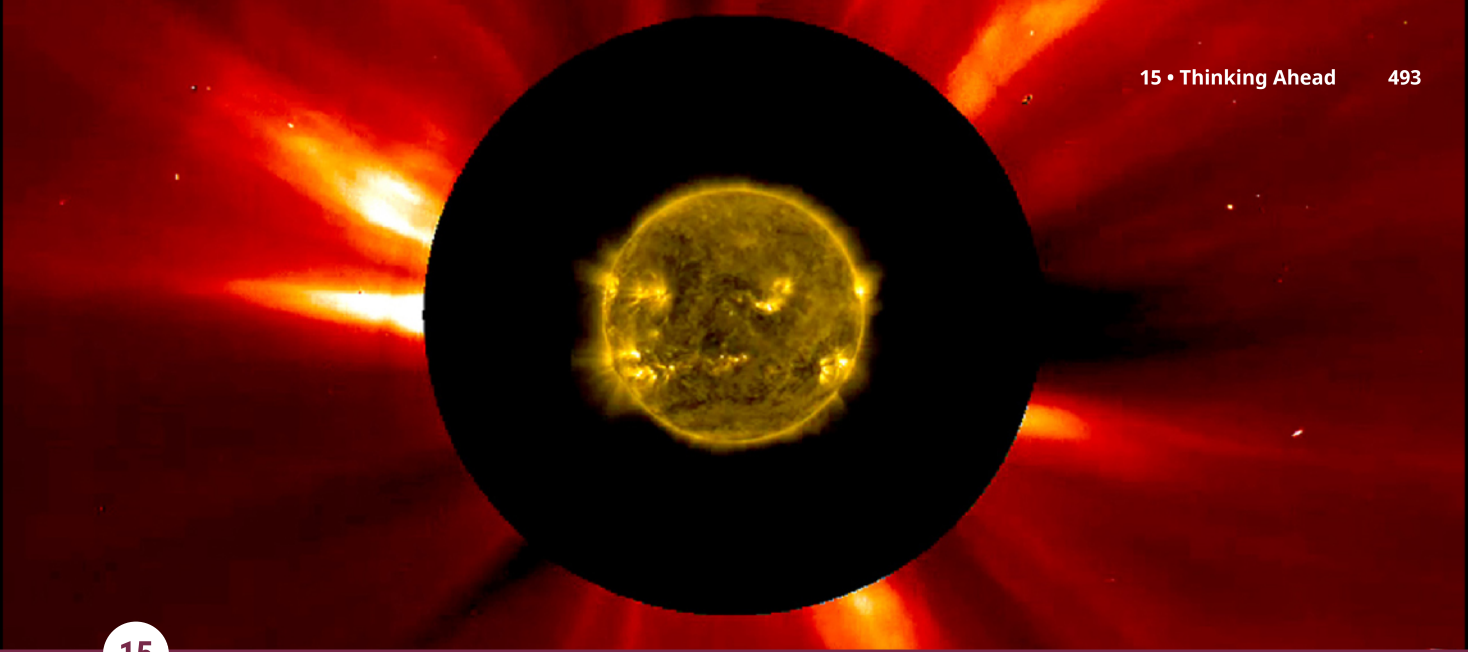

15

The Sun: A Garden-Variety Star

Figure 15.1 Our Star. The Sun—our local star—is quite average in many ways. However, that does not stop it from being a fascinating object to study. From solar flares and coronal mass ejections, like the one seen coming from the Sun in the top right of this image, the Sun is a highly dynamic body at the center of our solar system. This image combines two separate satellite pictures of the Sun—the inner one from the Solar Dynamics Observatory and the outer one from the Solar and Heliospheric Observatory. (credit: modification of work by ESA/NASA)

Chapter Outline

Thinking Ahead

“Space weather” may sound like a contradiction. How can there be weather in the vacuum of space? Yet space weather, which refers to changing conditions in space, is an active field of research and can have profound effects on Earth. We are all familiar with the ups and downs of weather on Earth, and how powerful storms can be devastating for people and vegetation. Although we are separated from the Sun by a large distance as well as by the vacuum of space, we now understand that great outbursts on the Sun (solar storms, in effect) can cause changes in the atmosphere and magnetic field of Earth, sometimes even causing serious problems on the ground. In this chapter, we will explore the nature of the Sun’s outer layers, the changing conditions and activity there, and the ways that the Sun affects Earth.

By studying the Sun, we also learn much that helps us understand stars in general. The Sun is, in astronomical terms, a rather ordinary star—not unusually hot or cold, old or young, large or small. Indeed, we are lucky that the Sun is typical. Just as studies of Earth help us understand observations of the more distant planets, so too does the Sun serve as a guide to astronomers in interpreting the messages contained in the light we receive from distant stars. As you will learn, the Sun is dynamic, continuously undergoing change, balancing the forces of nature to keep itself in equilibrium. In this chapter, we describe the components of the Sun, how it changes with time, and how those changes affect Earth.

15.1 The Structure and Composition of the Sun

Learning Objectives

By the end of this section, you will be able to:

- Explain how the composition of the Sun differs from that of Earth
- Describe the various layers of the Sun and their functions
- Explain what happens in the different parts of the Sun's atmosphere

The Sun, like all stars, is an enormous ball of extremely hot, largely ionized gas, shining under its own power. And we do mean enormous. The Sun could fit 109 Earths side-by-side across its diameter, and it has enough volume (takes up enough space) to hold about 1.3 million Earths.

The Sun does not have a solid surface or continents like Earth, nor does it have a solid core (Figure 15.2). However, it does have a lot of structure and can be discussed as a series of layers, not unlike an onion. In this section, we describe the huge changes that occur in the Sun's extensive interior and atmosphere, and the dynamic and violent eruptions that occur daily in its outer layers.

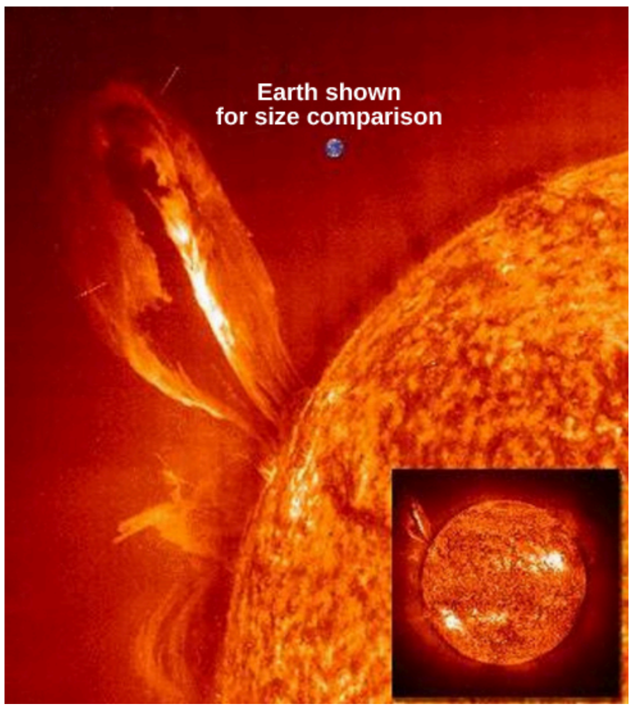

Figure 15.2 Earth and the Sun. Here, Earth is shown to scale with part of the Sun and a giant loop of hot gas erupting from its surface. The inset shows the entire Sun, smaller. (credit: modification of work by SOHO/EIT/ESA)

Some of the basic characteristics of the Sun are listed in Table 15.1. Although some of the terms in that table may be unfamiliar to you right now, you will get to know them as you read further.

Characteristics of the Sun

Characteristic	How Found	Value
Mean distance	Radar reflection from planets	1 AU (149,597,892 km)
Maximum distance from Earth		1.521×10^8 km

Table 15.1

Characteristic	How Found	Value
Minimum distance from Earth		1.471×10^8 km
Mass	Orbit of Earth	333,400 Earth masses (1.99×10^{30} kg)
Mean angular diameter	Direct measure	31´59´´.3
Diameter of photosphere	Angular size and distance	109.3 × Earth diameter (1.39×10^6 km)
Mean density	Mass/volume	1.41 g/cm^3 (1400 kg/m^3)
Gravitational acceleration at photosphere (surface gravity)	GM/R^2	27.9 × Earth surface gravity = 273 m/s^2
Solar constant	Instrument sensitive to radiation at all wavelengths	1370 W/m^2
Luminosity	Solar constant × area of spherical surface 1 AU in radius	3.8×10^{26} W
Spectral class	Spectrum	G2V
Effective temperature	Derived from luminosity and radius of the Sun	5800 K
Rotation period at equator	Sunspots and Doppler shift in spectra taken at the edge of the Sun	24 days 16 hours
Inclination of equator to ecliptic	Motions of sunspots	7°10´.5

Table 15.1

Composition of the Sun's Atmosphere

Let's begin by asking what the solar atmosphere is made of. As explained in Radiation and Spectra, we can use a star's *absorption line spectrum* to determine what elements are present. It turns out that the Sun contains the same elements as Earth but *not* in the same proportions. About 73% of the Sun's mass is hydrogen, and another 25% is helium. All the other chemical elements (including those we know and love in our own bodies, such as carbon, oxygen, and nitrogen) make up only 2% of our star. The 10 most abundant gases in the Sun's visible surface layer are listed in Table 15.2. Examine that table and notice that the composition of the Sun's outer layer is very different from Earth's crust, where we live. (In our planet's crust, the three most abundant elements are oxygen, silicon, and aluminum.) Although not like our planet's, the makeup of the Sun is quite typical of stars in general.

The Abundance of Elements in the Sun

Element	Percentage by Number of Atoms	Percentage By Mass
Hydrogen	92.0	73.4
Helium	7.8	25.0
Carbon	0.02	0.20
Nitrogen	0.008	0.09
Oxygen	0.06	0.80
Neon	0.01	0.16
Magnesium	0.003	0.06
Silicon	0.004	0.09
Sulfur	0.002	0.05
Iron	0.003	0.14

Table 15.2

The fact that our Sun and the stars all have similar compositions and are made up of mostly hydrogen and helium was first shown in a brilliant thesis in 1925 by Cecilia Payne-Gaposchkin, the first woman to get a PhD in astronomy in the United States (Figure 15.3). However, the idea that the simplest light gases—hydrogen and helium—were the most abundant elements in stars was so unexpected and so shocking that she was persuaded her analysis of the data must be wrong. At the time, she wrote, “The enormous abundance derived for these elements in the stellar atmosphere is almost certainly not real.” Even scientists sometimes find it hard to accept new ideas that do not agree with what everyone “knows” to be right.

Figure 15.3 Cecilia Payne-Gaposchkin (1900–1979). Her 1925 doctoral thesis laid the foundations for understanding the composition of the Sun and the stars. Yet, being a woman, she was not given a formal appointment at Harvard, where she worked, until 1938 and was not appointed a professor until 1956. (credit: Smithsonian Institution)

Before Payne-Gaposchkin’s work, everyone assumed that the composition of the Sun and stars would be much like that of Earth. It was 3 years after her thesis that other studies proved beyond a doubt that the enormous abundance of hydrogen and helium in the Sun is indeed real. (And, as we will see, the composition of the Sun and the stars is much more typical of the makeup of the universe than the odd concentration of heavier elements that characterizes our planet.)

Most of the elements found in the Sun are in the form of atoms, with a small number of molecules, all in the form of gases: the Sun is so hot that no matter can survive as a liquid or a solid. In fact, the Sun is so hot that many of the atoms in it are *ionized*, that is, stripped of one or more of their electrons. This removal of electrons from their atoms means that there is a large quantity of free electrons and positively charged ions in the Sun, making it an electrically charged environment—quite different from the neutral one in which you are reading this text. (Scientists call such a hot ionized gas a **plasma**.)

In the nineteenth century, scientists observed a spectral line at 530.3 nanometers in the Sun's outer atmosphere, called the corona (a layer we will discuss in a minute.) This line had never been seen before, and so it was assumed that this line was the result of a new element found in the corona, quickly named coronium. It was not until 60 years later that astronomers discovered that this emission was in fact due to highly ionized iron—iron with 13 of its electrons stripped off. This is how we first discovered that the Sun's atmosphere had a temperature of more than a million degrees.

The Layers of the Sun beneath the Visible Surface

Figure 15.4 shows what the Sun would look like if we could see all parts of it from the center to its outer atmosphere; the terms in the figure will become familiar to you as you read on.

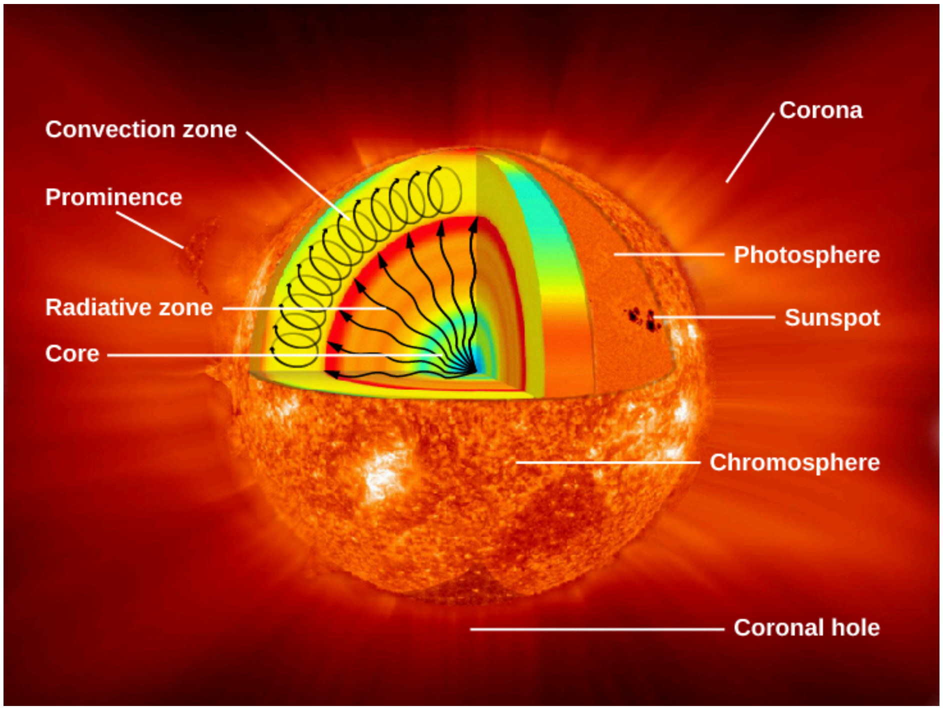

Figure 15.4 Parts of the Sun. This illustration shows the different parts of the Sun, from the hot core where the energy is generated through regions where energy is transported outward, first by radiation, then by convection, and then out through the solar atmosphere. The parts of the atmosphere are also labeled the photosphere, chromosphere, and corona. Some typical features in the atmosphere are shown, such as coronal holes and prominences. (credit: modification of work by NASA/Goddard)

The Sun's layers are different from each other, and each plays a part in producing the energy that the Sun ultimately emits. We will begin with the core and work our way out through the layers. The Sun's *core* is extremely dense and is the source of all of its energy. Inside the core, nuclear energy is being released (in ways we will discuss in The Sun: A Nuclear Powerhouse). The core is approximately 20% of the size of the solar interior and is thought to have a temperature of approximately 15 million K, making it the hottest part of the Sun.

