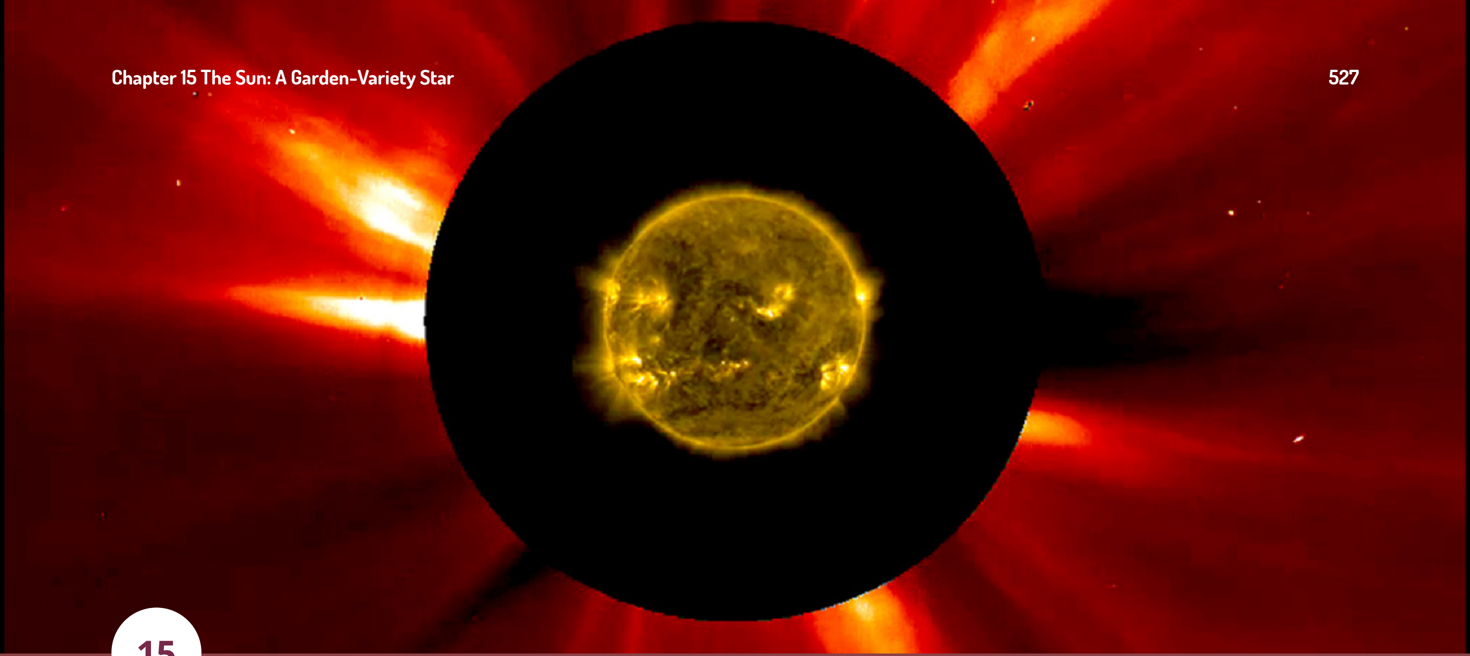
Astronomy



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.

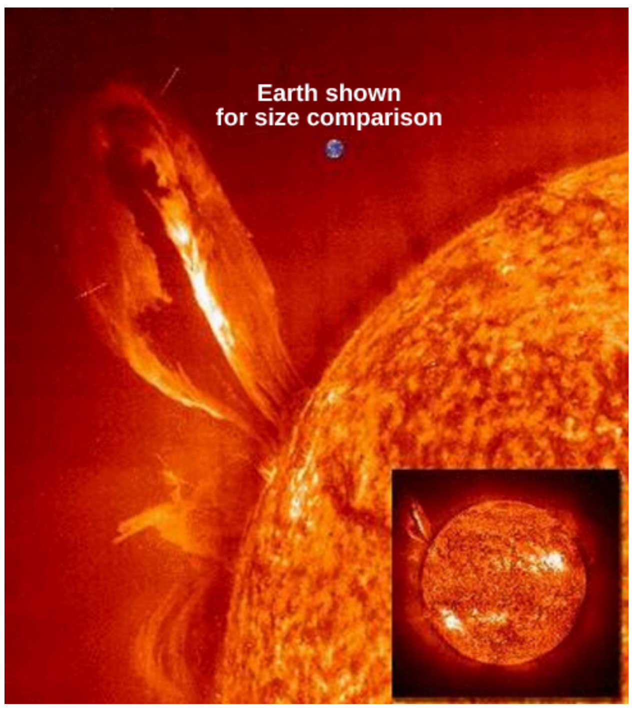


Figure 15.2 Earth and the Sun. Here, Earth is shown to scale with part of the Sun and a giant loop of hot gas erupting from its surface. The inset shows the entire Sun, smaller. (credit: modification of work by SOHO/EIT/ESA)

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
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 assumed 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.

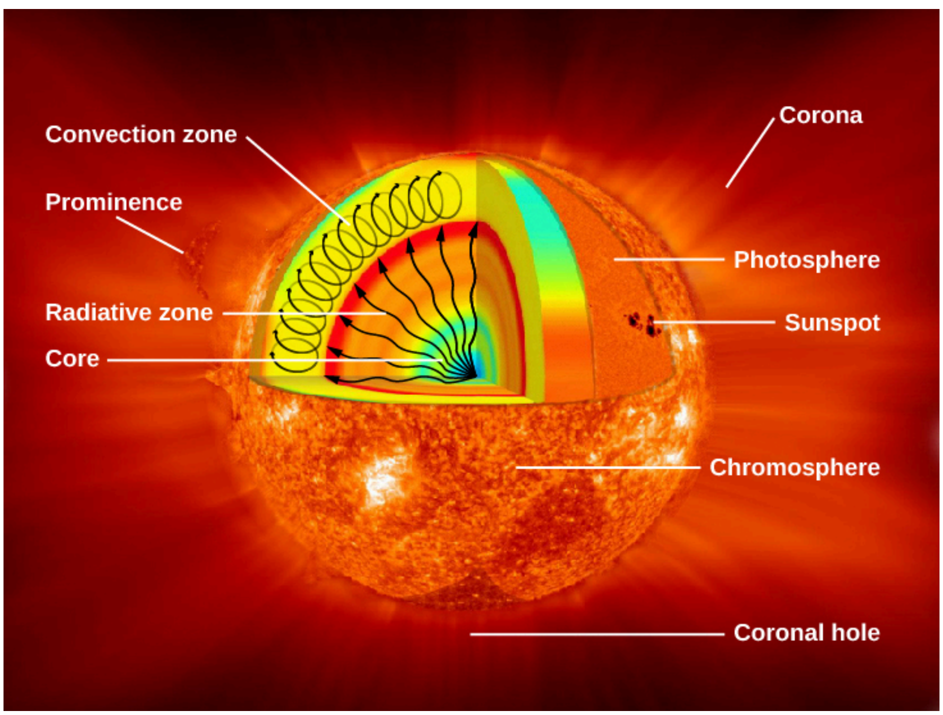


Figure 15.4 Parts of the Sun. This illustration shows the different parts of the Sun, from the hot core where the energy is generated through regions where energy is transported outward, first by radiation, then by convection, and then out through the solar atmosphere. The parts of the atmosphere are 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**).

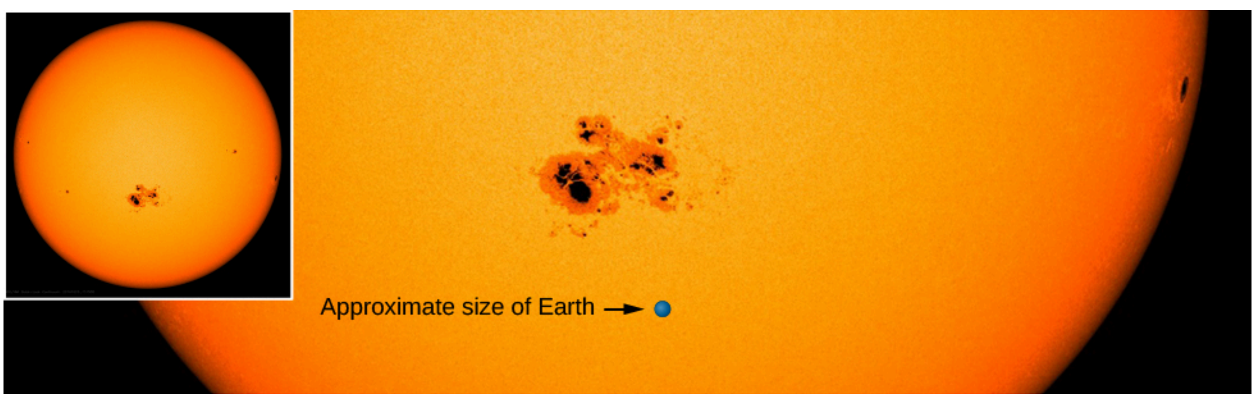


Figure 15.5 Solar Photosphere plus Sunspots. This photograph shows the photosphere—the visible surface of the Sun. Also shown is an enlarged image of a group of sunspots; the size of Earth is shown for comparison. Sunspots appear darker because they are cooler than their surroundings. The typical temperature 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.

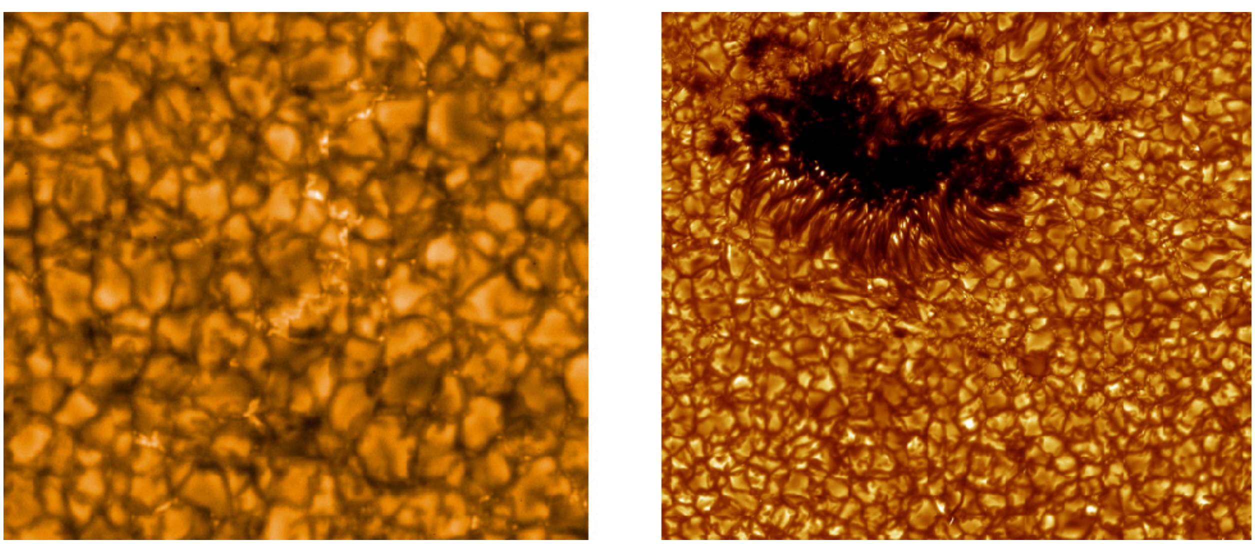


Figure 15.6 Granulation Pattern. The surface markings of the convection cells create a granulation pattern on this dramatic image (left) taken from the Japanese Hinode spacecraft. You can see the same pattern when you heat up miso soup. The right image shows an irregular-shaped sunspot and granules on 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.

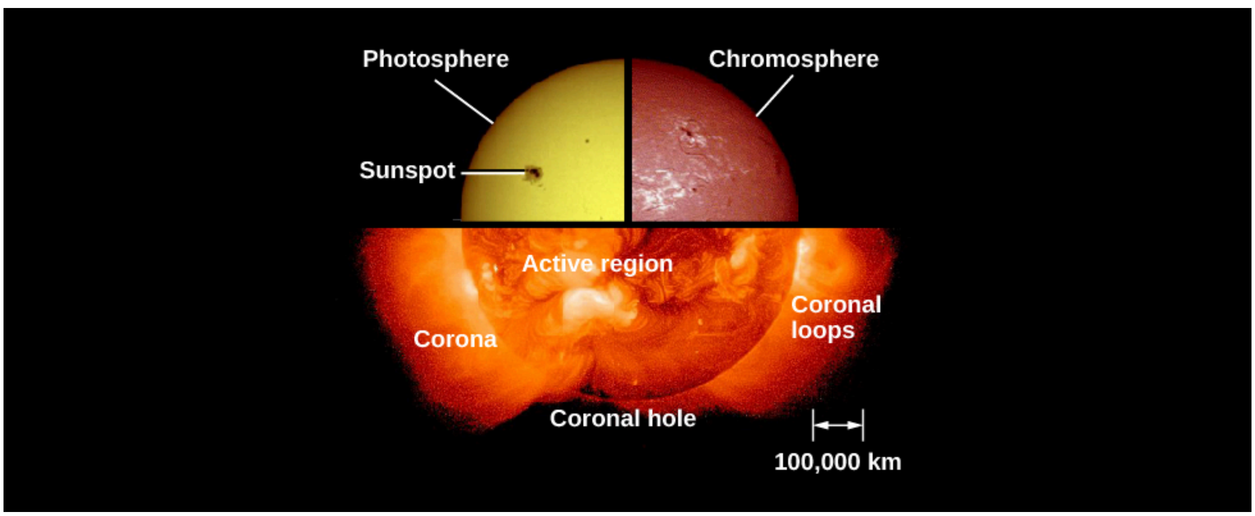


Figure 15.7 The Sun’s Atmosphere. Composite image showing the three components of the solar atmosphere: the photosphere or surface of the Sun taken in ordinary light; the chromosphere, imaged in the light of the strong red spectral line of hydrogen (H-alpha); and the corona as seen with X-rays. (credit: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

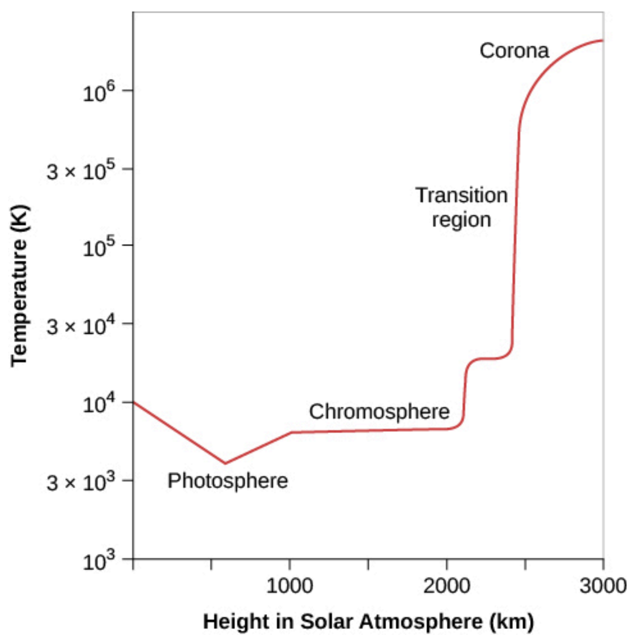


Figure 15.8 Temperatures in the Solar Atmosphere. On this graph, temperature is shown increasing upward, and height above the photosphere is shown increasing to the right. Note the very rapid increase in temperature over a very short distance in the transition region between the chromosphere and the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

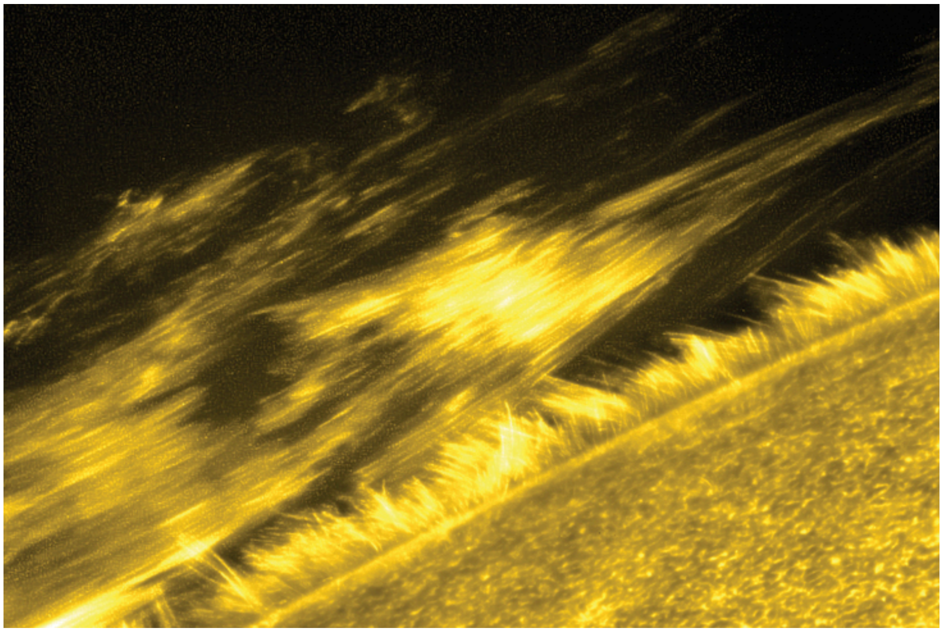


Figure 15.9 Portion of the Transition Region. This image shows a giant ribbon of relatively cool gas threading through the lower portion of the hot corona. This ribbon (the technical term is filament) is made up of many individual threads. Time-lapse movies of this filament showed that it gradually heated 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).

