The Space Environment

4.1.2

In This Section You'll Learn to...

- Explain where space begins and describe our place in the universe
- List the major hazards of the space environment and describe their effects on spacecraft
- List and describe the major hazards of the space environment that pose a problem for humans living and working in space

Outline

Space is a place. Some people think of space as a nebulous region far above their heads—extending out to infinity. But for us, space is a place where things happen: spacecraft orbit Earth, planets orbit the Sun, and the Sun revolves around the center of our galaxy.

In this chapter we'll look at this place we call space, exploring where it begins and how far it extends. We'll see that space is actually very close (Figure 4.1.2-1). Then, starting with our "local neighborhood," we'll take a mind-expanding tour beyond the galaxy to see what's in space. Next we'll see what space is like. Before taking any trip, we usually check the weather, so we'll know whether to pack a swim suit or a parka. In the same way, we'll look at the space environment to see how we must prepare ourselves and our machines to handle this hostile environment.

Figure 4.1.2-1. Earth and Moon. Although in the night sky the Moon looks really far away, Earth's atmosphere is relatively shallow, so space is close. *(Courtesy of NASA/Ames Research Center*

4.1.2.1 Cosmic Perspective

In This Section You'll Learn to...

- Explain where space is and how it's defined
- Describe the primary outputs from the Sun that dominate the space environment
- Provide some perspective on the size of space

Where is Space?

If space is a place, where is it? Safe within the cocoon of Earth's atmosphere, we can stare into the night sky at thousands of stars spanning millions of light years. We know space begins somewhere above our heads, but how far? If we "push the envelope" of a powerful jet fighter plane, we can barely make it to a height where the sky takes on a purplish color and stars become visible in daylight. But even then, we're not quite in space. Only by climbing aboard a rocket can we escape Earth's atmosphere into the realm we normally think of as space.

But the line between where the atmosphere ends and space begins is, by no means, clear. In fact, there is no universally accepted definition of precisely where space begins. If you ask NASA or the U.S. Air Force, you'll find their definition of space is somewhat arbitrary. To earn astronaut wings, for example, you must reach an altitude of more than 92.6 km (57.5 mi.) but don't actually have to go into orbit, as illustrated in Figure 4.1.2-2. (That's why X-15 pilots and the first United States' astronauts to fly suborbital flights in the Mercury program were able to wear these much-coveted wings.) Although this definition works, it's not very meaningful.

Figure 4.1.2-2. Where is Space? For awarding astronaut wings, NASA defines space at an altitude of 92.6 km (57.5 mi.). For our purposes, space begins where satellites can maintain orbit—about 130 km (81 mi.).

For our purposes, space begins at the altitude where an object in orbit will remain in orbit briefly (only a day or two in some cases) before the wispy air molecules in the upper atmosphere drag it back to Earth. This occurs above an altitude of about 130 km (81 mi.). That's about the distance you can drive in your car in just over an hour! So the next time someone asks you, "how do I get to space?" just tell them to "turn straight up and go about 130 km (81 mi.) until the stars come out."

As you can see, space is very close. Normally, when you see drawings of orbits around Earth (as you'll see in later chapters), they look far, far away. But these diagrams are seldom drawn to scale. To put low-Earth orbits (LEO), like the ones flown by the Space Shuttle, into perspective, imagine Earth were the size of a peach—then a typical Shuttle orbit would be just above the fuzz. A diagram closer to scale (but not exactly) is shown in Figure 4.1.2-3.

Now that we have some idea of where space is, let's take a grand tour of our "local neighborhood" to see what's out there. We'll begin by looking at the solar system, then expand our view to cover the galaxy.

Figure 4.1.2-3. Shuttle Orbit Drawn Closer to Scale. (If drawn exactly to scale, you wouldn't be able to see it!) As you can see, space is very close. Space Shuttle orbits are just barely above the atmosphere.

The Solar System

At the center of the solar system is the star closest to Earth—the Sun (Figure 4.1.2-4). As we'll see, the Sun has the biggest effect on the space environment. As stars go, our Sun is quite ordinary. It's just one small, yellow star out of billions in the galaxy. Fueled by nuclear fusion, it combines or "fuses" 600 million tons of hydrogen each second. (Don't worry, at that rate it won't run out of hydrogen for about 5,000,000,000 years!). We're most interested in two by-products of the fusion process

- Electromagnetic radiation
- Charged particles

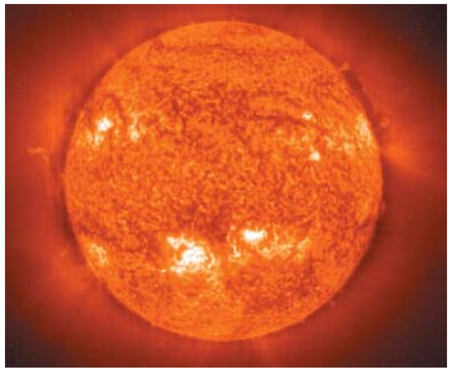

Figure 4.1.2-4. The Sun. It's our source of light and heat, but with the beneficial emissions, come some pretty nasty radiation. This Solar and Heliospheric Observatory (SOHO) satellite using the extreme ultraviolet imaging telescope shows how active our Sun is. *(Courtesy of SOHO/Extreme-ultraviolet Imaging Telescope consortium. SOHO is a project of international cooperation between ESA and NASA)*

The energy released by nuclear fusion is governed by Einstein's famous $E = m c^2$ formula. This energy, of course, makes life on Earth possible. And the Sun produces lots of energy, enough each second to supply all the energy the United States needs for about 624 million years! This energy is primarily in the form of electromagnetic radiation. In a clear, blue sky, the Sun appears as an intensely bright circle of light. With your eyes closed on a summer day, you can feel the Sun's heat beating on you. But light and heat are only part of it's *electromagnetic (EM) radiation*. The term "radiation" often conjures up visions of nuclear wars and mutant space creatures, but EM radiation is something we live with every day. EM radiation is a way for energy to get from one place to another. We can think of the Sun's intense energy as radiating from its surface in all directions in waves. We classify these waves of radiant energy in terms of the distance between wave crests, or *wavelength, λ*, as in Figure 4.1.2-5.

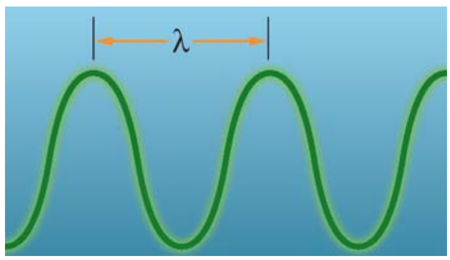

Figure 4.1.2-5. Electromagnetic (EM) Radiation. We classify EM radiation in terms of the wavelength, λ, (or frequency) of the energy.

What difference does changing the wavelength make? If you've ever seen a rainbow on a sunny spring day, you've seen the awesome beauty of changing the wavelength of EM radiation by only 0.0000003 meters (9.8×10^{-7} ft.)! The colors of the rainbow, from violet to red, represent only a very small fraction of the entire electromagnetic spectrum. This spectrum spans from high energy X-rays (like you get in the dentist's

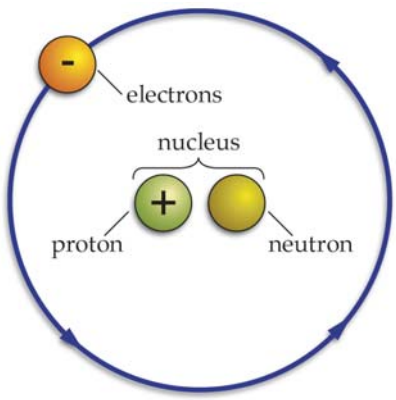

Figure 4.1.2-6. The Atom. The nucleus of an atom contains positively charged protons and neutral neutrons. Around the nucleus are negatively charged electrons.

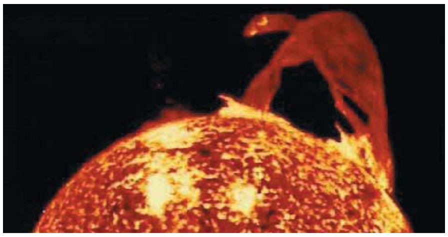

Figure 4.1.2-7. Solar Flares. They fly out from the Sun long distances, at high speeds, and can disrupt radio signals on Earth, and disturb spacecraft orbits near Earth. *(Courtesy of NASA/Johnson Space Center)*

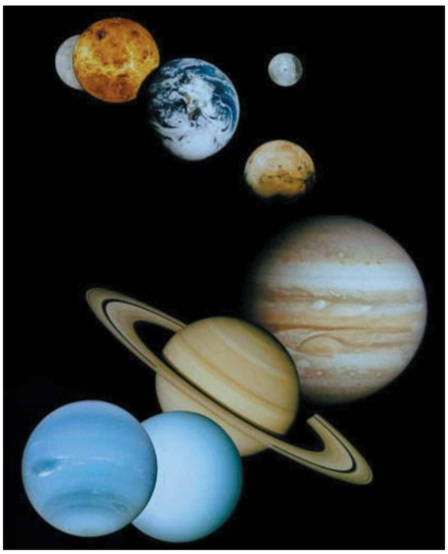

Figure 4.1.2-8. Solar System. Nine planets and many other objects orbit the Sun, which holds the solar system together with its gravity. *(Courtesy of NASA/Jet Propulsion Laboratory)*

office) at one end, to long-wavelength radio waves (like your favorite FM station) at the other. Light and all radiation move at the speed of light—300,000 km/s or more than 671 million m.p.h.! As we'll see, solar radiation can be both helpful and harmful to spacecraft and humans in space. We'll learn more about the uses for EM radiation in Chapter 11.

