Something About Environment

6

TO discuss how spacecraft are designed, we need to know a little bit about the environment in which they operate. The design of just about every machine built by engineers is influenced by its operating environment. For example, the design of an automobile is influenced by a number of factors, such as vehicle robustness, reliability, safety, the minimization of fuel consumption, reducing aerodynamic drag, and so on. These requirements are governed by the *environment* in which the vehicle will operate, that is, the conditions it will encounter on urban roads and highways. So, as you drive to work you can see the outcome of this environment-driven design process. Given that the design requirements for each vehicle are similar in terms of the encountered conditions, the computerized design process used by auto manufacturers these days results in all the cars (of the same vintage) looking similar to one another, apart from minor cosmetic tweaks!

As the environmental aspects become more dominant, such as in the case of an airplane, it becomes even more difficult to distinguish manufacturers, with only the connoisseurs being able to tell an Airbus from a Boeing.

In spacecraft, we have already seen in Chapter 5 how the flight environment of the launcher influences the spacecraft's design. In this case, the launch environment, which entails high levels of acceleration, vibration, and noise, governs how the spacecraft structure is designed. The designer has to ensure that the spacecraft survives the few minutes' ride from launch pad to orbit (we will return to this issue again in Chapter 9).

From the above discussion, it is easy to see that once the spacecraft has reached orbit, the natural space environment it finds there will also influence the spacecraft's design, and the designers need to know about this environment and take it into account as the design evolves. The characteristics of the space environment have been investigated by space scientists over many decades, and this information has been grasped enthusiastically by the engineers, thus enhancing the performance of spacecraft in the space environment. This environment has many different aspects, but the ones most influential in spacecraft design are *microgravity*

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(or weightlessness), *vacuum*, *radiation*, and *space debris*. This chapter briefly discusses each of these from the point of view of both the scientist and the engineer. The former is driven by curiosity to know the nature of what's out there, whereas the latter is interested in understanding the impact the environment has on the design of the spacecraft.

Hostile or Friendly?

As far as humans and our machines are concerned, there are some aspects of the space environment that are definitely hostile, and these include vacuum, high-energy electromagnetic and particle radiation, and space debris. However, there are other aspects that could be considered friendly: there is effectively no gravity, the environment is (mostly) clean, and we need not worry about factors that cause the erosion and deterioration that we find down here on the surface of Earth, such as wind and rain. As you might expect, it is the hostile elements that have most effect on how the spacecraft is designed, and these will be the focus of most of what follows. Interestingly, the Sun has a major effect on all of the hostile elements, and we need to say a few things about its dominant role in governing the space environment.

The Sun Rules OK!

Where does the Sun's energy come from?

The region of space surrounding the Sun is not called the solar system simply because of the gravitational grip that the Sun exercises over its attendant planets. It is also because of the total dominance it has in governing the space environment from the inner planets out to a distance on the order of 100 to 200 astronomical units (AU). This outer boundary of the solar system, called the *heliopause,* is the place where the Sun's influence ceases and the interstellar medium—the stuff between the stars in our galaxy, the Milky Way—begins.

The Sun, our star, is something we tend to take for granted. We never question that it will rise each day to illuminate our daily routine. We never give a second glance to the ever-present source of beautiful light and warmth that makes for a perfect summer's day. This rather laid-back attitude is encouraged perhaps by the Sun's small apparent size; it subtends an angle of only half a degree on the sky. However, this apparent size hides its true scale. The Sun is an object of about 1,400,000 km (870,000 miles) in diameter with a mass some 330,000 times that of our own planet! If we did stop to reflect for a moment, it is a rather sobering thought that we are living only 150 million kilometers (93 million miles) away from a star! Fortunately for us, it is a rather stable star, its output being more or less constant over the last few billion years, and the astrophysicists tell us that it will stay that way for a few more billions years to come. This stability is derived from a long-term balance between the energy source within the Sun tending to blow it apart and the force of gravitation tending to hold it together.

I find it amazing that we did not understand the source of the Sun's energy until as recently as the 1930s, when physicists began to uncover the mysteries of *nuclear fusion.* As the name suggests, this is the process of fusing atoms together to form heavier atoms. The basic energy source that powers the Sun is the fusing together of hydrogen atoms to make helium atoms, and this involves the release of nuclear energy. The destructive capability of the hydrogen bomb is also frightening testimony to the power of nuclear fusion. Some years ago many drivers displayed a green bumper sticker saying, "Nuclear energy—no thanks!" accompanied by a smiley Sun. Ironically, the antinuclear campaign's logo of the sun represented the largest source of nuclear energy in the neighbourhood!

How does nuclear fusion work? To begin, there are 92 different kinds of naturally occurring atoms, or *elements*. The *Periodic Table* lists these naturally occurring elements, starting at number 1, hydrogen, and ending with number 92, uranium. The currently accepted model of an atom is that it has a tiny, compact nucleus at its center composed of protons and neutrons, and this is surrounded by a cloud of orbiting electrons. The protons and neutrons are subatomic particles having about the same mass as each other, of the order of 0.000 000 000 000 000 000 000 000 001 of a kilogram, while the electrons are much smaller in mass (by a factor of around 2000). The protons each carry a positive electric charge and the electrons a negative one, while the neutrons are electrically neutral. This electric charge is the same as the static electricity that can sometimes build up on your clothing. You certainly get to know it's there if you touch a radiator, and the static charge gives you a mild electric shock as it dissipates to Earth. As the discussion above suggests, electric charges come in two varieties: positive and negative. We find that two like charges—two positives or two negatives—exert a force that repel each other, while a negative and a positive charge attract one another. The strength of this electric force between charges behaves like gravity in that it is governed by an inverse square law (see Chapter 1).

The numerical position of each element in the Periodic Table depends on the number of protons in the nucleus, so we have the simplest and lightest element hydrogen at number 1, consisting of a nucleus with one proton. At number 2 we have helium, with two protons (and two neutrons) in the nucleus, and so on up to uranium with 92 protons in the nucleus. To help visualize this, Figure 6.1 shows a hydrogen and a helium atom where the various particles are represented as billiard balls. Of course, the particles are not really like billiard balls, but instead have all sorts of weird properties that we need not discuss (if you are interested in knowing more, then I would suggest you find a popular book on *quantum mechanics*, which is the physics of the small world of subatomic particles). The nature of the subatomic world can be summed up by saying that we don't have any idea, for example, what an electron is! I find it remarkable that we can build a global consumer industry—the electronics business—on the basis of this fundamental ignorance. The saving grace, of course, is that our current theories are good at predicting *how* an electron behaves, so we don't really need to know *what* it is to build a television set or a computer games console.

We can complicate things a little by noting that atoms of a particular element can also exist in several forms, called *isotopes*, with different numbers of neutrons. For example, an atom with one proton and one neutron in the nucleus is an isotope of hydrogen called deuterium. One proton and two neutrons gives another isotope of hydrogen called tritium. These isotopes are also illustrated in Figure 6.1. The other puzzling thing about atoms with more than one proton in the nucleus is why the positively charged protons do not repel each other, and cause the nucleus to fly apart. The answer is that the physicists have discovered another force, the *strong nuclear force,* that binds the nucleus together. We have now come across three types of force so far in this book: gravity, electromagnetism (which includes the electric force), and now the strong nuclear force. So far, scientists have discovered only four fundamental forces in nature. The strength of the strong nuclear force exceeds that of the electric force, but it is

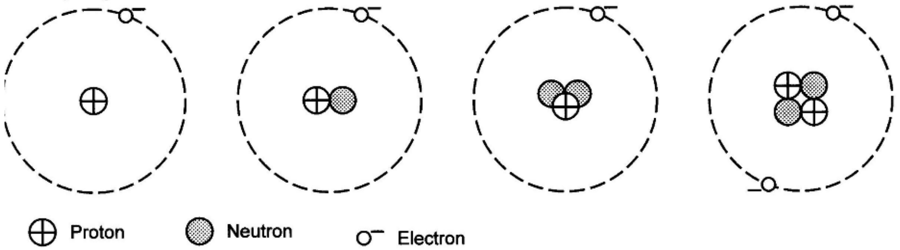

Figure 6.1: An illustration (not to scale!) of the hydrogen atom and the helium atom. The first two isotopes of hydrogen – deuterium and tritium – are also shown.

a very short-range force and so only acts, more or less, when the protons and neutrons come into contact with each other in a nucleus. The reason why there are only 92 *naturally* occurring elements is that when you get to number 93 (neptunium), it has 93 positively charged protons in its nucleus, and the repulsive electric force is just big enough to overcome the strong nuclear force, causing the nucleus to break up. At the time of this writing, scientists have created elements with up to 117 protons in the nucleus, but these heavy elements are unstable and don't hang around for long.