Above the core is a region known as the *radiative zone*—named for the primary mode of transporting energy across it. This region starts at about 25% of the distance to the solar surface and extends up to about 70% of the way to the surface. The light generated in the core is transported through the radiative zone very slowly, since the high density of matter in this region means a photon cannot travel too far without encountering a particle, causing it to change direction and lose some energy.

The *convective zone* is the outermost layer of the solar interior. It is a thick layer approximately 200,000 kilometers deep that transports energy from the edge of the radiative zone to the surface through giant convection cells, similar to a pot of boiling oatmeal. The plasma at the bottom of the convective zone is extremely hot, and it bubbles to the surface where it loses its heat to space. Once the plasma cools, it sinks back to the bottom of the convective zone.

Now that we have given a quick overview of the structure of the whole Sun, in this section, we will embark on a journey through the visible layers of the Sun, beginning with the photosphere—the visible surface.

The Solar Photosphere

Earth's air is generally transparent. But on a smoggy day in many cities, it can become opaque, which prevents us from seeing through it past a certain point. Something similar happens in the Sun. Its outer atmosphere is transparent, allowing us to look a short distance through it. But when we try to look through the atmosphere deeper into the Sun, our view is blocked. The **photosphere** is the layer where the Sun becomes opaque and marks the boundary past which we cannot see (Figure 15.5).

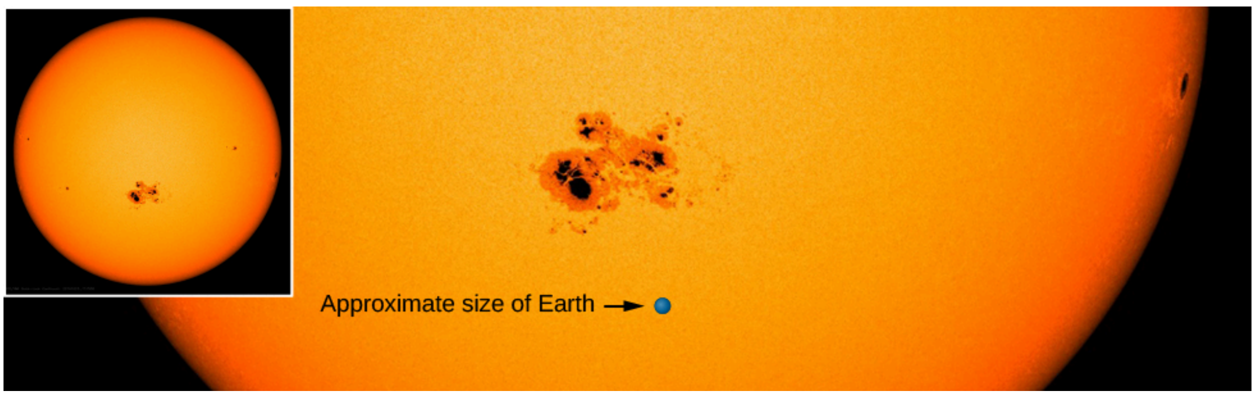

Figure 15.5 Solar Photosphere plus Sunspots. This photograph shows the photosphere—the visible surface of the Sun. Also shown is an enlarged image of a group of sunspots; the size of Earth is shown for comparison. Sunspots appear darker because they are cooler than their surroundings. The typical temperature at the center of a large sunspot is about 3800 K, whereas the photosphere has a temperature of about 5800 K. (credit: modification of work by NASA/SDO)

As we saw, the energy that emerges from the photosphere was originally generated deep inside the Sun (more on this in The Sun: A Nuclear Powerhouse). This energy is in the form of photons, which make their way slowly toward the solar surface. Outside the Sun, we can observe *only* those photons that are emitted into the solar photosphere, where the density of atoms is sufficiently low and the photons can finally escape from the Sun without colliding with another atom or ion.

As an analogy, imagine that you are attending a big campus rally and have found a prime spot near the center of the action. Your friend arrives late and calls you on your cell phone to ask you to join her at the edge of the crowd. You decide that friendship is worth more than a prime spot, and so you work your way out through the dense crowd to meet her. You can move only a short distance before bumping into someone, changing direction, and trying again, making your way slowly to the outside edge of the crowd. All this while, your efforts are not visible to your waiting friend at the edge. Your friend can't see you until you get very close to the edge because of all the bodies in the way. So too photons making their way through the Sun are constantly bumping into atoms, changing direction, working their way slowly outward, and becoming visible only when they reach the atmosphere of the Sun where the density of atoms is too low to block their outward progress.

Astronomers have found that the solar atmosphere changes from almost perfectly transparent to almost completely opaque in a distance of just over 400 kilometers; it is this thin region that we call the *photosphere*, a word that comes from the Greek for “light sphere.” When astronomers speak of the “diameter” of the Sun, they mean the size of the region surrounded by the photosphere.

The photosphere looks sharp only from a distance. If you were falling into the Sun, you would not feel any surface but would just sense a gradual increase in the density of the gas surrounding you. It is much the same as falling through a cloud while skydiving. From far away, the cloud looks as if it has a sharp surface, but you do not feel a surface as you fall into it. (One big difference between these two scenarios, however, is temperature. The Sun is so hot that you would be vaporized long before you reached the photosphere. Skydiving in Earth’s atmosphere is much safer.)

We might note that the atmosphere of the Sun is not a very dense layer compared to the air in the room where you are reading this text. At a typical point in the photosphere, the pressure is less than 10% of Earth’s pressure at sea level, and the density is about one ten-thousandth of Earth’s atmospheric density at sea level.

Observations with telescopes show that the photosphere has a mottled appearance, resembling grains of rice spilled on a dark tablecloth or a pot of boiling oatmeal. This structure of the photosphere is called **granulation** (see Figure 15.6). Granules, which are typically 700 to 1000 kilometers in diameter (about the width of Texas), appear as bright areas surrounded by narrow, darker (cooler) regions. The lifetime of an individual granule is only 5 to 10 minutes. Even larger are supergranules, which are about 35,000 kilometers across (about the size of two Earths) and last about 24 hours.

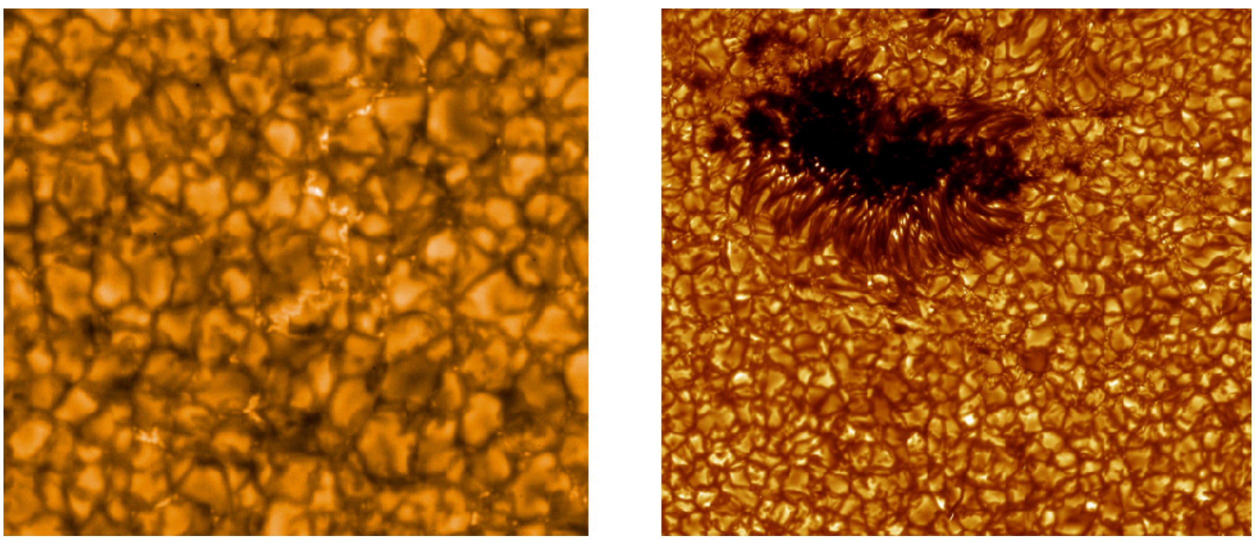

Figure 15.6 Granulation Pattern. The surface markings of the convection cells create a granulation pattern on this dramatic image (left) taken from the Japanese Hinode spacecraft. You can see the same pattern when you heat up miso soup. The right image shows an irregular-shaped sunspot and granules on the Sun’s surface, seen with the Swedish Solar Telescope on August 22, 2003. (credit left: modification of work by Hinode JAXA/NASA/PPARC; credit right: ISP/SST/Oddbjorn Engvold, Jun Elin Wiik, Luc Rouppe van der Voort)

The motions of the granules can be studied by examining the Doppler shifts in the spectra of gases just above them (see The Doppler Effect). The bright granules are columns of hotter gases rising at speeds of 2 to 3 kilometers per second from below the photosphere. As this rising gas reaches the photosphere, it spreads out, cools, and sinks down again into the darker regions between the granules. Measurements show that the centers of the granules are hotter than the intergranular regions by 50 to 100 K.

LINK TO LEARNING

See the “boiling” action of granulation in this 30-second time-lapse video (https://openstax.org/l/30SolarGran) from the Swedish Institute for Solar Physics.

The Chromosphere

The Sun's outer gases extend far beyond the photosphere (Figure 15.7). Because they are transparent to most visible radiation and emit only a small amount of light, these outer layers are difficult to observe. The region of the Sun's atmosphere that lies immediately above the photosphere is called the **chromosphere**. Until this century, the chromosphere was visible only when the photosphere was concealed by the Moon during a total solar eclipse (see the chapter on Earth, Moon, and Sky). In the seventeenth century, several observers described what appeared to them as a narrow red "streak" or "fringe" around the edge of the Moon during a brief instant after the Sun's photosphere had been covered. The name *chromosphere*, from the Greek for "colored sphere," was given to this red streak.

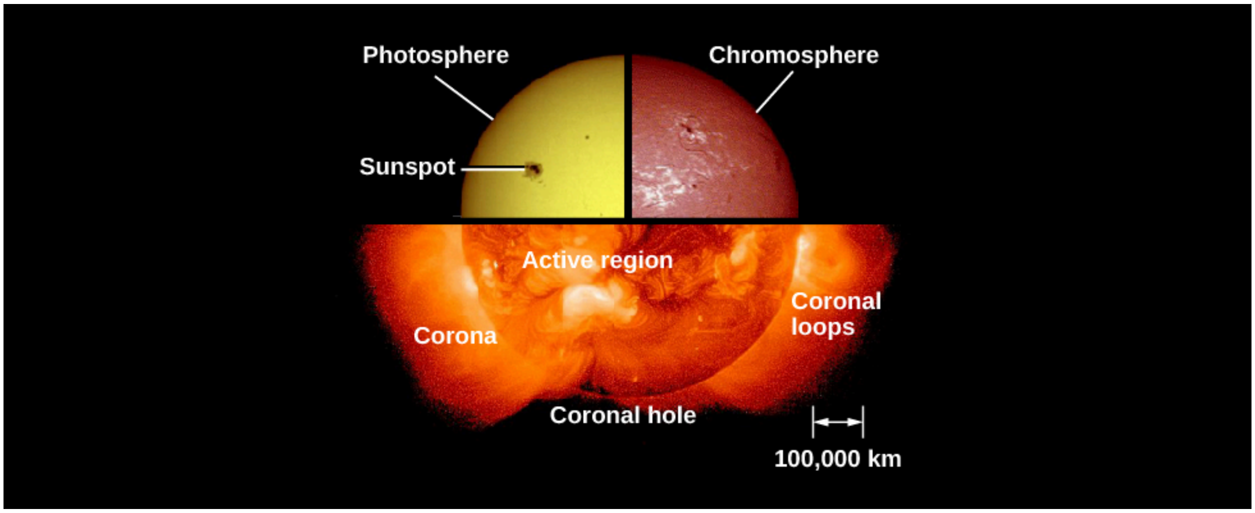

Figure 15.7 The Sun's Atmosphere. Composite image showing the three components of the solar atmosphere: the photosphere or surface of the Sun taken in ordinary light; the chromosphere, imaged in the light of the strong red spectral line of hydrogen (H-alpha); and the corona as seen with X-rays. (credit: modification of work by NASA)

Observations made during eclipses show that the chromosphere is about 2000 to 3000 kilometers thick, and its spectrum consists of bright emission lines, indicating that this layer is composed of hot gases emitting light at discrete wavelengths. The reddish color of the chromosphere arises from one of the strongest emission lines in the visible part of its spectrum—the bright red line caused by hydrogen, the element that, as we have already seen, dominates the composition of the Sun.

In 1868, observations of the chromospheric spectrum revealed a yellow emission line that did not correspond to any previously known element on Earth. Scientists quickly realized they had found a new element and named it *helium* (after *helios*, the Greek word for "Sun"). It took until 1895 for helium to be discovered on our planet. Today, students are probably most familiar with it as the light gas used to inflate balloons, although it turns out to be the second-most abundant element in the universe.

The temperature of the chromosphere is about 10,000 K. This means that the chromosphere is hotter than the photosphere, which should seem surprising. In all the situations we are familiar with, temperatures fall as one moves away from the source of heat, and the chromosphere is farther from the center of the Sun than the photosphere is.

The Transition Region

The increase in temperature does not stop with the chromosphere. Above it is a region in the solar atmosphere where the temperature changes from 10,000 K (typical of the chromosphere) to nearly a million degrees. The hottest part of the solar atmosphere, which has a temperature of a million degrees or more, is called the **corona**. Appropriately, the part of the Sun where the rapid temperature rise occurs is called the **transition region**. It is probably only a few tens of kilometers thick. Figure 15.8 summarizes how the temperature of the solar atmosphere changes from the photosphere outward.