The other fusion by-product we're concerned with is charged particles. Scientists model atoms with three building-block particles—protons, electrons, and neutrons, as illustrated in Figure 4.1.2-6. Protons and electrons are *charged particles*. Protons have a positive charge, and electrons have a negative charge. The neutron, because it doesn't have a charge, is neutral. Protons and neutrons make up the nucleus or center of an atom. Electrons swirl around this dense nucleus.

During fusion, the Sun's interior generates intense heat (more than 1,000,000° C). At these temperatures, a fourth state of matter exists. We're all familiar with the other three states of matter—solid, liquid, and gas. If we take a block of ice (a solid) and heat it, we get water (a liquid). If we continue to heat the water, it begins to boil, and turns into steam (a gas). However, if we continue to heat the steam, we'd eventually get to a point where the water molecules begin to break down. Eventually, the atoms will break into their basic particles and form a hot *plasma*. Thus, inside the Sun, we have a swirling hot soup of charged particles—free electrons and protons. (A neutron quickly decays into a proton plus an electron.)

These charged particles in the Sun don't stay put. All charged particles respond to electric and magnetic fields. Your television set, for example, takes advantage of this by using a magnet to focus a beam of electrons at the screen to make it glow. Similarly, the Sun has an intense magnetic field, so electrons and protons shoot away from the Sun at speeds of 300 to 700 km/s (about 671,000 to 1,566,000 m.p.h.). This stream of charged particles flying off the Sun is called the *solar wind*.

Occasionally, areas of the Sun's surface erupt in gigantic bursts of charged particles called *solar particle events* or *solar flares*, shown in Figure 4.1.2-7, that make all of the nuclear weapons on Earth look like pop guns. Lasting only a few days or less, these flares are sometimes so violent they extend out to Earth's orbit (150 million km or 93 million mi.)! Fortunately, such large flares are infrequent (every few years or so) and concentrated in specific regions of space, so they usually miss Earth. Later, we'll see what kinds of problems these charged particles from the solar wind and solar flares pose to machines and humans in space.

Besides the star of the show, the Sun, nine planets, dozens of moons, and thousands of asteroids are in our solar system (Figure 4.1.2-8). The planets range from the small terrestrial-class ones—Mercury, Venus, Earth, and Mars—to the mighty gas giants—Jupiter, Saturn, Uranus, and Neptune. Tiny Pluto is all alone at the edge of the solar system and may be a lost moon of Neptune. Figure 4.1.2-9 tries to give some perspective on the size of the solar system. However, because we tend to spend most of our time near Earth, we'll focus our discussion of the space environment on spacecraft and astronauts in Earth orbits.

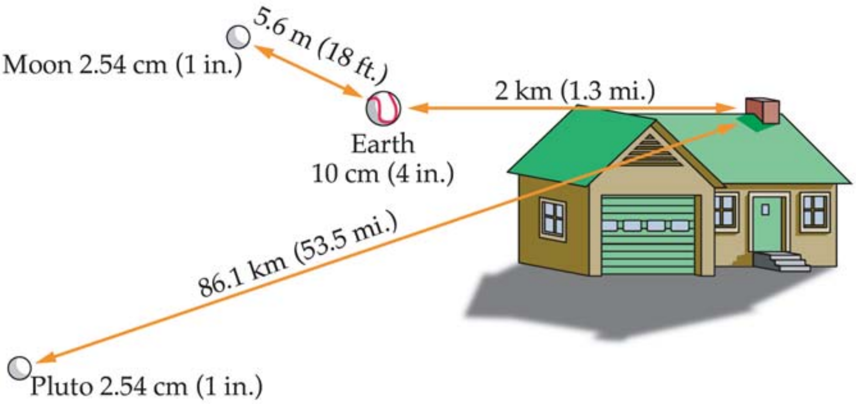

Figure 4.1.2-9. The Solar System in Perspective. If the Earth were the size of a baseball, about 10 cm (~4 in.) in diameter, the Moon would be only 2.54 cm (1 in.) in diameter and about 5.6 m (18 ft.) away. At the same scale the Sun would be a ball 10 m (33 ft.) in diameter (about the size and volume of a small two-bedroom house); it would be more than 2 km (nearly 1.3 mi.) away. Again, keeping the same scale, the smallest planet Pluto would be about the same size as Earth's Moon, 2.54 cm (1 in.), and 86.1 km (53.5 mi.) away from the house-sized Sun.

The Cosmos

Space is big. Really BIG. Besides our Sun, more than 300 billion other stars are in our neighborhood—the Milky Way galaxy. Because the distances involved are so vast, normal human reckoning (kilometers or miles) loses meaning. When trying to understand the importance of charged particles in the grand scheme of the universe, for example, the mind boggles. Figure 4.1.2-10 tries to put human references on a scale with the other micro and macro dimensions of the universe.

One convenient yardstick we use to discuss stellar distances is the light year. One *light year* is the distance light can travel in one year. At 300,000 km/s, this is about 9.46×10^{12} km (about 5.88 trillion mi.). Using this measure, we can begin to describe our location with respect to everything else in the universe. The Milky Way galaxy is spiral shaped and is about 100,000 light years across. Our Sun and its solar system is about half way out from the center (about 25,000 light years) on one of the spiral arms. The Milky Way (and we along with it) slowly revolves around the galactic center, completing one revolution every 240 million years or so. The time it takes to revolve once around the center of the galaxy is sometimes called a *cosmic year*. In these terms, astronomers think our solar system is about 20 cosmic years old (4.8 billion Earth years).

Stars in our galaxy are very spread out. The closest star to our solar system is Proxima Centauri at 4.22 light years or 4.0×10^{13} km away. The Voyager spacecraft, currently moving at 56,400 km/hr. (35,000 m.p.h.), would take more than 80,000 years to get there! Trying to imagine these kinds of distances gives most of us a headache. The nearest galaxy to our own is Andromeda, which is about 2 million light years away. Beyond Andromeda are billions and billions of other galaxies, arranged in strange configurations which astronomers are only now beginning to catalog.

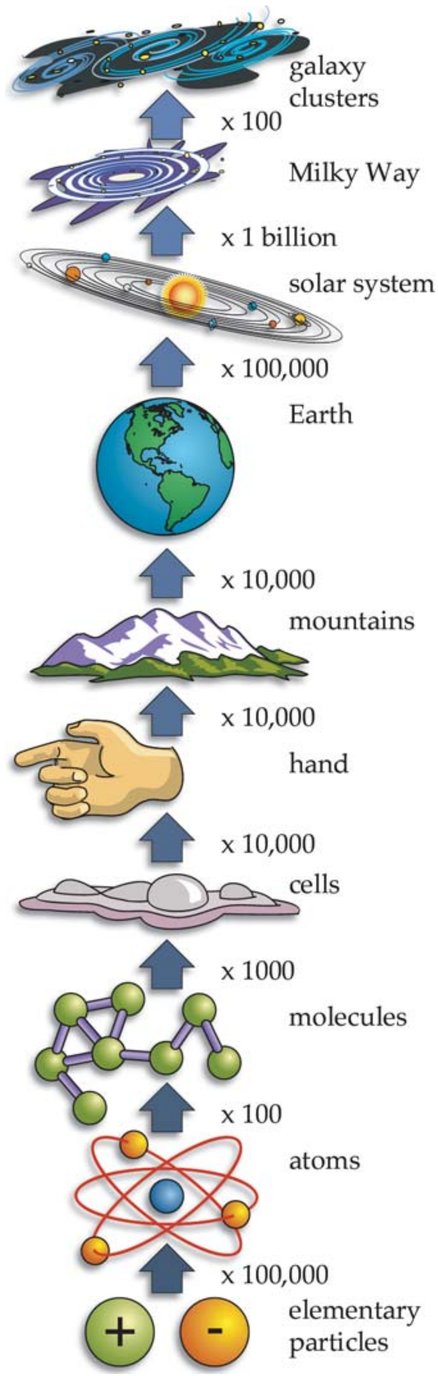

Figure 4.1.2-10. From Micro to Macro. To get an idea about the relative size of things in the universe, start with elementary particles—protons and electrons. You can magnify them 100,000 times to reach the size of an atom, etc.

Figure 4.1.2-11. Stellar Distances. Let our Sun (1.4×10^6 km or 8.6×10^6 mi. in diameter) be the size of a large marble, roughly 2.54 cm (1 in.) in diameter. At this scale, the nearest star to our solar system, Proxima Centauri, would be more than 1500 km (932 mi.) away. So, if the Sun were the size of a large marble (2.54 cm or 1 in. in diameter) in Denver, Colorado, the nearest star would be in Chicago, Illinois. At this stellar scale, the diameter of the Milky Way galaxy would then be 33.8 million km (21 million mi.) across! Still too big for us to visualize!

Figure 4.1.2-11 puts the distance between us and our next closest star into understandable terms. Figure 4.1.2-12 tries to do the same thing with the size of our galaxy. In the next section we'll beam back closer to home to understand the practical effects of sending machines and humans to explore the vast reaches of the cosmos.