Now we can return to the process of nuclear fusion, which powers the Sun. The basic mechanism is to fuse together atoms or isotopes of hydrogen to form helium, and this results in the release of nuclear energy. The problem with fusion is overcoming the repulsive electric force that the protons have, and getting them close enough so that the strong nuclear force can grab hold of them and squeeze them together as a nucleus. Fortunately, the conditions in the core of the Sun are ideal for this to happen. The density is extremely high so that the protons are already very close together. The temperature is also extreme, on the order of 15 million degrees Celsius, which is such a large number as to make its meaning difficult to grasp. But the consequences for the protons is that, at these temperatures, they have high energies, and are rushing about at high speeds. This combination of the density and energy of the protons means that they can overcome their mutual electric repulsion, and get close enough for the strong nuclear force to bind them together. Thus we can form the nucleus of heavier atoms from light ones.

But where does the nuclear energy come from? In Chapter 1, we discussed what Einstein did for us. Another thing he gave us is an understanding that energy and mass are essentially different forms of the same thing. This he summarized in his famous equation $E = mc^2$, which basically says that mass m can be converted into energy E and vice versa (where $c = 300{,}000{,}000$ meters per second is the speed of light). I know this book isn't supposed to have any equations in it, but this one is so well known that it has become a part of our culture. It pops up in the titles of books and television programs. The thing to note about a helium nucleus is that, remarkably, it weighs less than the two protons and two neutrons (Figure 6.1) that compose it. Some of the mass has been used up in the energy associated with the action of the strong nuclear force in binding the helium nucleus together. To be precise, the helium nucleus has a mass just 99.3% of the mass of its parts. When the protons and neutron fuse together to form a helium atom, 0.7% of their mass is converted to pure energy in a way described by Einstein's famous equation.

We can do a simple sum to calculate how much of the Sun's mass is being converted every second into energy by the process of nuclear fusion. If we go out into the garden and present an area of one square meter to the Sun, the solar power falling on that surface is roughly 1.4 kilowatts (neglecting any losses that may occur due to passage through the atmosphere). If we now multiply this power by the number of square meters on a sphere the size of the Earth's orbit around the Sun, we can calculate the total power radiated by the Sun. Using Einstein's equation, we can then estimate the amount of mass being converted to energy each second. This turns out to be a staggering 4¼ million metric tonnes! This may sound like rather a lot of mass loss for the Sun to sustain, but the Sun can easily keep this up for many billions of years without it making much of a dent in the total mass. In fact, over the last 4½ billion years or so of the Sun's history, during which it has been shining at more or less a steady rate, about 100 Earth masses have been converted into pure radiate energy! Although this is a rather amazing statistic, nevertheless it represents only a tiny fraction of the mass available for nuclear energy production in the Sun.

Our very existence here on Earth is dependent on the Sun's stability, which is maintained by the Sun's massive gravitational field containing the awesome power of this nuclear furnace at its core.

The Sun's Output

With all this activity going on in the Sun, how does it affect us and our Earth-orbiting spacecraft from a distance of 150 million kilometers away? The main output from the Sun is radiation, and this comes in two varieties: electromagnetic (EM) radiation and particle radiation.

Light is one form of *electromagnetic radiation.* All forms of EM radiation travel at the speed of light (see above), and are distinguished from each other by the wavelength of the radiation. Figure 6.2 shows different types of EM radiation, from short wavelength *gamma rays* to long wavelength *radio*

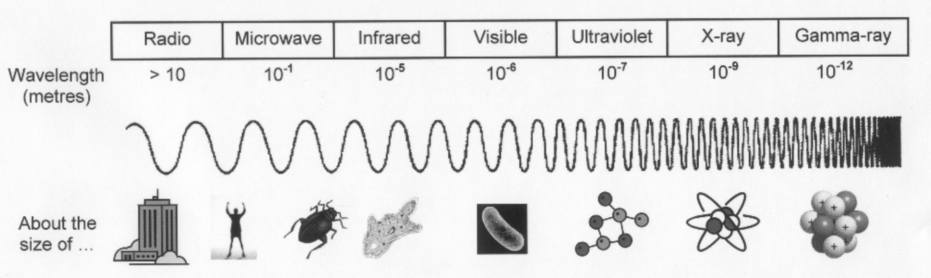

Figure 6.2: Visible light is just one part of the electromagnetic spectrum. Different types of EM radiation are distinguished by wavelength, from short wavelength gamma rays to long wavelength radio waves. The wavelength is about the size of the items pictured at the bottom of the diagram (the object that looks a bit like a peanut – about the size of the visible light wavelength – is supposed to be a small bacterium).

waves. The wavelength of each type of radiation is given in meters, using a shorthand notation used by scientists. For example, 10^{-1} m means 0.1 m, and 10^{-6} m means 0.000 001 m. Note that the number after the minus sign indicates how many digits there are after the decimal point. For example, gamma radiation has a tiny wavelength of 10^{-12} m = 0.000 000 000 001 m, about the size of an atom's nucleus.

The visible part of the spectrum—light—has a wavelength ranging from about 0.4 μm (violet) to 0.8 μm (red), where μm stands for micrometer (sometimes called a micron), which is a millionth of a meter = 10^{-6} m = 0.000 001 m. Slightly shorter wavelengths take us into the *ultraviolet* region (which can cause sunburn on a sunny day), and the slightly longer wavelengths take us into the *infrared* region (which is basically heat radiation, such as that which you feel on your face in front of a glowing open fire).

The Sun emits EM radiation across the entire spectrum, but the peak of its output is at a wavelength of about 0.5 μm, which is in the yellow part of the visible light spectrum. Evolutionary theory says that this is why our eyes are most sensitive in this part of the spectrum, the eye having evolved in an environment dominated by sunlight. The harmful emissions of gamma and X-rays from the Sun are fortunately (relatively) small. This short wavelength radiation is particularly hazardous to humans. It is, for example, one cause of radiation sickness after exposure to a nuclear bomb detonation. There is also a significant intensity of ultraviolet radiation, but fortunately we are protected from most of this at ground level by the famous *ozone layer*. We are now aware, however, that dangerous holes are being punched in this protective shield by the inadvisable use of certain artificial chemicals. Above the atmosphere, spacecraft are of course exposed to the full range of the EM radiation spectrum from the Sun.