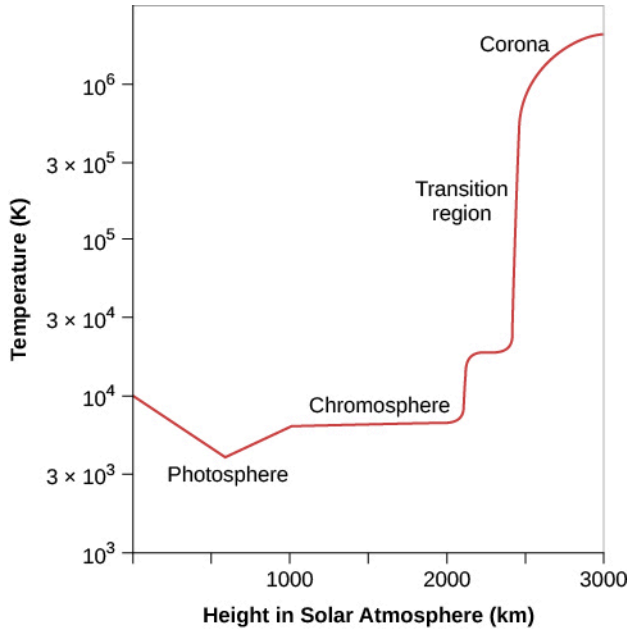

Figure 15.8 Temperatures in the Solar Atmosphere. On this graph, temperature is shown increasing upward, and height above the photosphere is shown increasing to the right. Note the very rapid increase in temperature over a very short distance in the transition region between the chromosphere and the corona.

In 2013, NASA launched the Interface Region Imaging Spectrograph (IRIS) to study the transition region to understand better how and why this sharp temperature increase occurs. IRIS is the first space mission that is able to obtain high spatial resolution images of the different features produced over this wide temperature range and to see how they change with time and location (Figure 15.9).

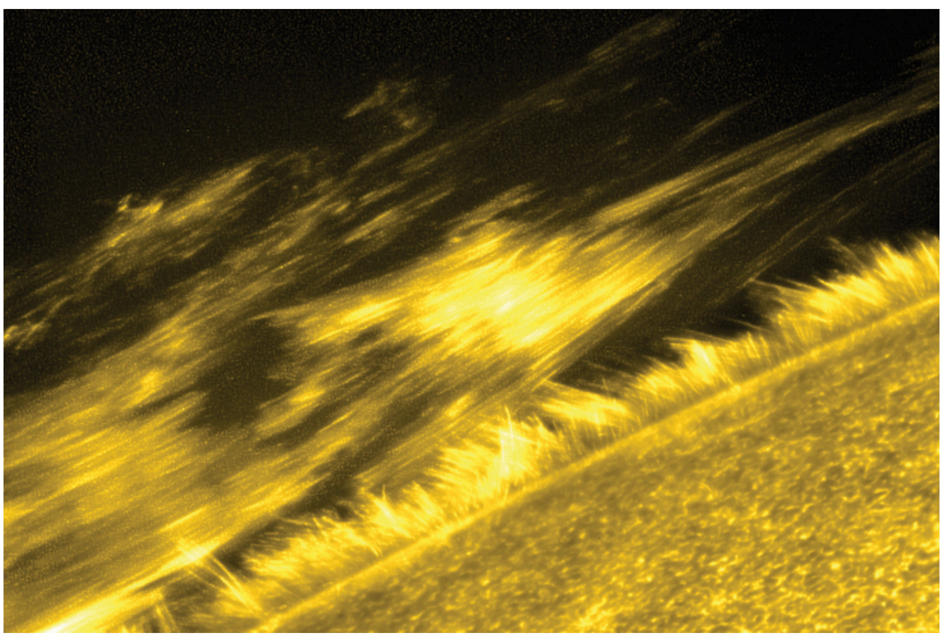

Figure 15.9 Portion of the Transition Region. This image shows a giant ribbon of relatively cool gas threading through the lower portion of the hot corona. This ribbon (the technical term is filament) is made up of many individual threads. Time-lapse movies of this filament showed that it gradually heated as it moved through the corona. Scientists study events like this in order to try to understand what heats the chromosphere and corona to high temperatures. The “whiskers” at the edge of the Sun are spicules, jets of gas that shoot material up from the Sun’s surface and disappear after only a few minutes. This single image gives a hint of just how complicated it is to construct a model of the all the different structures and heating mechanisms in the solar atmosphere. (credit: JAXA/NASA/Hinode)

Figure 15.4 and the red graph in Figure 15.8 make the Sun seem rather like an onion, with smooth spherical shells, each one with a different temperature. For a long time, astronomers did indeed think of the Sun this way. However, we now know that while this idea of layers—photosphere, chromosphere, transition region, corona—describes the big picture fairly well, the Sun's atmosphere is really more complicated, with hot and cool regions intermixed. For example, clouds of carbon monoxide gas with temperatures colder than 4000 K have now been found at the same height above the photosphere as the much hotter gas of the chromosphere.

The Corona

The outermost part of the Sun's atmosphere is called the *corona*. Like the chromosphere, the corona was first observed during total eclipses (Figure 15.10). Unlike the chromosphere, the corona has been known for many centuries: it was referred to by the Roman historian Plutarch and was discussed in some detail by Kepler.

The corona extends millions of kilometers above the photosphere and emits about half as much light as the full moon. The reason we don't see this light until an eclipse occurs is the overpowering brilliance of the photosphere. Just as bright city lights make it difficult to see faint starlight, so too does the intense light from the photosphere hide the faint light from the corona. While the best time to see the corona from Earth is during a total solar eclipse, it can be observed easily from orbiting spacecraft. Its brighter parts can now be photographed with a special instrument—a coronagraph—that removes the Sun's glare from the image with an occulting disk (a circular piece of material held so it is just in front of the Sun).

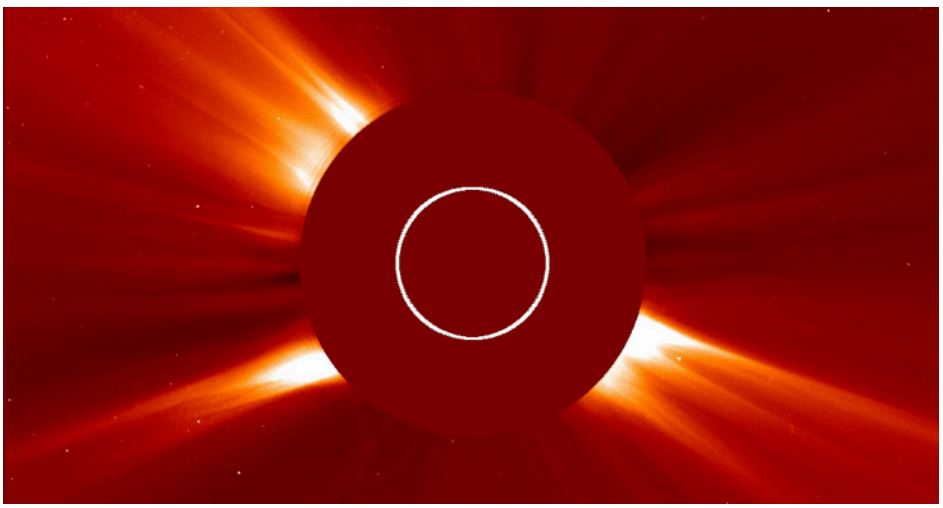

Figure 15.10 Coronagraph. This image of the Sun was taken March 2, 2016. The larger dark circle in the center is the disk the blocks the Sun's glare, allowing us to see the corona. The smaller inner circle is where the Sun would be if it were visible in this image. (credit: modification of work by NASA/SOHO)

Studies of its spectrum show the corona to be very low in density. At the bottom of the corona, there are only about 10^9 atoms per cubic centimeter, compared with about 10^{16} atoms per cubic centimeter in the upper photosphere and 10^{19} molecules per cubic centimeter at sea level in Earth's atmosphere. The corona thins out very rapidly at greater heights, where it corresponds to a high vacuum by Earth laboratory standards. The corona extends so far into space—far past Earth—that here on our planet, we are technically living in the Sun's atmosphere.

The Solar Wind

One of the most remarkable discoveries about the Sun's atmosphere is that it produces a stream of charged particles (mainly protons and electrons) that we call the **solar wind**. These particles flow outward from the Sun into the solar system at a speed of about 400 kilometers per second (almost 1 million miles per hour)! The solar wind exists because the gases in the corona are so hot and moving so rapidly that they cannot be held back by solar gravity. (This wind was actually discovered by its effects on the charged tails of comets; in a sense, we can see the comet tails blow in the solar breeze the way wind socks at an airport or curtains in an open window flutter on Earth.)

Although the solar wind material is very, very rarified (i.e., *extremely* low density), the Sun has an enormous surface area. Astronomers estimate that the Sun is losing about 1–2 million tons of material each second through this wind. Although this sounds like a lot, it's so trivial compared to the enormous mass of the Sun that it can be neglected as we study the Sun.

From where in the Sun does the solar wind emerge? In visible photographs, the solar corona appears fairly uniform and smooth. X-ray and extreme ultraviolet pictures, however, show that the corona has loops, plumes, and both bright and dark regions. Large dark regions of the corona that are relatively cool and quiet are called **coronal holes** (Figure 15.11). In these regions, magnetic field lines stretch far out into space away from the Sun, rather than looping back to the surface. The solar wind comes predominantly from coronal holes, where gas can stream away from the Sun into space unhindered by magnetic fields. Hot coronal gas, on the other hand, is present mainly where magnetic fields have trapped and concentrated it.

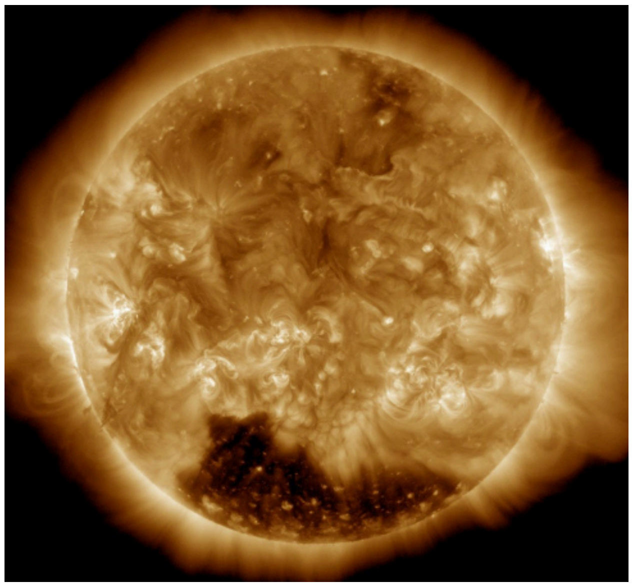

Figure 15.11 Coronal Hole. The dark area visible near the Sun's south pole on this Solar Dynamics Observer spacecraft image is a coronal hole. (credit: modification of work by NASA/SDO)

At the surface of Earth, we are protected to some degree from the solar wind by our atmosphere and Earth's magnetic field (see Earth as a Planet). However, the magnetic field lines come into Earth at the north and south magnetic poles. Here, charged particles accelerated by the solar wind can follow the field down into our atmosphere. As the particles strike molecules of air, they cause them to glow, producing beautiful curtains of light called the **auroras**, or the northern and southern lights (Figure 15.12).

Figure 15.12 Aurora. The colorful glow in the sky results from charged particles in a solar wind interacting with Earth's magnetic fields. The stunning display captured here occurred over Jokulsarlon Lake in Iceland in 2013. (credit: Moyan Brenn)

LINK TO LEARNING

This NASA video (https://openstax.org/l/30Aurora) explains and demonstrates the nature of the auroras and their relationship to Earth's magnetic field.

15.2 The Solar Cycle

Learning Objectives

By the end of this section, you will be able to:

- Describe the sunspot cycle and, more generally, the solar cycle
- Explain how magnetism is the source of solar activity

Before the invention of the telescope, the Sun was thought to be an unchanging and perfect sphere. We now know that the Sun is in a perpetual state of change: its surface is a seething, bubbling cauldron of hot gas. Areas that are darker and cooler than the rest of the surface come and go. Vast plumes of gas erupt into the chromosphere and corona. Occasionally, there are even giant explosions on the Sun that send enormous streamers of charged particles and energy hurtling toward Earth. When they arrive, these can cause power outages and other serious effects on our planet.

Sunspots

The first evidence that the Sun changes came from studies of **sunspots**, which are large, dark features seen on the surface of the Sun caused by increased magnetic activity. They look darker because the spots are typically at a temperature of about 3800 K, whereas the bright regions that surround them are at about 5800 K (Figure 15.13). Occasionally, these spots are large enough to be visible to the unaided eye, and we have records going back over a thousand years from observers who noticed them when haze or mist reduced the Sun's intensity. (We emphasize what your parents have surely told you: looking at the Sun for even a brief time can cause permanent eye damage. This is the one area of astronomy where we don't encourage you to do your own observing without getting careful instructions or filters from your instructor.)

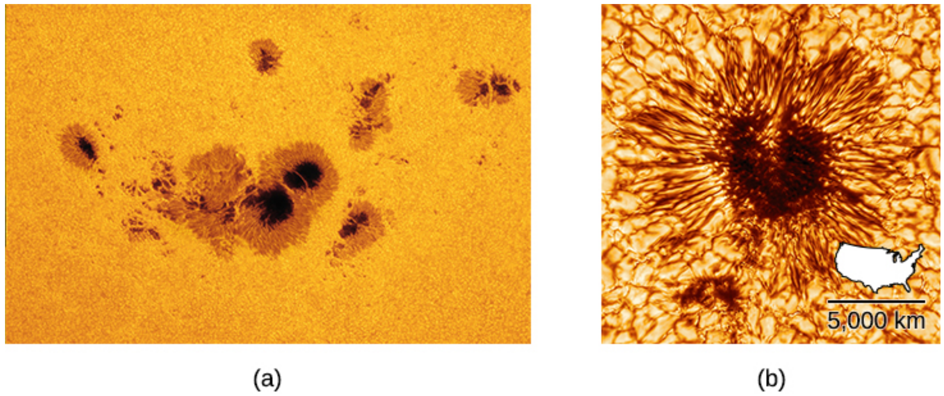

Figure 15.13 Sunspots. a) Image of sunspots, cooler and thus darker regions on the Sun, taken in July 2012. You can see the dark, central region of each sunspot (called the umbra) surrounded by a less dark region (the penumbra). The largest spot shown here is about 11 Earths wide. b) The new Daniel Inouye Solar Telescope took the most detailed image of a sunspot ever recorded in January 2020. A map of the United States is shown to scale. Although sunspots appear dark when seen next to the hotter gases of the photosphere, an average sunspot, cut out of the solar surface and left standing in the night sky, would be about as bright as the full moon. The mottled appearance of the Sun's surface is granulation. (credit a: modification of work by NASA Goddard Space Flight Center, Alan Friedman; credit b: modification of work by NSO/AURA/NSF)

While we understand that sunspots look darker because they are cooler, they are nevertheless hotter than the surfaces of many stars. If they could be removed from the Sun, they would shine brightly. They appear dark only in contrast with the hotter, brighter photosphere around them.