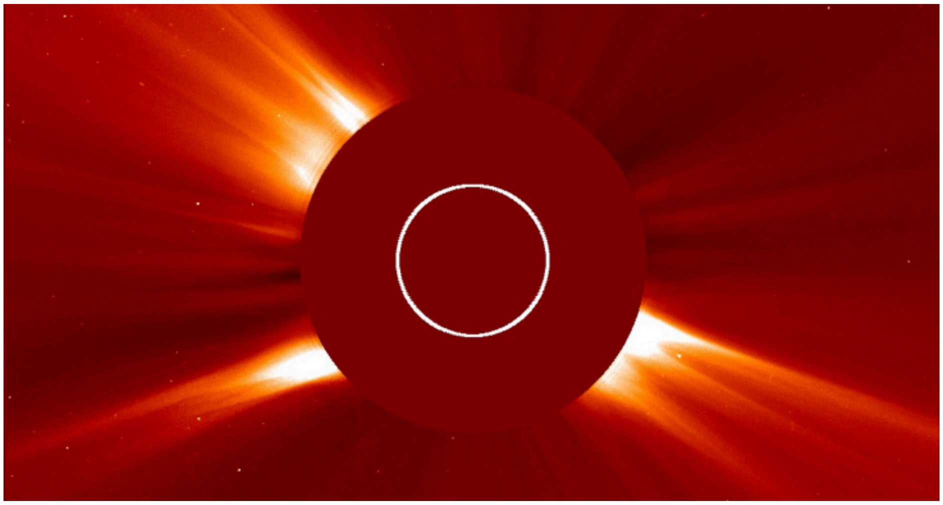


Figure 15.10 Coronagraph. This image of the Sun was taken March 2, 2016. The larger dark circle in the center is the disk the blocks the Sun's glare, allowing us to see the corona. The smaller inner circle is where the Sun would be if it were visible in this image. (credit: modification of work by NASA/SOHO)

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 10 million tons of material each year through this wind. While this amount of lost mass seems large by Earth standards, it is completely insignificant for 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.

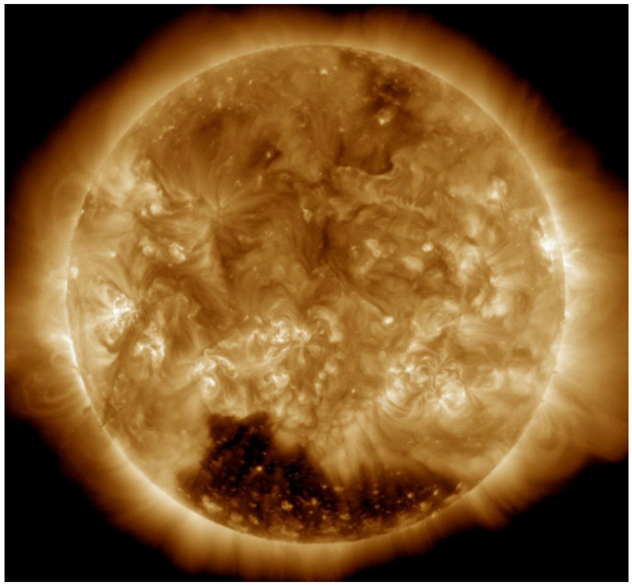


Figure 15.11 Coronal Hole. The dark area visible near the Sun's south pole on this Solar Dynamics Observer spacecraft image is a coronal hole. (credit: modification of work by NASA/SDO)

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.)

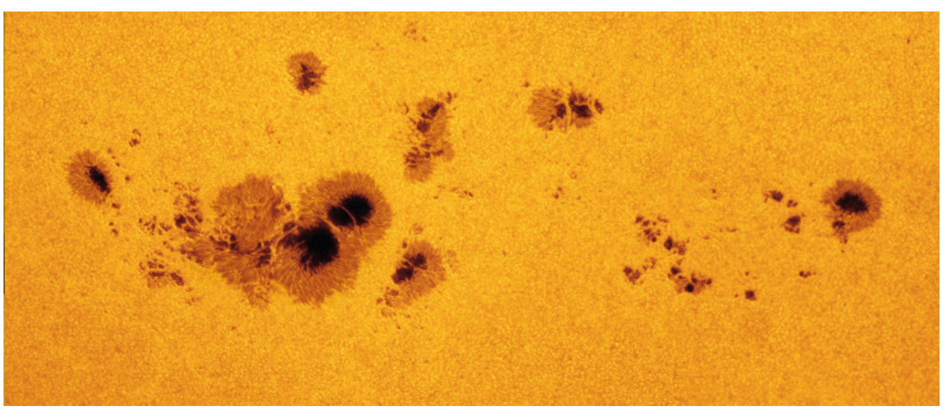


Figure 15.13 Sunspots. This image of sunspots, cooler and thus darker regions on the Sun, was taken in July 2012. You can see the dark, central region of each sunspot (called the umbra) surrounded by a less dark region (the penumbra). The largest spot shown here is about 11 Earths wide. Although sunspots 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: NASA Goddard Space Flight Center, Alan Friedman)

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**.

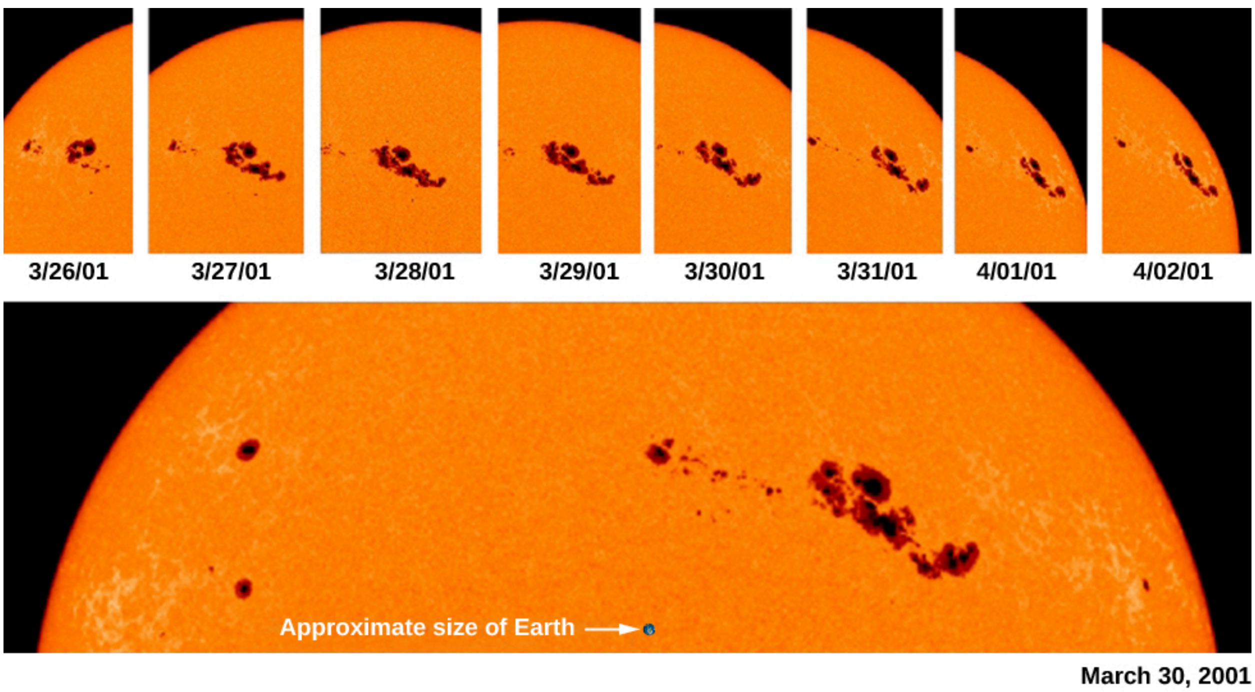


Figure 15.14 Sunspots Rotate Across Sun's Surface. This sequence of photographs of the Sun's surface tracks the movement of sunspots across the visible hemisphere of the Sun. On March 30, 2001, this group of sunspots extended across an area about 13 times the diameter of Earth. This region produced many 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.

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.

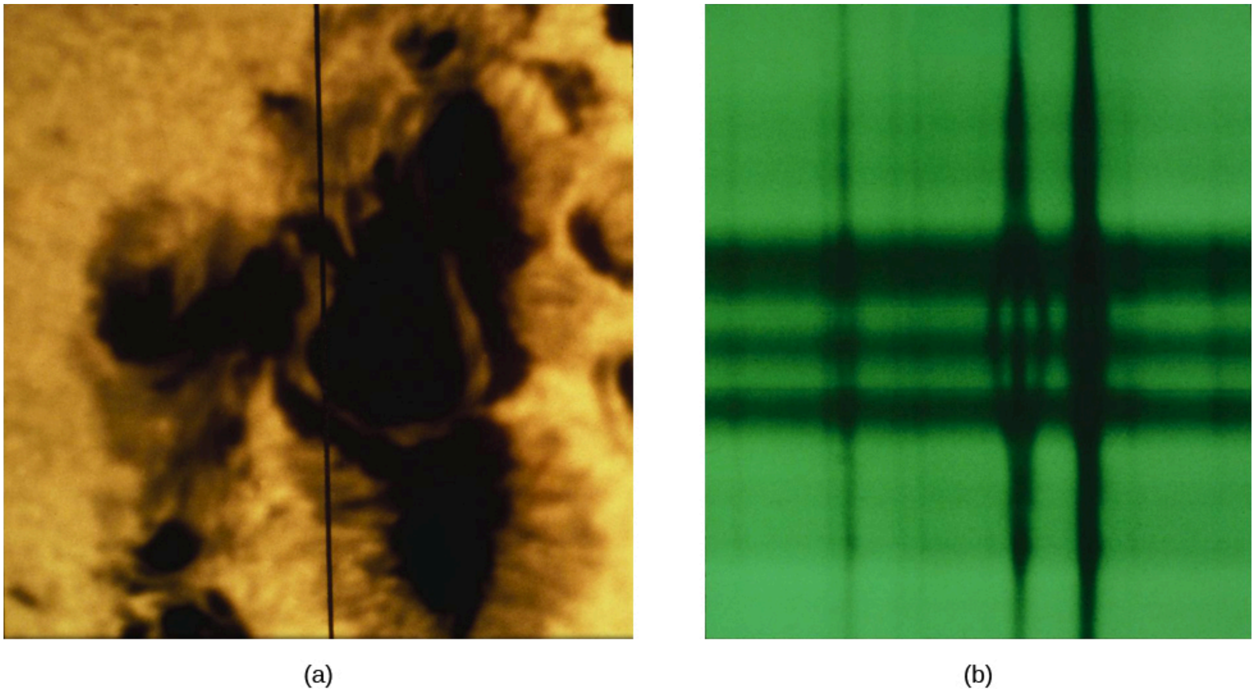


Figure 15.15 Zeeman Effect. These photographs show how magnetic fields in sunspots are measured by means of the Zeeman effect. (left) The vertical black line indicates the position of the spectrograph slit through which light is passed to obtain the spectrum in (right). (credit: modification of work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

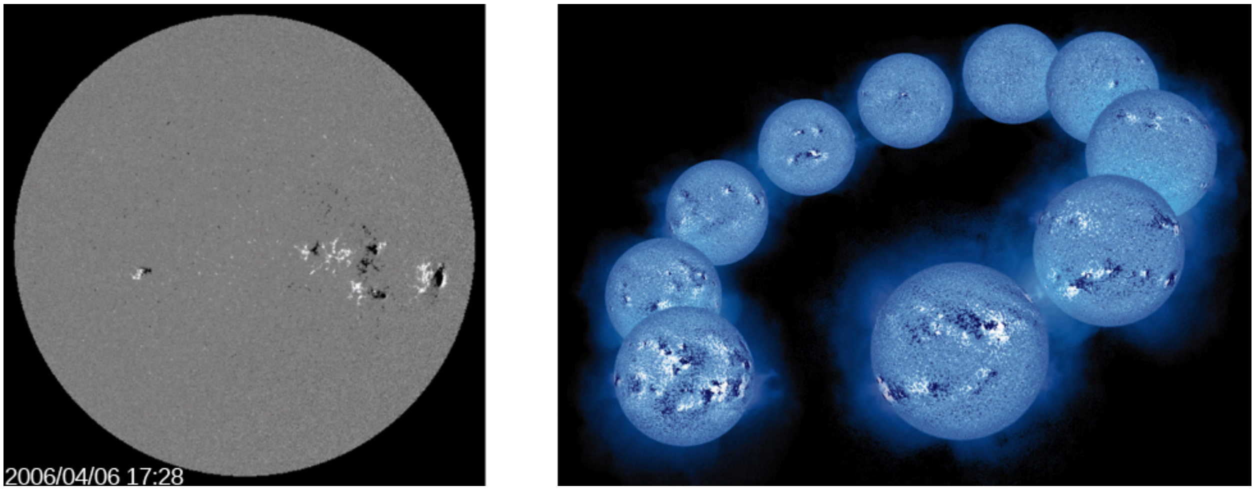


Figure 15.16 Magnetogram and Solar Cycle. In the image on the left, called a magnetogram, we see the magnetic polarity of sunspots. The black areas are where the magnetism is pointing toward the Sun’s core, whereas the white regions are where it is pointing away from the core, toward us. This dramatic 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**).

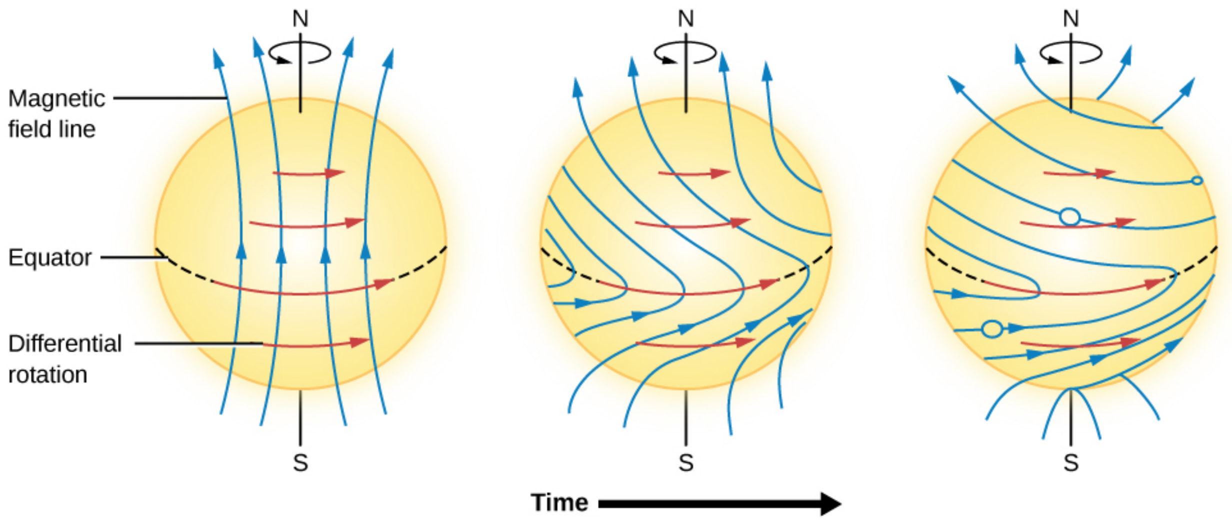


Figure 15.17 Magnetic Field Lines Wind Up. Because the Sun spins faster at the equator than near the poles, the magnetic fields in the Sun tend to wind up as shown, and after a while make loops. This is an idealized diagram; the real situation is much more complex.

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.

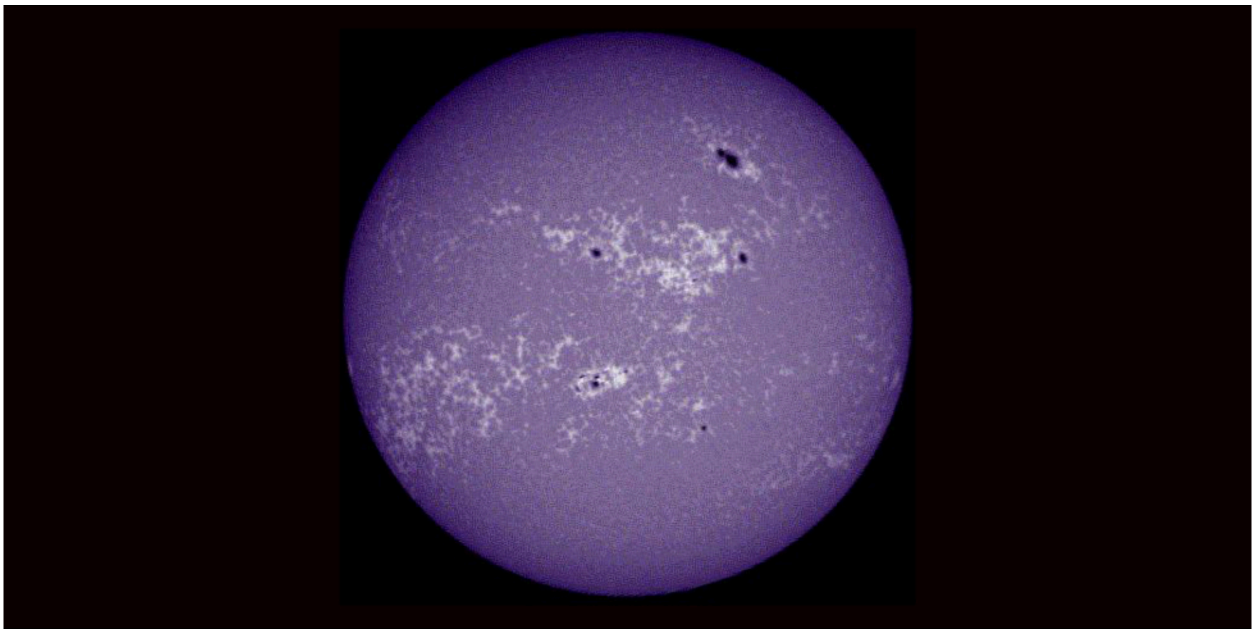


Figure 15.18 Plages on the Sun. This image of the Sun was taken with a filter that transmits only the light of the spectral line produced by singly ionized calcium. The bright cloud-like regions are the plages. (credit: modification of work by NASA)

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).