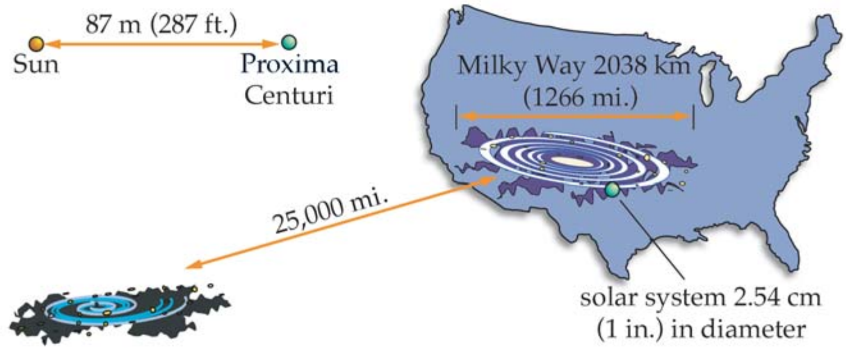

Figure 4.1.2-12. Galactic Distances. Imagine the entire solar system (11.8×10^9 km or 7.3×10^9 mi. across) were just the size of a large marble 2.54 cm (1 in.) in diameter. At this scale, the nearest star would be 87 m (287 ft.) away. The diameter of the Milky Way galaxy would then be 2038 km (1266 mi.). So, if the solar system were the size of a marble in Denver, Colorado, the Milky Way galaxy would cover most of the western United States. At this scale, the nearest galaxy would be 40,000 km (25,000 mi.) away.

Section Review

Key Concepts

- For our purposes, space begins at an altitude where a satellite can briefly maintain an orbit. Thus, space is close. It's only about 130 km (81 mi.) straight up.
- The Sun is a fairly average yellow star which burns by the heat of nuclear fusion. Its surface temperature is more than 6000 K and its output includes
  - Electromagnetic radiation that we see and feel here on Earth as light and heat
  - Streams of charged particles that sweep out from the Sun as part of the solar wind
  - Solar particle events or solar flares, which are brief but intense periods of charged-particle emissions
- Our solar system is about half way out on one of the Milky Way galaxy's spiral arms. Our galaxy is just one of billions and billions of galaxies in the universe.

4.1.2.2 The Space Environment and Spacecraft

In This Section You'll Learn to...

- List and describe major hazards of the space environment and their effect on spacecraft

To build spacecraft that will survive the harsh space environment, we must first understand what hazards they may face. Earth, the Sun, and the cosmos combined offer unique challenges to spacecraft designers, as shown in Figure 4.1.2-13.

- The gravitational environment causes some physiological and fluid containment problems but also provides opportunities for manufacturing
- Earth's atmosphere affects a spacecraft, even in orbit
- The vacuum in space above the atmosphere gives spacecraft another challenge
- Natural and man-made objects in space pose collision hazards
- Radiation and charged particles from the Sun and the rest of the universe can severely damage unprotected spacecraft

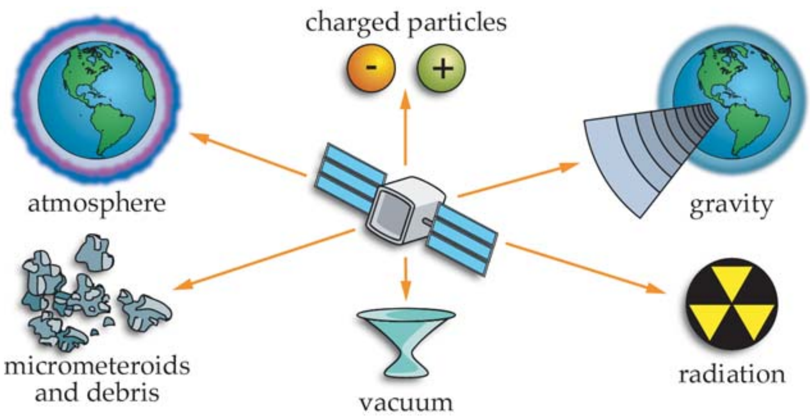

Figure 4.1.2-13. Factors Affecting Spacecraft in the Space Environment. There are six challenges unique to the space environment we deal with—gravity, the atmosphere, vacuum, micrometeroids and debris, radiation, and charged particles.

Figure 4.1.2-14. Astronauts in Free Fall. In the free-fall environment, astronauts Julie Payette (left) and Ellen Ochoa (STS-96) easily move supplies from the Shuttle Discovery to the Zarya module of the International Space Station. With no contact forces to slow them down, the supplies need only a gentle push to float smoothly to their new home. *(Courtesy of NASA/Johnson Space Center)*

Gravity

Whenever we see astronauts on television floating around the Space Shuttle, as in Figure 4.1.2-14, we often hear they are in "zero gravity." But this is not true! All objects attract each other with a gravitational force that depends on their mass (how much "stuff" they have). This force decreases as objects get farther away from each other, so gravity doesn't just disappear once we get into space. In a low-Earth orbit, for example, say at an altitude of 300 km, the pull of gravity is still 91% of what it is on Earth's surface.

So why do astronauts float around in their spacecraft? A spacecraft and everything in it are in *free fall*. As the term implies, an object in free fall is falling under the influence of gravity, free from any other forces. Free fall is that momentary feeling you get when you jump off a diving board. It's what skydivers feel before their parachutes open. In free fall you don't feel the force of gravity even though gravity is present. As you sit there in your chair, you don't feel gravity on your behind. You feel the chair pushing up at you with a force equal to the force of gravity. Forces that act only on the surface of an object are *contact forces*. Astronauts in orbit experience no contact forces because they and their spacecraft are in free fall, not in contact with Earth's surface. But if everything in orbit is falling, why doesn't it hit Earth? An object in orbit has enough horizontal velocity so that, as it falls, it keeps missing Earth.

Earth's gravitational pull dominates objects close to it. But as spacecraft move into higher orbits, the gravitational pull of the Moon and Sun begin to exert their influence. For Earth-orbiting applications, we can assume the Moon and Sun have no effect. For interplanetary spacecraft, this assumption isn't true—"the Sun's gravitational pull dominates" for most of an interplanetary trajectory (the Moon has little effect on IP trajectories).

Gravity dictates the size and shape of a spacecraft's orbit. Launch vehicles must first overcome gravity to fling spacecraft into space. Once a spacecraft is in orbit, gravity determines the amount of propellant its engines must use to move between orbits or link up with other spacecraft. Beyond Earth, the gravitational pull of the Moon, the Sun, and other planets similarly shape the spacecraft's path. Gravity is so important to the space environment that an entire branch of astronautics, called *astrodynamics*, deals with quantifying its effects on spacecraft and planetary motion.

Figure 4.1.2-15. Waterball. Astronaut Joseph Kerwin forms a perfect sphere with a large drop of water, which floats freely in the Skylab cabin. Left alone, the water ball may float to a solid surface and coat the surface, making a mess that doesn't run to the floor. *(Courtesy of NASA/Johnson Space Center)*

The free-fall environment of space offers many potential opportunities for space manufacturing. On Earth, if we mix two materials, such as rocks and water, the heavier rocks sink to the bottom of the container. In free fall, we can mix materials that won't mix on Earth. Thus, we can make exotic and useful metal alloys for electronics and other applications, or new types of medicines.

However, free fall does have its drawbacks. One area of frustration for engineers is handling fluids in space. Think about the gas gauge in your car. By measuring the height of a floating bulb, you can constantly track the amount of fuel in the tank. But in orbit nothing "floats" in the tank because the liquid and everything else is sloshing around in free fall (Figure 4.1.2-15). Thus, fluids are much harder to measure (and pump) in free fall. But these problems are relatively minor compared to the profound physiological problems humans experience when exposed to free fall for long periods. We'll look at these problems separately in the next section.

Atmosphere

Earth's atmosphere affects a spacecraft in low-Earth orbit (below about 600 km [375 mi.] altitude), in two ways

- Drag—shortens orbital lifetimes
- Atomic oxygen—degrades spacecraft surfaces

Take a deep breath. The air you breathe makes up Earth's atmosphere. Without it, of course, we'd all die in a few minutes. While this atmosphere forms only a thin layer around Earth, spacecraft in low-Earth orbit can still feel its effects. Over time, it can work to drag a spacecraft back to Earth, and the oxygen in the atmosphere can wreak havoc on many spacecraft materials.

Two terms are important to understanding the atmosphere—pressure and density. *Atmospheric pressure* represents the amount of force per unit area exerted by the weight of the atmosphere pushing on us. *Atmospheric density* tells us how much air is packed into a given volume. As we go higher into the atmosphere, the pressure and density begin to decrease at an ever-increasing rate, as shown in Figure 4.1.2-16. Visualize a column of air extending above us into space. As we go higher, there is less volume of air above us, so the pressure (and thus, the density) goes down. If we were to go up in an airplane with a pressure and density meter, we would see that as we go higher, the pressure and density begins to drop off more rapidly.