The other form of radiation from the Sun, which can damage orbiting spacecraft and people, comes as a stream of energetic (high speed) subatomic particles called the *solar wind*. The source of this is the violent eruptions that take place on the Sun's searingly hot surface (at a temperature of around 6000°C), and in its atmosphere. Material is flung into space mostly in the form of protons and electrons, but also in the form of the nuclei of atoms stripped of their electrons—called *ions*. By the time it reaches Earth, this steady stream of solar wind has a density of a few tens of particles per cubic centimeter and is traveling at a speed typically between 300 and 1000 km per second (670,000 to 2,240,000 miles per hour). Despite the relatively low density of this stream of ions, it does have a significant effect on our planet, and in particular on the Earth's magnetic field. The Earth has its own magnetic field, which looks a bit like that of a bar magnet. Science teachers often demonstrate magnetic fields by sprinkling iron filings onto a sheet of paper, which in turn is placed over a bar magnet. By jiggling the paper, the iron filings outline the shape of the bar's magnetic field, to reveal a pattern like that shown in Figure 6.3a. This classic shape of Earth's magnetic field is referred to as a *magnetic dipole*. However, the solar wind also carries a magnetic field, and when this encounters Earth's field, the classic dipole shape is disturbed considerably.

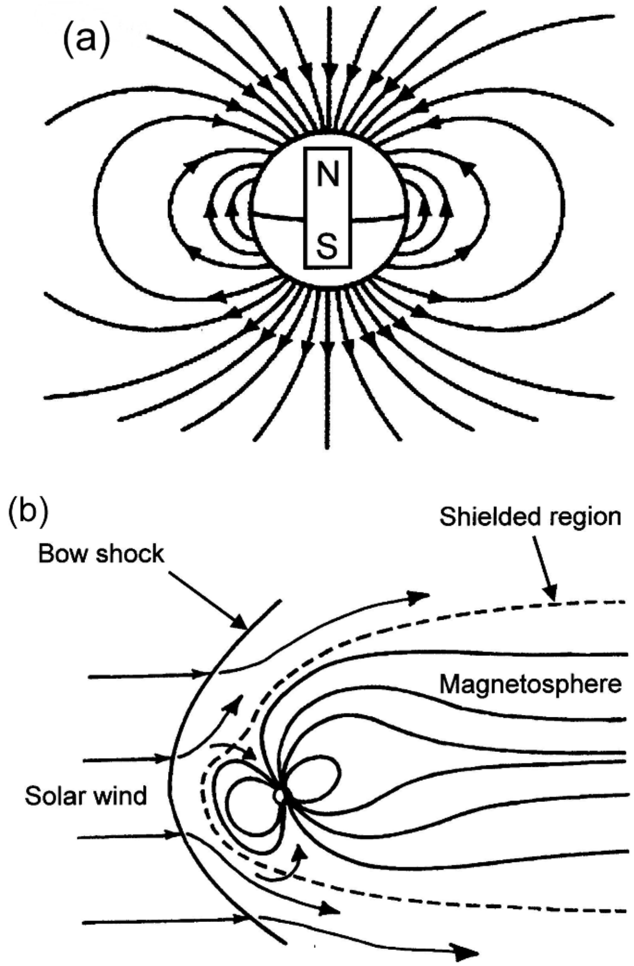

Figure 6.3: (a) The shape of the magnetic field of the Earth resembles that of a bar magnet. (b) Earth's magnetic field is changed by its interaction with the solar wind. Generally the solar wind particle radiation is deflected by Earth's protective magnetic field, although some charged particles are trapped in the magnetosphere, and some reach Earth over the polar regions causing auroral displays.

This *solar-terrestrial interaction* between the solar wind and the Earth's magnetic field is complex, and acquiring an understanding of it has stretched the intellect and imagination of many talented scientists over a number of decades of research. To gain some insight ourselves, and to appreciate why it is important, we need to think about some basic aspects of electricity and magnetism. The first thing to note is that an electric current in a wire produces a magnetic field. This idea has been around for a long time, being first demonstrated in 1820. That this is true can be easily seen by placing a compass needle near a wire carrying electricity. Normally the needle would align itself along Earth's magnetic field and point north, but the electrical current produces its own magnetic field that disturbs the needle so that it no longer does so. It is a simple job to repeat this historic experiment with a compass, a length of insulated wire with the insulation stripped off the ends, and a battery. To make it work, we need direct current (DC)—a flow of electrons in the wire in one direction only, which is provided by the battery. A nearly expired AA battery from a portable CD player or similar device would do fine, as opposed to a fresh one. (We are going to effectively short the battery with the wire, so the battery will probably be no good afterward!) The setup is illustrated in Figure 6.4. The wire is positioned as close as possible above the compass needle, such that the wire is parallel to the north-pointing compass needle. It is sometimes easier to tape one end of the wire onto one of the battery terminals to ensure good electrical contact. If we gently stroke the other end of the wire on the second battery terminal, completing the circuit, we can easily see the current's magnetic field kicking the compass needle, tending to cause it to point in a direction at right angles to the wire.

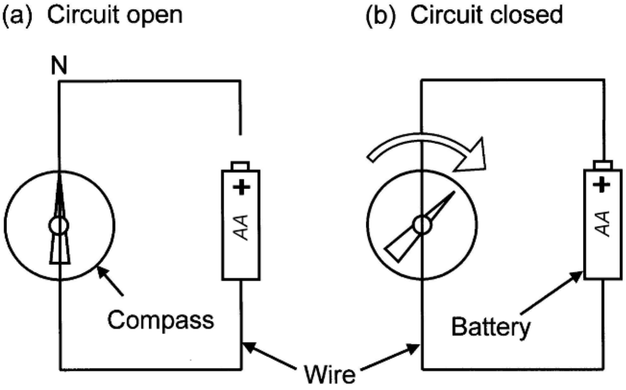

Figure 6.4: A simple setup to demonstrate that a current produces a magnetic field.

It is easy to see a similarity between the solar wind and the current in the wire: both are rapidly moving streams of charged particles. In the wire, the current is made up of a flow of charged electrons, whereas in the solar wind the current is generated by a stream of ionized (charged) particles emanating from the Sun. However, the point is that the solar wind carries its own magnetic field, and when this hits Earth's magnetic field, the classic dipole shape is squashed on the Sunward side, and stretched in the down-Sun direction into a shape something like that shown in Figure 6.3b. This region filled by Earth's magnetic field is referred to as the *magnetosphere*.

The fact that Earth has a magnetic field is a bit of a saving grace in itself, as it prevents the damaging effects of the solar wind from reaching Earth's surface directly. Instead, the solar wind's stream of particle radiation passes through the "bow shock," which slows down the flow, before it is deflected around the magnetosphere. The explanation of this shock front is a bit technical, but basically it is similar to the shock wave in front of a supersonic aircraft. Although the major part of the radiation is diverted, some particles are trapped in Earth's field, and some penetrate Earth's defenses and are funneled down onto the north and south magnetic poles, producing the spectacular manifestation of the Northern and Southern Lights. Otherwise know as *aurora*, these subtle, colorful, and dynamic displays of glowing lights seen in the night sky at high latitudes can arouse a sense of awe in even the most jaded and uninterested of individuals. The glow in the air is caused by exactly the same mechanism as the light coming from a neon strip light; when we switch it on, a flow of charged particles (electrons in this case) is passed through the neon gas, causing the atoms of neon to glow with a characteristic "white" color. Similarly, when the charged particles from the solar wind race down through the atmosphere over the polar regions, the air glows with colors characteristic of the different gases, mainly oxygen and nitrogen, thus producing the auroral display. This intense flux of charged particles also dumps vast amounts of energy into the atmosphere, resulting in an increase in atmospheric temperature of the order of hundreds of degrees Celsius at high altitudes.

The intensity of the Sun's output, both EM radiation and solar wind, varies over an 11-year period called the *solar cycle*. Roughly every 11 years the output goes from a maximum, through a minimum, and back to a maximum again, with the last peak (at the time of this writing) occurring approximately in the year 2001.