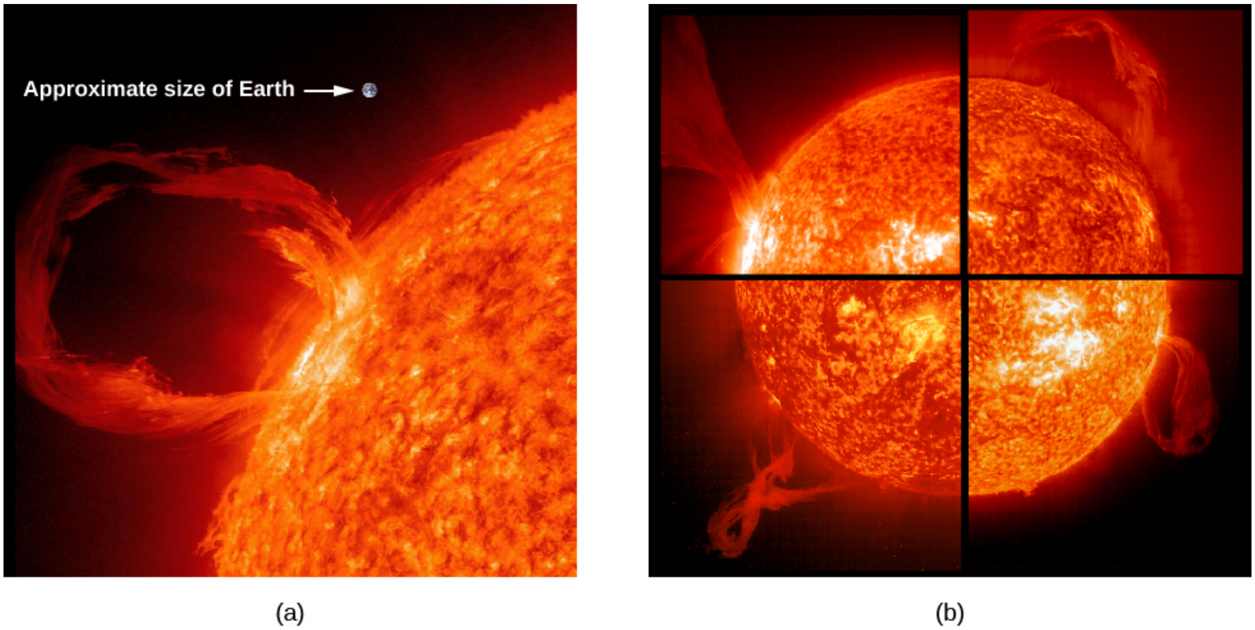


Figure 15.19 Prominences. (a) This image of an eruptive prominence was taken in the light of singly ionized helium in the extreme ultraviolet part of the spectrum. The prominence is a particularly large one. An image of Earth is shown at the same scale for comparison. (b) A prominence is a huge cloud 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.

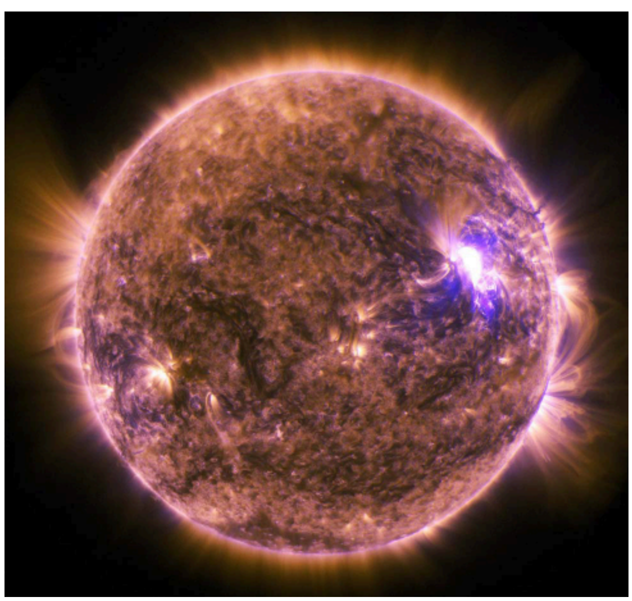
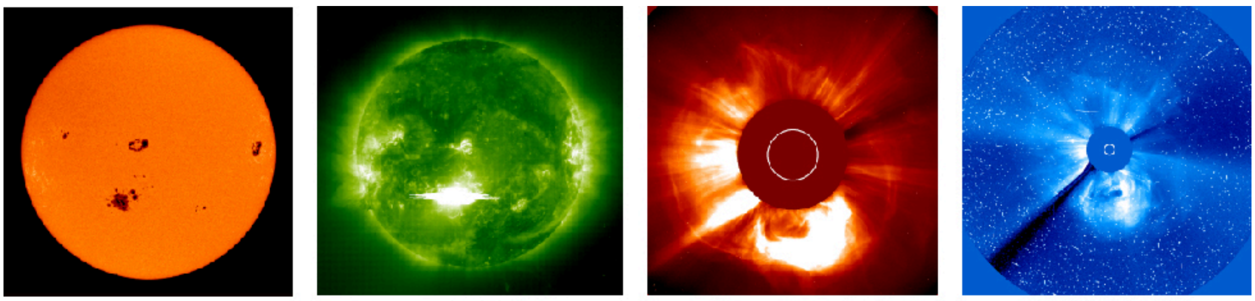


Figure 15.20 Solar Flare. The bright white area seen on the right side of the Sun in this image from the Solar Dynamics Observer spacecraft is a solar flare that was observed on June 25, 2015. (credit: NASA/SDO)

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).



(a) (b) (c) (d)

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.

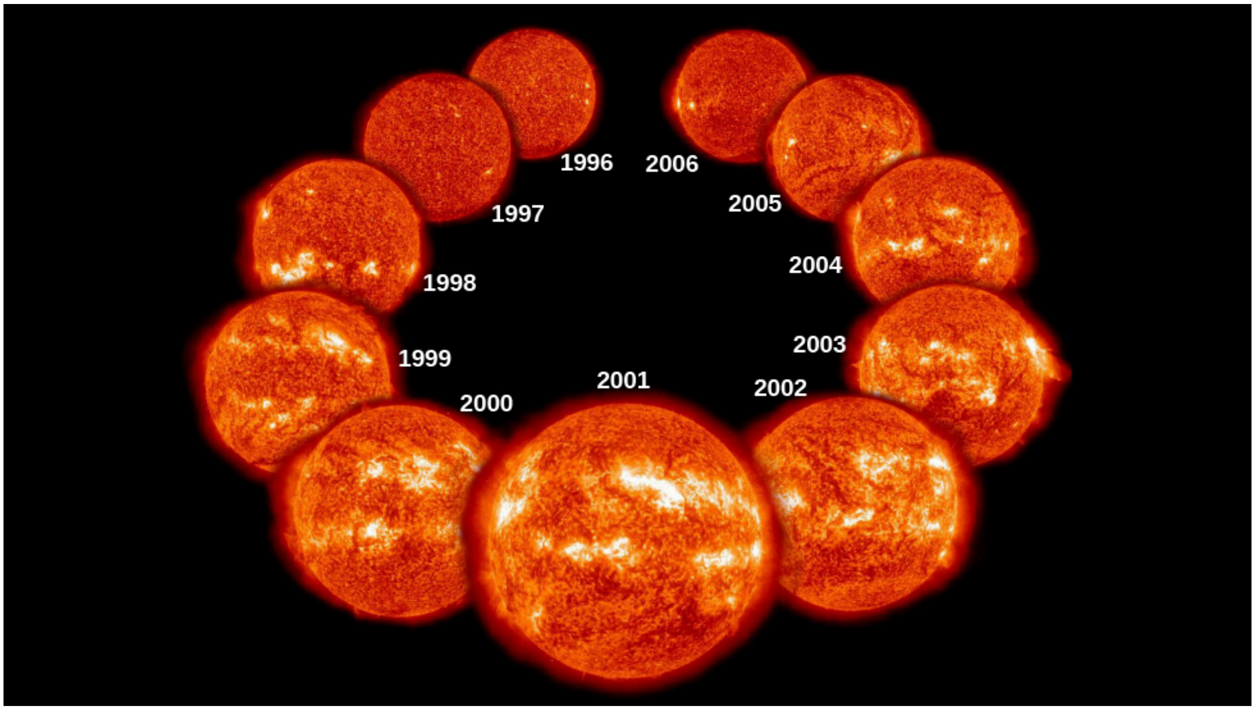


Figure 15.22 Solar Cycle. This dramatic sequence of images taken from the SOHO satellite over a period of 11 years shows how active regions change during the solar cycle. The images were taken in the ultraviolet region of the spectrum and show that active regions on the Sun increase and decrease during 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.

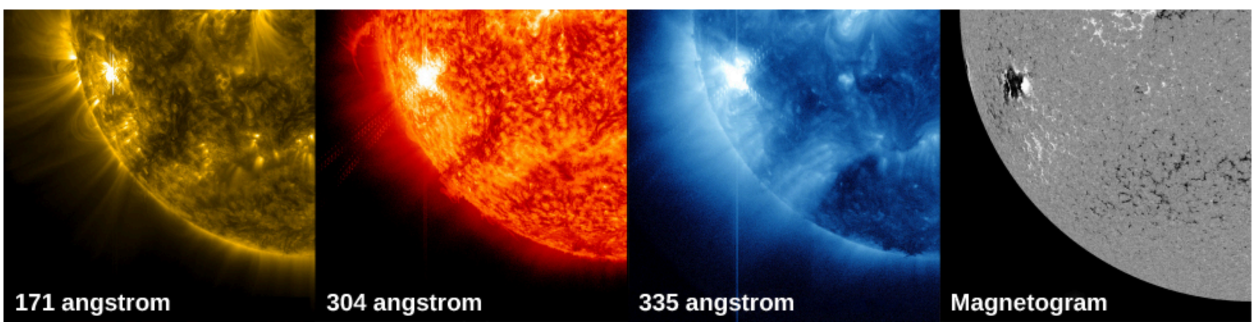


Figure 15.23 Solar Active Region Observed at Different Heights in the Sun's Atmosphere. These four images of a solar flare on October 22, 2012, show from the left: light from the Sun at a wavelength of 171 angstroms, which shows the structure of loops of solar material in the corona; ultraviolet at 304 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.

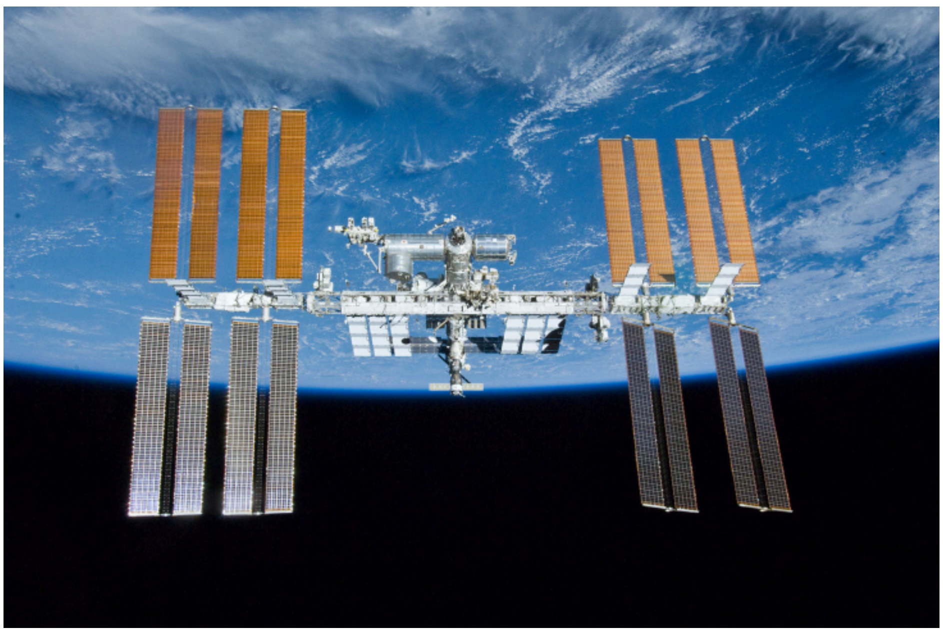


Figure 15.24 International Space Station. The International Space Station is see above Earth, as photographed in 2010 by the departing crew of the Space Shuttle Atlantis. (credit: NASA)

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).

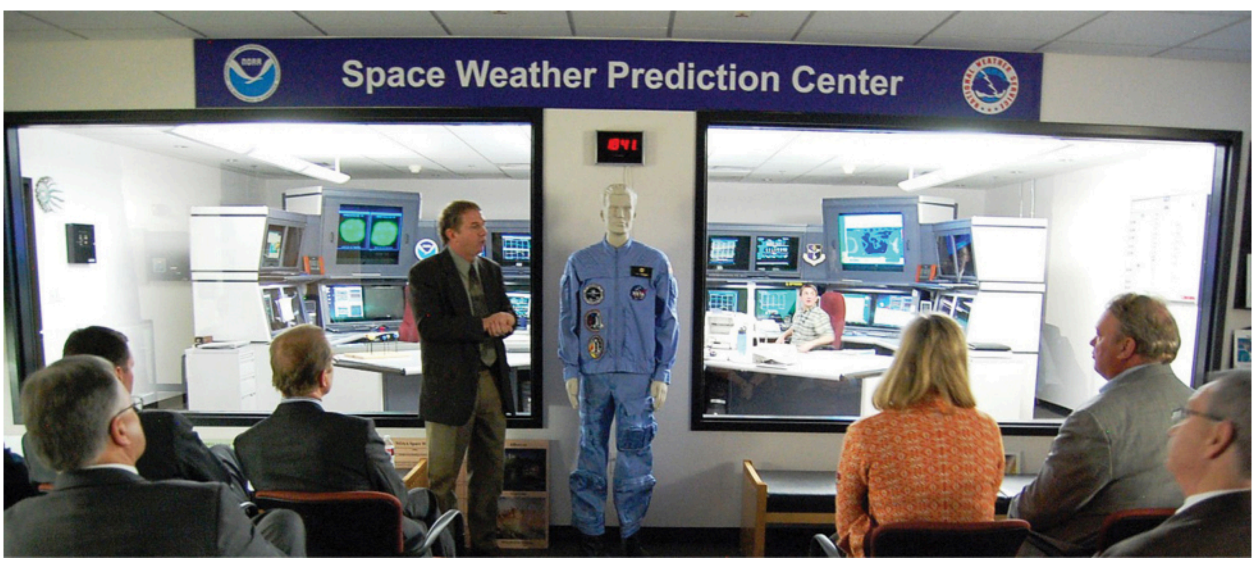


Figure 15.25 NOAA Space Weather Prediction Operations Center. Bill Murtagh, a space weather forecaster, leads a workshop on preparedness for events like geomagnetic storms. (credit: modification of work by FEMA/Jerry DeFelice)

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.

Fortunately, we can expect calmer space weather for the next few years, since the most recent solar maximum, which was relatively weak, occurred in 2014, and scientists believe the current solar cycle to be one of the least active in recent history. We expect more satellites to be 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 by the time of the next maximum, 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.

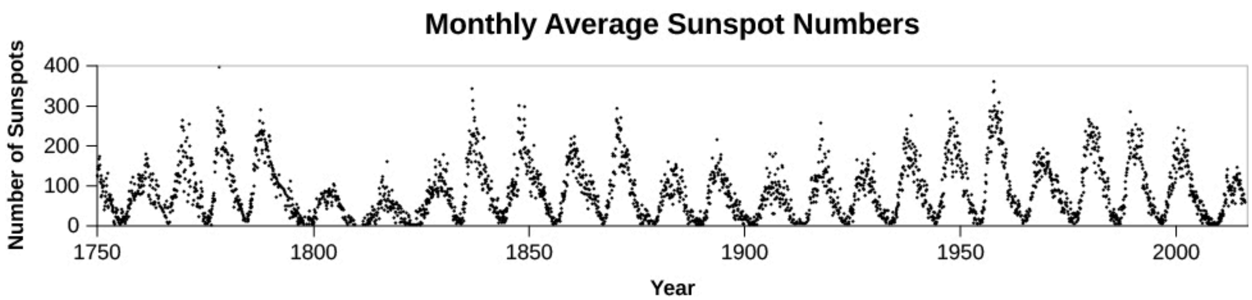


Figure 15.26 Numbers of Sunspots over Time. This diagram shows how the number of sunspots has changed with time since counts of the numbers of spots began to be recorded on a consistent scale. Note the low number of spots during the early years of the nineteenth century, the Little Maunder Minimum. (credit: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

CHAPTER 15 REVIEW

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 eighteenth 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: **http://www.hao.ucar.edu/education/basic.php (http://www.hao.ucar.edu/education/basic.php)** . 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://itunes.apple.com/us/app/nasa-space-weather/id422621403?mt=8 (https://itunes.apple.com/us/app/nasa-space-weather/id422621403?mt=8)** .

Solaris Alpha: **https://play.google.com/store/apps/details?id=com.tomoreilly.solarisalpha (https://play.google.com/store/apps/details?id=com.tomoreilly.solarisalpha)** .

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).

Out There Raining Fire: **http://www.nytimes.com/video/science/100000003489464/out-there-raining-fire.html?emc=eta1 (http://www.nytimes.com/video/science/100000003489464/out-there-raining-fire.html?emc=eta1)** . Nice overview and introduction to the Sun by science reporter Dennis Overbye of the NY Times (2:28)

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).

Sun Storms: **http://www.livescience.com/11754-sun-storms-havoc-electronic-world.html (http://www.livescience.com/11754-sun-storms-havoc-electronic-world.html)** . From the Starry Night company about storms from the Sun now and in the past (4:49).

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 2π*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.

16 THE SUN: A NUCLEAR POWERHOUSE

Figure 16.1 The Sun. It takes an incredible amount of energy for the Sun to shine, as it has and will continue to do for billions of years. (credit: modification of work by Ed Dunens)

Chapter Outline

Thinking Ahead

The Sun puts out an incomprehensible amount of energy—so much that its ultraviolet radiation can cause sunburns from 93 million miles away. It is also very old. As you learned earlier, evidence shows that the Sun formed about 4.5 billion years ago and has been shining ever since. How can the Sun produce so much energy for so long?

The Sun’s energy output is about 4×10^{26} watts. This is unimaginably bright: brighter than a trillion cities together each with a trillion 100-watt light bulbs. Most known methods of generating energy fall far short of the capacity of the Sun. The total amount of energy produced over the entire life of the Sun is staggering, since the Sun has been shining for billions of years. Scientists were unable to explain the seemingly unlimited energy of stars like the Sun prior to the twentieth century.

16.1 SOURCES OF SUNSHINE: THERMAL AND GRAVITATIONAL ENERGY

Learning Objectives

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

- Identify different forms of energy
- Understand the law of conservation of energy

- Explain ways that energy can be transformed

Energy is a challenging concept to grasp because it exists in so many different forms that it defies any single simple explanation. In many ways, comprehending energy is like comprehending wealth: There are very different forms of wealth and they follow different rules, depending on if they are the stock market, real estate, a collection of old comic books, great piles of cash, or one of the many other ways to make and lose money. It is easier to discuss one or two forms of wealth—or energy—than to discuss that concept in general.