Individual sunspots come and go, with lifetimes that range from a few hours to a few months. If a spot lasts and develops, it usually consists of two parts: an inner darker core, the *umbra*, and a surrounding less dark region, the *penumbra*. Many spots become much larger than Earth, and a few, like the largest one shown in Figure 15.13, have reached diameters over 140,000 kilometers. Frequently, spots occur in groups of 2 to 20 or more. The largest groups are very complex and may have over 100 spots. Like storms on Earth, sunspots are not fixed in position, but they drift slowly compared with the Sun's rotation.

By recording the apparent motions of the sunspots as the turning Sun carried them across its disk (Figure 15.14), Galileo, in 1612, demonstrated that the Sun rotates on its axis with a rotation period of approximately 1 month. Our star turns in a west-to-east direction, like the orbital motions of the planets. The Sun, however, is a gas and does not have to rotate rigidly, the way a solid body like Earth does. Modern observations show that the speed of rotation of the Sun varies according to latitude, that is, it's different as you go north or south of the Sun's equator. The rotation period is about 25 days at the equator, 28 days at latitude 40°, and 36 days at latitude 80°. We call this behavior **differential rotation**.

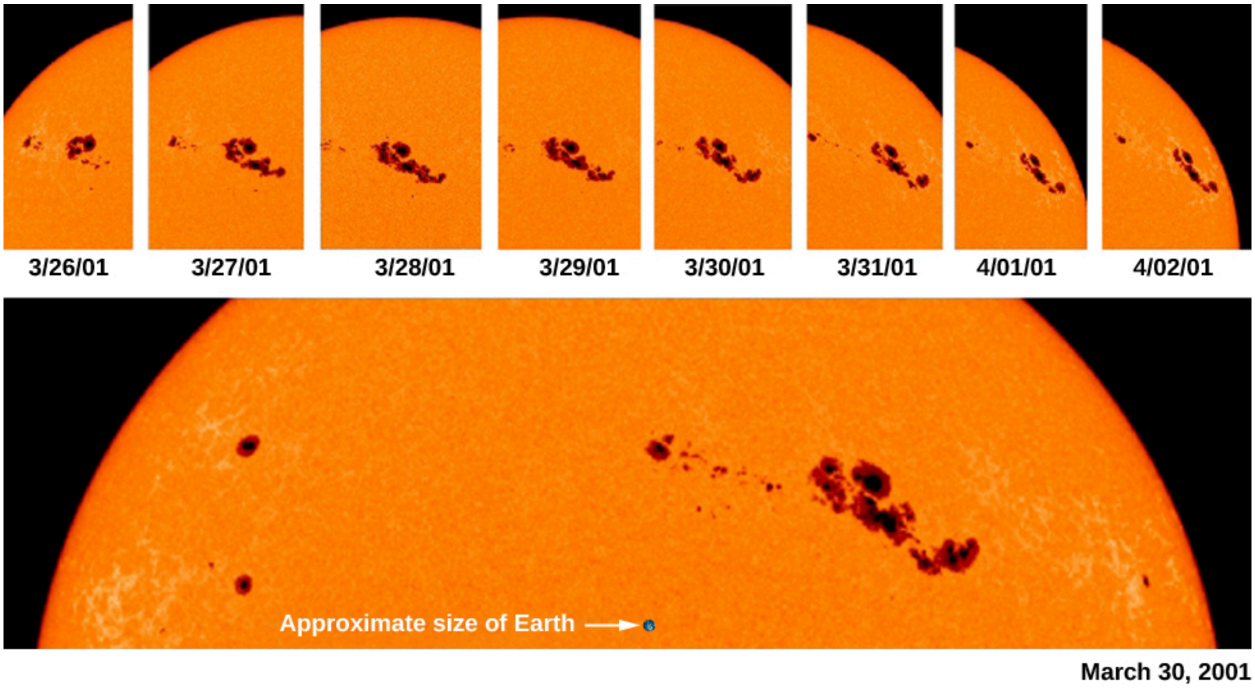

Figure 15.14 Sunspots Rotate Across Sun's Surface. This sequence of photographs of the Sun's surface tracks the movement of sunspots across the visible hemisphere of the Sun. On March 30, 2001, this group of sunspots extended across an area about 13 times the diameter of Earth. This region produced many flares and coronal mass ejections. (credit: modification of work by SOHO/NASA/ESA)

The Sunspot Cycle

Between 1826 and 1850, Heinrich Schwabe, a German pharmacist and amateur astronomer, kept daily records of the number of sunspots. What he was really looking for was a planet inside the orbit of Mercury, which he hoped to find by observing its dark silhouette as it passed between the Sun and Earth. He failed to find the hoped-for planet, but his diligence paid off with an even-more important discovery: the **sunspot cycle**. He found that the number of sunspots varied systematically, in cycles about a decade long.

What Schwabe observed was that, although individual spots are short lived, the total number visible on the Sun at any one time was likely to be very much greater at certain times—the periods of *sunspot maximum*—than at other times—the periods of *sunspot minimum*. We now know that sunspot maxima occur at an *average* interval of 11 years, but the intervals between successive maxima have ranged from as short as 9 years to as long as 14 years. During sunspot maxima, more than 100 spots can often be seen at once. Even then, less than one-half of one percent of the Sun's surface is covered by spots (Figure 15.22). During sunspot minima, sometimes no spots are visible. The Sun's activity reached its most recent maximum in 2014.

LINK TO LEARNING

Watch this brief video (https://openstax.org/l/30SolarCyc) from NASA's Goddard Space Flight Center that explains the sunspot cycle.

Explore the number of sunspots (https://openstax.org/l/30numsunspots) measured each year going back to 1707. Point your cursor at any year, and the diagram tells you the number of sunspots.

Magnetism and the Solar Cycle

Now that we have discussed the Sun's activity cycle, you might be asking, "Why does the Sun change in such a regular way?" Astronomers now understand that it is the Sun's changing magnetic field that drives solar activity.

The solar magnetic field is measured using a property of atoms called the *Zeeman effect*. Recall from Radiation and Spectra that an atom has many energy levels and that spectral lines are formed when electrons shift from one level to another. If each energy level is precisely defined, then the difference between them is also quite precise. As an electron changes levels, the result is a sharp, narrow spectral line (either an absorption or emission line, depending on whether the electron's energy increases or decreases in the transition).

In the presence of a strong magnetic field, however, each energy level is separated into several levels very close to one another. The separation of the levels is proportional to the strength of the field. As a result, spectral lines formed in the presence of a magnetic field are not single lines but a series of very closely spaced lines corresponding to the subdivisions of the atomic energy levels. This splitting of lines in the presence of a magnetic field is what we call the Zeeman effect (after the Dutch scientist who first discovered it in 1896).

Measurements of the Zeeman effect in the spectra of the light from sunspot regions show them to have strong magnetic fields (Figure 15.15). Bear in mind that magnets always have a north pole and a south pole. Whenever sunspots are observed in pairs, or in groups containing two principal spots, one of the spots usually has the magnetic polarity of a north-seeking magnetic pole and the other has the opposite polarity. Moreover, during a given cycle, the leading spots of pairs (or leading principle spots of groups) in the Northern Hemisphere all tend to have the same polarity, whereas those in the Southern Hemisphere all tend to have the opposite polarity.

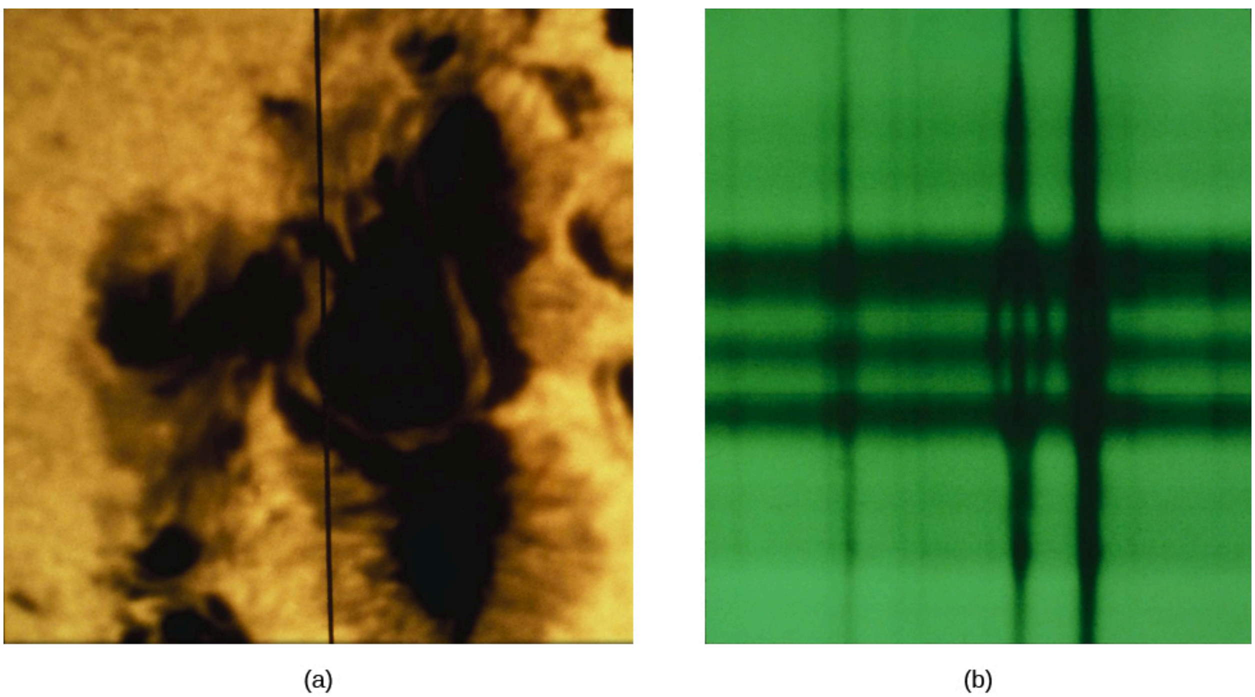

Figure 15.15 Zeeman Effect. These photographs show how magnetic fields in sunspots are measured by means of the Zeeman effect. (left) The vertical black line indicates the position of the spectrograph slit through which light is passed to obtain the spectrum in (right). (credit: modification of work by NSO/AURA/NSF)

During the next sunspot cycle, however, the polarity of the leading spots is reversed in each hemisphere. For example, if during one cycle, the leading spots in the Northern Hemisphere all had the polarity of a north-seeking pole, then the leading spots in the Southern Hemisphere would have the polarity of a south-seeking pole. During the next cycle, the leading spots in the Northern Hemisphere would have south-seeking polarity, whereas those in the Southern Hemisphere would have north-seeking polarity. Therefore, strictly speaking, the sunspot cycle does not repeat itself in regard to magnetic polarity until two 11-year cycles have passed. A visual representation of the Sun's magnetic fields, called a *magnetogram*, can be used to see the relationship between sunspots and the Sun’s magnetic field (Figure 15.16).

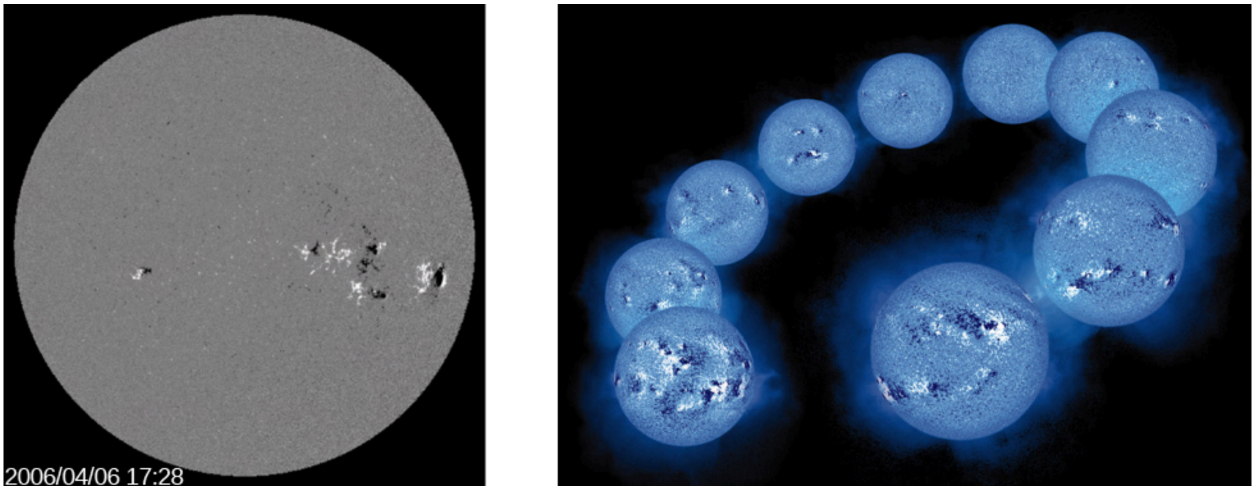

Figure 15.16 Magnetogram and Solar Cycle. In the image on the left, called a magnetogram, we see the magnetic polarity of sunspots. The black areas are where the magnetism is pointing toward the Sun’s core, whereas the white regions are where it is pointing away from the core, toward us. This dramatic sequence on the right shows the activity cycle of the Sun. The 10 maps of the magnetic field on the surface of the Sun span a period of 7.5 years. The two magnetic polarities (N and S) of the magnetic field are shown against a blue disk as dark blue to black (N) and as light blue to white (S). The earliest image, taken on January 8, 1992, is at the lower left and was taken just after solar maximum. Each image, from left to right around the arc, was taken one-half to one year after the preceding one. The last image was taken on July 25, 1999, as the Sun was approaching the next solar maximum. Note a few striking patterns in the magnetic maps: the direction from white to black polarity in the Southern Hemisphere is opposite from that in the Northern Hemisphere. (credit left: modification of work by NASA/SDO; credit right: modification of work by NASA/SOHO)

Why is the Sun such a strong and complicated magnet? Astronomers have found that it is the Sun’s *dynamo* that generates the magnetic field. A dynamo is a machine that converts kinetic energy (i.e., the energy of motion) into electricity. On Earth, dynamos are found in power plants where, for example, the energy from wind or flowing water is used to cause turbines to rotate. In the Sun, the source of kinetic energy is the churning of turbulent layers of ionized gas within the Sun’s interior that we mentioned earlier. These generate electric currents—moving electrons—which in turn generate magnetic fields.