At times of solar maximum, the disturbing effects of our nearest star become even more vigorous. The frequency and violence of outbursts on the Sun's surface, referred to as *solar flares*, increase. These hurl billions of metric tonnes of ionized material into interplanetary space. As a consequence, energetic "wodges" of solar wind move outward from the Sun at high speed, and if Earth just happens to be in the wrong place at the wrong time, it will be enveloped in this cloud of energetic charged particles—an event sometimes referred to as a *solar storm.* A picture of such a wodge—more correctly referred to as a *coronal mass ejection* (CME)—is shown in Figure 6.5. This lovely image was acquired by one of the Stereo spacecraft in January 2007. An intense pulse of solar wind is shown on the right-hand side of the picture, with Venus at the bottom left and Mercury at the bottom right. During solar maximum, the frequency and intensity of auroral displays increase, the upper atmosphere heats up and expands, and orbiting satellites can receive damaging and sometimes fatal doses of particle radiation. Electrical power grids on the ground can also come under attack, due to the interaction between the Earth's and the solar wind's magnetic fields. During a solar storm, the magnetic field of the solar wind is relatively intense and time-varying, and this buffets the Earth's field, squashing and stretching it in response to the solar bombardment. At ground level the resulting movement of the magnetic field can induce surges of electrical current in long

Figure 6.5: A coronal mass ejection propagating across the inner solar system, with Venus and Mercury clearly seen in the lower part of the image. The Sun is just off the right-hand side of the picture. (Image courtesy of the National Aeronautics and Space Administration [NASA].)

conductors, such as power lines and pipelines, which can cause terrestrial power systems to overload and blackout. Notably, such an occurrence caused a massive blackout in the province of Quebec, Canada, during a solar maximum storm in 1989.

The fact that the movement of a magnetic field relative to a wire induces an electric current in the wire has also long been known. This principle of electromagnetic induction was first discovered by Michael Faraday in 1831, and was greeted at the time as an interesting curiosity. However, in the years following, this discovery led to the vast industrial application of electrical power generation that has transformed every aspect of our technological world. Put simply, modern power generation is achieved by huge generators that are rotated rapidly by some means, such as heating a fluid to drive a turbine, which in turn drives the generator. The heat source can be through the burning of coal or oil, or by the harnessing of nuclear power. But the point is that the generator rotates a huge harness of wire in a magnetic field, which induces an electrical current in the wire, thus producing electrical power to supply the national grid. Consequently, we have seen that, on the one hand, a moving stream of charged particles (an electrical current) can produce a magnetic field, and, on the other, the relative movement between a wire and a magnetic field can induce an electrical current in the wire. During the latter half of the 19th century, electromagnetic theory was developed, principally by the Scottish physicist James Clerk Maxwell, and we have come to understand these two effects as opposite sides of the same coin. The development of Maxwell's equations, which lay down the theoretical framework for electromagnetism, ranks as one of the greatest achievements of 19th century physics.

Returning to the nature of the Sun's output, and its total dominance over the solar system environment, we are rather fortunate to have a planet that provides an ozone shield to protect us from electromagnetic ultraviolet radiation, and a magnetic field to protect us from high energy particle radiation. Today, as I write, just happens to be one of those cold, clear, bright November mornings that seem so rare in British winters. The Sun, despite being low on the horizon, is absolutely brilliant, seemingly dominating the whole of the eastern hemisphere of the sky, in keeping with its awesome power and its influence over life on Earth and over the solar system in general. After reading this, my hope is that when you're on your way to work tomorrow, you too might look skyward and contemplate how remarkable is our companion star—in fact, if you reflect on it too much, it can be daunting that all that stuff is happening just a short distance away (in cosmic terms) from where we live!

The Impact of the Space Environment on Spacecraft Design

Microgravity

One aspect of the space environment that is not affected by the Sun is microgravity. This term describes the state of *weightlessness* that we discussed in Chapter 2 (see Figure 2.2). As described earlier, once a spacecraft has reached its mission orbit, it is in a state of continuous free-fall so that it effectively encounters an extended period of weightlessness. Obviously, from the point of view of the design of the structure of the spacecraft, this is a gentle situation. It is interesting that, as a consequence, the structural design of the spacecraft is mostly driven by the few minutes' ride into orbit on a launch vehicle, and not by the 10 years or so of operational life on mission orbit. There may be the odd exception to this, such as highly maneuverable military spacecraft, but it does hold true in general for most civil scientific or commercial satellites.Microgravity is generally a rather friendly aspect of the space environment, but it can pose some intriguing problems for space engineers that sometimes require ingenious solutions. One of these, which we have already mentioned in Chapter 5, is how to persuade liquid rocket propellant to enter a rocket engine when it is in a weightless state in the fuel tanks. One common way to do this is to have a rubber diaphragm stretched across the middle of the fuel tank, with propellant on one side and a pressurized gas on the other. When the fuel outlet valve is opened, the diaphragm with the gas pressure behind it squeezes the fuel out of the tank and into the rocket engine.

Another puzzle is how to ground-test devices on the spacecraft that are intended to be deployed and operated in a microgravity environment. This is a common problem for spacecraft test engineers. To perform its mission, a spacecraft often has to deploy solar arrays, large antennas, and possibly other flexible pieces of equipment once it reaches its mission orbit. However, for this equipment to fit into the launcher, it has to be folded up and secured to the spacecraft in a compact and robust arrangement, to ensure its survival during the ride to orbit. Of course, this means that once in orbit, the various deployable items need to be unfurled into the operational arrangement, and this is often done using a variety of spring mechanisms. The problem for the engineers is how to test these deployment mechanisms on the ground (in a 1g environment) that are intended to be operated in weightlessness conditions on orbit. Although this is a complex problem that requires simulating zero gravity on the ground, it is often solved by simple means, such as hanging deployable items from wires to take their weight, or even attaching helium-filled balloons to counter their weight, while tests are carried out.

Vacuum

A pure vacuum—a volume devoid of any material whatsoever—is something not yet encountered by scientists. As we found in Chapter 3, even in Earth orbit at altitudes up to around 1000 km (620 miles) there is a residual atmospheric density, and even in the spaces between the planets in the solar system there is material, called the *interplanetary medium* (mainly emanating from the Sun, as we have seen). However, as far as people and spacecraft are concerned, the degree of vacuum is fairly academic. Over millions of years, we and our ancestors have adapted to an environment where every square centimeter of our bodies is exposed to an atmospheric force of about 10 Newtons, which translates into imperial units as the familiar sea-level pressure of about 15 pounds per square inch. If we remove this pressure by foolishly stepping out of a spacecraft without protection, then surprisingly tests show that we don't explode, or anything dramatic like that. The main problem is that there is no oxygen to breath, and consciousness is lost after a few tens of seconds, followed by death after a couple of minutes. Precisely what happens, and when, is not well known, as scientists are understandably reluctant to do too many experiments! For spacecraft, the effects of high vacuum are rather less spectacular, but nevertheless the spacecraft designer needs to know something about it to avoid using the wrong materials in the spacecraft's construction.

At about 800-km altitude in Earth orbit, the atmospheric pressure is tiny (of the order of 0.000 000 000 001 Newtons per square centimeter), and at these low pressures materials suffer an effect called *outgassing*. This is related to what happens to water when heated—the surface water molecules escape the body of the liquid, and if the process continues, all of the water will vaporize into gas. Similar things happen to metals in high vacuum, where the low pressure causes the surface atoms to outgas. For example, at temperatures of around 180°C, a surface composed of zinc will recede at a rate of around 1 mm per year. However, for a material like titanium—one much more commonly used in spacecraft construction—a temperature of 1250°C is required to achieve the same rate of recession. Thus, as long as the designer chooses the construction materials appropriately, outgassing will not be an issue as far as the strength of the structure is concerned. But sometimes there is a concern over the outgassing material contaminating the spacecraft's surfaces; for example, the performance of a space telescope may be compromised if outgassed material is deposited onto the system's optics.