When striving to understand how the Sun can put out so much energy for so long, scientists considered many different types of energy. Nineteenth-century scientists knew of two possible sources for the Sun's energy: chemical and gravitational energy. The source of chemical energy most familiar to them was the burning (the chemical term is *oxidation*) of wood, coal, gasoline, or other fuel. We know exactly how much energy the burning of these materials can produce. We can thus calculate that even if the immense mass of the Sun consisted of a burnable material like coal or wood, our star could not produce energy at its present rate for more than few thousand years. However, we know from geologic evidence that water was present on Earth's surface nearly 4 billion years ago, so the Sun must have been shining brightly (and making Earth warm) at least as long as that. Today, we also know that at the temperatures found in the Sun, nothing like solid wood or coal could survive.

ASTRONOMY BASICS

What's Watt?

Just a word about the units we are using. A watt (W) is a unit of *power*, which is energy used or given off per unit time. It is measured in joules per second (J/s). You know from your everyday experience that it is not just *how much* energy you expend, but *how long* you take to do it. (Burning 10 Calories in 10 minutes requires a very different kind of exercise than burning those 10 Calories in an hour.) Watts tell you the *rate* at which energy is being used; for example, a 100-watt bulb uses 100 joules (J) of energy every second.

And how big is a joule? A 73-kilogram (160-pound) astronomy instructor running at about 4.4 meters per second (10 miles per hour) because he is late for class has a motion energy of about 700 joules.

Conservation of Energy

Other nineteenth-century attempts to determine what makes the Sun shine used the law of conservation of energy. Simply stated, this law says that energy cannot be created or destroyed, but can be transformed from one type to another, such as from heat to mechanical energy. The steam engine, which was key to the Industrial Revolution, provides a good example. In this type of engine, the hot steam from a boiler drives the movement of a piston, converting heat energy into motion energy.

Conversely, motion can be transformed into heat. If you clap your hands vigorously at the end of an especially good astronomy lecture, your palms become hotter. If you rub ice on the surface of a table, the heat produced by friction melts the ice. The brakes on cars use friction to reduce speed, and in the process, transform motion energy into heat energy. That is why after bringing a car to a stop, the brakes can be very hot; this also explains why brakes can overheat when used carelessly while descending long mountain roads.

In the nineteenth century, scientists thought that the source of the Sun's heat might be the mechanical motion of meteorites falling into it. Their calculations showed, however, that in order to produce the total amount of energy emitted by the Sun, the mass in meteorites that would have to fall into the Sun every 100 years would equal the mass of Earth. The resulting increase in the Sun's mass would, according to Kepler's third law, change the period of Earth's orbit by 2 seconds per year. Such a change would be easily measurable and was not, in fact, occurring. Scientists could then disprove this as the source of the Sun's energy.

Gravitational Contraction as a Source of Energy

Proposing an alternative explanation, British physicist Lord Kelvin and German scientist Hermann von Helmholtz (**Figure 16.2**), in about the middle of the nineteenth century, proposed that the Sun might produce energy by the conversion of gravitational energy into heat. They suggested that the outer layers of the Sun might be "falling" inward because of the force of gravity. In other words, they proposed that the Sun could be shrinking in size, staying hot and bright as a result.

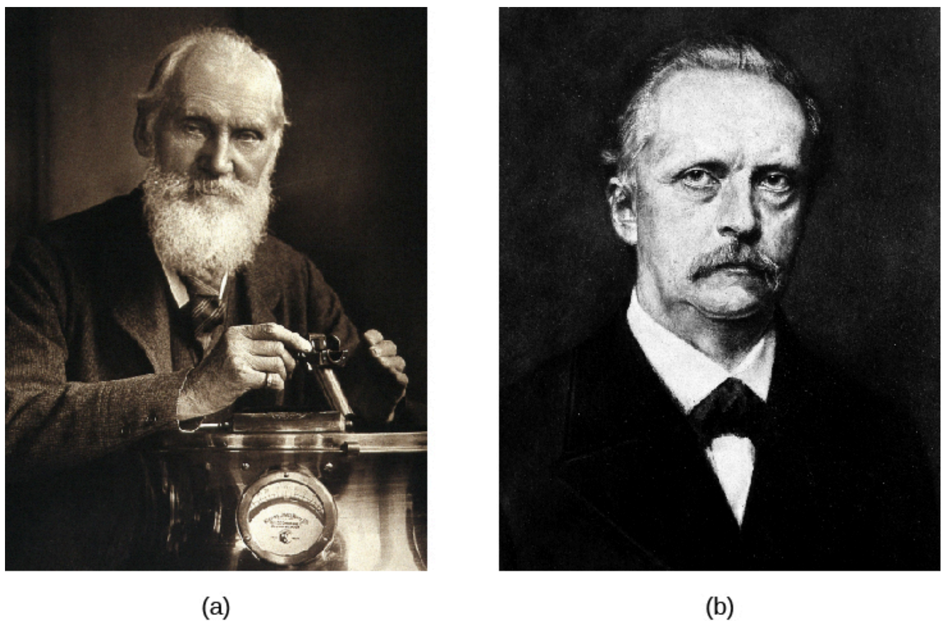


Figure 16.2 Kelvin (1824–1907) and Helmholtz (1821–1894). (a) British physicist William Thomson (Lord Kelvin) and (b) German scientist Hermann von Helmholtz proposed that the contraction of the Sun under its own gravity might account for its energy. (credit a: modification of work by Wellcome Library, London; credit b: modification of work by Wellcome Library, London)

To imagine what would happen if this hypothesis were true, picture the outer layer of the Sun starting to fall inward. This outer layer is a gas made up of individual atoms, all moving about in random directions. If a layer falls inward, the atoms acquire an additional speed because of falling motion. As the outer layer falls inward, it also contracts, moving the atoms closer together. Collisions become more likely, and some of them transfer the extra speed associated with the falling motion to other atoms. This, in turn, increases the speeds of those atoms. The temperature of a gas is a measure of the kinetic energy (motion) of the atoms within it; hence, the temperature of this layer of the Sun increases. Collisions also excite electrons within the atoms to higher-energy orbits. When these electrons return to their normal orbits, they emit photons, which can then escape from the Sun (see **Radiation and Spectra**).

Kelvin and Helmholtz calculated that a contraction of the Sun at a rate of only about 40 meters per year would be enough to produce the amount of energy that it is now radiating. Over the span of human history, the decrease in the Sun's size from such a slow contraction would be undetectable.

If we assume that the Sun began its life as a large, diffuse cloud of gas, then we can calculate how much energy has been radiated by the Sun during its entire lifetime as it has contracted from a very large diameter to its present size. The amount of energy is on the order of 10^{42} joules. Since the solar luminosity is 4×10^{26} watts (joules/second) or about 10^{34} joules per year, contraction could keep the Sun shining at its present rate for roughly 100 million years.

In the nineteenth century, 100 million years at first seemed plenty long enough, since Earth was then widely thought to be much younger than this. But toward the end of that century and into the twentieth, geologists and physicists showed that Earth (and, hence, the Sun) is actually much older. Contraction therefore cannot be the primary source of solar energy (although, as we shall see in **The Birth of Stars and the Discovery of Planets Outside the Solar System**, contraction is an important source of energy for a while in stars that are just being born). Scientists were thus confronted with a puzzle of enormous proportions. Either an unknown type of energy was responsible for the most important energy source known to humanity, or estimates of the age of the solar system (and life on Earth) had to be seriously modified. Charles Darwin, whose theory of evolution required a longer time span than the theories of the Sun seemed to permit, was discouraged by these results and continued to worry about them until his death in 1882.

It was only in the twentieth century that the true source of the Sun's energy was identified. The two key pieces of information required to solve the puzzle were the structure of the nucleus of the atom and the fact that mass can be converted into energy.

16.2 MASS, ENERGY, AND THE THEORY OF RELATIVITY

Learning Objectives

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

- Explain how matter can be converted into energy
- Describe the particles that make up atoms
- Describe the nucleus of an atom
- Understand the nuclear forces that hold atoms together
- Trace the nuclear reactions in the solar interior

As we have seen, energy cannot be created or destroyed, but only converted from one form to another. One of the remarkable conclusions derived by Albert Einstein (see **Albert Einstein**) when he developed his theory of relativity is that matter can be considered a form of energy too and can be converted into energy. Furthermore, energy can also be converted into matter. This seemed to contradict what humans had learned over thousands of years by studying nature. Matter is something we can see and touch, whereas energy is something objects have when they do things like move or heat up. The idea that matter or energy can be converted into each other seemed as outrageous as saying you could accelerate a car by turning the bumper into more speed, or that you could create a bigger front seat by slowing down your car. That would be pretty difficult to believe; yet, the universe actually works somewhat like that.

Converting Matter into Energy

The remarkable equivalence between matter and energy is given in one of the most famous equations:

$$E = mc^2$$

In this equation, *E* stands for energy, *m* stands for mass, and *c*, the constant that relates the two, is the speed of light (3×10^8 meters per second). Note that mass is a measure of the quantity of matter, so the significance of this equation is that matter can be converted into energy and energy can be converted into matter. Let's compare this equation of converting matter and energy to some common conversion equations that have the same form:

$$\text{inches} = \text{feet} \times 12, \text{ or cents} = \text{dollars} \times 100$$

Just as each conversion formula allows you to calculate the conversion of one thing into another, when we convert matter into energy, we consider how much mass the matter has. The conversion factor in this case turns out not to be either 12 or 100, as in our examples, but another constant quantity: the speed of light squared. Note that matter does not have to travel at the speed of light (or the speed of light squared) for this conversion to occur. The factor of c^2 is just the number that Einstein showed must be used to relate mass and energy.

Notice that this formula does not tell us *how* to convert mass into energy, just as the formula for cents does not tell us where to exchange coins for a dollar bill. The formulas merely tell us what the equivalent values are if we succeed in making the conversion. When Einstein first derived his formula in 1905, no one had the faintest idea how to convert mass into energy in any practical way. Einstein himself tried to discourage speculation that the large-scale conversion of atomic mass into energy would be feasible in the near future. Today, as a result of developments in nuclear physics, we regularly convert mass into energy in power plants, nuclear weapons, and high-energy physics experiments in particle accelerators.

Because the speed of light squared (c^2) is a very large quantity, the conversion of even a small amount of mass results in a very large amount of energy. For example, the complete conversion of 1 gram of matter (about 1/28 ounce, or approximately 1 paperclip) would produce as much energy as the burning of 15,000 barrels of oil.

Scientists soon realized that the conversion of mass into energy is the source of the Sun's heat and light. With Einstein's equation of $E = mc^2$, we can calculate that the amount of energy radiated by the Sun could be produced by the complete conversion of about 4 million tons of matter into energy inside the Sun each second. Destroying 4 million tons per second sounds like a lot when compared to earthly things, but bear in mind that the Sun is a very big reservoir of matter. In fact, we will see that the Sun contains more than enough mass to destroy such huge amounts of matter and still continue shining at its present rate for billions of years.

But knowing all that still does not tell us *how* mass can be converted into energy. To understand the process that actually occurs in the Sun, we need to explore the structure of the atom a bit further.

VOYAGERS IN ASTRONOMY

Albert Einstein

For a large part of his life, Albert Einstein (**Figure 16.3**) was one of the most recognized celebrities of his day. Strangers stopped him on the street, and people all over the world asked him for endorsements, advice, and assistance. In fact, when Einstein and the great film star Charlie Chaplin met in California, they found they shared similar feelings about the loss of privacy that came with fame. Einstein's name was a household word despite the fact that most people did not understand the ideas that had made him famous.

Einstein was born in 1879 in Ulm, Germany. Legend has it that he did not do well in school (even in arithmetic), and thousands of students have since attempted to justify a bad grade by referring to this story. Alas, like many legends, this one is not true. Records indicate that although he tended to rebel against the authoritarian teaching style in vogue in Germany at that time, Einstein was a good student.

After graduating from the Federal Polytechnic Institute in Zurich, Switzerland, Einstein at first had trouble getting a job (even as a high school teacher), but he eventually became an examiner in the Swiss Patent Office. Working in his spare time, without the benefit of a university environment but using his superb physical intuition, he wrote four papers in 1905 that would ultimately transform the way physicists looked at the world.

One of these, which earned Einstein the Nobel Prize in 1921, set part of the foundation of *quantum mechanics*—the rich, puzzling, and remarkable theory of the subatomic realm. But his most important paper presented the *special theory of relativity*, a reexamination of space, time, and motion that added a whole new level of sophistication to our understanding of those concepts. The famed equation $E = mc^2$ was actually a relatively minor part of this theory, added in a later paper.

In 1916, Einstein published his *general theory of relativity*, which was, among other things, a fundamentally new description of gravity (see **Black Holes and Curved Spacetime**). When this theory was confirmed by measurements of the "bending of starlight" during a 1919 eclipse (*The New York Times* headline read, "Lights All Askew in the Heavens"), Einstein became world famous.

In 1933, to escape Nazi persecution, Einstein left his professorship in Berlin and settled in the United States at the newly created Institute for Advanced Studies at Princeton. He remained there until his death in 1955, writing, lecturing, and espousing a variety of intellectual and political causes. For example, he agreed to sign a letter written by Leo Szilard and other scientists in 1939, alerting President Roosevelt to the dangers of allowing Nazi Germany to develop the atomic bomb first. And in 1952, Einstein was offered the second presidency of Israel. In declining the position, he said, "I know a little about nature and hardly anything about men."

Figure 16.3 Albert Einstein (1879–1955). This portrait of Einstein was taken in 1912. (credit: modification of work by J. F. Langhans)

Elementary Particles

The fundamental components of atoms are the proton, neutron, and electron (see **The Structure of the Atom**).

Protons, neutrons, and electrons are by no means all the particles that exist. First, for each kind of particle, there is a corresponding but opposite *antiparticle*. If the particle carries a charge, its antiparticle has the opposite charge. The antielectron is the *positron*, which has the same mass as the electron but is positively charged. Similarly, the antiproton has a negative charge. The remarkable thing about such *antimatter* is that when a particle comes into contact with its antiparticle, the original particles are annihilated, and substantial amounts of energy in the form of photons are produced.

Since our world is made exclusively of ordinary particles of matter, antimatter cannot survive for very long. But individual antiparticles are found in cosmic rays (particles that arrive at the top of Earth's atmosphere from space) and can be created in particle accelerators. And, as we will see in a moment, antimatter is created in the core of the Sun and other stars.

Science fiction fans may be familiar with antimatter from the *Star Trek* television series and films. The Starship Enterprise is propelled by the careful combining of matter and antimatter in the ship's engine room. According to $E = mc^2$, the annihilation of matter and antimatter can produce a huge amount of energy, but keeping the antimatter fuel from touching the ship before it is needed must be a big problem. No wonder Scotty, the chief engineer in the original TV show, always looked worried!

In 1933, physicist Wolfgang Pauli (**Figure 16.4**) suggested that there might be another type of elementary particle. Energy seemed to disappear when certain types of nuclear reactions took place, violating the law of conservation of energy. Pauli was reluctant to accept the idea that one of the basic laws of physics was wrong, and he suggested a "desperate remedy." Perhaps a so-far-undetected particle, which was given the name **neutrino** ("little neutral one"), carried away the "missing" energy. He suggested that neutrinos were particles with zero mass, and that like photons, they moved with the speed of light.

Figure 16.4 Wolfgang Pauli in 1945. Pauli is considered the "father" of the neutrino, having conceived of it in 1933.

The elusive neutrino was not detected until 1956. The reason it was so hard to find is that neutrinos interact very weakly with other matter and therefore are very difficult to detect. Earth is more transparent to a neutrino than the thinnest and cleanest pane of glass is to a photon of light. In fact, most neutrinos can pass completely through a star or planet without being absorbed. As we shall see, this behavior of neutrinos makes them a very important tool for studying the Sun. Since Pauli's prediction, scientists have learned a lot more about the neutrino. We now know that there are three different types of neutrinos, and in 1998, neutrinos were discovered to have a tiny amount of mass. Indeed, it is so tiny that electrons are at least 500,000 times more massive. Ongoing research is focused on determining the mass of neutrinos more precisely, and it may still turn out that one of the three types is massless. We will return to the subject of neutrinos later in this chapter.

Some of the properties of the proton, electron, neutron, and neutrino are summarized in **Table 16.1**. (Other subatomic particles have been produced by experiments with particle accelerators, but they do not play a role in the generation of solar energy.)

Properties of Some Common Particles

Particle	Mass (kg)	Charge
Proton	1.67265×10^{-27}	+1
Neutron	1.67495×10^{-27}	0
Electron	9.11×10^{-31}	−1
Neutrino	$<2 \times 10^{-36}$ (uncertain)	0

Table 16.1

The Atomic Nucleus

The nucleus of an atom is not just a loose collection of elementary particles. Inside the nucleus, particles are held together by a very powerful force called the strong nuclear force. This is short-range force, only capable of acting over distances about the size of the atomic nucleus. A quick thought experiment shows how important this force is. Take a look at your finger and consider the atoms composing it. Among them is carbon, one of the basic elements of life. Focus your imagination on the nucleus of one of your carbon atoms. It contains six protons, which have a positive charge, and six neutrons, which are neutral. Thus, the nucleus has a net charge of six positives. If only the electrical force were acting, the protons in this and every carbon atom would find each other very repulsive and fly apart.

The strong nuclear force is an attractive force, stronger than the electrical force, and it keeps the particles of the nucleus tightly bound together. We saw earlier that if under the force of gravity a star "shrinks"—bringing its atoms closer together—gravitational energy is released. In the same way, if particles come together under the strong nuclear force and unite to form an atomic nucleus, some of the nuclear energy is released. The energy given up in such a process is called the *binding energy* of the nucleus.

When such binding energy is released, the resulting nucleus has slightly less mass than the sum of the masses of the particles that came together to form it. In other words, the energy comes from the loss of mass. This slight deficit in mass is only a small fraction of the mass of one proton. But because each bit of lost mass can provide a lot of energy (remember, $E = mc^2$), this nuclear energy release can be quite substantial.

Measurements show that the binding energy is greatest for atoms with a mass near that of the iron nucleus (with a combined number of protons and neutrons equal to 56) and less for both the lighter and the heavier nuclei. Iron, therefore, is the most stable element: since it gives up the most energy when it forms, it would require the most energy to break it back down into its component particles.

What this means is that, in general, when light atomic nuclei come together to form a heavier one (up to iron), mass is lost and energy is released. This joining together of atomic nuclei is called nuclear **fusion**.

