place to place by means of electromagnetic waves. Also, a somewhat ambiguous term applied to high energy waves and particles coming from the Sun, interstellar space, or radioactive substances.

radiation sickness Illness caused by exposure to large doses of radiation, in severe cases involving nausea, diarrhea, vomiting, dehydration, destruction of blood cells, and perhaps death.

ramjet A reaction engine in which only the air entering the front intake at high speed prevents exhaust gases from leaving in that direction.

RCS The Space Shuttle Orbiter's reaction control system, 44 thrusters which control its orientation in space.

reaction engine An engine that produces thrust by the directed expulsion of mass, usually hot gases.

reconnaissance Gathering images and other data about an area of interest, usually applied to military intelligence.

reentry The return of a spacecraft into the Earth's atmosphere.

refraction Bending of electromagnetic waves from a straight line path as they pass from one medium into another.

regression In orbital mechanics, the rotation of the major axis of an elliptical orbit due to variations of gravity in different parts of the parent body.

regressive burn The burn of a solid propellent grain during which the thrust decreases with time.

rehydrate Add water to a dehydrated food to prepare it for eating.

remote sensing Learning something about an object at a distance from the electromagnetic waves emitted and reflected from it.

rendezvous Come together at a specified time and place.

resolution Referring to remote sensing, the size of the smallest object that can be distinguished from its surroundings.

retrofire To fire a rocket in the direction of motion in order to reduce the energy of the orbit.

retrorocket A rocket that fires in the direction of motion.

rocket A reaction engine that carries both fuel and oxidizer so it can operate in the absence of air.

roll Rotation of an aircraft or spacecraft around the axis through the nose and tail. See also **pitch** and **yaw.**

satellite An object in orbit around a larger object. In space technology, a man-made object in orbit around Earth, usually one which has some useful purpose. Also, moons are satellites of planets; planets are satellites of the Sun.

scramjet Supersonic ram jet.

SDI Strategic Defense Initiative, the U.S. program for development of a defense against ballistic missiles.

sensor A device which responds to electromagnetic waves impinging on it, usually by producing or modifying an electrical current.

SETI Search for extraterrestrial intelligence.

signature Referring to remote sensing, the characteristic intensities of various wavelengths of electromagnetic radiation coming from an object which uniquely identify that object.

sinter Compress and fuse together by heat.

solar cell See **photovoltaic cell.**

solar wind A steady flow of particles, mostly protons and electrons, from the Sun into interplanetary space, an extension of the solar atmosphere.

solid rocket booster A booster rocket using solid propellants.

space adaptation syndrome Illness similar to seasickness, experienced by many astronauts during the first day or two of weightlessness.

spacecraft Any vehicle designed to operate in space. An unmanned spacecraft in a closed orbit around Earth is usually called a satellite.

Space Shuttle A four part, mostly reuseable vehicle consisting of an Orbiter-spacecraft-aircraft, two solid rocket boosters, and an external fuel tank.

space station A habitat-workshop-laboratory permanently in orbit, with crews and supplies brought from Earth as needed.

specific impulse A number which indicates the effectiveness of a fuel-oxidizer combination; the time it takes to burn one pound of fuel while it is producing one pound of thrust.

spectral bands A range of wavelengths which a particular sensor responds to or which has some particular meaning for interpreting the image.

spectrum See **electromagnetic spectrum.**

SRB The Space Shuttle's solid rocket booster.

sunspot A "cool," dark region in the photosphere of the Sun where magnetic fields retard the flow of heat from the interior to the surface.

Sun-synchronous An orbit around Earth which crosses the equator at precisely the same local time on each pass.

tang The part of a fitting that fits into a clevis.

teleoperate Operate equipment or instruments by remote control using a television monitor and radio link.

terminator On a planet, the line which divides daylight from darkness.

terraform Modify the environment of a planet to make it more Earth-like and habitable by humans.

tetrahedron A solid object with four equilateral triangles for sides.

thermostabilize Cook food at temperatures which preserve it by destroying the bacteria.

thrust Force produced by a rocket engine.

thruster A small rocket engine or gas jet used to control the attitude and, to a lesser extent, the orbital speed of a spacecraft.

trajectory Path followed by a vehicle.

transfer orbit Segment of an orbit which a spacecraft follows to move from one orbit to another.

troposphere The lowest six miles, approximately, of the Earth's atmosphere, the region in which all weather occurs.

turbojet A reaction engine in which air is taken in at the front and compressed, fuel is mixed and burned, and the exhaust gases are ejected out the back.

ultraviolet Electromagnetic waves with wavelengths shorter than visible light but longer than x-rays.

valence An integer number which tells how one element combines chemically with another; refers to the number of outermost electrons in an atom.

Van Allen belts Regions in the Earth's magnetosphere where solar electrons and protons become trapped by the magnetic field.

velocity The motion of an object described by its speed and direction.

vernier engine A small rocket or thruster used to make fine adjustments in speed or attitude.

vestibular apparatus Organ in the inner ear which gives a sense of balance and motion.

wavelength The distance between two adjacent crests or troughs of a wave.

weight The force of gravity acting on a mass.

weightlessness Condition of free fall or zero g in which objects in a spacecraft are weightless.

x-rays Electromagnetic waves with wavelength in the range from one-hundredth to one-millionth of a micrometer.

yaw Left and right rotational motion of the nose and tail of an aircraft or spacecraft. See also **pitch** and **roll.**

zero g A misleading term implying the absence of gravity, but meaning weightlessness.

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