A related problem for spacecraft is the effect of vacuum upon commonly used terrestrial lubricants. The highly volatile oil-based lubricants we use in our machines down here would outgas (or boil away) in no time at all in the vacuum of space, which has given rise to a whole new science of *space tribology.* To overcome this problem, engineers have had to develop solid lubricant coatings for use in spacecraft bearings and mechanisms. Interested readers can 'google' the term *molybdenum disulfide* which is commonly used as a solid lubricant.

The Effects of Earth's Atmosphere

As we saw in Chapter 3, the motion of spacecraft in low Earth orbit is affected by the atmosphere. The cause of this is air drag, which you may recall is a tiny force that acts in a direction opposite to the motion of the spacecraft. We saw how this takes energy out of the orbit, causing the spacecraft's height to decrease, with the ultimate prospect of a fiery reentry into the denser, lower atmosphere. Of course, there is no altitude where we can say that the atmosphere stops and the interplanetary medium begins. The density of the atmosphere falls steadily, from the breathable mix of oxygen and nitrogen at Earth's surface, to something approaching a vacuum at high altitude. However, we can measure the effects of air drag at altitudes up to about 1000 km (620 miles). Earlier we discussed the Sun's dominant influence on Earth's environment. The drag effects on a low Earth orbiting spacecraft are also significantly affected by the Sun. Over the 11-year solar cycle, the level of solar activity varies, resulting in peaks and troughs in its electromagnetic and particle radiation output. At times of solar maximum, intense EM radiation from the Sun, in particular in the ultraviolet part of the spectrum, causes the temperature of Earth's upper atmosphere to rise.

It's worth thinking for a moment about what we mean by temperature in this outermost layer of Earth's atmosphere, referred to as the *exosphere.* Given that the atmosphere is close to a vacuum at these high altitudes, if we tried to use a thermometer to measure the temperature, there would not be enough air around to give any sort of sensible reading. Instead, when we refer to temperature in such tenuous material, we usually talk about something called *kinetic temperature.* When the Sun's ultraviolet radiation heats up the atmosphere, it essentially "excites" the atmospheric particles and causes them to race around at a higher speed, thus increasing their kinetic temperature.

It is important to realize how tenuous the atmosphere is at high altitudes. For example, an atom of oxygen moving around at an altitude of, say, 600 km (370 miles) will not find another atom to bump into for about 300 km (185 miles), and at an altitude of 800 km (500 miles), this increases to over 1000 km (620 miles). The precise values of these numbers actually vary with the level of solar activity, but the main point is how thin the atmosphere is at these heights. Essentially the atoms and molecules that make up the upper atmosphere move around on *ballistic trajectories*, similar to how cannonballs fly in a gravity field. This may be simplifying the matter a little, but it does help us understand how solar heating of the atmosphere causes its density to increase.

Putting it all together, then, at times of solar maximum the Sun's ultraviolet output increases, which in turn causes a rise in temperature of Earth's atmosphere. This causes the atmospheric atoms and molecules to rush around more rapidly, allowing them to reach higher altitudes in Earth's gravity field. At a particular height the numbers of atmospheric particles per cubic meter increase, producing a higher density. This effect on the atmosphere is significant; for example, the density of the atmosphere at, say, 600 km at high solar activity can be larger than that at low solar activity by more than a factor of 10. We are not just talking about increases of two or three times, but more than an order of magnitude.

In considering the perturbing effect on a spacecraft orbiting at a 600-km altitude, the drag acting on it is related directly to the atmospheric density, so drag at times of high solar activity can be more than a factor of 10 greater than when the Sun is quiet. This will have a significant effect on spacecraft operations, and the mission analysis team will have to take the solar cycle into account in planning the orbit control activities and in the estimation of how much rocket propellant will be required to compensate for these drag effects.

To show the huge effect that the solar cycle has on atmospheric temperature, Figure 6.6 is a chart of the variation in the average exospheric temperature (the temperature of the atmosphere at orbital altitudes) over the last five solar maxima—since the dawn of the space age. Most surprisingly, the upper atmosphere reaches kinetic temperatures of the order of 1000°C when the Sun's level of activity is high. The 11-year solar activity cycle can also be clearly seen, with the atmospheric temperature at solar maximum being something like 600°C above that at solar minimum. Another striking feature of Figure 6.6 is the spiky nature of the temperature profile at times of solar maximum. This spike is due to temperature variations caused by more short-lived events such as the solar storms mentioned above. During such storms, some of the solar wind particles from the Sun are focused down into the atmosphere at the north and south polar regions by Earth's magnetic field, causing auroral displays. This influx dumps massive amounts of energy into the atmosphere, which causes heating locally at the poles. Within a short period (of the order of hours), this heating propagates toward the

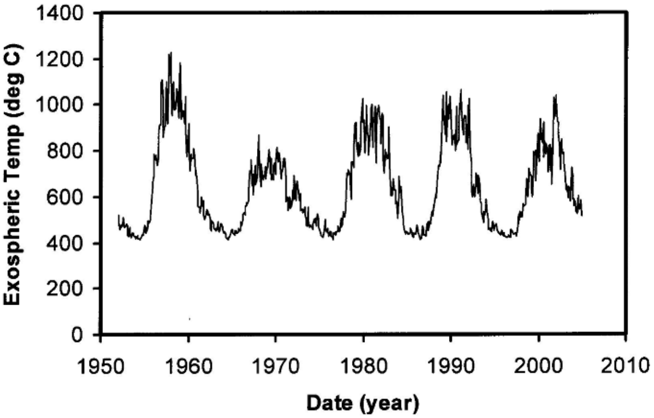

Figure 6.6: The variation of average exospheric temperature over the last five solar maxima. (Figure compiled from data supplied courtesy of Dr. Hugh Lewis, University of Southampton, UK.)

equator, again causing the atmosphere to expand. This produces an increase in atmospheric densities at orbital altitudes, giving a corresponding increase in drag perturbations on spacecraft orbits.

The atmosphere also has more direct effects on spacecraft and the materials used in their construction. Perhaps the best example of this is *atomic oxygen erosion*. Down on the Earth's surface we breathe molecular oxygen O_2, composed of two oxygen atoms chemically bonded together. We know that the oxygen we find down here gives us life, but it is also aggressive in forming oxides such as rust, which if left untreated over a period of years will have a damaging effect on our machines (bikes, cars, lawn mowers). As you go up to orbital altitudes, the atmosphere is no longer shielded from solar ultraviolet radiation. This causes the O_2 bond to be broken, so that at low Earth orbit (LEO) altitudes single oxygen atoms (referred to as atomic oxygen and denoted by the symbol O) wander around and become the dominant atmospheric constituent.

Atomic oxygen on orbit has a similar erosive character, not only arising from its chemical activity, but also because it hits spacecraft at around 8 km/sec (5 miles/sec) (due to the vehicle's orbital speed through the atmosphere). The importance of this was first registered when most of the thermal blanket on a camera mounted on the Space Shuttle during its third mission in March 1982 disappeared due to the effects of atomic oxygen erosion. Thermal blankets are used extensively on spacecraft to insulate them from the heating effects of direct solar radiation (see next section), and often give the vehicle its characteristic appearance of being wrapped in gold or silver foil. The blanket is composed of multiple layers of a thin plastic film with a metallic coating, such as aluminium, silver, or gold, similar to the survival blankets handed out at the end of marathons to keep the runners warm (see Chapter 9). In addition to the thermal blanket, various other materials are also particularly prone to atomic oxygen attack, one example being silver, which is commonly used in the construction of solar panels (solar panels are used on spacecraft to convert sunlight into electrical power; see Chapter 9). Clearly, the spacecraft designer needs to be familiar with these environmental effects when choosing appropriate materials in the design.