Energy can also be produced by breaking up heavy atomic nuclei into lighter ones (down to iron); this process is called nuclear **fission**. Nuclear fission was the process we learned to use first—in atomic bombs and in nuclear reactors used to generate electrical power—and it may therefore be more familiar to you. Fission also sometimes occurs spontaneously in some unstable nuclei through the process of natural radioactivity. But fission requires big, complex nuclei, whereas we know that the stars are made up predominantly of small, simple nuclei. So we must look to fusion first to explain the energy of the Sun and the stars (Figure 16.5).

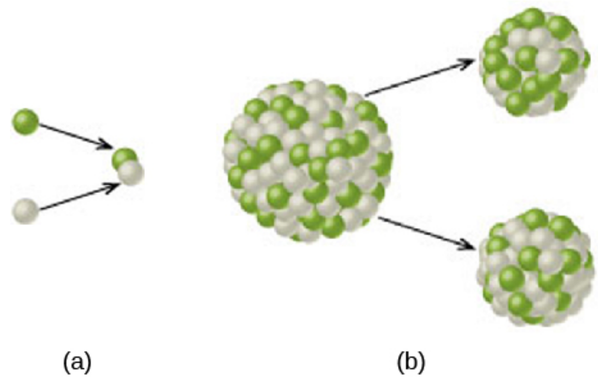


Figure 16.5 Fusion and Fission. (a) In fusion, light atomic nuclei join together to form a heavier nuclei, releasing energy in the process. (b) In fission, energy is produced by the breaking up of heavy, complex nuclei into lighter ones.

Nuclear Attraction versus Electrical Repulsion

So far, we seem to have a very attractive prescription for producing the energy emitted by the Sun: "roll" some nuclei together and join them via nuclear fusion. This will cause them to lose some of their mass, which then turns into energy. However, every nucleus, even simple hydrogen, has protons—and protons all have positive charges. Since like charges repel via the electrical force, the closer we get two nuclei to each other, the more they repel. It's true that if we can get them within "striking distance" of the nuclear force, they will then come together with a much stronger attraction. But that striking distance is very tiny, about the size of a nucleus. How can we get nuclei close enough to participate in fusion?

The answer turns out to be heat—tremendous heat—which speeds the protons up enough to overcome the electrical forces that try to keep protons apart. Inside the Sun, as we saw, the most common element is hydrogen, whose nucleus contains only a single proton. Two protons can fuse only in regions where the temperature is greater than about 12 million K, and the speed of the protons average around 1000 kilometers per second or more. (In old-fashioned units, that's over 2 million miles per hour!)

In our Sun, such extreme temperatures are reached only in the regions near its center, which has a temperature of 15 million K. Calculations show that nearly all of the Sun's energy is generated within about 150,000 kilometers of its core, or within less than 10% of its total volume.

Even at these high temperatures, it is exceedingly difficult to force two protons to combine. On average, a proton will rebound from other protons in the Sun's crowded core for about 14 billion years, at the rate of *100 million collisions per second*, before it fuses with a second proton. This is, however, only the *average* waiting time. Some of the enormous numbers of protons in the Sun's inner region are "lucky" and take only a few collisions to achieve a fusion reaction: they are the protons responsible for producing the energy radiated by the Sun. Since the Sun is about 4.5 billion years old, most of its protons have not yet been involved in fusion reactions.

Nuclear Reactions in the Sun's Interior

The Sun, then, taps the energy contained in the nuclei of atoms through nuclear fusion. Let's look at what happens in more detail. Deep inside the Sun, a three-step process takes four hydrogen nuclei and fuses them together to form a single helium nucleus. The helium nucleus is slightly less massive than the four hydrogen nuclei that combine to form it, and that mass is converted into energy.

The initial step required to form one helium nucleus from four hydrogen nuclei is shown in **Figure 16.6**. At the high temperatures inside the Sun's core, two protons combine to make a *deuterium* nucleus, which is an isotope (or version) of hydrogen that contains one proton and one neutron. In effect, one of the original protons has been converted into a neutron in the fusion reaction. Electric charge has to be conserved in nuclear reactions, and it is conserved in this one. A **positron** (antimatter electron) emerges from the reaction and carries away the positive charge originally associated with one of the protons.

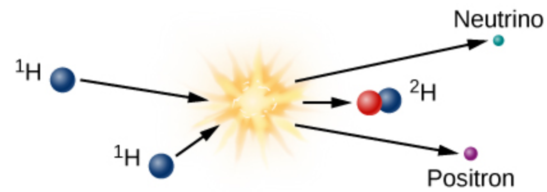


Figure 16.6 Proton-Proton Chain, Step 1. This is the first step in the process of fusing hydrogen into helium in the Sun. High temperatures are required because this reaction starts with two hydrogen nuclei, which are protons (shown in blue at left) that must overcome electrical repulsion to combine, forming a hydrogen nucleus with a proton and a neutron (shown in red). Note that hydrogen containing one proton and one neutron is given its own name: deuterium. Also produced in this reaction are a positron, which is an antielectron, and an elusive particle named the neutrino.

Since it is antimatter, this positron will instantly collide with a nearby electron, and both will be annihilated, producing electromagnetic energy in the form of gamma-ray photons. This gamma ray, which has been created in the center of the Sun, finds itself in a world crammed full of fast-moving nuclei and electrons. The gamma ray collides with particles of matter and transfers its energy to one of them. The particle later emits another gamma-ray photon, but often the emitted photon has a bit less energy than the one that was absorbed.

Such interactions happen to gamma rays again and again and again as they make their way slowly toward the outer layers of the Sun, until their energy becomes so reduced that they are no longer gamma rays but X-rays (recall what you learned in The Electromagnetic Spectrum). Later, as the photons lose still more energy through collisions in the crowded center of the Sun, they become ultraviolet photons.

By the time they reach the Sun's surface, most of the photons have given up enough energy to be ordinary light—and they are the sunlight we see coming from our star. (To be precise, each gamma-ray photon is ultimately converted into many separate lower-energy photons of sunlight.) So, the sunlight given off by the Sun today had its origin as a gamma ray produced by nuclear reactions deep in the Sun's core. The length of time that photons require to reach the surface depends on how far a photon on average travels between collisions, and the travel time depends on what model of the complicated solar interior we accept. Estimates are somewhat uncertain but indicate that the emission of energy from the surface of the Sun can lag its production in the interior by 100,000 years to as much as 1,000,000 years.

In addition to the positron, the fusion of two hydrogen atoms to form deuterium results in the emission of a neutrino. Because neutrinos interact so little with ordinary matter, those produced by fusion reactions near the center of the Sun travel directly to the Sun's surface and then out into space, in all directions. Neutrinos move at nearly the speed of light, and they escape the Sun about two seconds after they are created.

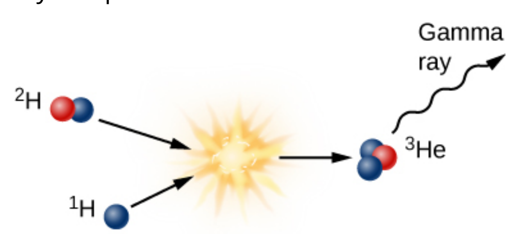


Figure 16.7 Proton-Proton Chain, Step 2. This is the second step of the proton-proton chain, the fusion reaction that converts hydrogen into helium in the Sun. This step combines one hydrogen nucleus, which is a proton (shown in blue), with the deuterium nucleus from the previous step (shown as a red and blue particle). The product of this is an isotope of helium with two protons (blue) and one neutron (red) and energy in the form of gamma-ray radiation.

The second step in forming helium from hydrogen is to add another proton to the deuterium nucleus to create a helium nucleus that contains two protons and one neutron (Figure 16.7). In the process, some mass is again lost and more gamma radiation is emitted. Such a nucleus is helium because an element is defined by its number of protons; any nucleus with two protons is called helium. But this form of helium, which we call helium-3 (and write in shorthand as ^{3}He) is not the isotope we see in the Sun's atmosphere or on Earth. That helium has two neutrons and two protons and hence is called helium-4 (^{4}He).

To get to helium-4 in the Sun, helium-3 must combine with another helium-3 in the third step of fusion (illustrated in Figure 16.8). Note that two energetic protons are left over from this step; each of them comes out of the reaction ready to collide with other protons and to start step 1 in the chain of reactions all over again.

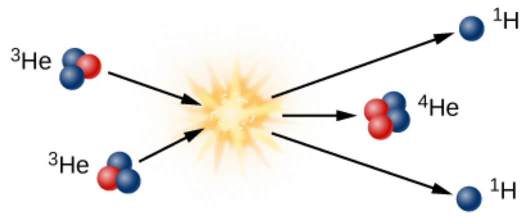


Figure 16.8 Proton-Proton Chain, Step 3. This is the third step in the fusion of hydrogen into helium in the Sun. Note that the two helium-3 nuclei from the second step (see Figure 16.7) must combine before the third step becomes possible. The two protons that come out of this step have the energy to collide with other protons in the Sun and start step one again.

LINK TO LEARNING

These animations of **proton-proton reactions (https://openstaxcollege.org/l/30proproreactio)** show the steps required for fusion of hydrogen into helium in the Sun.

LINK TO LEARNING

Visit the **Tokamak Fusion Reactor (https://openstaxcollege.org/l/30tokamakfusrea)** at the General Atomics Lab in San Diego, CA, for an 8-minute tour.

The Proton-Proton Chain

The nuclear reactions in the Sun that we have been discussing can be described succinctly through the following nuclear formulas:

$$
\begin{aligned}
&{}^1\mathrm{H} + {}^1\mathrm{H} \longrightarrow {}^2\mathrm{H} + \mathrm{e}^+ + \nu \\
&{}^2\mathrm{H} + {}^1\mathrm{H} \longrightarrow {}^3\mathrm{He} + \gamma \\
&{}^3\mathrm{He} + {}^3\mathrm{He} \longrightarrow {}^4\mathrm{He} + {}^1\mathrm{H} + {}^1\mathrm{H}
\end{aligned}
$$

Here, the superscripts indicate the total number of neutrons plus protons in the nucleus, e^+ is the positron, v is the neutrino, and γ indicates that gamma rays are emitted. Note that the third step requires two helium-3 nuclei to start; the first two steps must happen twice before the third step can occur.

Although, as we discussed, the first step in this chain of reactions is very difficult and generally takes a long time, the other steps happen more quickly. After the deuterium nucleus is formed, it survives an average of only about 6 seconds before being converted into ^{3}He. About a million years after that (on average), the ^{3}He nucleus will combine with another to form ^{4}He.

We can compute the amount of energy these reactions generate by calculating the difference in the initial and final masses. The masses of hydrogen and helium atoms in the units normally used by scientists are 1.007825 *u* and 4.00268 *u*, respectively. (The unit of mass, *u*, is defined to be 1/12 the mass of an atom of carbon, or approximately the mass of a proton.) Here, we include the mass of the entire atom, not just the nucleus, because electrons are involved as well. When hydrogen is converted into helium, two positrons are created (remember, the first step happens twice), and these are annihilated with two free electrons, adding to the energy produced.

$$\begin{aligned} 4 \times 1.007825 &= 4.03130\,u \text{ (mass of initial hydrogen atoms)} \\ &- 4.00268\,u \text{ (mass of final helium a oms)} \\ &= 0.02862\,u \text{ (mass lost in the transformation)} \end{aligned}$$

The mass lost, 0.02862 *u*, is 0.71% of the mass of the initial hydrogen. Thus, if 1 kilogram of hydrogen is converted into helium, then the mass of the helium is only 0.9929 kilogram, and 0.0071 kilogram of material is converted into energy. The speed of light (*c*) is 3 × 10^8 meters per second, so the energy released by the conversion of just 1 kilogram of hydrogen into helium is:

$$\begin{aligned} E &= mc^2 \\ E &= 0.0071\text{ kg} \times \left(3 \times 10^8\text{ m/s}\right)^2 = 6.4 \times 10^{14}\text{ J} \end{aligned}$$

This amount, the energy released when a single kilogram (2.2 pounds) of hydrogen undergoes fusion, would supply all of the electricity used in the United States for about 2 weeks.

To produce the Sun's luminosity of 4 × 10^{26} watts, some 600 million tons of hydrogen must be converted into helium *each second*, of which about 4 million tons are converted from matter into energy. As large as these numbers are, the store of hydrogen (and thus of nuclear energy) in the Sun is still *more* enormous, and can last a long time—billions of years, in fact.

At the temperatures inside the stars with masses smaller than about 1.2 times the mass of our Sun (a category that includes the Sun itself), most of the energy is produced by the reactions we have just described, and this set of reactions is called the **proton-proton chain** (or sometimes, the p-p chain). In the proton-proton chain, protons collide directly with other protons to form helium nuclei.

In hotter stars, another set of reactions, called the carbon-nitrogen-oxygen (CNO) cycle, accomplishes the same net result. In the CNO cycle, carbon and hydrogen nuclei collide to initiate a series of reactions that form nitrogen, oxygen, and ultimately, helium. The nitrogen and oxygen nuclei do not survive but interact to form carbon again. Therefore, the outcome is the same as in the proton-proton chain: four hydrogen atoms disappear, and in their place, a single helium atom is created. The CNO cycle plays only a minor role in the Sun but is the main source of energy for stars with masses greater than about the mass of the Sun.

So you can see that we have solved the puzzle that so worried scientists at the end of the nineteenth century. The Sun can maintain its high temperature and energy output for billions of years through the fusion of the simplest element in the universe, hydrogen. Because most of the Sun (and the other stars) is made of hydrogen, it is an ideal "fuel" for powering a star. As will be discussed in the following chapters, we can define a star as a ball of gas capable of getting its core hot enough to initiate the fusion of hydrogen. There are balls of gas that lack the mass required to do this (Jupiter is a local example); like so many hopefuls in Hollywood, they will never be stars.

MAKING CONNECTIONS

Fusion on Earth

Wouldn’t it be wonderful if we could duplicate the Sun’s energy mechanism in a controlled way on Earth? (We have already duplicated it in an uncontrolled way in hydrogen bombs, but we hope our storehouses of these will never be used.) Fusion energy would have many advantages: it would use hydrogen (or deuterium, which is heavy hydrogen) as fuel, and there is abundant hydrogen in Earth’s lakes and oceans. Water is much more evenly distributed around the world than oil or uranium, meaning that a few countries would no longer hold an energy advantage over the others. And unlike fission, which leaves dangerous byproducts, the nuclei that result from fusion are perfectly safe.

The problem is that, as we saw, it takes extremely high temperatures for nuclei to overcome their electrical repulsion and undergo fusion. When the first hydrogen bombs were exploded in tests in the 1950s, the “fuses” to get them hot enough were fission bombs. Interactions at such temperatures are difficult to sustain and control. To make fusion power on Earth, after all, we have to do what the Sun does: produce temperatures and pressures high enough to get hydrogen nuclei on intimate terms with one another.

The European Union, the United States, South Korea, Japan, China, Russia, Switzerland, and India are collaborating on the International Thermonuclear Experimental Reactor (ITER), a project to demonstrate the feasibility of controlled fusion (**Figure 16.9**). The facility is being built in France. Construction will require over 10,000,000 components and 2000 workers for assembly. The date for the start of operations is yet to be determined.

ITER is based on the Tokamak design, in which a large doughnut-shaped container is surrounded by superconducting magnets to confine and control the hydrogen nuclei in a strong magnetic field. Previous fusion experiments have produced about 15 million watts of energy, but only for a second or two, and they have required 100 million watts to produce the conditions necessary to achieve fusion. The goal of ITER is to build the first fusion device capable of producing 500 million watts of fusion energy for up to 1000 seconds. The challenge is keeping the deuterium and tritium—which will participate in fusion reactions—hot enough and dense enough, for a long enough time to produce energy.

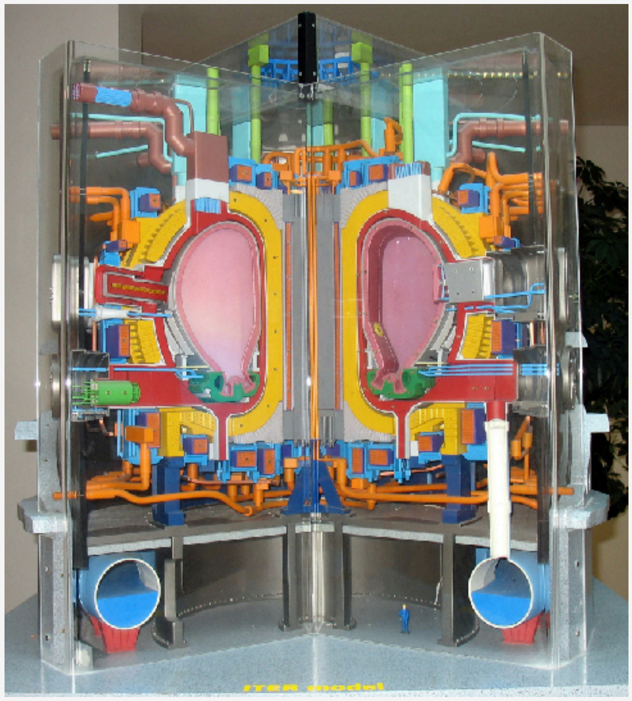


Figure 16.9 ITER Design. The bright yellow areas in this model show where the superconducting magnets will circle the chamber within which fusion will take place. A huge magnet will keep the charged nuclei of heavy hydrogen confined. The goal is to produce 500 megawatts of energy. (credit: modification of work by Stephan Mosel)

16.3 THE SOLAR INTERIOR: THEORY

Learning Objectives

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

- Describe the state of equilibrium of the Sun
- Understand the energy balance of the Sun
- Explain how energy moves outward through the Sun
- Describe the structure of the solar interior

Fusion of protons can occur in the center of the Sun only if the temperature exceeds 12 million K. How do we know that the Sun is actually this hot? To determine what the interior of the Sun might be like, it is necessary to resort to complex calculations. Since we can't see the interior of the Sun, we have to use our understanding of physics, combined with what we see at the surface, to construct a mathematical model of what must be happening in the interior. Astronomers use observations to build a computer program containing everything they think they know about the physical processes going on in the Sun's interior. The computer then calculates the temperature and pressure at every point inside the Sun and determines what nuclear reactions, if any, are taking place. For some calculations, we can use observations to determine whether the computer program is producing results that match what we see. In this way, the program evolves with ever-improving observations.