Most solar researchers agree that the solar dynamo is located in the convection zone or in the interface layer between the convection zone and the radiative zone below it. As the magnetic fields from the Sun’s dynamo interact, they break, reconnect, and rise through the Sun’s surface.

We should say that, although we have good observations that show us *how* the Sun changes during each solar cycle, it is still very difficult to build physical models of something as complicated as the Sun that can account satisfactorily for *why* it changes. Researchers have not yet developed a generally accepted model that describes in detail the physical processes that control the solar cycle. Calculations do show that differential rotation (the idea that the Sun rotates at different rates at different latitudes) and convection just below the solar surface can twist and distort the magnetic fields. This causes them to grow and then decay, regenerating with opposite polarity approximately every 11 years. The calculations also show that as the fields grow stronger near solar maximum, they flow from the interior of the Sun toward its surface in the form of loops. When a large loop emerges from the solar surface, it creates regions of sunspot activity (Figure 15.17).

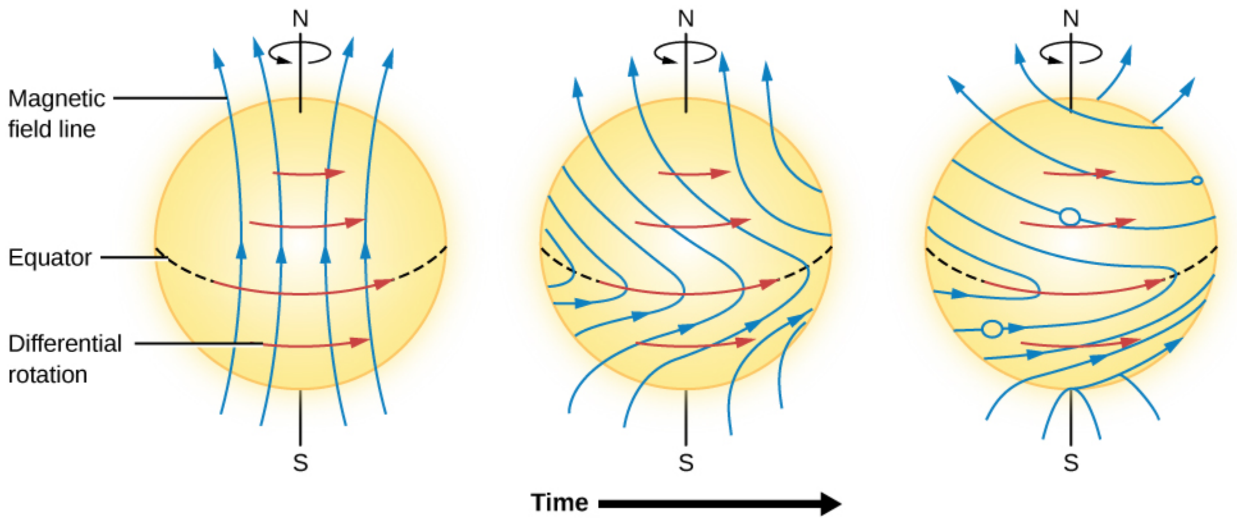

Figure 15.17 Magnetic Field Lines Wind Up. Because the Sun spins faster at the equator than near the poles, the magnetic fields in the Sun tend to wind up as shown, and after a while make loops. This is an idealized diagram; the real situation is much more complex.

This idea of magnetic loops offers a natural explanation of why the leading and trailing sunspots in an active region have opposite polarity. The leading sunspot coincides with one end of the loop and the trailing spot with the other end. Magnetic fields also hold the key to explaining why sunspots are cooler and darker than the regions without strong magnetic fields. The forces produced by the magnetic field resist the motions of the bubbling columns of rising hot gases. Since these columns carry most of the heat from inside the Sun to the surface by means of convection, and strong magnetic fields inhibit this convection, the surface of the Sun is allowed to cool. As a result, these regions are seen as darker, cooler sunspots.

Beyond this general picture, researchers are still trying to determine why the magnetic fields are as large as they are, why the polarity of the field in each hemisphere flips from one cycle to the next, why the length of the solar cycle can vary from one cycle to the next, and why events like the Maunder Minimum occur.

LINK TO LEARNING

In this video (https://openstax.org/l/30MagField) solar scientist Holly Gilbert discusses the Sun's magnetic field.

15.3 Solar Activity above the Photosphere

Learning Objectives

By the end of this section, you will be able to:

- Describe the various ways in which the solar activity cycle manifests itself, including flares, coronal mass ejections, prominences, and plages

Sunspots are not the only features that vary during a solar cycle. There are dramatic changes in the chromosphere and corona as well. To see what happens in the chromosphere, we must observe the emission lines from elements such as hydrogen and calcium, which emit useful spectral lines at the temperatures in that layer. The hot corona, on the other hand, can be studied by observations of X-rays and of extreme ultraviolet and other wavelengths at high energies.

Plages and Prominences

As we saw, emission lines of hydrogen and calcium are produced in the hot gases of the chromosphere.

Astronomers routinely photograph the Sun through filters that transmit light only at the wavelengths that correspond to these emission lines. Pictures taken through these special filters show bright "clouds" in the chromosphere around sunspots; these bright regions are known as **plages** (Figure 15.18). These are regions within the chromosphere that have higher temperature and density than their surroundings. The plages actually contain all of the elements in the Sun, not just hydrogen and calcium. It just happens that the spectral lines of hydrogen and calcium produced by these clouds are bright and easy to observe.

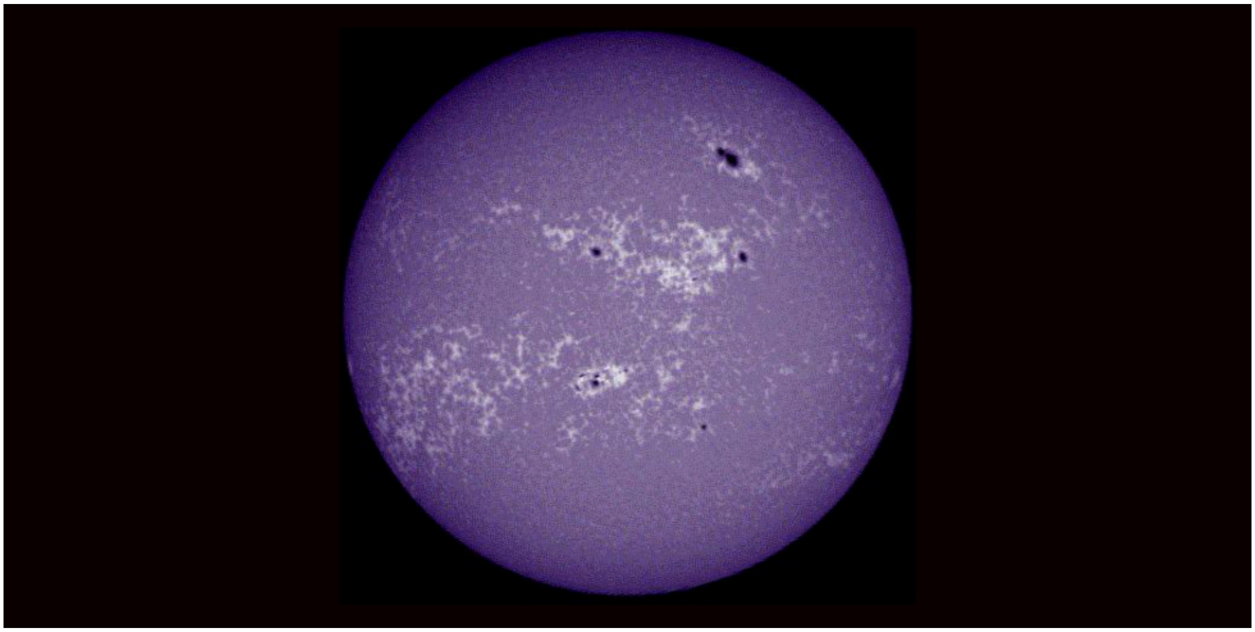

Figure 15.18 Plages on the Sun. This image of the Sun was taken with a filter that transmits only the light of the spectral line produced by singly ionized calcium. The bright cloud-like regions are the plages. (credit: modification of work by NASA)

Moving higher into the Sun's atmosphere, we come to the spectacular phenomena called **prominences** (Figure 15.19), which usually originate near sunspots. Eclipse observers often see prominences as red features rising above the eclipsed Sun and reaching high into the corona. Some, the *quiescent* prominences, are graceful loops of plasma (ionized gas) that can remain nearly stable for many hours or even days. The relatively rare *eruptive* prominences appear to send matter upward into the corona at high speeds, and the most active *surge* prominences may move as fast as 1300 kilometers per second (almost 3 million miles per hour). Some eruptive prominences have reached heights of more than 1 million kilometers above the photosphere; Earth would be completely lost inside one of those awesome displays (Figure 15.19).

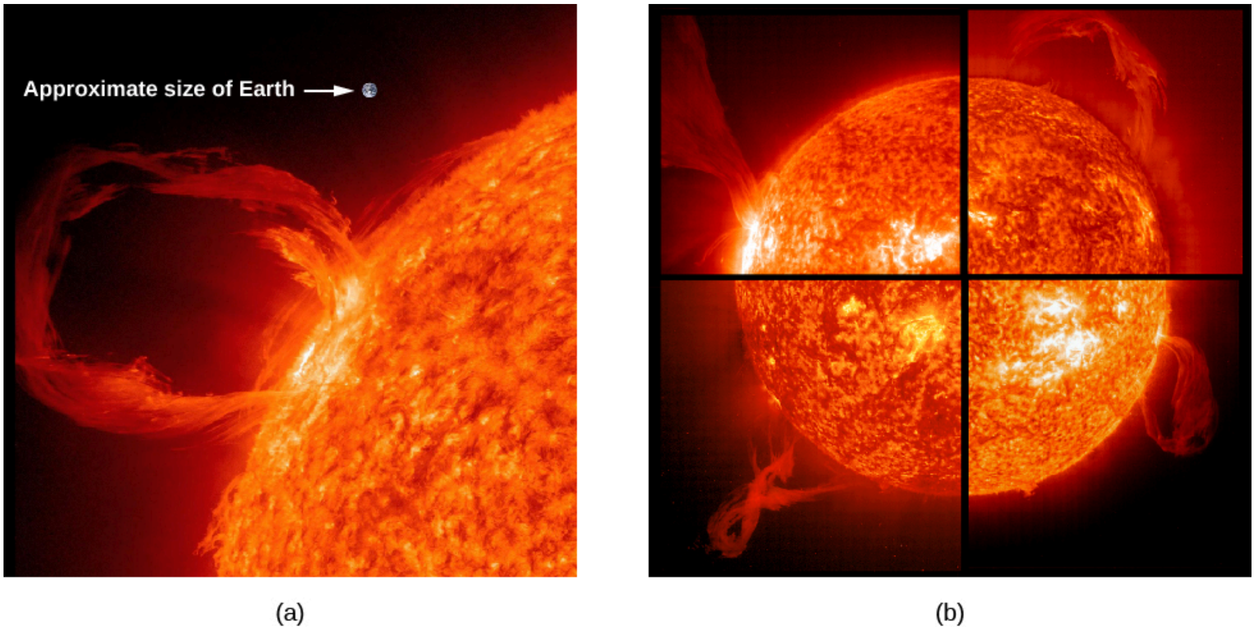

Figure 15.19 Prominences. (a) This image of an eruptive prominence was taken in the light of singly ionized helium in the extreme ultraviolet part of the spectrum. The prominence is a particularly large one. An image of Earth is shown at the same scale for comparison. (b) A prominence is a huge cloud of relatively cool (about 60,000 K in this case), fairly dense gas suspended in the much hotter corona. These pictures, taken in ultraviolet, are color coded so that white corresponds to the hottest temperatures and dark red to cooler ones. The four images were taken, moving clockwise from the upper left, on May 15, 2001; March 28, 2000; January 18, 2000; and February 2, 2001. (credit a: modification of work by NASA/SOHO; credit b: modification of work by NASA/SDO)

Flares and Coronal Mass Ejections

The most violent event on the surface of the Sun is a rapid eruption called a **solar flare** (Figure 15.20). A typical flare lasts for 5 to 10 minutes and releases a total amount of energy equivalent to that of perhaps a million hydrogen bombs. The largest flares last for several hours and emit enough energy to power the entire United States at its current rate of electrical consumption for 100,000 years. Near sunspot maximum, small flares occur several times per day, and major ones may occur every few weeks.

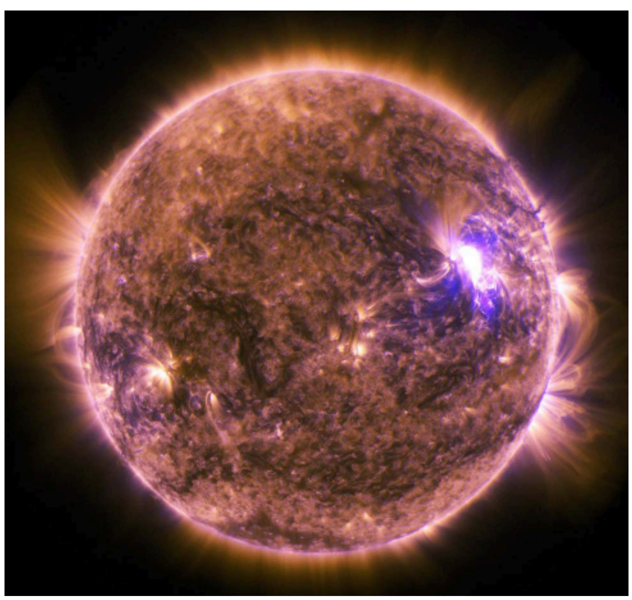

Figure 15.20 Solar Flare. The bright white area seen on the right side of the Sun in this image from the Solar Dynamics Observer spacecraft is a solar flare that was observed on June 25, 2015. (credit: NASA/SDO)

Flares, like the one shown in Figure 15.21, are often observed in the red light of hydrogen, but the visible emission is only a tiny fraction of the energy released when a solar flare explodes. At the moment of the explosion, the matter associated with the flare is heated to temperatures as high as 10 million K. At such high temperatures, a flood of X-ray and ultraviolet radiation is emitted.

Flares seem to occur when magnetic fields pointing in opposite directions release energy by interacting with and destroying each other—much as a stretched rubber band releases energy when it breaks.

What is different about flares is that their magnetic interactions cover a large volume in the solar corona and release a tremendous amount of electromagnetic radiation. In some cases, immense quantities of coronal material—mainly protons and electrons—may also be ejected at high speeds (500–1000 kilometers per second) into interplanetary space. Such a **coronal mass ejection (CME)** can affect Earth in a number of ways (which we will discuss in the section on space weather).