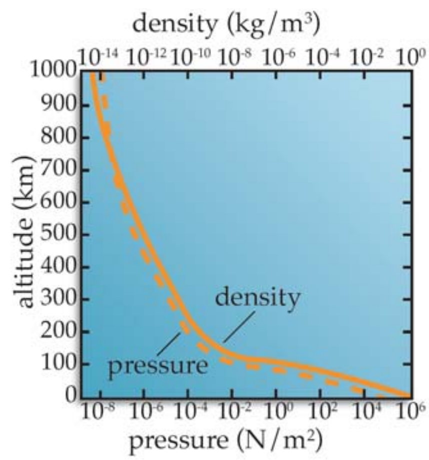

Figure 4.1.2-16. Structure of Earth's Atmosphere. The density of Earth's atmosphere decreases exponentially as you go higher. Even in low-Earth orbit, however, you can still feel the effects of the atmosphere in the form of drag.

Earth's atmosphere doesn't just end abruptly. Even at fairly high altitudes, up to 600 km (375 mi.), the atmosphere continues to create drag on orbiting spacecraft. *Drag* is the force you feel pushing your hand backward when you stick it out the window of a car rushing along the freeway. The amount of drag you feel on your hand depends on the air's density, your speed, the shape and size of your hand, and the orientation of your hand with respect to the airflow. Similarly, the drag on spacecraft in orbit depends on these same variables: the air's density plus the spacecraft's speed, shape, size, and orientation to the airflow.

Drag immediately affects spacecraft returning to Earth. For example, as the Space Shuttle re-enters the atmosphere enroute to a landing at Edwards AFB in California, the astronauts use the force of drag to slow the Shuttle (Figure 4.1.2-17) from an orbital velocity of over 25 times the speed of sound (27,900 km/hr or 17,300 m.p.h.) to a runway landing at about 360 km/hr. (225 m.p.h.). Similarly, drag quickly affects any spacecraft in a very low orbit (less than 130 km or 81 mi. altitude), pulling them back to a fiery encounter with the atmosphere in a few days or weeks.

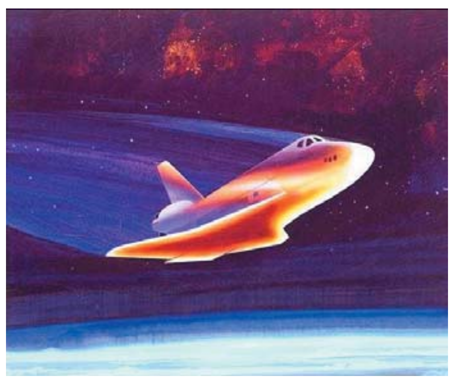

Figure 4.1.2-17. Shuttle Re-entry. Atmospheric drag slows the Shuttle to landing speed, but the air friction heats the protective tiles to extremely high temperatures. *(Courtesy of NASA/Ames Research Center)*

The effect of drag on spacecraft in higher orbits is much more variable. Between 130 km and 600 km (81 mi. and 375 mi.), it will vary greatly depending on how the atmosphere changes (expands or contracts) due to variations in solar activity. Acting over months or years, drag can cause spacecraft in these orbits to gradually lose altitude until they re-enter the atmosphere and burn up. In 1979, the Skylab space station succumbed to the long-term effects of drag and plunged back to Earth. Above 600 km

(375 mi.), the atmosphere is so thin the drag effect is almost insignificant. Thus, spacecraft in orbits above 600 km are fairly safe from drag.

Besides drag, we must also consider the nature of air. At sea level, air is about 21% oxygen, 78% nitrogen, and 1% miscellaneous other gasses, such as argon and carbon dioxide. Normally, oxygen atoms like to hang out in groups of two--molecules, abbreviated O_2. Under normal conditions, when an oxygen molecule splits apart for any reason, the atoms quickly reform into a new molecule. In the upper parts of the atmosphere, oxygen molecules are few and far between. When radiation and charged particles cause them to split apart, they're sometimes left by themselves as *atomic oxygen*, abbreviated O.

Figure 4.1.2-18. Long Duration Exposure Facility (LDEF). The mission of LDEF, deployed and retrieved by the Space Shuttle (STS-41-C) in April, 1984, was to determine the extent of space environment hazards such as atomic oxygen and micrometeoroids. *(Courtesy of NASA/Johnson Space Center)*

So what's the problem with O? We've all seen the results of exposing a piece of steel outside for a few months or years—it starts to rust. Chemically speaking, rust is *oxidation*. It occurs when oxygen molecules in the air combine with the metal creating an oxide-rust. This oxidation problem is bad enough with O_2, but when O by itself is present, the reaction is much, much worse. Spacecraft materials exposed to atomic oxygen experience breakdown or "rusting" of their surfaces, which can eventually weaken components, change their thermal characteristics, and degrade sensor performance. One of the goals of NASA's Long Duration Exposure Facility (LDEF), shown in Figure 4.1.2-18, was to determine the extent of atomic oxygen damage over time, which it did very well. In many cases, depending on the material, the results were as dramatic as we just described.

On the good side, most atomic oxygen floating around in the upper atmosphere combines with oxygen molecules to form a special molecule, O_3, called *ozone*. Ozone acts like a window shade to block harmful radiation, especially the ultraviolet radiation that causes sunburn and skin cancer.

Vacuum

Beyond the thin skin of Earth's atmosphere, we enter the vacuum of space. This vacuum environment creates three potential problems for spacecraft

- Out-gassing—release of gasses from spacecraft materials
- Cold welding—fusing together of metal components
- Heat transfer—limited to radiation

As we've seen, atmospheric density decreases dramatically with altitude. At a height of about 80 km (50 mi.), particle density is 10,000 times less than what it is at sea level. If we go to 960 km (596 mi.), we would find a given volume of space to contain one trillion times less air than at the surface. A pure vacuum, by the strictest definition of the word, is a volume of space completely devoid of all material. In practice, however, a pure vacuum is nearly unattainable. Even at an altitude of 960 km (596 mi.), we still find about 1,000,000 particles per cubic centimeter.

So when we talk about the vacuum of space, we're talking about a "near" or "hard" vacuum.

Under standard atmospheric pressure at sea level, air exerts more than 101,325 N/m^2 (14.7 lb./in.^{2}) of force on everything it touches. The soda inside a soda can is under slightly higher pressure, forcing carbon dioxide (CO_2) into the solution. When you open the can, you release the pressure, causing some of the CO_2 to come out of the solution, making it foam. Spacecraft face a similar, but less tasty, problem. Some materials used in their construction, especially composites, such as graphite/epoxy, can trap tiny bubbles of gas while under atmospheric pressure. When this pressure is released in the vacuum of space, the gasses begin to escape. This release of trapped gasses in a vacuum is called *out-gassing*. Usually, out-gassing is not a big problem; however, in some cases, the gasses can coat delicate sensors, such as lenses or cause electronic components to arc, damaging them. When this happens, out-gassing can be destructive. For this reason, we must carefully select and test materials used on spacecraft. We often "bake" a spacecraft in a thermal-vacuum chamber prior to flight, as shown in Figure 4.1.2-19, to ensure it won't outgas in space.

Another problem created by vacuum is cold welding. *Cold welding* occurs between mechanical parts that have very little separation between them. When we test the moving part on Earth, a tiny air space may allow the parts to move freely. After launch, the hard vacuum in space eliminates this tiny air space, causing the two parts to effectively "weld" together. When this happens, ground controllers must try various techniques to "unstick" the two parts. For example, they may expose one part to the Sun and the other to shade so that differential heating causes the parts to expand and contract, respectively, allowing them to separate.

Due to cold welding, as well as practical concerns about mechanical failure, spacecraft designers carefully try to avoid the use of moving parts. However, in some cases, such as with spinning wheels used to control spacecraft attitude, there is no choice. On Earth, moving parts, like you find in your car engine, are protected by lubricants such as oil. Similarly, spacecraft components sometimes need lubrication. However, because of the surrounding vacuum, we must select these lubricants carefully, so they don't evaporate or outgas. Dry graphite (the "lead" in your pencil) is an effective lubricant because it lubricates well and won't evaporate into the vacuum as a common oil would.

Finally, the vacuum environment creates a problem with heat transfer. As we'll see in greater detail in Chapter 13, heat gets from one place to another in three ways. *Conduction* is heat flow directly from one point to another through a medium. If you hold a piece of metal in a fire long enough, you'll quickly discover how conduction works when it burns your fingers (Figure 4.1.2-20). The second method of heat transfer is convection. *Convection* takes place when gravity, wind, or some other force moves a liquid or gas over a hot surface (Figure 4.1.2-21). Heat transfers from the surface to the fluid. Convection takes place whenever we feel chilled by a breeze or boil water on the stove. We can use both of these methods to move heat around inside a spacecraft but not to remove

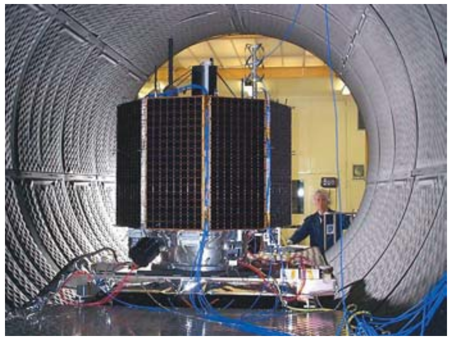

Figure 4.1.2-19. Spacecraft in a Vacuum Chamber. Prior to flight, spacecraft undergo rigorous tests, including exposure to a hard vacuum in vacuum chambers. In this way we can test for problems with out-gassing, cold welding, or heat transfer. *(Courtesy of Surrey Satellite Technologies, Ltd., U.K.)*

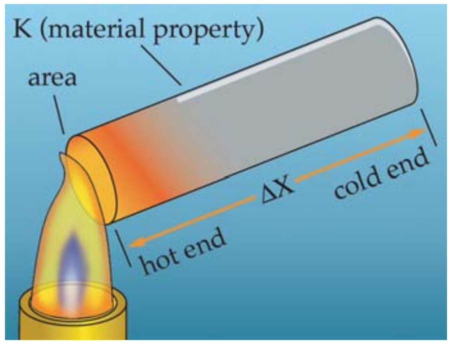

Figure 4.1.2-20. Conduction. Heat flows by conduction through an object from the hot end to the cool end. Spacecraft use conduction to remove heat from hot components.