The computer program can also calculate how the Sun will change with time. After all, the Sun must change. In its center, the Sun is slowly depleting its supply of hydrogen and creating helium instead. Will the Sun get hotter? Cooler? Larger? Smaller? Brighter? Fainter? Ultimately, the changes in the center could be catastrophic, since eventually all the hydrogen fuel hot enough for fusion will be exhausted. Either a new source of energy must be found, or the Sun will cease to shine. We will describe the ultimate fate of the Sun in later chapters. For now, let’s look at some of the things we must teach the computer about the Sun in order to carry out such calculations.

The Sun Is a Plasma

The Sun is so hot that all of the material in it is in the form of an ionized gas, called a plasma. Plasma acts much like a hot gas, which is easier to describe mathematically than either liquids or solids. The particles that constitute a gas are in rapid motion, frequently colliding with one another. This constant bombardment is the *pressure* of the gas (**Figure 16.10**).

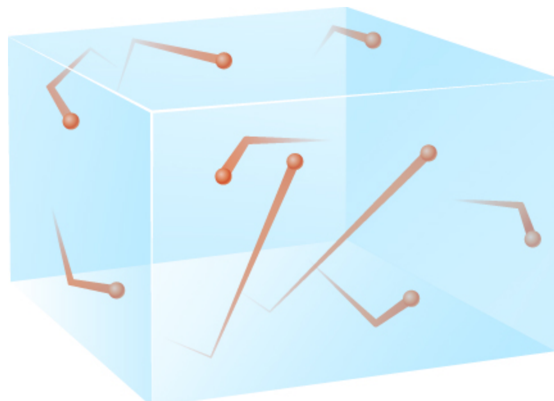


Figure 16.10 Gas Pressure. The particles in a gas are in rapid motion and produce pressure through collisions with the surrounding material. Here, particles are shown bombarding the sides of an imaginary container.

More particles within a given volume of gas produce more pressure because the combined impact of the moving particles increases with their number. The pressure is also greater when the molecules or atoms are moving faster. Since the molecules move faster when the temperature is hotter, higher temperatures produce higher pressure.

The Sun Is Stable

The Sun, like the majority of other stars, is stable; it is neither expanding nor contracting. Such a star is said to be in a condition of *equilibrium*. All the forces within it are balanced, so that at each point within the star, the temperature, pressure, density, and so on are maintained at constant values. We will see in later chapters that even these stable stars, including the Sun, are changing as they evolve, but such evolutionary changes are so gradual that, for all intents and purposes, the stars are still in a state of equilibrium at any given time.

The mutual gravitational attraction between the masses of various regions within the Sun produces tremendous forces that tend to collapse the Sun toward its center. Yet we know from the history of Earth that the Sun has been emitting roughly the same amount of energy for billions of years, so clearly it has managed to resist collapse for a very long time. The gravitational forces must therefore be counterbalanced by some other force. That force is due to the pressure of gases within the Sun (**Figure 16.11**). Calculations show that, in order to exert enough pressure to prevent the Sun from collapsing due to the force of gravity, the gases at its center must be maintained at a temperature of 15 million K. Think about what this tells us. Just from the fact that the Sun is not contracting, we can conclude that its temperature must indeed be high enough at the center for protons to undergo fusion.

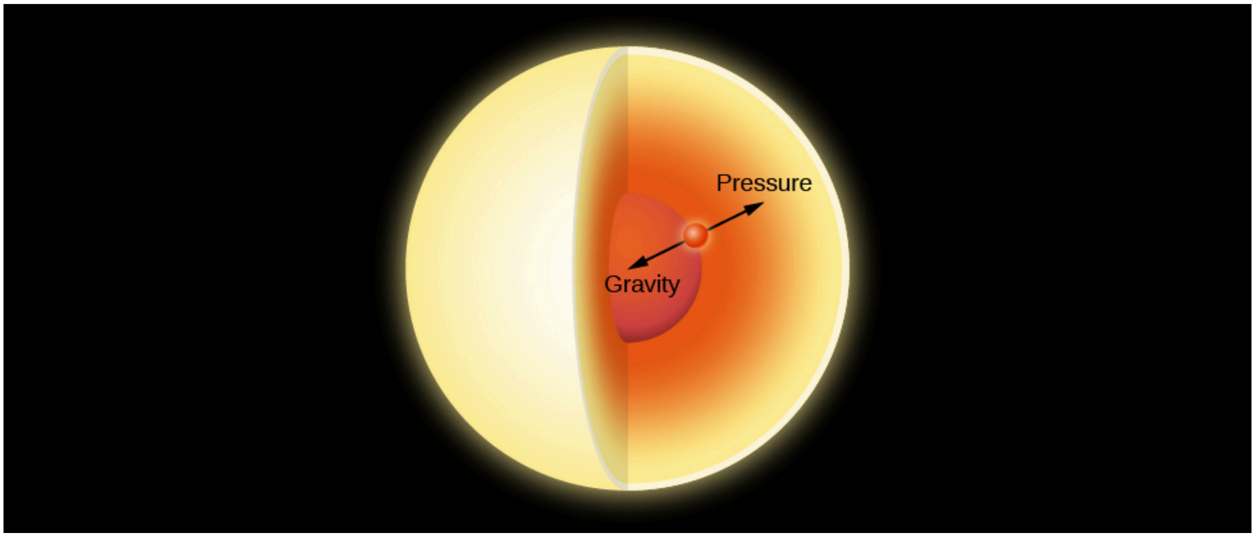


Figure 16.11 Hydrostatic Equilibrium. In the interior of a star, the inward force of gravity is exactly balanced at each point by the outward force of gas pressure.

The Sun maintains its stability in the following way. If the internal pressure in such a star were not great enough to balance the weight of its outer parts, the star would collapse somewhat, contracting and building up the pressure inside. On the other hand, if the pressure were greater than the weight of the overlying layers, the star would expand, thus decreasing the internal pressure. Expansion would stop, and equilibrium would again be reached when the pressure at every internal point equaled the weight of the stellar layers above that point. An analogy is an inflated balloon, which will expand or contract until an equilibrium is reached between the pressure of the air inside and outside. The technical term for this condition is **hydrostatic equilibrium**. Stable stars are all in hydrostatic equilibrium; so are the oceans of Earth as well as Earth's atmosphere. The air's own pressure keeps it from falling to the ground.

The Sun Is Not Cooling Down

As everyone who has ever left a window open on a cold winter night knows, heat always flows from hotter to cooler regions. As energy filters outward toward the surface of a star, it must be flowing from inner, hotter regions. The temperature cannot ordinarily get cooler as we go inward in a star, or energy would flow in and heat up those regions until they were at least as hot as the outer ones. Scientists conclude that the temperature is highest at the center of a star, dropping to lower and lower values toward the stellar surface. (The high temperature of the Sun's chromosphere and corona may therefore appear to be a paradox. But remember from **The Sun: A Garden-Variety Star** that these high temperatures are maintained by magnetic effects, which occur in the Sun's atmosphere.)

The outward flow of energy through a star robs it of its internal heat, and the star would cool down if that energy were not replaced. Similarly, a hot iron begins to cool as soon as it is unplugged from its source of electric energy. Therefore, a source of fresh energy must exist within each star. In the Sun's case, we have seen that this energy source is the ongoing fusion of hydrogen to form helium.

Heat Transfer in a Star

Since the nuclear reactions that generate the Sun's energy occur deep within it, the energy must be transported from the center of the Sun to its surface—where we see it in the form of both heat and light. There are three ways in which energy can be transferred from one place to another. In **conduction**, atoms or molecules pass on their energy by colliding with others nearby. This happens, for example, when the handle of a metal spoon heats up as you stir a cup of hot coffee. In **convection**, currents of warm material rise, carrying their energy with them to cooler layers. A good example is hot air rising from a fireplace. In **radiation**, energetic photons move away from hot material and are absorbed by some material to which they convey some or all of their energy. You can feel this when you put your hand close to the coils of an electric heater, allowing infrared photons to heat up your hand. Conduction and convection are both important in the interiors of planets. In stars, which are much more transparent, radiation and convection are important, whereas conduction can usually be ignored.

Stellar *convection* occurs as currents of hot gas flow up and down through the star (**Figure 16.12**). Such currents travel at moderate speeds and do not upset the overall stability of the star. They don't even result in a net transfer of mass either inward or outward because, as hot material rises, cool material falls and replaces it. This results in a convective circulation of rising and falling cells as seen in **Figure 16.12**. In much the same way, heat from a fireplace can stir up air currents in a room, some rising and some falling, without driving any air into or out the room. Convection currents carry heat very efficiently outward through a star. In the Sun, convection turns out to be important in the central regions and near the surface.

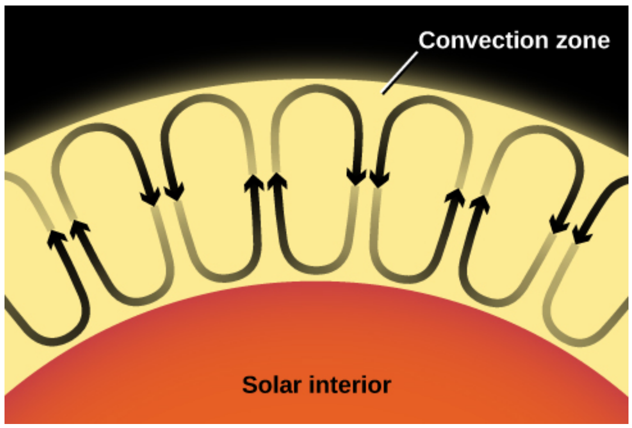


Figure 16.12 Convection. Rising convection currents carry heat from the Sun's interior to its surface, whereas cooler material sinks downward. Of course, nothing in a real star is as simple as diagrams in textbooks suggest.

Unless convection occurs, the only significant mode of energy transport through a star is by electromagnetic radiation. Radiation is not an efficient means of energy transport in stars because gases in stellar interiors are very opaque, that is, a photon does not go far (in the Sun, typically about 0.01 meter) before it is absorbed. (The processes by which atoms and ions can interrupt the outward flow of photons—such as becoming ionized—were discussed in the section on the **Formation of Spectral Lines**.) The absorbed energy is always reemitted, but it can be reemitted in any direction. A photon absorbed when traveling outward in a star has almost as good a chance of being radiated back toward the center of the star as toward its surface.

A particular quantity of energy, therefore, zigzags around in an almost random manner and takes a long time to work its way from the center of a star to its surface (**Figure 16.13**). Estimates are somewhat uncertain, but in the Sun, as we saw, the time required is probably between 100,000 and 1,000,000 years. If the photons were not absorbed and reemitted along the way, they would travel at the speed of light and could reach the surface in a little over 2 seconds, just as neutrinos do (**Figure 16.14**).

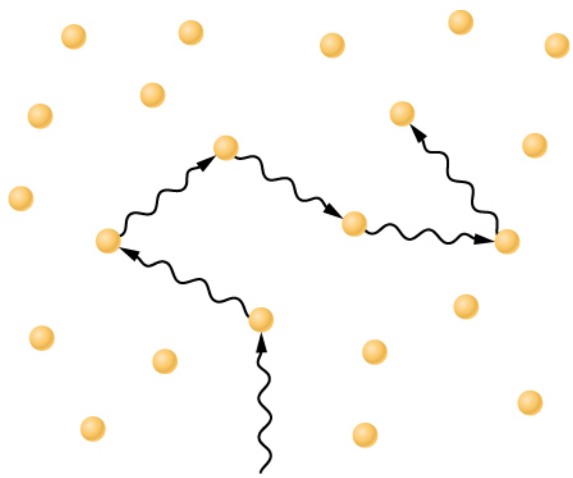


Figure 16.13 Photons Deep in the Sun. A photon moving through the dense gases in the solar interior travels only a short distance before it interacts with one of the surrounding atoms. The resulting photon usually has a lower energy after each interaction and may then travel in any random direction.

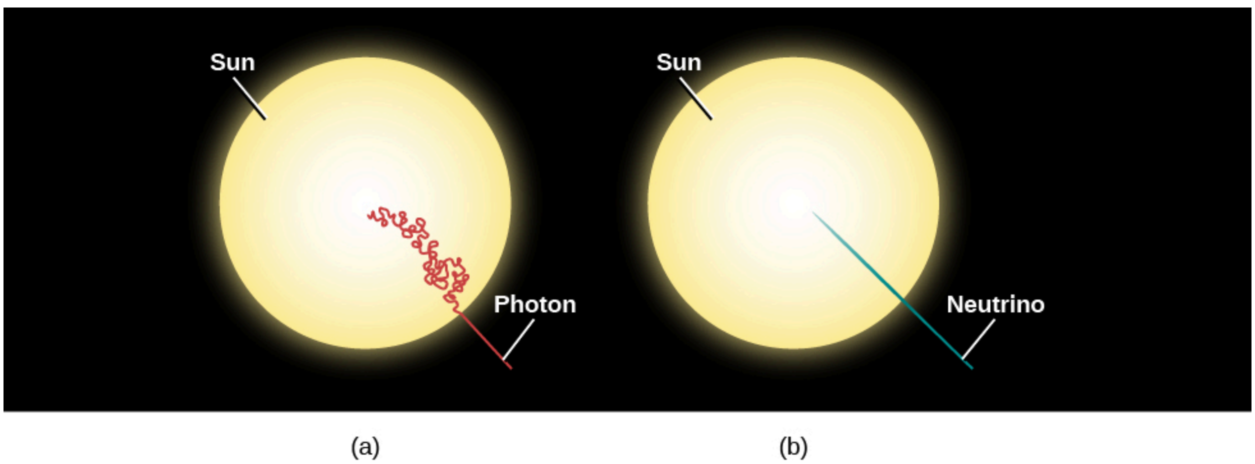


Figure 16.14 Photon and Neutrino Paths in the Sun. (a) Because photons generated by fusion reactions in the solar interior travel only a short distance before being absorbed or scattered by atoms and sent off in random directions, estimates are that it takes between 100,000 and 1,000,000 years for energy to make its way from the center of the Sun to its surface. (b) In contrast, neutrinos do not interact with matter but traverse straight through the Sun at the speed of light, reaching the surface in only a little more than 2 seconds.

MAKING CONNECTIONS

Heat Transfer and Cooking

The three ways that heat energy moves from higher-temperature regions to cooler regions are all used in cooking, and this is important to all of us who enjoy making or eating food.

Conduction is heat transfer by physical contact during which the energetic motion of particles in one region spread to other regions and even to adjacent objects in close contact. A tasty example of this is cooking a steak on a hot iron skillet. When a flame makes the bottom of a skillet hot, the particles in it vibrate actively and collide with neighboring particles, spreading the heat energy throughout the skillet (the ability to spread heat uniformly is a key criterion for selecting materials for cookware). A steak sitting on the surface of the skillet picks up heat energy by the particles in the surface of the skillet colliding with particles on the surface of the steak. Many cooks will put a little oil on the pan, and this layer of oil, besides preventing sticking, increases heat transfer by filling in gaps and increasing the contact surface area.

Convection is heat transfer by the motion of matter that rises because it is hot and less dense. Heating a fluid makes it expand, which makes it less dense, so it rises. An oven is a great example of this: the fire is at the bottom of the oven and heats the air down there, causing it to expand (becoming less dense), so it rises up to where the food is. The rising hot air carries the heat from the fire to the food by convection. This is how conventional ovens work. You may also be familiar with convection ovens that use a fan to circulate hot air for more even cooking. A scientist would object to that name because normal non-fan ovens that rely on hot air rising to circulate the heat are convection ovens; technically, the ovens that use fans to help move heat are “advection” ovens. (You may not have heard about this because the scientists who complain loudly about misusing the terms convection and advection don’t get out much.)

Radiation is the transfer of heat energy by electromagnetic radiation. Although microwave ovens are an obvious example of using radiation to heat food, a simpler example is a toy oven. Toy ovens are powered by a very bright light bulb. The child-chefs prepare a mix for brownies or cookies, put it into a tray, and place it in the toy oven under the bright light bulb. The light and heat from the bulb hit the brownie mix and cook it. If you have ever put your hand near a bright light, you have undoubtedly noticed your hand getting warmed by the light.

Model Stars

Scientists use the principles we have just described to calculate what the Sun’s interior is like. These physical ideas are expressed as mathematical equations that are solved to determine the values of temperature, pressure, density, the efficiency with which photons are absorbed, and other physical quantities throughout the Sun. The solutions obtained, based on a specific set of physical assumptions, provide a theoretical model for the interior of the Sun.

Figure 16.15 schematically illustrates the predictions of a theoretical model for the Sun’s interior. Energy is generated through fusion in the core of the Sun, which extends only about one-quarter of the way to the surface but contains about one-third of the total mass of the Sun. At the center, the temperature reaches a maximum of approximately 15 million K, and the density is nearly 150 times that of water. The energy generated in the core is transported toward the surface by radiation until it reaches a point about 70% of the distance from the center to the surface. At this point, convection begins, and energy is transported the rest of the way, primarily by rising columns of hot gas.

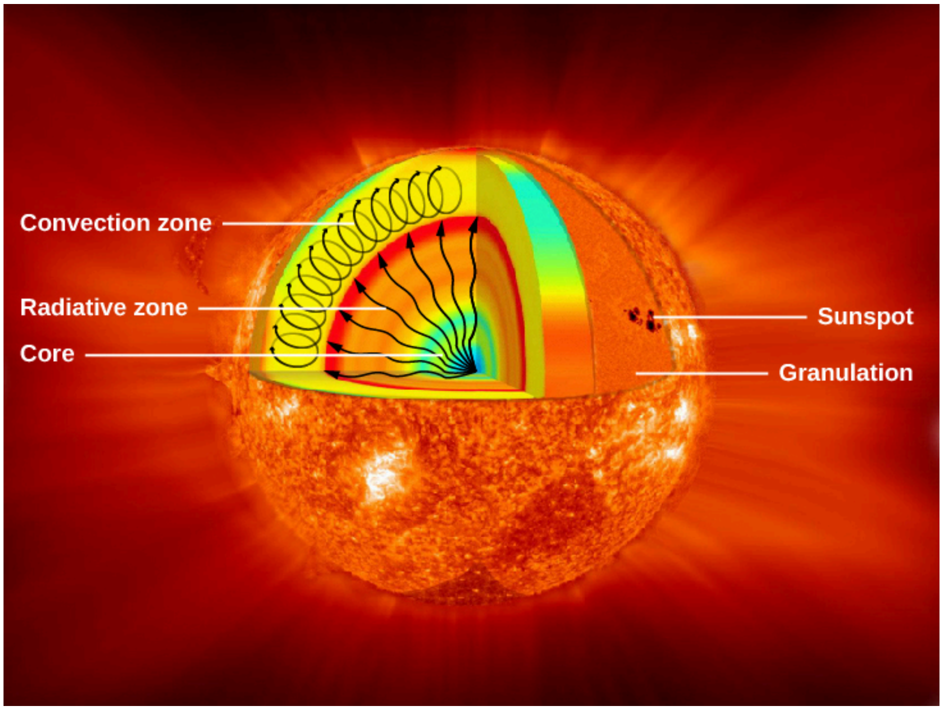


Figure 16.15 Interior Structure of the Sun. Energy is generated in the core by the fusion of hydrogen to form helium. This energy is transmitted outward by radiation—that is, by the absorption and reemission of photons. In the outermost layers, energy is transported mainly by convection. (credit: modification of work by NASA/Goddard)

Figure 16.16 shows how the temperature, density, rate of energy generation, and composition vary from the center of the Sun to its surface.