Electromagnetic Radiation

Most of the energy in the Sun's electromagnetic spectrum is contained within wavelengths ranging from about 0.2 to 3 μm (see Figure 6.2), ranging from short wavelength ultraviolet radiation, through visible light, to longer wavelength infrared (heat) radiation. The most obvious effect of this radiation on an orbiting spacecraft is the thermal heating that it causes. For an Earth-orbiting spacecraft, the solar power falling on every square meter of surface presented to the Sun is about 1.4 kilowatts, so that the heat input to the spacecraft surfaces is substantial. By contrast, a spacecraft in a LEO usually enters Earth's shadow on each orbit, and when this happens the vehicle's surface temperature drops drastically. Management of this thermal cycling is a critical job to be done by the thermal control subsystem engineer (see Chapter 9) to ensure that the equipment inside the spacecraft does not suffer a damaging level of temperature variation.

Other more direct impacts on design come from the damaging effects of the short wavelength solar ultraviolet radiation. Down here at the Earth's surface, as we have seen, its harsh effects are softened by the protective ozone layer, but an orbiting spacecraft is exposed long-term to its erosive effects. The chemical structure of paints and thermal blanket material can be modified by ultraviolet radiation, causing them to become brittle and flaky. In general, the spacecraft's surfaces will erode, due to ultraviolet radiation, in such a way that the amount of the Sun's heat that they absorb will increase over time, which again is of concern to the thermal control engineer (see Chapter 9).

Trapped Particle Radiation

As we saw earlier, some of the solar wind particles emanating from the Sun, generally charged particles such as electrons, protons, and atomic nuclei stripped of their attendant electrons, penetrate the protective shield of Earth's magnetic field. Some are focused by the field into the atmosphere above the north and south polar regions, causing auroral displays. Others are trapped by the magnetic field, producing radiation belts that pose a hazard to people and spacecraft alike. These belts are called the *Van Allen belts,* after their discoverer James Van Allen, who was the first to confirm their existence using data from the Explorer 1 and 3 satellites in 1958.

These charged particles, once trapped by Earth's magnetic field, move rapidly in a particular way governed by the field, to give the Van Allen belts their characteristic shape of giant doughnuts stretched around Earth's equator (see Figure 6.8).

To understand how this structure comes about, we need to consider how charged particles move in a magnetic field. Put simply, they tend to gyrate about the magnetic field lines; their paths through space echo a shape a bit like a corkscrew, as shown in Figure 6.7a. If we also recall the shape of Earth's magnetic field, which is similar to that of a bar magnet (see Figure 6.3a), then the particles travel paths like that shown in Figure 6.7b. A trapped

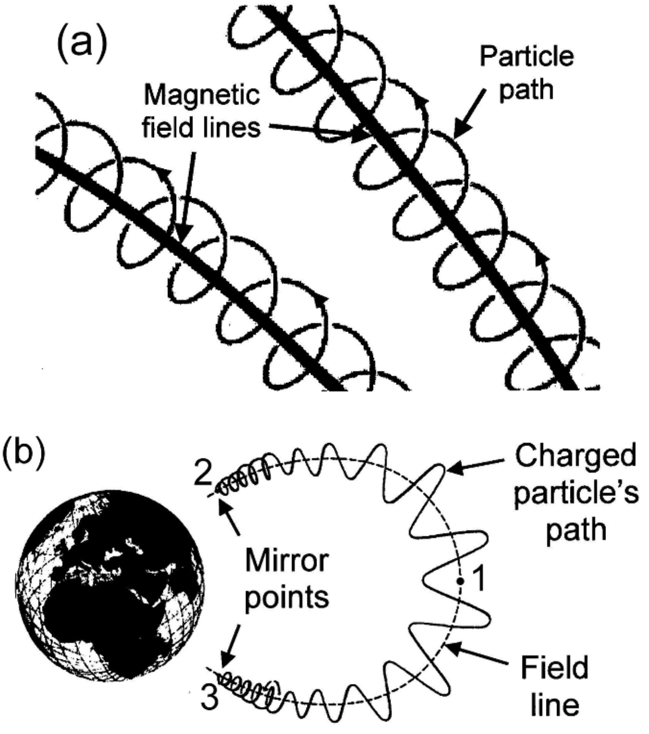

Figure 6.7: (a) Charged particles gyrate around the magnetic field lines, traveling paths that resemble a corkscrew. (b) Charged particle radiation is trapped in Earth's magnetic field, bouncing rapidly between mirror points 2 and 3, producing the Van Allen radiation belts.

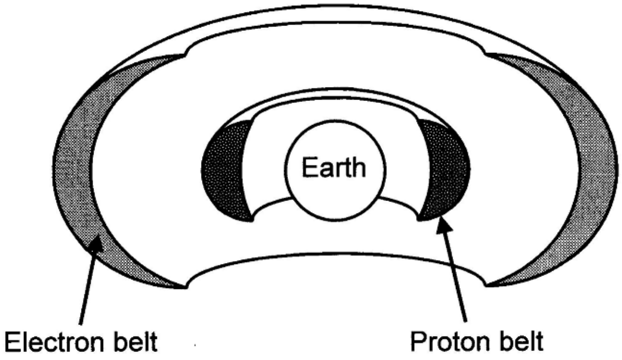

Figure 6.8: A slice through Earth's trapped radiation belts reveal a shape that echoes the magnetic field. The regions of maximum intensity of the proton and electron belts are shown.

particle moving north across the equator at point 1 will corkscrew about the field line toward point 2. As it approaches Earth at point 2, the magnetic field strength increases and the field lines converge, producing a *mirror point*, which causes the particle to bounce back along the field line toward point 1 again. At the other end of its journey, point 3 also acts as a mirror point, which reflects the particle back toward its starting point again. Thus our trapped particle is destined to bounce back and forth between points 2 and 3 indefinitely, unless it leaks away into space or is captured by Earth's tenuous upper atmosphere. This gives the characteristic shape of the Van Allen belts as shown in Figure 6.8. These are regions where spacecraft and people should not linger, due to the high density of energetic particle radiation, composed mainly of high-energy electrons and protons. The maximum intensity of electron radiation occurs at an altitude of approximately 27,500 km (17,000 miles), and the greatest intensity of the more damaging proton radiation occurs at around a height of 4500 km (2800 miles).

We would not contemplate orbiting a manned space station at these sorts of heights, as the consequences for the crew would be serious. However, we do know that exposure of humans to the radiation belts for a short spell, although not desirable, is tolerable; for example, the Apollo astronauts had to fly through the belts on their way to the moon and on their return.

Long-term exposure of unmanned spacecraft to the radiation belts is also damaging, mainly causing degradation of electronic and electrical power systems. Deploying a satellite in a circular orbit at the heart of the Van Allen proton belt would be foolhardy, but as mentioned in Chapter 2, many spacecraft occupy large elliptical orbits and fly through the radiation belts on each orbit revolution. The main problem for these vehicles is that their solar panels suffer radiation damage, which causes the amount of power they produce from sunlight to decrease with time. A spacecraft in this type of orbit for many years may suffer a power loss up to 50% of the solar panel's original output. However, the power subsystem engineer is able to predict the likely deterioration for the particular type of orbit flown, and make due allowance in the spacecraft's design.