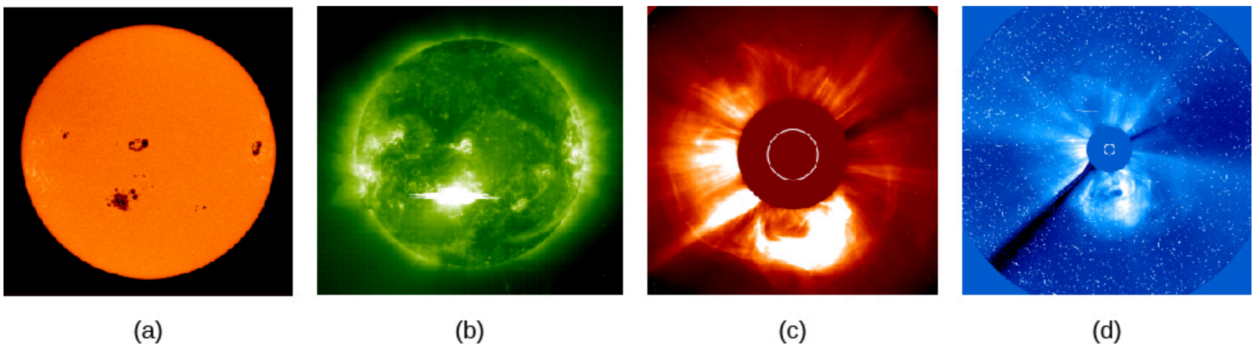

Figure 15.21 Flare and Coronal Mass Ejection. This sequence of four images shows the evolution over time of a giant eruption on the Sun. (a) The event began at the location of a sunspot group, and (b) a flare is seen in far-ultraviolet light. (c) Fourteen hours later, a CME is seen blasting out into space. (d) Three hours later, this CME has expanded to form a giant cloud of particles escaping from the Sun and is beginning the journey out into the solar system. The white circle in (c) and (d) shows the diameter of the solar photosphere. The larger dark area shows where light from the Sun has been blocked out by a specially designed instrument to make it possible to see the faint emission from the corona. (credit a, b, c, d: modification of work by SOHO/EIT, SOHO/LASCO, SOHO/MDI (ESA & NASA))

LINK TO LEARNING

See a coronal mass ejection (https://openstax.org/l/30CorMaEj) recorded by the Solar Dynamics Observatory.

Active Regions

To bring the discussion of the last two sections together, astronomers now realize that sunspots, flares, and bright regions in the chromosphere and corona tend to occur together on the Sun in time and space. That is, they all tend to have similar longitudes and latitudes, but they are located at different heights in the atmosphere. Because they all occur together, they vary with the sunspot cycle.

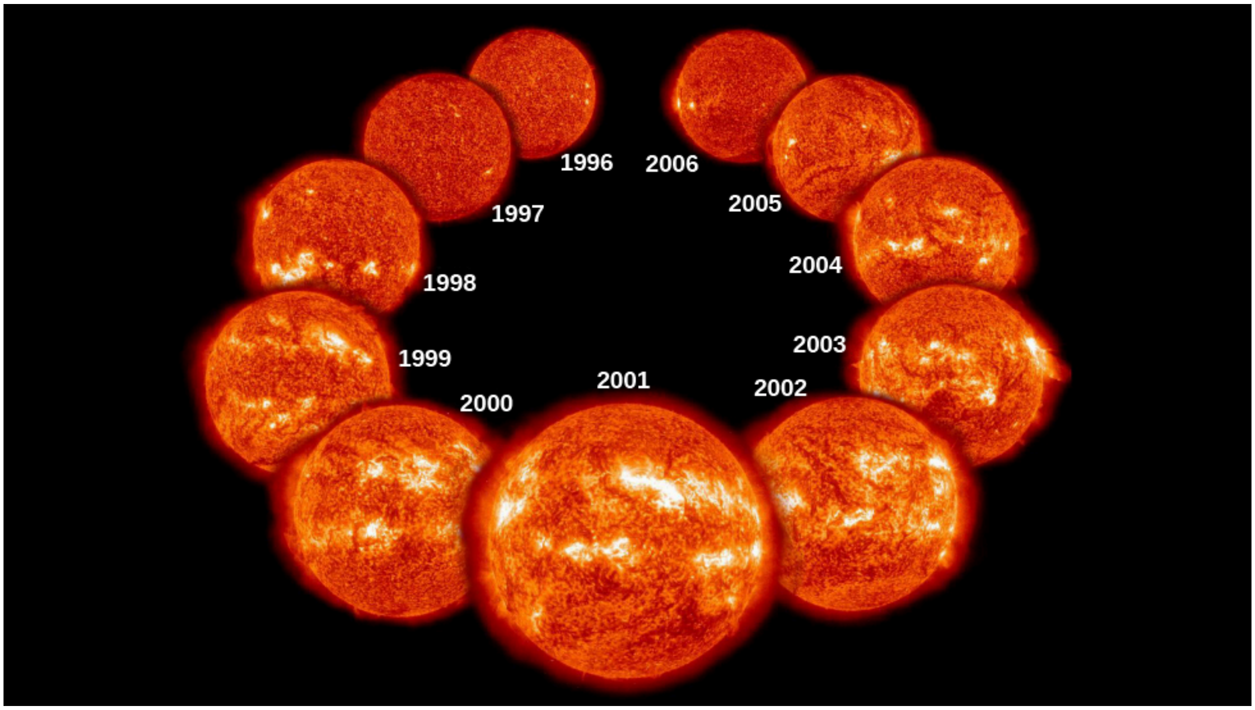

Figure 15.22 Solar Cycle. This dramatic sequence of images taken from the SOHO satellite over a period of 11 years shows how active regions change during the solar cycle. The images were taken in the ultraviolet region of the spectrum and show that active regions on the Sun increase and decrease during the cycle. Sunspots are located in the cooler photosphere, beneath the hot gases shown in this image, and vary in phase with the emission from these hot gases—more sunspots and more emission from hot gases occur together. (credit: modification of work by ESA/NASA/SOHO)

For example, flares are more likely to occur near sunspot maximum, and the corona is much more conspicuous at that time (see Figure 15.22). A place on the Sun where a number of these phenomena are seen is called an **active region** (Figure 15.23). As you might deduce from our earlier discussion, active regions are always associated with strong magnetic fields.

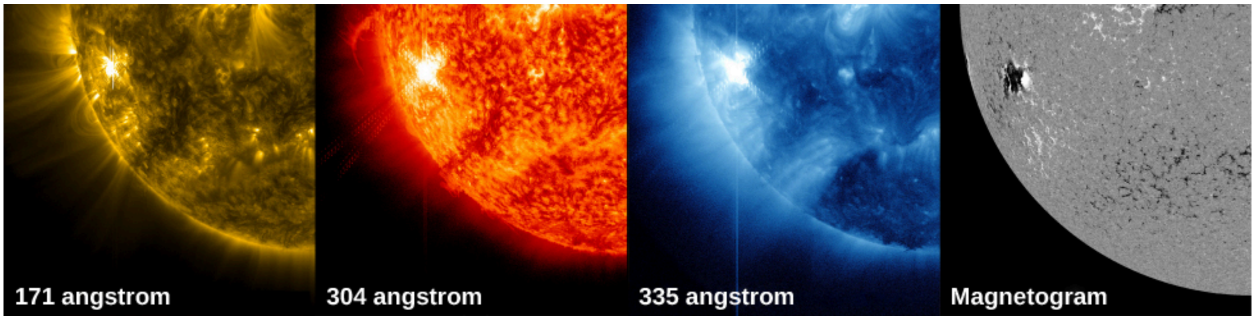

Figure 15.23 Solar Active Region Observed at Different Heights in the Sun's Atmosphere. These four images of a solar flare on October 22, 2012, show from the left: light from the Sun at a wavelength of 171 angstroms, which shows the structure of loops of solar material in the corona; ultraviolet at 304 angstroms, which shows light from the region of the Sun's atmosphere where flares originate; light at 335 angstroms, which highlights radiation from active regions in the corona; a magnetogram, which shows magnetically active regions on the Sun. Note how these different types of activity all occur above a sunspot region with a strong magnetic field. (credit: modification of work by NASA/SDO/Goddard)

15.4 Space Weather

Learning Objectives

By the end of this section, you will be able to:

- Explain what space weather is and how it affects Earth

In the previous sections, we have seen that some of the particles coming off the Sun—either steadily as in the solar wind or in great bursts like CMEs—will reach Earth and its *magnetosphere* (the zone of magnetic influence that surrounds our planet). As if scientists did not have enough trouble trying to predict weather on Earth, this means that they are now facing the challenge of predicting the effects of solar storms on Earth. This field of research is called *space weather*; when that weather turns stormy, our technology turns out to be at risk.

With thousands of satellites in orbit, astronauts taking up long-term residence in the International Space Station, millions of people using cell phones, GPS, and wireless communication, and nearly everyone relying on the availability of dependable electrical power, governments are now making major investments in trying to learn how to predict when solar storms will occur and how strongly they will affect Earth.

Some History

What we now study as space weather was first recognized (though not yet understood) in 1859, in what is now known as the Carrington Event. In early September of that year, two amateur astronomers, including Richard Carrington in England, independently observed a solar flare. This was followed a day or two later by a significant solar storm reaching the region of Earth's magnetic field, which was soon overloaded with charged particles (see Earth as a Planet).

As a result, aurora activity was intense and the northern lights were visible well beyond their normal locations near the poles—as far south as Hawaii and the Caribbean. The glowing lights in the sky were so intense that some people reported getting up in the middle of the night, thinking it must be daylight.

The 1859 solar storm happened at a time when a new technology was beginning to tie people in the United States and some other countries together: the telegraph system. This was a machine and network for sending messages in code through overhead electrical wires (a bit like a very early version of the internet). The charged particles that overwhelmed Earth's magnetic field descended toward our planet's surface and affected the wires of the telegraph system. Sparks were seen coming out of exposed wires and out of the telegraph machines in the system's offices.

The observation of the bright flare that preceded these effects on Earth led to scientific speculation that a connection existed between solar activity and impacts on Earth—this was the beginning of our understanding of what today we call space weather.

LINK TO LEARNING

Watch NASA scientists answer some questions (https://openstax.org/l/30SpcWeath) about space weather, and discuss (https://openstax.org/l/30SpcWeath2) some effects it can have in space and on Earth.

Sources of Space Weather

Three solar phenomena—coronal holes, solar flares, and CMEs—account for most of the space weather we experience. Coronal holes allow the solar wind to flow freely away from the Sun, unhindered by solar magnetic fields. When the solar wind reaches Earth, as we saw, it causes Earth's magnetosphere to contract and then expand after the solar wind passes by. These changes can cause (usually mild) electromagnetic disturbances on Earth.

More serious are solar flares, which shower the upper atmosphere of Earth with X-rays, energetic particles, and intense ultraviolet radiation. The X-rays and ultraviolet radiation can ionize atoms in Earth's upper atmosphere, and the freed electrons can build up a charge on the surface of a spacecraft. When this static charge discharges, it can damage the electronics in the spacecraft—just as you can receive a shock when you walk across a carpet in your stocking feet in a dry climate and then touch a light switch or some other metal object.

Most disruptive are coronal mass ejections. A CME is an erupting bubble of tens of millions of tons of gas blown away from the Sun into space. When this bubble reaches Earth a few days after leaving the Sun, it heats the ionosphere, which expands and reaches farther into space. As a consequence, friction between the atmosphere and spacecraft increases, dragging satellites to lower altitudes.

At the time of a particularly strong flare and CME in March 1989, the system responsible for tracking some 19,000 objects orbiting Earth temporarily lost track of 11,000 of them because their orbits were changed by the expansion of Earth’s atmosphere. During solar maximum, a number of satellites are brought to such a low altitude that they are destroyed by friction with the atmosphere. Both the Hubble Space Telescope and the International Space Station (Figure 15.24) require reboosts to higher altitude so that they can remain in orbit.

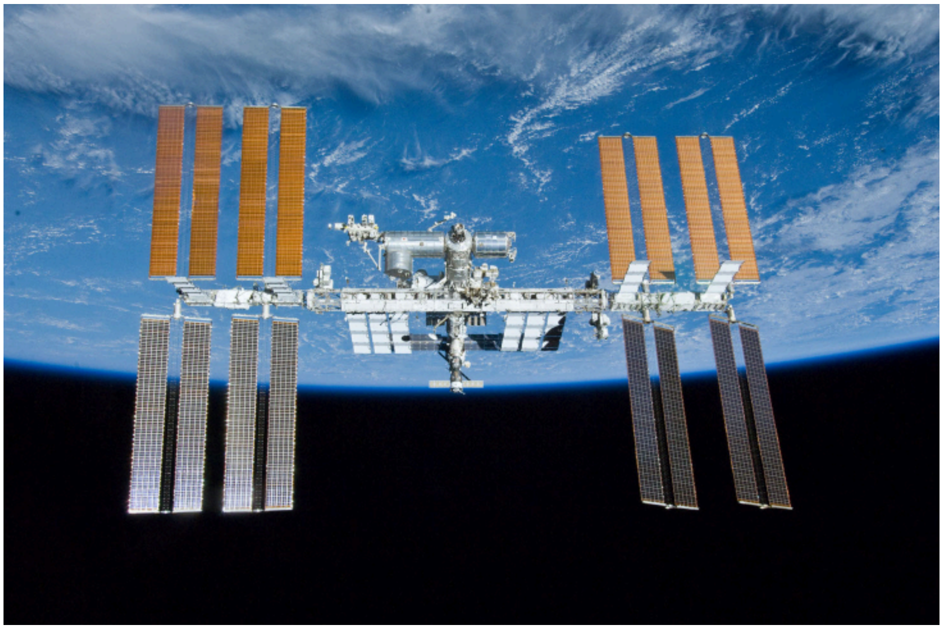

Figure 15.24 International Space Station. The International Space Station is seen above Earth, as photographed in 2010 by the departing crew of the Space Shuttle Atlantis. (credit: NASA)

Solar Storm Damage on Earth

When a CME reaches Earth, it distorts Earth’s magnetic field. Since a changing magnetic field induces electrical current, the CME accelerates electrons, sometimes to very high speeds. These “killer electrons” can penetrate deep into satellites, sometimes destroying their electronics and permanently disabling operation. This has happened with some communications satellites.