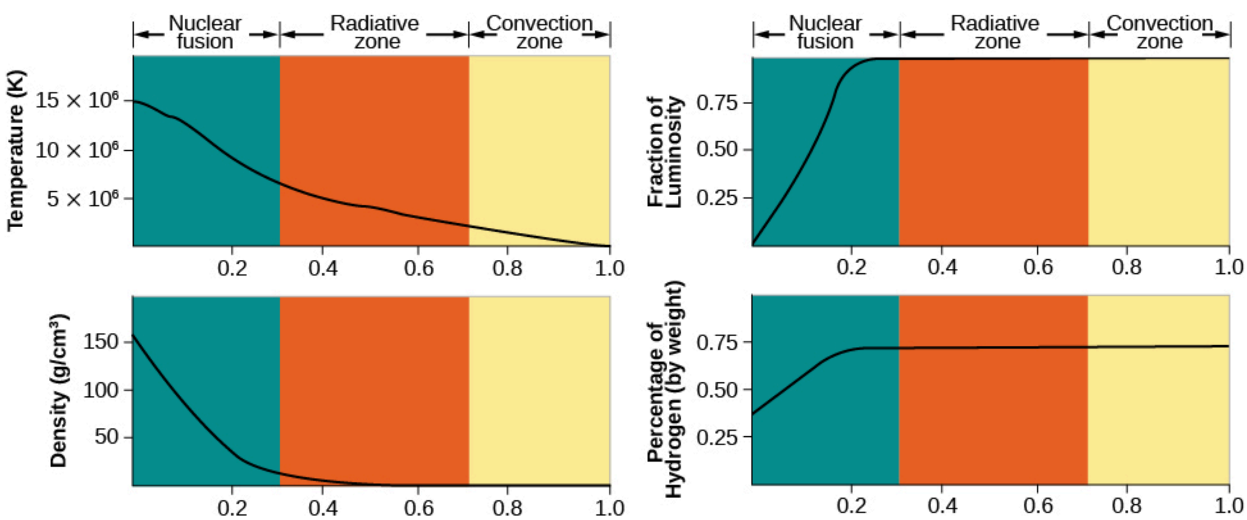


Figure 16.16 Interior of the Sun. Diagrams showing how temperature, density, rate of energy generation, and the percentage (by mass) abundance of hydrogen vary inside the Sun. The horizontal scale shows the fraction of the Sun's radius: the left edge is the very center, and the right edge is the visible surface of the Sun, which is called the photosphere.

16.4 THE SOLAR INTERIOR: OBSERVATIONS

Learning Objectives

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

- Explain how the Sun pulsates
- Explain what helioseismology is and what it can tell us about the solar interior
- Discuss how studying neutrinos from the Sun has helped understand neutrinos

Recall that when we observe the Sun’s photosphere (the surface layer we see from the outside), we are not seeing very deeply into our star, certainly not into the regions where energy is generated. That’s why the title of this section—observations of the solar interior—should seem very surprising. However, astronomers have indeed devised two types of measurements that can be used to obtain information about the inner parts of the Sun. One technique involves the analysis of tiny changes in the motion of small regions at the Sun’s surface. The other relies on the measurement of the neutrinos emitted by the Sun.

Solar Pulsations

Astronomers discovered that the Sun pulsates—that is, it alternately expands and contracts—just as your chest expands and contracts as you breathe. This pulsation is very slight, but it can be detected by measuring the *radial velocity* of the solar surface—the speed with which it moves toward or away from us. The velocities of small regions on the Sun are observed to change in a regular way, first toward Earth, then away, then toward, and so on. It is as if the Sun were “breathing” through thousands of individual lungs, each having a size in the range of 4000 to 15,000 kilometers, each fluctuating back and forth (**Figure 16.17**).

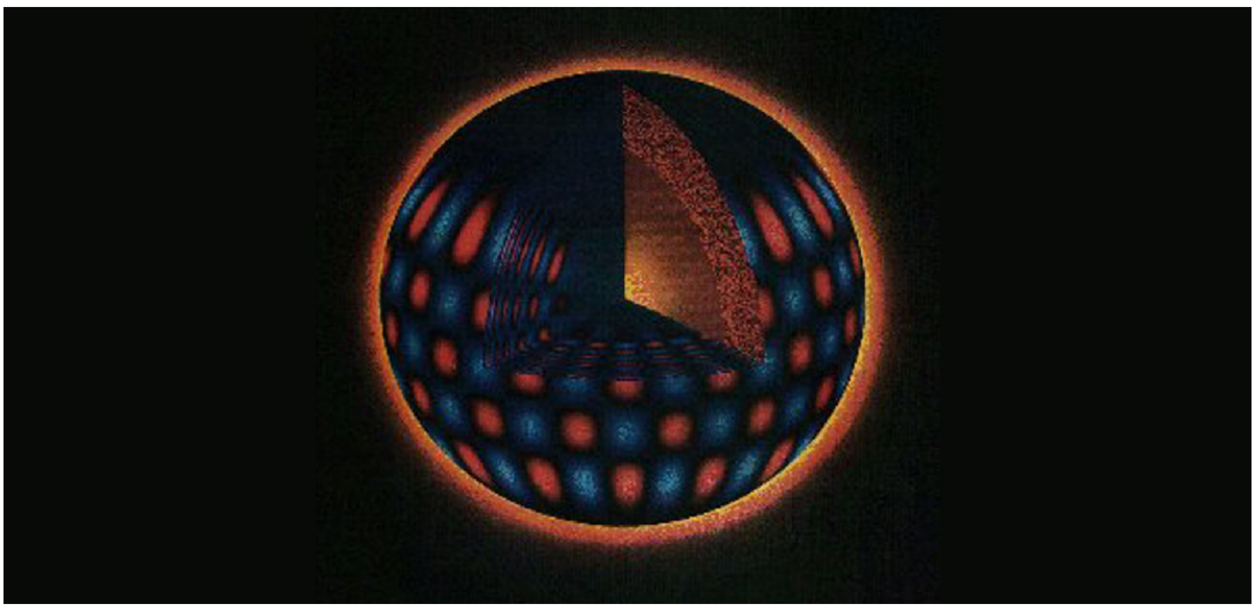


Figure 16.17 Oscillations in the Sun. New observational techniques permit astronomers to measure small differences in velocity at the Sun’s surface to infer what the deep solar interior is like. In this computer simulation, red shows surface regions that are moving away from the observer (inward motion); blue marks regions moving toward the observer (outward motion). Note that the velocity changes penetrate deep into the Sun’s interior. (credit: modification of work by GONG, NOAO)

The typical velocity of one of the oscillating regions on the Sun is only a few hundred meters per second, and it takes about 5 minutes to complete a full cycle from maximum to minimum velocity and back again. The change in the size of the Sun measured at any given point is no more than a few kilometers.

The remarkable thing is that these small velocity variations can be used to determine what the interior of the Sun is like. The motion of the Sun’s surface is caused by waves that reach it from deep in the interior. Study of the amplitude and cycle length of velocity changes provides information about the temperature, density, and composition of the layers through which the waves passed before they reached the surface. The situation is somewhat analogous to the use of seismic waves generated by earthquakes to infer the properties of Earth’s interior. For this reason, studies of solar oscillations (back-and-forth motions) are referred to as **helioseismology**.

It takes a little over an hour for waves to traverse the Sun from center to surface, so the waves, like neutrinos, provide information about what the solar interior is like at the present time. In contrast, remember that the sunlight we see today emerging from the Sun was actually generated in the core several hundred thousand years ago.

Helioseismology has shown that convection extends inward from the surface 30% of the way toward the center; we have used this information in drawing **Figure 16.15**. Pulsation measurements also show that the *differential rotation* that we see at the Sun’s surface, with the fastest rotation occurring at the equator, persists down through the convection zone. Below the convection zone, however, the Sun, even though it is gaseous throughout, rotates as if it were a solid body like a bowling ball. Another finding from helioseismology is that the abundance of helium inside the Sun, except in the center where nuclear reactions have converted hydrogen into helium, is about the same as at its surface. That result is important to astronomers because it means we are correct when we use the abundance of the elements measured in the solar atmosphere to construct models of the solar interior.

Helioseismology also allows scientists to look beneath a sunspot and see how it works. In **The Sun: A Garden-Variety Star**, we said that sunspots are cool because strong magnetic fields block the outward flow of energy. **Figure 16.18** shows how gas moves around underneath a sunspot. Cool material from the sunspot flows downward, and material surrounding the sunspot is pulled inward, carrying magnetic field with it and thus maintaining the strong field that is necessary to form a sunspot. As the new material enters the sunspot region, it too cools, becomes denser, and sinks, thus setting up a self-perpetuating cycle that can last for weeks.

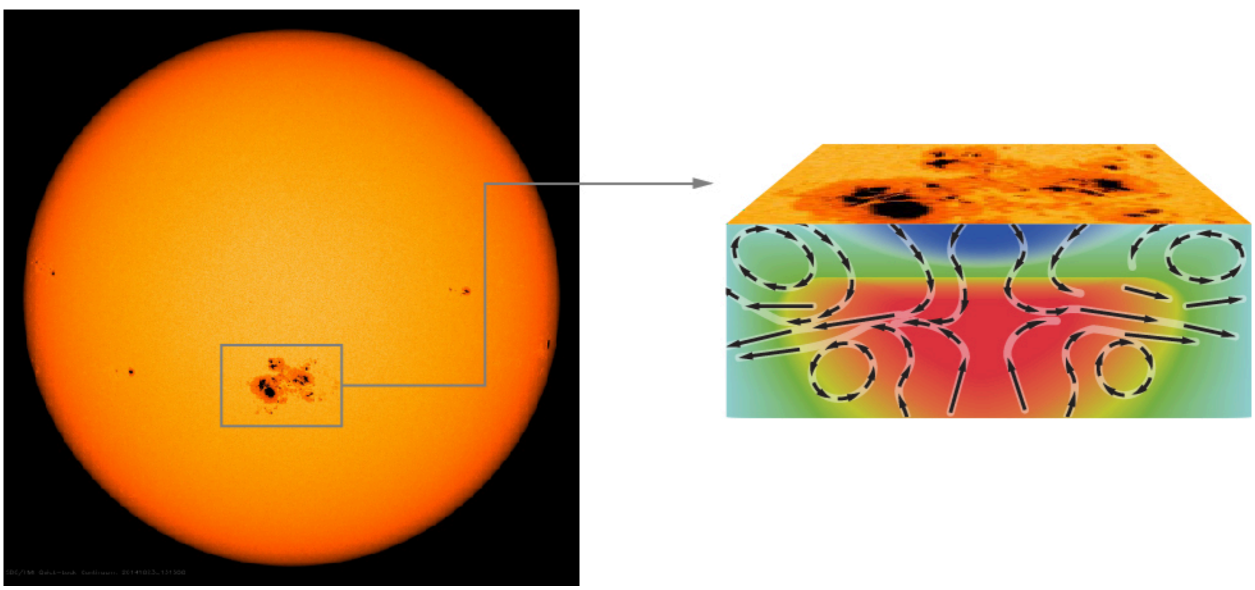


Figure 16.18 Sunspot Structure. This drawing shows our new understanding, from helioseismology, of what lies beneath a sunspot. The black arrows show the direction of the flow of material. The intense magnetic field associated with the sunspot stops the upward flow of hot material and creates a kind of plug that blocks the hot gas. As the material above the plug cools (shown in blue), it becomes denser and plunges inward, drawing more gas and more magnetic field behind it into the spot. The concentrated magnetic field causes more cooling, thereby setting up a self-perpetuating cycle that allows a spot to survive for several weeks. Since the plug keeps hot material from flowing up into the sunspot, the region below the plug, represented by red in this picture, becomes hotter. This material flows sideways and then upward, eventually reaching the solar surface in the area surrounding the sunspot. (credit: modification of work by NASA, SDO)

The downward-flowing cool material acts as a kind of plug that block the upward flow of hot material, which is then diverted sideways and eventually reaches the solar surface in the region around the sunspot. This outward flow of hot material accounts for the paradox that we described in **The Sun: A Garden-Variety Star**—namely, that the Sun emits slightly more energy when more of its surface is covered by cool sunspots.

Helioseismology has become an important tool for predicting solar storms that might impact Earth. Active regions can appear and grow large in only a few days. The solar rotation period is about 28 days. Therefore, regions capable of producing solar flares and coronal mass ejections can develop on the far side of the Sun, where, for a long time, we couldn't see them directly.

Fortunately, we now have space telescopes monitoring the Sun from all angles, so we know if there are sunspots forming on the opposite side of the Sun. Moreover, sound waves travel slightly faster in regions of high magnetic field, and waves generated in active regions traverse the Sun about 6 seconds faster than waves generated in quiet regions. By detecting this subtle difference, scientists can provide warnings of a week or more to operators of electric utilities and satellites about when a potentially dangerous active region might rotate into view. With this warning, it is possible to plan for disruptions, put key instruments into safe mode, or reschedule spacewalks in order to protect astronauts.

Solar Neutrinos

The second technique for obtaining information about the Sun's interior involves the detection of a few of those elusive neutrinos created during nuclear fusion. Recall from our earlier discussion that neutrinos created in the center of the Sun make their way directly out of the Sun and travel to Earth at nearly the speed of light. As far as neutrinos are concerned, the Sun is transparent.

About 3% of the total energy generated by nuclear fusion in the Sun is carried away by neutrinos. So many protons react and form neutrinos inside the Sun's core that, scientists calculate, 35 million billion (3.5×10^{16}) solar neutrinos pass through each square meter of Earth's surface every second. If we can devise a way to detect even a few of these solar neutrinos, then we can obtain information directly about what is going on in the center of the Sun. Unfortunately for those trying to "catch" some neutrinos, Earth and everything on it are also nearly transparent to passing neutrinos, just like the Sun.

On very, very rare occasions, however, one of the billions and billions of solar neutrinos will interact with another atom. The first successful detection of solar neutrinos made use of cleaning fluid (C_2Cl_4), which is the least expensive way to get a lot of chlorine atoms together. The nucleus of a chlorine (Cl) atom in the cleaning fluid can be turned into a radioactive argon nucleus by an interaction with a neutrino. Because the argon is radioactive, its presence can be detected. However, since the interaction of a neutrino with chlorine happens so rarely, a huge amount of chlorine is needed.

Raymond Davis, Jr. (**Figure 16.19**) and his colleagues at Brookhaven National Laboratory, placed a tank containing nearly 400,000 liters of cleaning fluid 1.5 kilometers beneath Earth's surface in a gold mine at Lead, South Dakota. A mine was chosen so that the surrounding material of Earth would keep cosmic rays (high-energy particles from space) from reaching the cleaning fluid and creating false signals. (Cosmic-ray particles are stopped by thick layers of Earth, but neutrinos find them of no significance.) Calculations show that solar neutrinos should produce about one atom of radioactive argon in the tank each day.

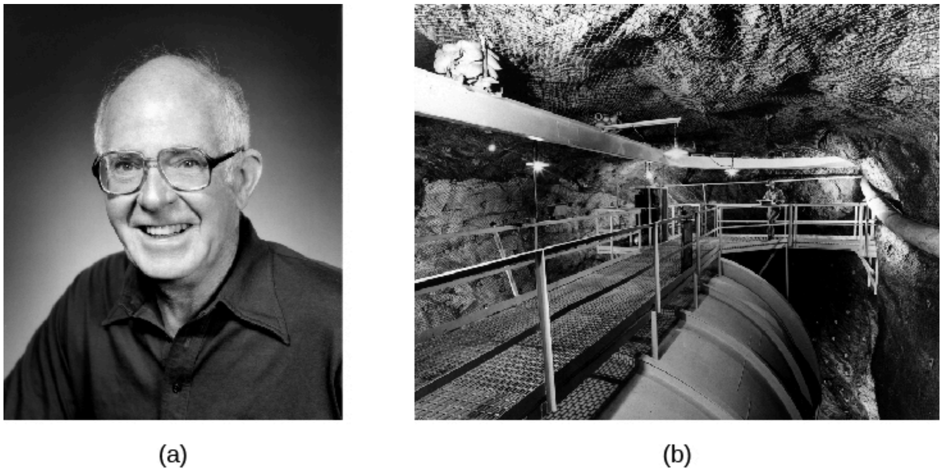


Figure 16.19 Davis Experiment. (a) Raymond Davis received the Nobel Prize in physics in 2002. (b) Davis' experiment at the bottom of an abandoned gold mine first revealed problems with our understanding of neutrinos. (credit a: modification of work by Brookhaven National Laboratory; credit b: modification of work by the United States Department of Energy)

This was an amazing project: they counted argon atoms about once per month—and remember, they were looking for a tiny handful of argon atoms in a massive tank of chlorine atoms. When all was said and done, Davis' experiment, begun in 1970, detected only about one-third as many neutrinos as predicted by solar models! This was a shocking result because astronomers thought they had a pretty good understanding of both neutrinos and the Sun's interior. For many years, astronomers and physicists wrestled with Davis' results, trying to find a way out of the dilemma of the "missing" neutrinos.

Eventually Davis' result was explained by the surprising discovery that there are actually three types of neutrinos. Solar fusion produces only one type of neutrino, the so-called electron neutrino, and the initial experiments to detect solar neutrinos were designed to detect this one type. Subsequent experiments showed that these neutrinos change to a different type during their journey from the center of the Sun through space to Earth in a process called *neutrino oscillation*.