Other electronic components onboard are also subject to radiation damage, but unlike solar panels, they can be shielded to some degree from the energetic particles by increasing the thickness of the walls of the metal boxes (typically made of aluminium) in which they are usually mounted. However, this needs to be done carefully as it will increase the spacecraft's mass, and as we have seen in Chapter 5, an increase in mass means a larger, more expensive launch vehicle. Another way of providing radiation protection, which goes some way toward solving this mass-growth problem, is to place radiation-sensitive components sensibly within the spacecraft so that they are shielded by less sensitive adjacent equipment.

As well as these *total dose effects*, the operation of onboard electronic equipment is also disrupted by *single-event upsets* (SEUs). These are temporary effects caused by the passage of a single high-speed particle through a computer processor, for example, producing random bit flips in onboard software, that is, switching a 0 bit to a 1 bit in a computer program, which can have undesirable and unpredictable results onboard! To help overcome this, spacecraft computer programs include error correction codes, which continuously and routinely check the onboard computer memory. Another type of problem caused by particle radiation, a *single event burnout* (SEB), is much more serious as it can cause permanent damage to the spacecraft's electronic systems. In this case a single energetic particle can kick off a runaway current in an electronic component, causing the device to burn out. To overcome this, the designer can build in more shielding, or choose to protect the device with current-sensing and -limiting circuitry, but again there is a balance to be struck to prevent mass growth in the spacecraft design.

In this brief tour of how environmental effects influence spacecraft design, the final topic involves impacting particles again, but this time somewhat larger ones than the subatomic particles we find in the Van Allen belts.

Space Debris

Space debris comes in two varieties: natural and artificial. *Natural space debris* consists of the meteoroids that Earth encounters on its orbital journey around the Sun. These meteoroids themselves are in orbits around the Sun, and they vary in size from a few meters in diameter to tiny specks of material smaller than a grain of sand. It is estimated that around 100 metric tonnes of such material rains down into Earth's atmosphere on a daily basis, although there is controversy about this estimate. Fortunately, most of it burns up harmlessly in the atmosphere, producing the fleeting flash of light that is associated with a shooting star. The vast majority of such meteoroids are at the tiny end of the size spectrum. However, they can still have significant energy, due to speeds on the order of a few tens of kilometers per second. Fortunately, the chances of an orbiting spacecraft encountering a large meteor (say a few centimeters across) are negligible, which is just as well as the consequences would be catastrophic. For example, the energy of a 2.5-cm (1-inch) rocky meteoroid traveling at 20 km/sec (12.4 miles/sec) is about the same as a 20-ton truck traveling at 110 km per hour (70 mph), and such a projectile would make short work of an orbiting satellite! But the probabilities are such that the main issue with natural debris is the peppering of the spacecraft's surfaces by high-velocity dust particles, producing a general degradation of thermal blanketed and painted surfaces.

The threat to satellites posed by *artificial debris*, on the other hand, is much greater, as once the debris size reaches a millimeter and above, the artificial debris objects in orbit begin to outnumber the natural debris objects. And this trend continues, so that the chances of an impact with a 10-cm (4-inch) chunk of artificial debris is much greater than the odds of encountering a meteoroid of similar size.

Artificial debris, as the name implies, are useless lumps of man-made material in space that have ended up in orbit as a by-product of launching spacecraft. Various agencies have proposed formal definitions of artificial space debris. The United Nations Committee on the Peaceful Uses of Outer Space states, "Space debris is defined as all man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional." Space turns out to be just another arena of human activity that is being steadily polluted. However, the junk we leave in space is generally more dangerous than our terrestrial garbage as it is moving about at high speeds, posing a potentially lethal hazard to people and spacecraft in near-Earth orbits. Since the dawn of the space age in October 1957, when the first satellite Sputnik 1 was launched, there have been a total of 27,000 catalogued objects launched, with about 9000 catalogued objects still currently in orbit (at the time of this writing). Indeed, the upper stage of the launch vehicle that put Sputnik 1 into orbit also entered orbit, and became the first item of artificial space debris with a mass of about 4 metric tonnes. A *catalogued object* is any object large enough to be routinely tracked by a number of ground-based sensors to allow its orbit to be determined. Once the object's orbit is known, its details are placed in the U.S. Space Command catalogue, with its own unique catalogue number. The sensors used to do this job are mostly large radars, which once comprised the ballistic missile early warning system used during the Cold War. The sensitivity of these sensors is such that any object larger than about 10 cm (4 inches) in LEO and larger than around 1 m (3 feet) in geostationary Earth orbit (GEO) are tracked and catalogued.

Of the 9000 current catalogued objects, about 5% are operational spacecraft, but the majority have no useful function. Of this majority, many are large derelict upper stages of launch vehicles, which have accompanied their spacecraft payload into orbit. Others are smaller objects that are released into space during the process of launching spacecraft. About 40% of the total are fragments resulting from the accidental, explosive breakup of upper stages or spacecraft in orbit. In many cases the unintentional mixing of leftover propellant and oxidizer in a launcher upper stage has produced an explosive event that has torn the upper stage apart, producing several hundred new catalogued objects overnight!

A simple subtraction—27,000 minus 9000—gives us about 18,000 objects that have either flown away into interplanetary space or have fallen from orbit and reentered Earth's atmosphere. Most of these objects have indeed come back through the atmosphere, burning up harmlessly, although there are some famous instances when large pieces of spacecraft have reached the ground (such as the unwelcome arrival of parts of a nuclear reactor from Cosmos 954 over Canada in 1978, and Skylab's reentry over Australia in 1979). Figure 6.9 shows the number of catalogued objects in LEO over time from 1957 to 2001. There are about another 1000 or so objects in other orbital regions, making up our total number of approximately 9000. Figure 6.9 shows an almost continuously rising trend. However, interestingly we can see that this trend is interrupted, particularly in the early 1980s, the early 1990s, and around the year 2000, when the curve dips or flattens out. These periods correspond to times when the Sun's activity was at a maximum, producing atmospheric heating, with a resulting increase in atmospheric density (see The Effects of Earth's Atmosphere, above). This in turn produced a rise in drag on orbiting satellites, increasing the numbers of reentries into the atmosphere. So we can say that solar maximum is a time to put on the hard hats!

The distribution of catalogued objects in LEO with orbit height is shown in Figure 6.10. We see that there are few objects at low altitude, say, less than 500 km. This is because the drag perturbations on debris are relatively large (due to the higher atmospheric density at low altitudes), sweeping the debris

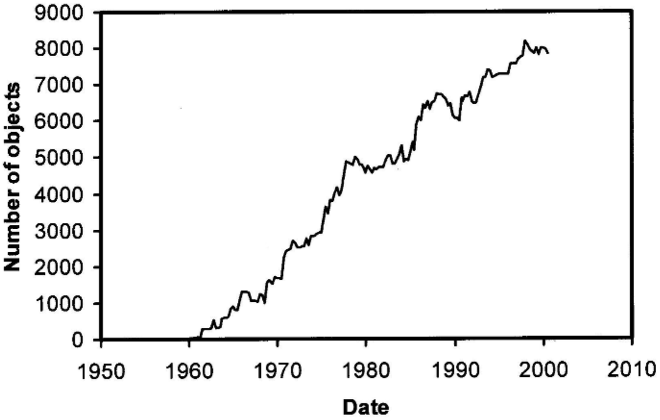

Figure 6.9: Numbers of objects greater than 10 cm (4 inches) in size in low Earth orbit (LEO) over time, from Sputnik 1 (October 1957) to 2001. (Figure compiled from data supplied courtesy of Dr. Hugh Lewis, University of Southampton, UK.)