Disturbances in Earth’s magnetic field can cause disruptions in communications, especially cell phone and wireless systems. In fact, disruptions can be expected to occur several times a year during solar maximum. Changes in Earth’s magnetic field due to CMEs can also cause surges in power lines large enough to burn out transformers and cause major power outages. For example, in 1989, parts of Montreal and Quebec Province in Canada were without power for up to 9 hours as a result of a major solar storm. Electrical outages due to CMEs are more likely to occur in North America than in Europe because North America is closer to Earth’s magnetic pole, where the currents induced by CMEs are strongest.

Besides changing the orbits of satellites, CMEs can also distort the signals sent by them. These effects can be large enough to reduce the accuracy of GPS-derived positions so that they cannot meet the limits required for airplane systems, which must know their positions to within 160 feet. Such disruptions caused by CMEs have occasionally forced the Federal Aviation Administration to restrict flights for minutes or, in a few cases, even days.

Solar storms also expose astronauts, passengers in high-flying airplanes, and even people on the surface of

Earth to increased amounts of radiation. Astronauts, for example, are limited in the total amount of radiation to which they can be exposed during their careers. A single ill-timed solar outburst could end an astronaut's career. This problem becomes increasingly serious as astronauts spend more time in space. For example, the typical *daily* dose of radiation aboard the Russian Mir space station was equivalent to about eight chest X-rays. One of the major challenges in planning the human exploration of Mars is devising a way to protect astronauts from high-energy solar radiation.

Advance warning of solar storms would help us minimize their disruptive effects. Power networks could be run at less than their full capacity so that they could absorb the effects of power surges. Communications networks could be prepared for malfunctions and have backup plans in place. Spacewalks could be timed to avoid major solar outbursts. Scientists are now trying to find ways to predict where and when flares and CMEs will occur, and whether they will be big, fast events or small, slow ones with little consequence for Earth.

The strategy is to relate changes in the appearance of small, active regions and changes in local magnetic fields on the Sun to subsequent eruptions. However, right now, our predictive capability is still poor, and so the only real warning we have is from actually seeing CMEs and flares occur. Since a CME travels outward at about 500 kilometers per second, an observation of an eruption provides several days warning at the distance of Earth. However, the severity of the impact on Earth depends on how the magnetic field associated with the CME is oriented relative to Earth's magnetic field. The orientation can be measured only when the CME flows past a satellite we have put up for this purpose. However, it is located only about an hour upstream from Earth.

Space weather predictions are now available online to scientists and the public. Outlooks are given a week ahead, bulletins are issued when there is an event that is likely to be of interest to the public, and warnings and alerts are posted when an event is imminent or already under way (Figure 15.25).

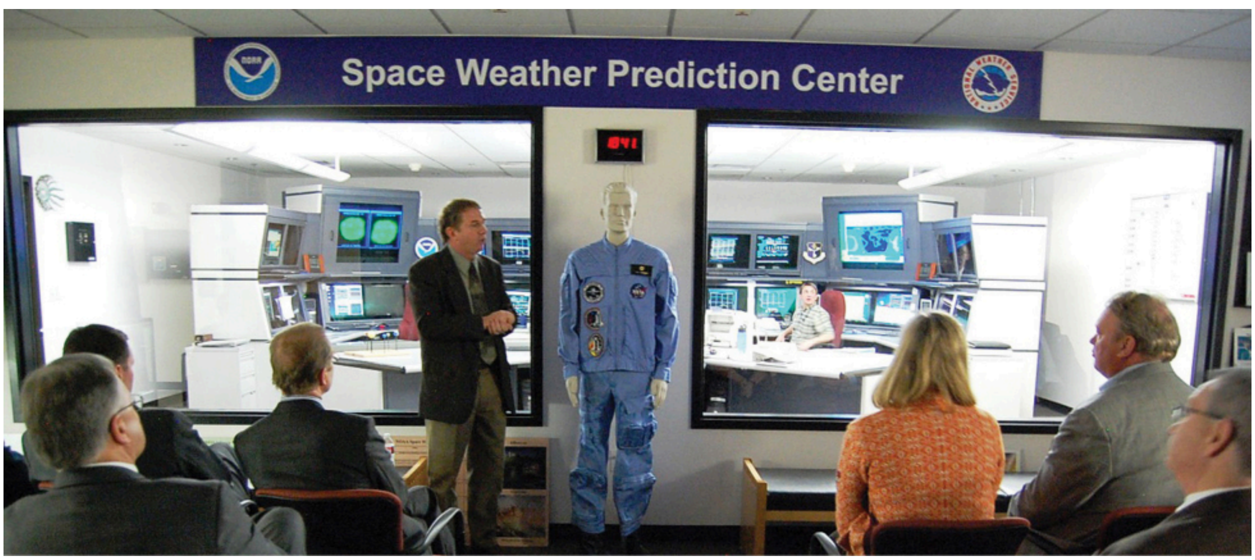

Figure 15.25 NOAA Space Weather Prediction Operations Center. Bill Murtagh, a space weather forecaster, leads a workshop on preparedness for events like geomagnetic storms. (credit: modification of work by FEMA/Jerry DeFelice)

LINK TO LEARNING

To find public information and alerts about space weather, you can turn to the National Space Weather Prediction Center (https://openstax.org/l/30NSWPC) or SpaceWeather (https://openstax.org/l/30SpcWeath3) for consolidated information from many sources.

More satellites are being launched that will allow us to determine whether CMEs are headed toward Earth and how big they are. Models are being developed that will then allow scientists to use early information about the CME to predict its likely impact on Earth.

The hope is that soon, solar weather forecasting will have some of the predictive capability that meteorologists have achieved for terrestrial weather at Earth's surface. However, the most difficult events to predict are the largest and most damaging storms—hurricanes on Earth and extreme, rare storm events on the Sun. Thus, it is inevitable that the Sun will continue to surprise us.

EXAMPLE 15.1

The Timing of Solar Events

A basic equation is useful in figuring out when events on the Sun will impact Earth:

$$\text{distance} = \text{velocity} \times \text{time, or } D = v \times t$$

Dividing both sides by *v*, we get

$$T = D/v$$

Suppose you observe a major solar flare while astronauts are orbiting Earth. If the average speed of solar wind is 400 km/s and the distance to the Sun as 1.496×10^8 km, how long it will before the charged particles ejected from the Sun during the flare reach the space station?

Solution

The time required for solar wind particles to reach Earth is $T = D/v$.

$$\frac{1.496 \times 10^8 \text{ km}}{400 \text{ km/s}} = 3.74 \times 10^5 \text{ s, or } \frac{3.74 \times 10^5 \text{ s}}{60 \text{ s/min} \times 60 \text{ min/h} \times 24 \text{ h/d}} = 4.3 \text{ d}$$

Check Your Learning

How many days would it take for the particles to reach Earth if the solar wind speed increased to 500 km/s?

Answer:

$$\frac{1.496 \times 10^8 \text{ km}}{500 \text{ km/s}} = 2.99 \times 10^5 \text{ s, or } \frac{2.99 \times 10^5 \text{ s}}{60 \text{ s/min} \times 60 \text{ min/h} \times 24 \text{ h/d}} = 3.46 \text{ d}$$

Earth's Climate and the Sunspot Cycle: Is There a Connection?

While the Sun rises faithfully every day at a time that can be calculated precisely, scientists have determined that the Sun's energy output is not truly constant but varies over the centuries by a small amount—probably less than 1%. We've seen that the number of sunspots varies, with the time between sunspot maxima of about 11 years, and that the number of sunspots at maximum is not always the same. Considerable evidence shows that between the years 1645 and 1715, the number of sunspots, even at sunspot maximum, was much lower than it is now. This interval of significantly low sunspot numbers was first noted by Gustav Spörer in 1887 and then by E. W. Maunder in 1890; it is now called the **Maunder Minimum**. The variation in the number of sunspots over the past three centuries is shown in Figure 15.26. Besides the Maunder Minimum in the seventeenth century, sunspot numbers were somewhat lower during the first part of the nineteenth century than they are now; this period is called the Little Maunder Minimum.

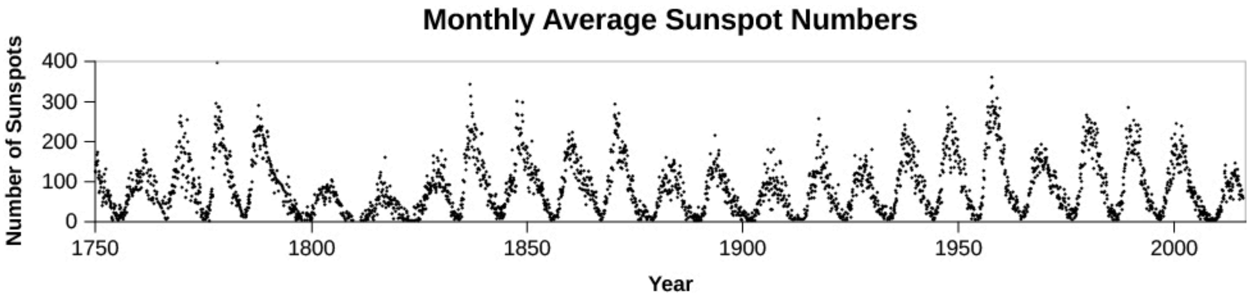

Figure 15.26 Numbers of Sunspots over Time. This diagram shows how the number of sunspots has changed with time since counts of the numbers of spots began to be recorded on a consistent scale. Note the low number of spots during the early years of the nineteenth century, the Little Maunder Minimum. (credit: modification of work by NASA/ARC)

When the number of sunspots is high, the Sun is active in various other ways as well, and, as we will see in several sections below, some of this activity affects Earth directly. For example, there are more auroral displays when the sunspot number is high. Auroras are caused when energetically charged particles from the Sun interact with Earth's magnetosphere, and the Sun is more likely to spew out particles when it is active and the sunspot number is high. Historical accounts also indicate that auroral activity was abnormally low throughout the several decades of the Maunder Minimum.

The Maunder Minimum was a time of exceptionally low temperatures in Europe—so low that this period is described as the Little Ice Age. This coincidence in time caused scientists to try to understand whether small changes in the Sun could affect the climate on Earth. There is clear evidence that it was unusually cold in Europe during part of the seventeenth century. The River Thames in London froze at least 11 times, ice appeared in the oceans off the coasts of southeast England, and low summer temperatures led to short growing seasons and poor harvests. However, whether and how changes on the Sun on this timescale influence Earth's climate is still a matter of debate among scientists.

Other small changes in climate like the Little Ice Age have occurred and have had their impacts on human history. For example, explorers from Norway first colonized Iceland and then reached Greenland by 986. From there, they were able to make repeated visits to the northeastern coasts of North America, including Newfoundland, between about 1000 and 1350. (The ships of the time did not allow the Norse explorers to travel all the way to North America directly, but only from Greenland, which served as a station for further exploration.)

Most of Greenland is covered by ice, and the Greenland station was never self-sufficient; rather, it depended on imports of food and other goods from Norway for its survival. When a little ice age began in the thirteenth century, voyaging became very difficult, and support of the Greenland colony was no longer possible. The last-known contact with it was made by a ship from Iceland blown off course in 1410. When European ships again began to visit Greenland in 1577, the entire colony there had disappeared.

The estimated dates for these patterns of migration follow what we know about solar activity. Solar activity was unusually high between 1100 and 1250, which includes the time when the first European contacts were made with North America. Activity was low from 1280 to 1340 and there was a little ice age, which was about the time regular contact with North America and between Greenland and Europe stopped.

One must be cautious, however, about assuming that low sunspot numbers or variations in the Sun's output of energy *caused* the Little Ice Age. There is no satisfactory model that can explain how a reduction in solar activity might cause cooler temperatures on Earth. An alternative possibility is that the cold weather during the Little Ice Age was related to volcanic activity. Volcanoes can eject aerosols (tiny droplets or particles) into the atmosphere that efficiently reflect sunlight. Observations show, for example, that the Pinatubo eruption in 1991 ejected SO_2 aerosols into the atmosphere, which reduced the amount of sunlight reaching Earth's surface enough to lower global temperatures by 0.4 °C.

Satellite data show that the energy output from the Sun during a solar cycle varies by only about 0.1%. We know of no physical process that would explain how such a small variation could cause global temperature changes. The level of solar activity may, however, have other effects. For example, although the Sun’s total energy output varies by only 0.1% during a solar cycle, its extreme ultraviolet radiation is 10 times higher at times of solar maximum than at solar minimum. This large variation can affect the chemistry and temperature structure of the upper atmosphere. One effect might be a reduction in the ozone layer and a cooling of the stratosphere near Earth’s poles. This, in turn, could change the circulation patterns of winds aloft and, hence, the tracks of storms. There is some recent evidence that variations in regional rainfall correlate better with solar activity than does the global temperature of Earth. But, as you can see, the relationship between what happens on the Sun and what happens to Earth’s climate over the short term is still an area that scientists are investigating and debating.

Whatever the effects of solar activity may be on local rainfall or temperature patterns, we want to emphasize one important idea: Our climate change data and the models developed to account for the data consistently show that solar variability is *not* the cause of the global warming that has occurred during the past 50 years.

Key Terms

active region an area on the Sun where magnetic fields are concentrated; sunspots, prominences, flares, and CMEs all tend to occur in active regions
aurora light radiated by atoms and ions in the ionosphere excited by charged particles from the Sun, mostly seen in the magnetic polar regions
chromosphere the part of the solar atmosphere that lies immediately above the photospheric layers
corona (of the Sun) the outer (hot) atmosphere of the Sun
coronal hole a region in the Sun's outer atmosphere that appears darker because there is less hot gas there
coronal mass ejection (CME) a solar flare in which immense quantities of coronal material—mainly protons and electrons—is ejected at high speeds (500–1000 kilometers per second) into interplanetary space
differential rotation the phenomenon that occurs when different parts of a rotating object rotate at different rates at different latitudes
granulation the rice-grain-like structure of the solar photosphere; granulation is produced by upwelling currents of gas that are slightly hotter, and therefore brighter, than the surrounding regions, which are flowing downward into the Sun
Maunder Minimum a period during the seventeenth century when the number of sunspots seen throughout the solar cycle was unusually low
photosphere the region of the solar (or stellar) atmosphere from which continuous radiation escapes into space
plage a bright region of the solar surface observed in the light of some spectral line
plasma a hot ionized gas
prominence a large, bright, gaseous feature that appears above the surface of the Sun and extends into the corona
solar flare a sudden and temporary outburst of electromagnetic radiation from an extended region of the Sun's surface
solar wind a flow of hot, charged particles leaving the Sun
sunspot large, dark features seen on the surface of the Sun caused by increased magnetic activity
sunspot cycle the semiregular 11-year period with which the frequency of sunspots fluctuates
transition region the region in the Sun's atmosphere where the temperature rises very rapidly from the relatively low temperatures that characterize the chromosphere to the high temperatures of the corona

Summary

15.1 The Structure and Composition of the Sun

The Sun, our star, has several layers beneath the visible surface: the core, radiative zone, and convective zone. These, in turn, are surrounded by a number of layers that make up the solar atmosphere. In order of increasing distance from the center of the Sun, they are the photosphere, with a temperature that ranges from 4500 K to about 6800 K; the chromosphere, with a typical temperature of 10^4 K; the transition region, a zone that may be only a few kilometers thick, where the temperature increases rapidly from 10^4 K to 10^6 K; and the corona, with temperatures of a few million K. The Sun's surface is mottled with upwelling convection currents seen as hot, bright granules. Solar wind particles stream out into the solar system through coronal holes. When such particles reach the vicinity of Earth, they produce auroras, which are strongest near Earth's magnetic poles. Hydrogen and helium together make up 98% of the mass of the Sun, whose composition is much more characteristic of the universe at large than is the composition of Earth.