An experiment, conducted at the Sudbury Neutrino Observatory in Canada, was the first one designed to capture all three types of neutrinos (**Figure 16.20**). The experiment was located in a mine 2 kilometers underground. The neutrino detector consisted of a 12-meter-diameter transparent acrylic plastic sphere, which contained 1000 metric tons of heavy water. Remember that an ordinary water nucleus contains two hydrogen atoms and one oxygen atom. Heavy water instead contains two deuterium atoms and one oxygen atom, and incoming neutrinos can occasionally break up the loosely bound proton and neutron that make up the deuterium nucleus. The sphere of heavy water was surrounded by a shield of 1700 metric tons of very pure water, which in turn was surrounded by 9600 photomultipliers, devices that detect flashes of light produced after neutrons interact with the heavy water.

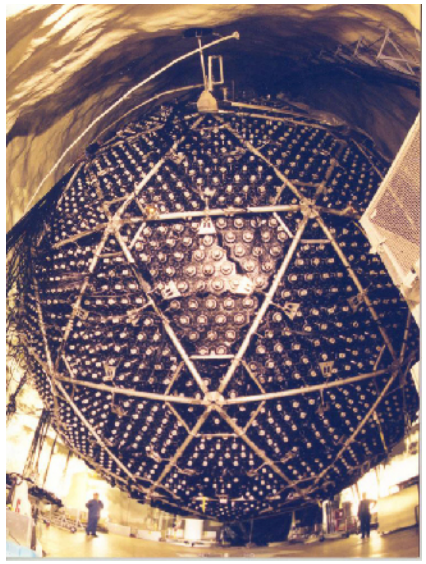


Figure 16.20 Sudbury Neutrino Detector. The 12-meter sphere of the Sudbury Neutrino Detector lies more than 2 kilometers underground and holds 1000 metric tons of heavy water. (credit: A.B. McDonald (Queen's University) et al., The Sudbury Neutrino Observatory Institute)

To the enormous relief of astronomers who make models of the Sun, the Sudbury experiment detected about 1 neutrino per hour and has shown that the *total* number of neutrinos reaching the heavy water is just what solar models predict. Only one-third of these, however, are electron neutrinos. It appears that two-thirds of the electron neutrinos produced by the Sun transform themselves into one of the other types of neutrinos as they make their way from the core of the Sun to Earth. This is why the earlier experiments saw only one-third the number of neutrinos expected.

Although it is not intuitively obvious, such neutrino oscillations can happen only if the mass of the electron neutrino is not zero. Other experiments indicate that its mass is tiny (even compared to the electron). The 2015 Nobel Prize in physics was awarded to researchers Takaaki Kajita and Arthur B. McDonald for their work establishing the changeable nature of neutrinos. (Raymond Davis shared the 2002 Nobel Prize with Japan's Masatoshi Koshiba for the experiments that led to our understanding of the neutrino problem in the first place.) But the fact that the neutrino has mass at all has deep implications for both physics and astronomy. For example, we will look at the role that neutrinos play in the inventory of the mass of the universe in **The Big Bang**.

The Borexino experiment, an international experiment conducted in Italy, detected neutrinos coming from the Sun that were identified as coming from different reactions. Whereas the p-p chain is the reaction producing most of the Sun's energy, it is not the only nuclear reaction occurring in the Sun's core. There are side reactions involving nuclei of such elements as beryllium and boron. By probing the number of neutrinos that come from each reaction, the Borexino experiment has helped us confirm in detail our understanding of nuclear fusion in the Sun. In 2014, the Borexino experiment also identified neutrinos that were produced by the first step in the p-p chain, confirming the models of solar astronomers.

It's amazing that a series of experiments that began with enough cleaning fluid to fill a swimming pool brought down the shafts of an old gold mine is now teaching us about the energy source of the Sun and the properties of matter! This is a good example of how experiments in astronomy and physics, coupled with the best theoretical models we can devise, continue to lead to fundamental changes in our understanding of nature.

CHAPTER 16 REVIEW

KEY TERMS

conduction process by which heat is directly transmitted through a substance when there is a difference of temperature between adjoining regions caused by atomic or molecular collisions

convection movement caused within a gas or liquid by the tendency of hotter, and therefore less dense material, to rise and colder, denser material to sink under the influence of gravity, which consequently results in transfer of heat

fission breaking up of heavier atomic nuclei into lighter ones

fusion building up of heavier atomic nuclei from lighter ones

helioseismology study of pulsations or oscillations of the Sun in order to determine the characteristics of the solar interior

hydrostatic equilibrium balance between the weights of various layers, as in a star or Earth's atmosphere, and the pressures that support them

neutrino fundamental particle that has no charge and a mass that is tiny relative to an electron; it rarely interacts with ordinary matter and comes in three different types

positron particle with the same mass as an electron, but positively charged

proton-proton chain series of thermonuclear reactions by which nuclei of hydrogen are built up into nuclei of helium

radiation emission of energy as electromagnetic waves or photons also the transmitted energy itself

SUMMARY

16.1 Sources of Sunshine: Thermal and Gravitational Energy

The Sun produces an enormous amount of energy every second. Since Earth and the solar system are roughly 4.5 billion years old, this means that the Sun has been producing vast amounts for energy for a very, very long time. Neither chemical burning nor gravitational contraction can account for the total amount of energy radiated by the Sun during all this time.

16.2 Mass, Energy, and the Theory of Relativity

Solar energy is produced by interactions of particles—that is, protons, neutrons, electrons, positrons, and neutrinos. Specifically, the source of the Sun's energy is the fusion of hydrogen to form helium. The series of reactions required to convert hydrogen to helium is called the proton-proton chain. A helium atom is about 0.71% less massive than the four hydrogen atoms that combine to form it, and that lost mass is converted to energy (with the amount of energy given by the formula $E = mc^2$).

16.3 The Solar Interior: Theory

Even though we cannot see inside the Sun, it is possible to calculate what its interior must be like. As input for these calculations, we use what we know about the Sun. It is made entirely of hot gas. Apart from some very tiny changes, the Sun is neither expanding nor contracting (it is in hydrostatic equilibrium) and puts out energy at a constant rate. Fusion of hydrogen occurs in the center of the Sun, and the energy generated is carried to the surface by radiation and then convection. A solar model describes the structure of the Sun's interior. Specifically, it describes how pressure, temperature, mass, and luminosity depend on the distance from the center of the Sun.

16.4 The Solar Interior: Observations

Studies of solar oscillations (helioseismology) and neutrinos can provide observational data about the Sun's interior. The technique of helioseismology has so far shown that the composition of the interior is much like that of the surface (except in the core, where some of the original hydrogen has been converted into helium), and that the convection zone extends about 30% of the way from the Sun's surface to its center. Helioseismology can also detect active regions on the far side of the Sun and provide better predictions of solar storms that may affect Earth. Neutrinos from the Sun call tell us about what is happening in the solar interior. A recent experiment has shown that solar models do predict accurately the number of electron neutrinos produced by nuclear reactions in the core of the Sun. However, two-thirds of these neutrinos are converted into different types of neutrinos during their long journey from the Sun to Earth, a result that also indicates that neutrinos are not massless particles.

FOR FURTHER EXPLORATION

Articles

Harvey, J. et al. "GONG: To See Inside Our Sun." *Sky & Telescope* (November 1987): 470.

Hathaway, D. "Journey to the Heart of the Sun." *Astronomy* (January 1995): 38.

Kennedy, J. "GONG: Probing the Sun's Hidden Heart." *Sky & Telescope* (October 1996): 20. A discussion on hydroseismology.

LoPresto, J. "Looking Inside the Sun." *Astronomy* (March 1989): 20. A discussion on hydroseismology.

McDonald, A. et al. "Solving the Solar Neutrino Problem." *Scientific American* (April 2003): 40. A discussion on how underground experiments with neutrino detectors helped explain the seeming absence of neutrinos from the Sun.

Trefil, J. "How Stars Shine." *Astronomy* (January 1998): 56.

Websites

Albert Einstein Online: **http://www.westegg.com/einstein/ (http://www.westegg.com/einstein/)** .

Ghost Particle: **http://www.pbs.org/wgbh/nova/neutrino/ (http://www.pbs.org/wgbh/nova/neutrino/)** .

GONG Project Site: **http://gong.nso.edu/ (http://gong.nso.edu/)** .

Helioseismology: **http://solar-center.stanford.edu/about/helioseismology.html (http://solar-center.stanford.edu/about/helioseismology.html)** .

Princeton Plasma Physics Lab: **http://www.pppl.gov/ (http://www.pppl.gov/)** .

Solving the Mystery of the Solar Neutrinos: **http://www.nobelprize.org/nobel_prizes/themes/physics/bahcall/ (http://www.nobelprize.org/nobel_prizes/themes/physics/bahcall/)** .

Super Kamiokande Neutrino Mass Page: **http://www.ps.uci.edu/~superk/ (http://www.ps.uci.edu/~superk/)** .

Videos

Deep Secrets of the Neutrino: Physics Underground: **https://www.youtube.com/watch?v=Ar9ydagYkYg (https://www.youtube.com/watch?v=Ar9ydagYkYg)** . 2010 Public Lecture by Peter Rowson at the Stanford Linear Accelerator Center (1:22:00).

The Elusive Neutrino and the Nature of Physics: **https://www.youtube.com/watch?v=CBfUHzkcaHQ (https://www.youtube.com/watch?v=CBfUHzkcaHQ)** . Panel at the 2014 World Science Festival (1:30:00).

The Ghost Particle: **http://www.dailymotion.com/video/x20rn7s_nova-the-ghost-particle-discovery-science-universe-documentary_tv (http://www.dailymotion.com/video/x20rn7s_nova-the-ghost-particle-discovery-science-universe-documentary_tv)** . 2006 NOVA episode (52:49).

COLLABORATIVE GROUP ACTIVITIES

A. In this chapter, we learned that meteorites falling into the Sun could not be the source of the Sun's energy because the necessary increase in the mass of the Sun would lengthen Earth's orbital period by 2 seconds per year. Have your group discuss what effects this would cause for our planet and for us as the centuries went on.

B. Solar astronomers can learn more about the Sun's interior if they can observe the Sun's oscillations 24 hours each day. This means that they cannot have their observations interrupted by the day/night cycle. Such an experiment, called the GONG (Global Oscillation Network Group) project, was first set up in the 1990s. To save money, this experiment was designed to make use of the minimum possible number of telescopes. It turns out that if the sites are selected carefully, the Sun can be observed all but about 10% of the time with only six observing stations. What factors do you think have to be taken into consideration in selecting the observing sites? Can your group suggest six general geographic locations that would optimize the amount of time that the Sun can be observed? Check your answer by looking at the GONG website.

C. What would it be like if we actually manage to get controlled fusion on Earth to be economically feasible? If the hydrogen in *water* becomes the fuel for releasing enormous amounts of energy (instead of fossil fuels), have your group discuss how this affects the world economy and international politics. (Think of the role that oil and natural gas deposits now play on the world scene and in international politics.)

D. Your group is a delegation sent to the city council of a small mining town to explain why the government is putting a swimming-pool-sized vat of commercial cleaning fluid down one of the shafts of an old gold mine. How would you approach this meeting? Assuming that the members of the city council do not have much science background, how would you explain the importance of the project to them? Suggest some visual aids you could use.

E. When Raymond Davis first suggested his experiment in the underground gold mine, which had significant costs associated with it, some people said it wasn't worth the expense since we already understood the conditions and reactions in the core of the Sun. Yet his experiment led to a major change in our understanding of neutrinos and the physics of subatomic particles. Can your group think of other "expensive" experiments in astronomy that led to fundamental improvements in our understanding of nature?

EXERCISES

Review Questions

1. How do we know the age of the Sun?

2. Explain how we know that the Sun's energy is not supplied either by chemical burning, as in fires here on Earth, or by gravitational contraction (shrinking).

3. What is the ultimate source of energy that makes the Sun shine?

4. What are the formulas for the three steps in the proton-proton chain?

5. How is a neutrino different from a neutron? List all the ways you can think of.

6. Describe in your own words what is meant by the statement that the Sun is in hydrostatic equilibrium.

7. Two astronomy students travel to South Dakota. One stands on Earth's surface and enjoys some sunshine. At the same time, the other descends into a gold mine where neutrinos are detected, arriving in time to detect the creation of a new radioactive argon nucleus. Although the photon at the surface and the neutrinos in the mine arrive at the same time, they have had very different histories. Describe the differences.

8. What do measurements of the number of neutrinos emitted by the Sun tell us about conditions deep in the solar interior?

9. Do neutrinos have mass? Describe how the answer to this question has changed over time and why.

10. Neutrinos produced in the core of the Sun carry energy to its exterior. Is the mechanism for this energy transport conduction, convection, or radiation?

11. What conditions are required before proton-proton chain fusion can start in the Sun?

12. Describe the two main ways that energy travels through the Sun.

Thought Questions

13. Someone suggests that astronomers build a special gamma-ray detector to detect gamma rays produced during the proton-proton chain in the core of the Sun, just like they built a neutrino detector. Explain why this would be a fruitless effort.

14. Earth contains radioactive elements whose decay produces neutrinos. How might we use neutrinos to determine how these elements are distributed in Earth's interior?

15. The Sun is much larger and more massive than Earth. Do you think the average density of the Sun is larger or smaller than that of Earth? Write down your answer before you look up the densities. Now find the values of the densities elsewhere in this text. Were you right? Explain clearly the meanings of density and mass.

16. A friend who has not had the benefit of an astronomy course suggests that the Sun must be full of burning coal to shine as brightly as it does. List as many arguments as you can against this hypothesis.

17. Which of the following transformations is (are) fusion and which is (are) fission: helium to carbon, carbon to iron, uranium to lead, boron to carbon, oxygen to neon? (See **Appendix K** for a list of the elements.)

18. Why is a higher temperature required to fuse hydrogen to helium by means of the CNO cycle than is required by the process that occurs in the Sun, which involves only isotopes of hydrogen and helium?

19. Earth's atmosphere is in hydrostatic equilibrium. What this means is that the pressure at any point in the atmosphere must be high enough to support the weight of air above it. How would you expect the pressure on Mt. Everest to differ from the pressure in your classroom? Explain why.

20. Explain what it means when we say that Earth's oceans are in hydrostatic equilibrium. Now suppose you are a scuba diver. Would you expect the pressure to increase or decrease as you dive below the surface to a depth of 200 feet? Why?

21. What mechanism transfers heat away from the surface of the Moon? If the Moon is losing energy in this way, why does it not simply become colder and colder?

22. Suppose you are standing a few feet away from a bonfire on a cold fall evening. Your face begins to feel hot. What is the mechanism that transfers heat from the fire to your face? (Hint: Is the air between you and the fire hotter or cooler than your face?)

23. Give some everyday examples of the transport of heat by convection and by radiation.

24. Suppose the proton-proton cycle in the Sun were to slow down suddenly and generate energy at only 95% of its current rate. Would an observer on Earth see an immediate decrease in the Sun's brightness? Would she immediately see a decrease in the number of neutrinos emitted by the Sun?

25. Do you think that nuclear fusion takes place in the atmospheres of stars? Why or why not?

26. Why is fission not an important energy source in the Sun?

27. Why do you suppose so great a fraction of the Sun's energy comes from its central regions? Within what fraction of the Sun's radius does practically all of the Sun's luminosity originate (see **Figure 16.16**)? Within what radius of the Sun has its original hydrogen been partially used up? Discuss what relationship the answers to these questions bear to one another.

28. Explain how mathematical computer models allow us to understand what is going on inside of the Sun.

Figuring For Yourself

29. Estimate the amount of mass that is converted to energy when a proton combines with a deuterium nucleus to form tritium, ^{3}He.

30. How much energy is released when a proton combines with a deuterium nucleus to produce tritium, ^{3}He?

31. The Sun converts 4×10^9 kg of mass to energy every second. How many years would it take the Sun to convert a mass equal to the mass of Earth to energy?

32. Assume that the mass of the Sun is 75% hydrogen and that all of this mass could be converted to energy according to Einstein's equation $E = mc^2$. How much total energy could the Sun generate? If m is in kg and c is in m/s, then E will be expressed in J. (The mass of the Sun is given in **Appendix E**.)

33. In fact, the conversion of mass to energy in the Sun is not 100% efficient. As we have seen in the text, the conversion of four hydrogen atoms to one helium atom results in the conversion of about 0.02862 times the mass of a proton to energy. How much energy in joules does one such reaction produce? (See **Appendix E** for the mass of the hydrogen atom, which, for all practical purposes, is the mass of a proton.)

34. Now suppose that all of the hydrogen atoms in the Sun were converted into helium. How much total energy would be produced? (To calculate the answer, you will have to estimate how many hydrogen atoms are in the Sun. This will give you good practice with scientific notation, since the numbers involved are very large! See **Appendix C** for a review of scientific notation.)

35. Models of the Sun indicate that only about 10% of the total hydrogen in the Sun will participate in nuclear reactions, since it is only the hydrogen in the central regions that is at a high enough temperature. Use the total energy radiated per second by the Sun, 3.8×10^{26} watts, alongside the exercises and information given here to estimate the lifetime of the Sun. (Hint: Make sure you keep track of the units: if the luminosity is the energy radiated per second, your answer will also be in seconds. You should convert the answer to something more meaningful, such as years.)

36. Show that the statement in the text is correct: namely, that roughly 600 million tons of hydrogen must be converted to helium in the Sun each second to explain its energy output. (Hint: Recall Einstein's most famous formula, and remember that for each kg of hydrogen, 0.0071 kg of mass is converted into energy.) How long will it be before 10% of the hydrogen is converted into helium? Does this answer agree with the lifetime you calculated in **Exercise 16.35**?

37. Every second, the Sun converts 4 million tons of matter to energy. How long will it take the Sun to reduce its mass by 1% (the mass of the Sun is 2×10^{30} kg)? Compare your answer with the lifetime of the Sun so far.

38. Raymond Davis Jr.'s neutrino detector contained approximately 10^{30} chlorine atoms. During his experiment, he found that one neutrino reacted with a chlorine atom to produce one argon atom each day.

A. How many days would he have to run the experiment for 1% of his tank to be filled with argon atoms?

B. Convert your answer from A. into years.

C. Compare this answer to the age of the universe, which is approximately 14 billion years (1.4×10^{10} y).

D. What does this tell you about how frequently neutrinos interact with matter?