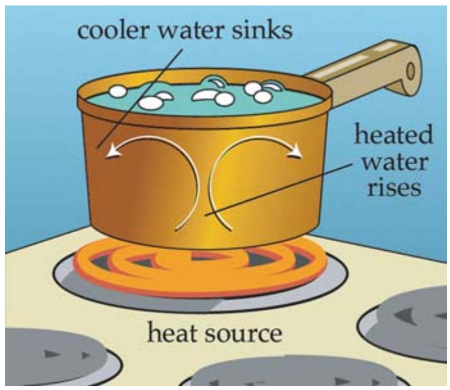

Figure 4.1.2-21. Convection. Boiling water on a stove shows how convection moves heat through a fluid from the fluid near a hot surface to the cooler fluid on top. Special devices on spacecraft use convection to remove heat from a hot components.

heat from a spacecraft in the free fall, vacuum environment of space. So we're left with the third method—radiation. We've already discussed electromagnetic radiation. *Radiation* is a way to transfer energy from one point to another. The heat you feel coming from the glowing coils of a space heater is radiated heat (Figure 4.1.2-22). Because radiation doesn't need a solid or fluid medium, it's the primary method of moving heat into and out of a spacecraft.

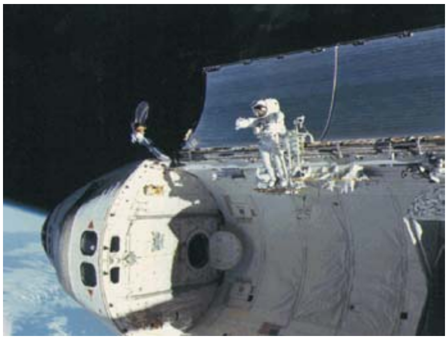

Figure 4.1.2-22. Radiation. The Shuttle Bay doors contain radiators that collect heat from the equipment bay and dump it into space. Because objects emit radiation, the bay door radiators efficiently remove heat from the Shuttle. *(Courtesy of NASA/Johnson Space Center)*

Micrometeoroids and Space Junk

The space around Earth is not empty. In fact, it contains lots of debris or space junk most of which we're used to. If you've seen a falling star, you've witnessed just one piece of the more than 20,000 tons of natural materials—dust, meteoroids, asteroids, and comets—that hit Earth every year. For spacecraft or astronauts in orbit, the risk of getting hit by a meteoroid or micrometeoroid, our name for these naturally occurring objects, is remote. However, since the beginning of the space age, debris has begun to accumulate from another source—human beings.

With nearly every space mission, broken spacecraft, pieces of old booster segments or spacecraft, and even an astronaut's glove have been left in space. The environment near Earth is getting full of this space debris (about 2200 tons of it). The problem is posing an increasing risk to spacecraft and astronauts in orbit. A spacecraft in low orbit is now more likely to hit a piece of junk than a piece of natural material. In 1996, the CERISE spacecraft, shown in Figure 4.1.2-23, became the first certified victim of space junk when its 6 m gravity-gradient boom was clipped off during a collision with a left-over piece of an Ariane launch vehicle.

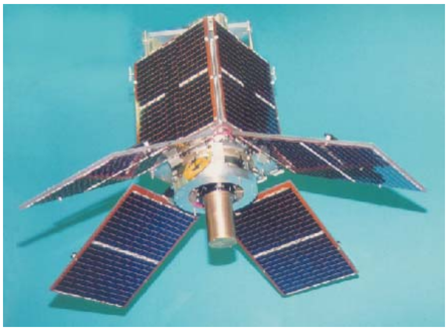

Figure 4.1.2-23. CERISE. The CERISE spacecraft lost its long boom when a piece of an Ariane rocket struck it at orbital speed. Without its boom, the spacecraft could not hold its attitude and perform its mission. *(Courtesy of Surrey Satellite Technologies, Ltd., U.K.)*

Keeping track of all this junk is the job of the North American Aerospace Defense Command (NORAD) in Colorado Springs, Colorado. NORAD uses radar and optical telescopes to track more than 8000 objects, baseball sized and larger, in Earth orbit. Some estimates say at least 40,000 golf-ball-sized pieces (too small for NORAD to track) are also in orbit [Wertz and Larson, 1999]. To make matters worse, there also may be billions of much smaller pieces—paint flakes, slivers of metal, etc.

If you get hit by a paint flake no big deal, right? Wrong! In low-Earth orbit, this tiny chunk is moving at fantastic speeds—7000 m/s or greater when it hits. This gives it a great amount of energy—much more than a rifle bullet! The potential danger of all this space junk was brought home during a Space Shuttle mission in 1983. During the mission, a paint flake only 0.2 mm (0.008 in.) in diameter hit the Challenger window, making a crater 4 mm (0.16 in.) wide. Luckily, it didn't go all the way through. The crater, shown in Figure 4.1.2-24, cost more than $50,000 to repair. Analysis of other spacecraft shows collisions with very small objects are common. Russian engineers believe a piece of space debris may have incapacitated one of their spacecraft in a transfer orbit.

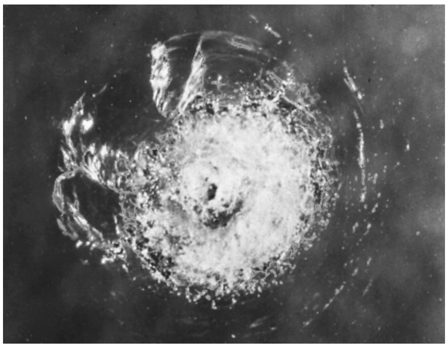

Figure 4.1.2-24. Shuttle Hit by Space Junk. At orbital speeds, even a paint flake can cause significant damage. The Space Shuttle was hit by a tiny paint flake, causing this crater in the front windshield. *(Courtesy of NASA/Johnson Space Center)*

Because there are billions of very small objects and only thousands of very large objects, spacecraft have a greater chance of getting hit by a very small object. For a spacecraft with a cross-sectional area of 50–200 m^2 at an altitude of 300 km (186 mi.) (typical for Space Shuttle missions), the chance of getting hit by an object larger than a baseball during one year in orbit is about one in 100,000 or less [Wertz and Larson, 1999]. The chance of getting hit by something only 1 mm or less in diameter, however, is about one hundred times more likely, or about one in a thousand during one year in orbit.

One frightening debris hazard is the collision of two spacecraft at orbital velocity. A collision between two medium-sized spacecraft would result in an enormous amount of high velocity debris. The resulting cloud would expand as it orbited and greatly increase the likelihood of impacting another spacecraft. The domino effect could ruin a band of space for decades. Thus, there is a growing interest in the level of debris at various altitudes.

Right now, there are no plans to clean up this space junk. Some international agreements aim at decreasing the rate at which the junk accumulates—for instance, by requiring operators to boost worn-out spacecraft into "graveyard" orbits. Who knows? Maybe a lucrative 21st century job will be "removing trash from orbit."

The Radiation Environment

As we saw in the previous section, one of the Sun's main outputs is electromagnetic (EM) radiation. Most of this radiation is in the visible and near-infrared parts of the EM spectrum. Of course, we see the light and feel the heat of the Sun every day. However, a smaller but significant part of the Sun's output is at other wavelengths of radiation, such as X-rays and gamma rays.

Spacecraft and astronauts are well above the atmosphere, so they bear the full brunt of the Sun's output. The effect on a spacecraft depends on the wavelength of the radiation. In many cases, visible light hitting the spacecraft solar panels generates electric power through *solar cells* (also called photovoltaic cells). This is a cheap, abundant, and reliable source of electricity for a spacecraft (Figure 4.1.2-25). This radiation can also lead to several problems for spacecraft

- Heating on exposed surfaces
- Degradation or damage to surfaces and electronic components
- Solar pressure

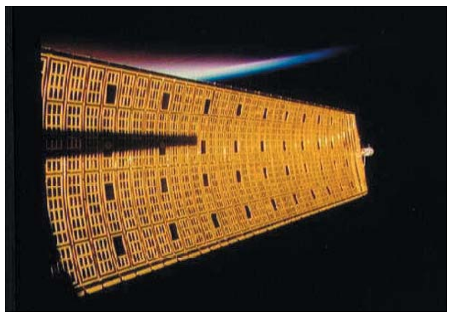

Figure 4.1.2-25. Solar Cells. Solar radiation provides electricity to spacecraft through solar cells mounted on solar panels, but it also degrades the solar cells over time, reducing their efficiency. Here the gold colored solar array experiment extends from the Space Shuttle Discovery. *(Courtesy of NASA/Johnson Space Center)*

The infrared or thermal radiation a spacecraft endures leads to heating on exposed surfaces that can be either helpful or harmful to the spacecraft, depending on the overall thermal characteristics of its surfaces. Electronics in a spacecraft need to operate at about normal room temperature (20° C or 68° F). In some cases, the Sun's thermal energy can help to warm electronic components. In other cases, this solar input—in addition to the heat generated onboard from the operation of electronic components—can make the spacecraft too hot. As we'll see in Chapter 13, we must design the spacecraft's thermal control system to moderate its temperature.