15.2 The Solar Cycle

Sunspots are dark regions where the temperature is up to 2000 K cooler than the surrounding photosphere. Their motion across the Sun's disk allows us to calculate how fast the Sun turns on its axis. The Sun rotates more rapidly at its equator, where the rotation period is about 25 days, than near the poles, where the period is slightly longer than 36 days. The number of visible sunspots varies according to a sunspot cycle that averages 11 years in length. Spots frequently occur in pairs. During a given 11-year cycle, all leading spots in the Northern Hemisphere have the same magnetic polarity, whereas all leading sports in the Southern Hemisphere have the opposite polarity. In the subsequent 11-year cycle, the polarity reverses. For this reason, the magnetic activity cycle of the Sun is understood to last for 22 years. This activity cycle is connected with the behavior of the Sun's magnetic field, but the exact mechanism is not yet understood.

15.3 Solar Activity above the Photosphere

Signs of more intense solar activity, an increase in the number of sunspots, as well as prominences, plages, solar flares, and **c**oronal mass ejections, all tend to occur in active regions—that is, in places on the Sun with the same latitude and longitude but at different heights in the atmosphere. Active regions vary with the solar cycle, just like sunspots do.

15.4 Space Weather

Space weather is the effect of solar activity on our own planet, both in our magnetosphere and on Earth's surface. Coronal holes allow more of the Sun's material to flow out into space. Solar flares and coronal mass ejections can cause auroras, disrupt communications, damage satellites, and cause power outages on Earth.

For Further Exploration

Articles

Berman, B. "How Solar Storms Could Shut Down Earth." *Astronomy* (September 2013): 22. Up-to-date review of how events on the Sun can hurt our civilization.

Frank, A. "Blowin' in the Solar Wind." *Astronomy* (October 1998): 60. On results from the SOHO spacecraft.

Holman, G. "The Mysterious Origins of Solar Flares." *Scientific American* (April 2006): 38. New ideas involving magnetic reconnection and new observations of flares.

James, C. "Solar Forecast: Storm Ahead." *Sky & Telescope* (July 2007): 24. Nice review on the effects of the Sun's outbursts and on Earth and how we monitor "space weather."

Schaefer, B. "Sunspots That Changed the World." *Sky & Telescope* (April 1997): 34. Historical events connected with sunspots and solar activity.

Schrijver, C. and Title, A. "Today's Science of the Sun." *Sky & Telescope* (February 2001): 34; (March 2001): 34. Excellent reviews of recent results about the solar atmosphere.

Wadhwa, M. "Order from Chaos: Genesis Samples the Solar Wind." *Astronomy* (October 2013): 54. On a satellite that returned samples of the Sun's wind.

Websites

Dr. Sten Odenwald's "Solar Storms" site: http://www.solarstorms.org/ (http://www.solarstorms.org/).

ESA/NASA's Solar & Heliospheric Observatory: http://sohowww.nascom.nasa.gov (http://sohowww.nascom.nasa.gov). A satellite mission with a rich website to explore.

High Altitude Observatory Introduction to the Sun: https://www2.hao.ucar.edu/Education/sun-pictorial-introduction (https://www2.hao.ucar.edu/Education/sun-pictorial-introduction). For beginners.

NASA's Solar Missions: https://www.nasa.gov/mission_pages/sunearth/missions/index.html (https://www.nasa.gov/mission_pages/sunearth/missions/index.html). Good summary of the many satellites and missions NASA has.

NOAA Profile of Space Weather: http://www.swpc.noaa.gov/sites/default/files/images/u33/

primer_2010_new.pdf (http://www.swpc.noaa.gov/sites/default/files/images/u33/primer_2010_new.pdf). A primer.

NOAA Space Weather Prediction Center Information Pages: http://www.swpc.noaa.gov/content/education-and-outreach (http://www.swpc.noaa.gov/content/education-and-outreach). Includes primers, videos, a curriculum and training modules.

Nova Sun Lab: http://www.pbs.org/wgbh/nova/labs/lab/sun/ (http://www.pbs.org/wgbh/nova/labs/lab/sun/). Videos, scientist profiles, a research challenge related to the active Sun from the PBS science program.

Space Weather: Storms on the Sun: http://www.swpc.noaa.gov/sites/default/files/images/u33/swx_booklet.pdf (http://www.swpc.noaa.gov/sites/default/files/images/u33/swx_booklet.pdf). An illustrated booklet from NOAA.

Stanford Solar Center: http://solar-center.stanford.edu/ (http://solar-center.stanford.edu/). An excellent site with information for students and teachers.

Apps

These can tell you and your students more about what's happening on the Sun in real time.

NASA Space Weather: https://play.google.com/store/apps/details?id=gov.nasa.gsfc.iswa.NASASpaceWeatherApp (https://play.google.com/store/apps/details?id=gov.nasa.gsfc.iswa.NASASpaceWeatherApp).

Solaris Alpha: https://www.androidweather.net/download-solaris-alpha.html (https://www.androidweather.net/download-solaris-alpha.html).

Videos

Journey into the Sun: https://www.youtube.com/watch?v=fqKFQ7z0Nuk (https://www.youtube.com/watch?v=fqKFQ7z0Nuk). 2010 KQED Quest TV Program mostly about the Solar Dynamics Observatory spacecraft, its launch and capabilities, but with good general information on how the Sun works (12:24).

NASA | SDO: Three Years in Three Minutes--With Expert Commentary: https://www.youtube.com/watch?v=QaCG0wAjJSY&src (https://www.youtube.com/watch?v=QaCG0wAjJSY&src). Video of 3 years of observations of the Sun by the Solar Dynamics Observatory made into a speeded up movie, with commentary by solar physicist Alex Young (5:03).

Our Explosive Sun: http://www.youtube.com/watch?v=kI6YGSIJqrE (http://www.youtube.com/watch?v=kI6YGSIJqrE). Video of a 2011 public lecture in the Silicon Valley Astronomy Lecture Series by Dr. Thomas Berger about solar activity and recent satellite missions to observe and understand it (1:20:22).

Space Weather Impacts: http://www.swpc.noaa.gov/content/education-and-outreach (http://www.swpc.noaa.gov/content/education-and-outreach). Video from NOAA (2:47); https://www.youtube.com/playlist?list=PLBdd8cMH5jFmvVR2sZubIUzBO6JI0Pvx0 (https://www.youtube.com/playlist?list=PLBdd8cMH5jFmvVR2sZubIUzBO6JI0Pvx0). Videos from the National Weather Service (four short videos) (14:41).

Space Weather: Storms on the Sun: http://www.youtube.com/watch?v=vWsmp4o-qVg (http://www.youtube.com/watch?v=vWsmp4o-qVg). Science bulletin from the American Museum of Natural History, giving the background to what happens on the Sun to cause space weather (6:10).

Sunspot Group AR 2339 Crosses the Sun: http://apod.nasa.gov/apod/ap150629.html (http://apod.nasa.gov/apod/ap150629.html). Short video (with music) animates Solar Dynamics Observatory images of an especially large sunspot group going across the Sun's face (1:15).

What Happens on the Sun Doesn't Stay on the Sun: https://www.youtube.com/watch?v=bg_gD2-ujCk (https://www.youtube.com/watch?v=bg_gD2-ujCk). From the National Oceanic and Atmospheric Administration: introduction to the Sun, space weather, its effects, and how we monitor it (4:56).

Collaborative Group Activities

A. Have your group make a list of all the ways the Sun personally affects your life on Earth. (Consider the everyday effects as well as the unusual effects due to high solar activity.)

B. Long before the nature of the Sun was fully understood, astronomer (and planet discoverer) William Herschel (1738–1822) proposed that the hot Sun may have a cool interior and may be inhabited. Have your group discuss this proposal and come up with modern arguments against it.

C. We discussed how the migration of Europeans to North America was apparently affected by short-term climate change. If Earth were to become significantly hotter, either because of changes in the Sun or because of greenhouse warming, one effect would be an increase in the rate of melting of the polar ice caps. How would this affect modern civilization?

D. Suppose we experience another Maunder Minimum on Earth, and it is accompanied by a drop in the average temperature like the Little Ice Age in Europe. Have your group discuss how this would affect civilization and international politics. Make a list of the most serious effects that you can think of.

E. Watching sunspots move across the disk of the Sun is one way to show that our star rotates on its axis. Can your group come up with other ways to show the Sun's rotation?

F. Suppose in the future, we are able to forecast space weather as well as we forecast weather on Earth. And suppose we have a few days of warning that a big solar storm is coming that will overload Earth's magnetosphere with charged particles and send more ultraviolet and X-rays toward our planet. Have your group discuss what steps we might take to protect our civilization?

G. Have your group members research online to find out what satellites are in space to help astronomers study the Sun. In addition to searching for NASA satellites, you might also check for satellites launched by the European Space Agency and the Japanese Space Agency.

H. Some scientists and engineers are thinking about building a "solar sail"—something that can use the Sun's wind or energy to propel a spacecraft away from the Sun. The Planetary Society is a nonprofit organization that is trying to get solar sails launched, for example. Have your group do a report on the current state of solar-sail projects and what people are dreaming about for the future.

Exercises

Review Questions

1. Describe the main differences between the composition of Earth and that of the Sun.

2. Describe how energy makes its way from the nuclear core of the Sun to the atmosphere. Include the name of each layer and how energy moves through the layer.

3. Make a sketch of the Sun's atmosphere showing the locations of the photosphere, chromosphere, and corona. What is the approximate temperature of each of these regions?

4. Why do sunspots look dark?

5. Which aspects of the Sun's activity cycle have a period of about 11 years? Which vary during intervals of about 22 years?

6. Summarize the evidence indicating that over several hundreds of years or more there have been variations in the level of the solar activity.

7. What it the Zeeman effect and what does it tell us about the Sun?

8. Explain how the theory of the Sun's dynamo results in an average 22-year solar activity cycle. Include the location and mechanism for the dynamo.

9. Compare and contrast the four different types of solar activity above the photosphere.

10. What are the two sources of particles coming from the Sun that cause space weather? How are they different?

11. How does activity on the Sun affect human technology on Earth and in the rest of the solar system?

12. How does activity on the Sun affect natural phenomena on Earth?

Thought Questions

13. Table 15.1 indicates that the density of the Sun is 1.41 g/cm^3. Since other materials, such as ice, have similar densities, how do you know that the Sun is not made of ice?

14. Starting from the core of the Sun and going outward, the temperature decreases. Yet, above the photosphere, the temperature increases. How can this be?

15. Since the rotation period of the Sun can be determined by observing the apparent motions of sunspots, a correction must be made for the orbital motion of Earth. Explain what the correction is and how it arises. Making some sketches may help answer this question.

16. Suppose an (extremely hypothetical) elongated sunspot forms that extends from a latitude of 30° to a latitude of 40° along a fixed of longitude on the Sun. How will the appearance of that sunspot change as the Sun rotates? (Figure 15.17 should help you figure this out.)

17. The text explains that plages are found near sunspots, but Figure 15.18 shows that they appear even in areas without sunspots. What might be the explanation for this?

18. Why would a flare be observed in visible light, when they are so much brighter in X-ray and ultraviolet light?

19. How can the prominences, which are so big and 'float' in the corona, stay gravitationally attached to the Sun while flares can escape?

20. If you were concerned about space weather and wanted to avoid it, where would be the safest place on Earth for you to live?

21. Suppose you live in northern Canada and an extremely strong flare is reported on the Sun. What precautions might you take? What might be a positive result?

Figuring for Yourself

22. The edge of the Sun doesn't have to be absolutely sharp in order to look that way to us. It just has to go from being transparent to being completely opaque in a distance that is smaller than your eye can resolve. Remember from Astronomical Instruments that the ability to resolve detail depends on the size of the telescope's aperture. The pupil of your eye is very small relative to the size of a telescope and therefore is very limited in the amount of detail you can see. In fact, your eye cannot see details that are smaller than 1/30 of the diameter of the Sun (about 1 arcminute). Nearly all the light from the Sun emerges from a layer that is only about 400 km thick. What fraction is this of the diameter of the Sun? How does this compare with the ability of the human eye to resolve detail? Suppose we could see light emerging directly from a layer that was 300,000 km thick. Would the Sun appear to have a sharp edge?

23. Show that the statement that 92% of the Sun's atoms are hydrogen is consistent with the statement that 73% of the Sun's mass is made up of hydrogen, as found in Table 15.2. (Hint: Make the simplifying assumption, which is nearly correct, that the Sun is made up entirely of hydrogen and helium.)

24. From Doppler shifts of the spectral lines in the light coming from the east and west edges of the Sun, astronomers find that the radial velocities of the two edges differ by about 4 km/s, meaning that the Sun's rotation rate is 2 km/s. Find the approximate period of rotation of the Sun in days. The circumference of a sphere is given by $2\pi R$, where R is the radius of the sphere.

25. Assuming an average sunspot cycle of 11 years, how many revolutions does the equator of the Sun make during that one cycle? Do higher latitudes make more or fewer revolutions compared to the equator?

26. This chapter gives the average sunspot cycle as 11 years. Verify this using Figure 15.26.

27. The escape velocity from any astronomical object can be calculated as $v_{\text{escape}} = \sqrt{2GM/R}$. Using the data in Appendix E, calculate the escape velocity from the photosphere of the Sun. Since coronal mass ejections escape from the corona, would the escape velocity from there be more or less than from the photosphere?

28. Suppose you observe a major solar flare while astronauts are orbiting Earth. Use the data in the text to calculate how long it will before the charged particles ejected from the Sun during the flare reach them.

29. Suppose an eruptive prominence rises at a speed of 150 km/s. If it does not change speed, how far from the photosphere will it extend after 3 hours? How does this distance compare with the diameter of Earth?

30. From the information in Figure 15.21, estimate the speed with which the particles in the CME in parts (c) and (d) are moving away from the Sun.