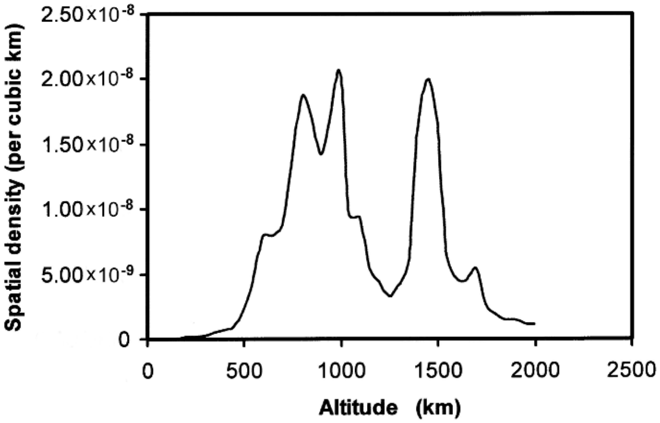

Figure 6.10: The current distribution of objects in LEO, greater than 10 cm (4 inches) in size, plotted against height. (Figure compiled from data supplied courtesy of Dr. Hugh Lewis, University of Southampton, UK.)

into Earth's atmosphere. Also, peaks in debris density occur in orbital regions where there are lots of spacecraft and where the atmospheric density is too low for *drag sweeping* to be effective in removing objects from orbit. A good example of this are the peaks in debris density at altitudes of around 800 to 1000 km (500 to 620 miles), where there are a large number of Earth observation satellites, and where the atmosphere is too tenuous for drag to be effective in removing the resulting junk caused by operating these spacecraft. Figure 6.10 also gives us an idea of the average spacing between large (greater than about 10 cm in size) objects currently in LEO.

The vertical axis suggests that the peak in debris spatial density is around 2×10^{-8} objects per cubic kilometer. A simple calculation reveals the significance of this obscure statistic. If the objects were distributed evenly, then each one would have its own volume of space in which to wander around, equivalent to a cube about 370 km (230 miles) across. On the one hand, it seems like a huge amount of space for the chunk of debris to get lost in. A cube of this size contains about 50 million cubic kilometers! On the other hand, traveling at typical LEO speed, the object can traverse this space in less than a minute. The bottom line is that space debris is not evenly spaced out in orbit, and debris does come together now and again. However, the low spatial density tells us that this does not happen often; indeed, at the time of this writing, only three collisions between catalogued objects have been verified. The first of these occurred in 1996 between a small French satellite called Cerise and a fragment of an old Ariane launch vehicle.

People who operate shiny, expensive spacecraft in LEO are understandably protective of their investment in orbit, and debris is an obvious threat to their spacecraft's mission. Clearly, if the spacecraft were to be hit by a large chunk of space debris, the impact would be catastrophic, given that relative speeds in orbit are typically on the order of 10 km/sec (6.2 mile/sec). Remember, however, that all of the large objects in orbit are catalogued and their orbits are known. So, using computer simulation, the spacecraft's operators are able to keep an eye on all 8000 or so LEO objects in the catalogue to see if any of them are predicted to make a close approach to their valued asset. This is done routinely in operations rooms around the world. If an uncomfortably close encounter is predicted, the spacecraft's orbit is changed to reduce the threat. This type of maneuver has been performed many times by manned shuttles in orbit, as well as by numerous unmanned spacecraft in LEO.

In addition to these large objects in orbit, there are huge numbers of smaller debris objects in near-earth orbits. At the small end of the size spectrum, it is estimated that there are tens of millions of objects in the 1-mm to 1-cm size range. Many of these result from explosive breakups in orbit, but they also have more benign origins, associated with the degradation of spacecraft surfaces exposed to the space environment. The effects of solar ultraviolet radiation and atomic oxygen erosion, combined with repeated thermal cycling on each orbit (due to the spacecraft being exposed to the heat of direct sunlight followed by extreme cold when in Earth's shadow), causes paints and thermal blankets to become brittle. Over time, flakes of material peel off, leaving a wake of small debris particles around the spacecraft as it orbits the Earth. This does not pose any threat to the spacecraft itself, other than the gradual process of general deterioration. But if these small particles are encountered by spacecraft in other orbits, they can impinge on them at high speeds, typically 10 km/sec (6.2 miles/sec). One well-known consequence of this is the frequent need to replace space shuttle windows, due to damage caused by paint flake cratering.

The space debris that poses perhaps the greatest threat to spacecraft is the intermediate-sized objects in the range of 1 to 10 cm, of which it is estimated that there are a few hundreds of thousands in orbit. This is because they are generally too small for their orbits to be determined (and thus they are not in the catalogue), but they are large enough to deliver a lethal blow to an operational spacecraft. Obviously, if you cannot predict when they are coming, then you cannot perform orbit change maneuvers to avoid potential impacts.

Despite the large number of objects in this size range, there is an awful lot of space in LEO, so thankfully the chances of an impact with this size of object is still very small. For objects smaller than about 2 cm (about 1 inch) in size, however, it is possible to adopt a different protection strategy—*shielding*. This has been used extensively to protect the International Space Station (ISS) from debris impact, and may be used more widely in future unmanned spacecraft in orbital regions where the debris impact threat is considered significant. How can a shield be devised to stop a 2-cm chunk of aluminium traveling at speeds that make a high-velocity bullet look harmless? The idea for such a shield was first proposed by Fred Whipple in 1946, and the simplest form of the *Whipple shield* is shown in Figure 6.11. The construction is straightforward; a bumper shield plate is fixed to the

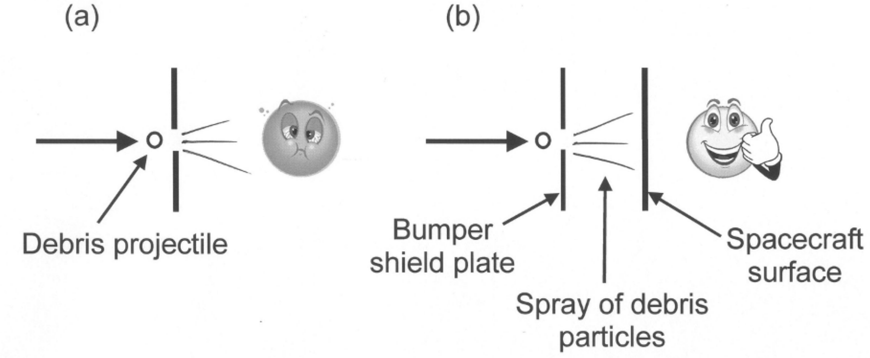

Figure 6.11: Encounter with a debris projectile (a) without a Whipple shield and (b) with a shield.

spacecraft's surface, such that there is a gap between them. The idea is that an impacting debris object is disrupted and vaporized by its encounter with the outer bumper plate, producing a spray of smaller debris particles that impact on the inner spacecraft surface. Since the energy of this spray is spread over a wider area of the spacecraft's surface, the chances of penetration are reduced. The effectiveness of the shield can be improved by introducing multiple bumper shield plates, and playing tunes on the separation distances between them. Generally, however, spacecraft designers would prefer not to implement such shields, as they introduce complexity and mass into the design, with the potential to increase mission costs.

Summary

The space environment is complex, especially the aspects associated with the dominant influence the Sun has over the near-Earth environment—the so-called solar–terrestrial interaction. Several textbooks could be written to describe the decades of research that have been done in this area. In writing this chapter, it has been a struggle to keep it brief, and it was difficult to decide what to leave out. Thus, the chapter focuses on the highlights. However, despite this disclaimer, there is enough here to indicate the importance of environment on space vehicle design. The influence of environment in design is not so apparent in the overall spacecraft configuration, as it is for an automobile or airplane. But it can be seen that much research and engineering trial and error have been needed to develop appropriate manufacturing techniques and materials to give the spacecraft a sporting chance of surviving in orbit long enough to fulfill its mission objectives.