Normally, the EM radiation in the other regions of the spectrum have little effect on a spacecraft. However, prolonged exposure to ultraviolet radiation can begin to degrade spacecraft coatings. This radiation is especially harmful to solar cells, but it can also harm electronic components, requiring them to be shielded, or *hardened*, to handle the environment. In addition, during intense solar flares, bursts of radiation in the radio region of the spectrum can interfere with communications equipment onboard.

When you hold your hand up to the Sun, all you feel is heat. However, all that light hitting your hand is also exerting a very small amount of pressure. Earlier, we said EM radiation could be thought of as waves, like ripples on a pond. Another way to look at it is as tiny bundles of energy called photons. *Photons* are massless bundles of energy that move at the speed of light. These photons strike your hand, exerting pressure similar in effect to atmospheric drag (Figure 4.1.2-26). But this *solar pressure* is much, much smaller than drag. In fact, it's only about 5 N of force (about one pound) for a square kilometer of surface (one-third square mile). While that may not sound like much, over time this solar pressure can disturb the orientation of spacecraft, causing them to point in the wrong direction.

Figure 4.1.2-26. Solar Max Spacecraft. Spacecraft with large surface areas, such as solar panels, must correct for the pressure from solar radiation that may change their attitude. *(Courtesy of NASA/Johnson Space Center)*

Charged Particles

Perhaps the most dangerous aspect of the space environment is the pervasive influence of charged particles. Three primary sources for these particles are

- The solar wind and flares
- Galactic cosmic rays (GCRs)
- The Van Allen radiation belts

As we saw in Section 3.1, the Sun puts out a stream of charged particles (protons and electrons) as part of the solar wind—at a rate of 1×10^9 kg/s (2.2×10^9 lb/s). During intense solar flares (Figure 4.1.2-27), the number of particles ejected can increase dramatically.

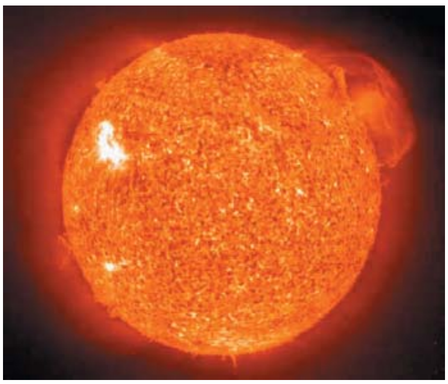

Figure 4.1.2-27. Solar Flares. Solar flares send many more charged particles into space than usual, so spacecraft orbiting Earth receive many times their normal dose, causing electronic problems. *(Courtesy of NASA/Jet Propulsion Laboratory)*

As if this source of charged particles wasn't enough, we must also consider high-energy particles from *galactic cosmic rays (GCRs)*. GCRs are particles similar to those found in the solar wind or in solar flares, but they originate outside of the solar system. GCRs represent the solar wind from distant stars, the remnants of exploded stars, or, perhaps, shrapnel from the "Big Bang" explosion that created the Universe. In many cases, however, GCRs are much more massive and energetic than particles of solar origin. Ironically, the very thing that protects us on Earth from these charged particles creates a third hazard, potentially harmful to orbiting spacecraft and astronauts—the Van Allen radiation belts.

To understand the Van Allen belts, we must remember that Earth has a strong magnetic field as a result of its liquid iron core. This magnetic field behaves in much the same way as those toy magnets you used to play with as a kid, but it's vastly more powerful. Although you can't feel this field around you, it's always there. Pick up a compass and you'll see how the field moves the needle to point north. Magnets always come with a North Pole at one end and a South Pole at the other. If you've ever played with magnets, you've discovered that the north pole attracts the south pole (and vice versa), whereas two north poles (or south poles) repel each other. These magnetic field lines wrap around Earth to form the *magnetosphere*, as shown in Figure 4.1.2-28.

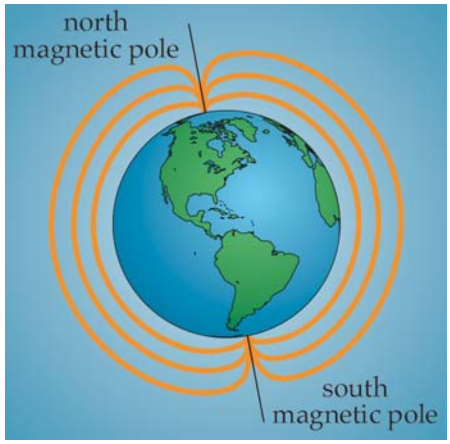

Figure 4.1.2-28. Earth's Magnetosphere. Earth's liquid iron core creates a strong magnetic field. This field is represented by field lines extending from the south magnetic pole to the north magnetic pole. The volume this field encloses is the magnetosphere.

Remember, magnetic fields affect charged particles. This basic principle allows us to "steer" electron beams with magnets inside television sets. Similarly, the solar wind's charged particles and the GCRs form streams which hit Earth's magnetic field like a hard rain hitting an umbrella. Just as the umbrella deflects the raindrops over its curved surface, Earth's magnetic field wards off the charged particles, keeping us safe. (For Sci-fi buffs, perhaps a more appropriate analogy is the fictional force field or "shields" from Star Trek, used to divert Romulan disrupter beams, protecting the ship.)

The point of contact between the solar wind and Earth's magnetic field is the *shock front* or *bow shock*. As the solar wind bends around Earth's magnetic field, it stretches out the field lines along with it, as you can see in Figure 4.1.2-29. In the electromagnetic spectrum, Earth resembles a boat traveling through the water with a wake behind it. Inside the shock front, the point of contact between the charged particles of the solar wind and the magnetic field lines is the *magnetopause*, and the area directly behind the Earth is the *magnetotail*. As we'll see, charged particles can affect spacecraft orbiting well within Earth's protective magnetosphere.

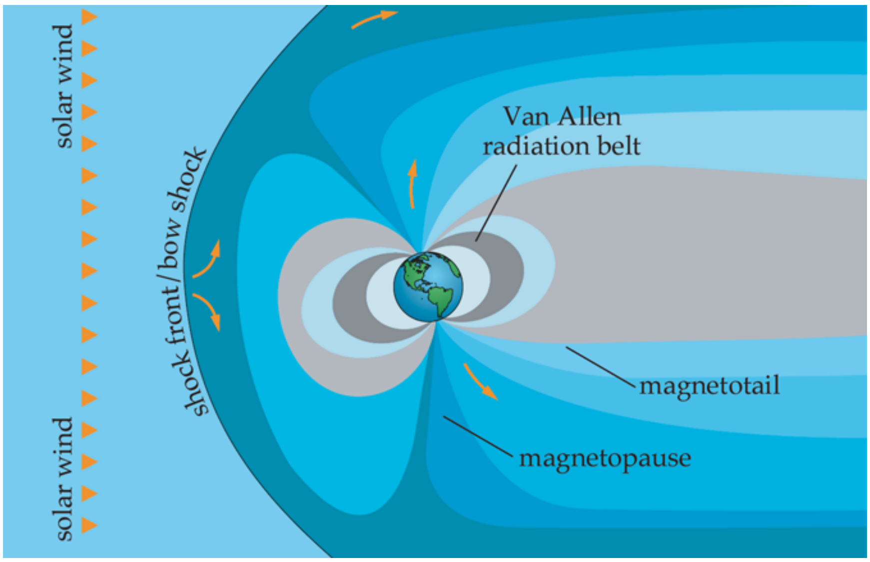

Figure 4.1.2-29. Interaction Between Solar Wind and Earth's Magnetic Field. As the solar wind and GCRs hit Earth's magnetosphere, they are deflected, keeping us safe.

As the solar wind interacts with Earth's magnetic field, some high-energy particles get trapped and concentrated between field lines. These areas of concentration are the *Van Allen radiation belts*, named after Professor James Van Allen of the University of Iowa. Professor Van Allen discovered them based on data collected by Explorer 1, America's first satellite, launched in 1958.

Although we call them "radiation belts," space is not really radioactive. Scientists often lump charged particles with EM radiation and call them radiation because their effects are similar. Realize, however, that we're really dealing with charged particles in this case. (Perhaps we should call the radiation belts, "charged-particle suspenders," because they're really full of charged particles and occupy a region from pole to pole around Earth!)

Whether charged particles come directly from the solar wind, indirectly from the Van Allen belts, or from the other side of the galaxy, they can harm spacecraft in three ways

- Charging
- Sputtering
- Single-event phenomenon

Spacecraft charging isn't something the government does to buy a spacecraft! The effect of charged particles on spacecraft is similar to us walking across a carpeted floor wearing socks. We build up a static charge that discharges when we touch something metallic—resulting in a nasty shock. *Spacecraft charging* results when charges build up on different parts of a spacecraft as it moves through concentrated areas of charged particles. Once this charge builds up, discharge can occur with disastrous effects—damage to surface coatings, degrading of solar panels, loss of power, or switching off or permanently damaging electronics.

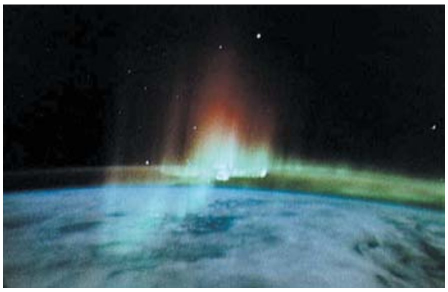

Figure 4.1.2-30. Lights in the Sky. As charged particles from the solar wind interact with Earth's upper atmosphere, they create a spectacular sight known as the Northern (or Southern) Lights. People living in high latitudes can see this light show. Shuttle astronauts took this picture while in orbit. *(Courtesy of NASA/Johnson Space Center)*

Sometimes, these charged particles trapped by the magnetosphere interact with Earth's atmosphere in a dazzling display called the Northern Lights or Aurora Borealis, as shown in Figure 4.1.2-30. This light show comes from charged particles streaming toward Earth along magnetic field lines converging at the poles. As the particles interact with the atmosphere, the result is similar to what happens in a neon light—charged particles interact with a gas, exciting it, and making it glow. On Earth we see an eerie curtain of light in the sky.

These particles can also damage a spacecraft's surface because of their high speed. It's as if they were "sand blasting" the spacecraft. We refer to this as *sputtering*. Over a long time, sputtering can damage a spacecraft's thermal coatings and sensors.

Finally, a single charged particle can penetrate deep into the guts of the spacecraft to disrupt electronics. Each disruption is known as a *single event phenomenon (SEP)*. Solar flares and GCR can cause a SEP. One type of SEP is a *single event upset (SEU)* or "bitflip." This occurs when the impact of a high-energy particle resets one part of a computer's memory from 1 to 0, or vice versa. This can cause subtle but significant changes to spacecraft functions. For example, setting a bit from 1 to 0 may cause the spacecraft to turn off or forget which direction to point its antenna. Some scientists believe an SEU was the cause of problems with the Magellan spacecraft when it first went into orbit around Venus and acted erratically.

It's difficult for us to prevent these random impacts. Spacecraft shielding offers some protection, but spacecraft operators must be aware of the possibility of these events and know how to recover the spacecraft should they occur.

Section Review

Key Concepts

- Six major environmental factors affect spacecraft in Earth orbit.
  - Gravity
  - Atmosphere
  - Vacuum
  - Micrometeoroids and space junk
  - Radiation
  - Charged particles
- Earth exerts a gravitational pull which keeps spacecraft in orbit. We best describe the condition of spacecraft and astronauts in orbit as free fall, because they're falling around Earth.
- Earth's atmosphere isn't completely absent in low-Earth orbit. It can cause
  - Drag—which shortens orbit lifetimes
  - Atomic oxygen—which can damage exposed surfaces
- In the vacuum of space, spacecraft can experience
  - Out-gassing—a condition in which a material releases trapped gas particles when the atmospheric pressure drops to near zero
  - Cold welding—a condition that can cause metal parts to fuse together
  - Heat transfer problems—a spacecraft can rid itself of heat only through radiation
- Micrometeoroids and space junk can damage spacecraft during a high speed impact
- Radiation, primarily from the Sun, can cause
  - Heating on exposed surfaces
  - Damage to electronic components and disruption in communication
  - Solar pressure, which can change a spacecraft's orientation
- Charged particles come from three sources
  - Solar wind and flares
  - Galactic cosmic rays (GCRs)
  - Van Allen radiation belts
- Earth's magnetic field (magnetosphere) protects it from charged particles. The Van Allen radiation belts contain charged particles, trapped and concentrated by this magnetosphere.
- Charged particles from all sources can cause
  - Charging
  - Sputtering
  - Single event phenomena (SEP)

4.1.2.3 Living and Working in Space

In This Section You'll Learn to...

- Describe the free-fall environment's three effects on the human body
- Discuss the hazards posed to humans from radiation and charged particles
- Discuss the potential psychological challenges of spaceflight

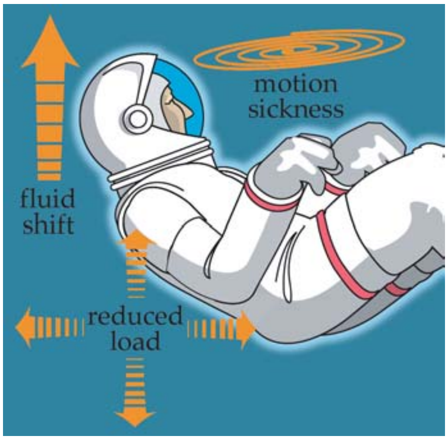

Figure 4.1.2-31. The Free-fall Environment and Humans. The free-fall environment offers many hazards to humans living and working in space. These include fluid shift, motion sickness, and reduced load on weight-bearing tissue.

Figure 4.1.2-32. Lower Body Negative Pressure Device. To reverse the effects of fluid shift while on orbit, astronauts "soak" in the Lower Body Negative Pressure device, which draws fluid back to their legs and feet. *(Courtesy of NASA/Johnson Space Center)*

Humans and other living things on Earth have evolved to deal with Earth's unique environment. We have a strong backbone, along with muscle and connective tissue, to support ourselves against the pull of gravity. On Earth, the ozone layer and the magnetosphere protect us from radiation and charged particles. We don't have any natural, biological defenses against them. When we leave Earth to travel into space, however, we must learn to adapt in an entirely different environment. In this section, we'll discover how free fall, radiation, and charged particles can harm humans in space. Then we'll see some of the psychological challenges for astronauts venturing into the final frontier.

Free fall

Earlier, we learned that in space there is no such thing as "zero gravity"; orbiting objects are actually in a free-fall environment. While free fall can benefit engineering and materials processing, it poses a significant hazard to humans. Free fall causes three potentially harmful physiological changes to the human body, as summarized in Figure 4.1.2-31.

- Decreased hydrostatic gradient—fluid shift
- Altered vestibular functions—motion sickness
- Reduced load on weight-bearing tissues

Hydrostatic gradient refers to the distribution of fluids in our body. On Earth's surface, gravity acts on this fluid and pulls it into our legs. So, blood pressure is normally higher in our feet than in our heads. Under free fall conditions, the fluid no longer pools in our legs but distributes equally. As a result, fluid pressure in the lower part of the body decreases while pressure in the upper parts of the body increases. The shift of fluid from our legs to our upper body is called a *decreased hydrostatic gradient* or *fluid shift* (Figure 4.1.2-32). Each leg can lose as much as 1 liter of fluid and about 10% of its volume. This effect leads to several changes.

To begin with, the kidneys start working overtime to eliminate what they see as "extra" fluid in the upper part of the body. Urination increases, and total body plasma volume can decrease by as much as 20%. One effect of this is a decrease in red blood cell production.

The fluid shift also causes *edema* of the face (a red "puffiness"), so astronauts in space appear to be blushing. In addition, the heart begins to beat faster with greater irregularity and it loses mass because it doesn't have to work as hard in free fall. Finally, astronauts experience a minor "head rush" on return to Earth. We call this condition *orthostatic intolerance*—that feeling we sometimes get when we stand up too fast after sitting or lying down for a long time. For astronauts returning from space, this condition is sometimes very pronounced and can cause blackouts.

Vestibular functions have to do with a human's built-in ability to sense movement. If we close our eyes and move our head around, tiny sensors in our inner ear detect this movement. Together, our eyes and inner ears determine our body's orientation and sense acceleration. Our vestibular system allows us to walk without falling down. Sometimes, what we feel with our inner ear and what we see with our eyes gets out of synch (such as on a high-speed roller coaster). When this happens, we can get disoriented or even sick. That also explains why we tend to experience more motion sickness riding in the back seat of a car than while driving—we can feel the motion, but our eyes don't see it.

Because our vestibular system is calibrated to work under a constant gravitational pull on Earth's surface (or 1 "g"), this calibration is thrown off when we go into orbit and enter a free-fall environment. As a result, nearly all astronauts experience some type of motion sickness during the first few days in space until they can re-calibrate. Veteran astronauts report that over repeated spaceflights this calibration time decreases.

Free fall results in a loss of cardiovascular conditioning and body fluid volume, skeletal muscle atrophy, loss of lean body mass, and bone degeneration accompanied by calcium loss from the body. These changes may not be detrimental as long as an individual remains in free fall or microgravity. However, they can be debilitating upon return to a higher-gravity environment. Calcium loss and related bone weakening, in particular, seem progressive, and we don't know what level of gravity or exercise (providing stress on the weight-bearing bones) we need to counter the degenerative effects of free fall. However, if unchecked, unacceptable fragility of the bones could develop in a person living in microgravity for 1–2 years [Churchill, 1997]

If you're bedridden for a long time, your muscles will grow weak from lack of use and begin to atrophy. Astronauts in free fall experience a similar reduced load on weight bearing tissue such as on muscles (including the heart) and bones. Muscles lose mass and weaken. Bones lose calcium and weaken. Bone marrow, which produces blood, is also affected, reducing the number of red blood cells.

Scientists are still working on ways to alleviate all these problems of free fall. Vigorous exercise offers some promise in preventing long-term atrophy of muscles (Figure 4.1.2-33), but no one has found a way to prevent changes within the bones. Some scientists suggest astronauts should have "artificial gravity" for very long missions, such as missions to Mars.

Figure 4.1.2-33. Shuttle Exercise. To maintain fitness and control the negative effects of free fall, astronauts workout everyday on one of several aerobic devices on the Shuttle. Here, astronaut Steven Hawley runs on the Shuttle's treadmill. *(Courtesy of NASA/Johnson Space Center)*

Spinning the spacecraft would produce this force, which would feel like gravity pinning them to the wall. This is the same force we feel when we take a corner very fast in a car and we're pushed to the outside of the curve. This artificial gravity could maintain the load on all weight-bearing tissue and alleviate some of the other detrimental effects of free fall. However, building and operating such a system is an engineering challenge.

Radiation and Charged Particles

As we've seen, the ozone layer and magnetosphere protect us from charged particles and electromagnetic (EM) radiation down here on Earth. In space, however, we're well above the ozone layer and may enter the Van Allen radiation belts or even leave Earth's vicinity altogether, thus exposing ourselves to the full force of galactic cosmic rays (GCRs).

Until now, we've been careful to delineate the differences between the effects of EM radiation and charged particles. However, from the standpoint of biological damage, we can treat exposure to EM radiation and charged particles in much the same way. The overall severity of this damage depends on the total dosage. Dosage is a measure of accumulated radiation or charged particle exposure.

Quantifying the dosage depends on the energy contained in the radiation or particles and the *relative biological effectiveness (RBE)*, rating of the exposure. We measure dosage energy in terms of *RADs*, with one RAD representing 100 erg (10^{-5} J) of energy per gram of target material (1.08×10^{-3} cal/lb.). (This is about as much energy as it takes to lift a paper clip 1 mm [3.9×10^{-2} in.] off a desk). The RBE represents the destructive power of the dosage on living tissue. This depends on whether the exposure is EM radiation (photons) with an RBE of one, or charged particles with an RBE of as much as ten, or more. An RBE of ten is ten times more destructive to tissue than an RBE of one. The total dosage is then quantified as the product of RAD and RBE to get a dosage measurement in *roentgen equivalent man (REM)*. The REM dosage is cumulative over a person's entire lifetime.

The potential effects on humans exposed to radiation and charged particles depend to some extent on the time over which a dosage occurs. For example, a 50-REM dosage accumulated in one day will be much more harmful than the same dosage spread over one year. Such short-term dosages are called *acute dosages*. They tend to be more damaging, primarily because of their effect on fast reproducing cells within our bodies, specifically in the gastrointestinal tract, bone marrow, and testes. Table 4.1.2-1 gives the effects of acute dosages on humans, including blood count changes, vomiting, diarrhea, and death. The cumulative effects of dosage spread over much longer periods include cataracts, and various cancers, such as leukemia.

Just living on Earth, we all accumulate dosage. For example, living one year in Houston, Texas, (at sea level) gives us a dosage of 0.1 REM. As we get closer to space there is less atmosphere protecting us, so living in Denver, Colorado, (the "Mile-high City") gives us a dosage of twice that

Table 4.1.2-1. Effects of Acute Radiation and Charged Particle Dosages on Humans. (From Nicogossian, et al.) The higher the dosage and the faster it comes, the worse the effects on humans.

Effect	Dosage (REM)
Blood count changes	15–50
Vomiting "effective threshold"*	100
Mortality "effective threshold"*	150
LD_{50}† with minimal supportive care	320–360
LD_{50}† with full supportive medical treatment required	480–540

* Effective threshold is the lowest dosage causing these effects in at least one member of the exposed population

† LD_{50} is the lethal dosage in 50% of the exposed population

amount. Certain medical procedures also contribute to our lifetime dosage. One chest X-ray, for example, gives you 0.01 REM exposure. Table 4.1.2-2 shows some typical dosages for various events.

Table 4.1.2-2. Dosages for Some Common Events (from SICSA Outreach and Nicogossian, et al.).

Event	Dosage (REM)
Transcontinental round trip in a jet	0.004
Chest X-ray (lung dose)	0.01
Living one year in Houston, Texas (sea level)	0.1
Living one year in Denver, Colorado (elev. 1600 m)	0.2
Skylab 3 for 84 days (skin dose)	17.85
Space Shuttle Mission (STS-41D)	0.65

Except for solar flares, which can cause very high short-term dosages with the associated effects, astronauts concern themselves with dosage spread over an entire mission or career. NASA sets dosage limits for astronauts at 50 REM per year. Few astronauts will be in space for a full year, so their dosages will be much less than 50 REM. By comparison, the nuclear industry limits workers to one tenth that, or five REM per year. A typical Shuttle mission exposes the crew to a dosage of less than one REM. The main concern is for very long missions, such as in the space station or on a trip to Mars.

For the most part, it is relatively easy to build shielding made of aluminum or other light metals to protect astronauts from the solar EM radiation and the protons from solar wind. In the case of solar flares, long missions may require "storm shelters"—small areas deep within the ship that would protect astronauts for a few days until the flare subsides. However, GCRs cause our greatest concern. Because these particles are so massive, it's impractical to provide enough shielding. To make matters worse, as the GCRs interact with the shield material, they produce secondary radiation (sometimes called "bremsstrahlung" radiation after a German word for braking), which is also harmful.

Space-mission planners try to avoid areas of concentrated charged particles such as those in the Van Allen belts. For example, because space suits provide very little shielding, NASA plans extra vehicular activities (EVA—or space walks) for when astronauts won't pass through the "South Atlantic Anomaly." In this area between South America and Africa, shown in Figure 4.1.2-34, the Van Allen belts "dip" toward Earth. Long missions, however, such as those to Mars, will require special safety measures, such as "storm shelters" and a radiation warning device when solar flares erupt. As for GCRs, we need to do more research to better quantify this hazard and to minimize trip times.

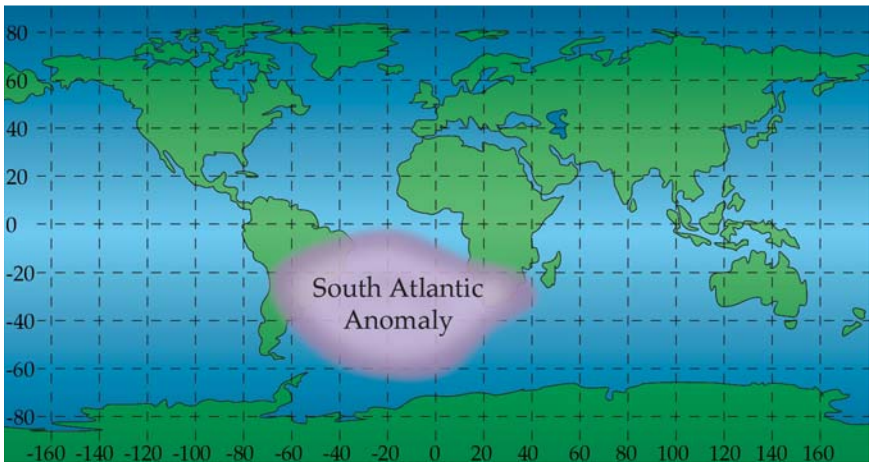

Figure 4.1.2-34. The South Atlantic Anomaly. The South Atlantic Anomaly is an area over the Earth where the Van Allen belts "dip" closer to the surface. Astronauts should avoid space walks in this region because of the high concentration of charged particles.

Psychological Effects

Because sending humans to space costs so much, we typically try to get our money's worth by scheduling grueling days of activities for the crew. This excessive workload can begin to exhaust even the best crews, seriously degrading their performance, and even endangering the mission. It can also lead to morale problems. For instance, during one United States Skylab mission, the crew actually went on strike for a day to protest the excessive demands on their time. Similar problems have been reported aboard the Russian Mir space station.

The crew's extreme isolation also adds to their stress and may cause loneliness and depression on long missions. Tight living conditions with the same people day-after-day can also take its toll. Tempers can flare, and team performance suffers. This problem is not unique to missions in space. Scientists at remote Antarctic stations during the long, lonely winters have reported similar episodes of extreme depression and friction between team members.

We must take these human factors into account when planning and designing missions. Crew schedules must include regular breaks or "mini-vacations." On long missions, crews will need frequent contact with loved ones at home to alleviate their isolation. Planners also must select crew members who can work closely, in tight confines, for long periods (Figure 4.1.2-35). Psychological diversions such as music, video games, and movies will help on very long missions to relieve boredom.

Figure 4.1.2-35. Shuttle Close Quarters. Living with seven crew members for ten days on the Shuttle can put a strain on relationships. Careful screening and busy schedules help prevent friction. Here, the crew of STS 96 pose for their traditional inflight portrait. *(Courtesy of NASA/Johnson Space Center)*

Section Review

Key Concepts

- Effects of the space environment on humans come from
  - Free fall
  - Radiation and charged particles
  - Psychological effects
- The free-fall environment can cause
  - Decreased hydrostatic gradient—a condition where fluid in the body shifts to the head
  - Altered vestibular functions—motion sickness
  - Decreased load on weight bearing tissue—causing weakness in bones and muscles
- Depending on the dosage, the radiation and charged particle environment can cause short-term and long-term damage to the human body, or even death
- Psychological stresses on astronauts include
  - Excessive workload
  - Isolation, loneliness, and depression

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