SCIENCE OVERVIEW

Sunlight is the source of life-sustaining energy on Earth. Its effects range from allowing temperatures on our planet to remain hospitable for life to providing energy for photosynthesis. This lesson discusses how much power the Sun provides to Earth.

The Sun in the Solar System

The Sun is at the center of the Solar System. The nine planets, their moons, as well as the smaller bodies—asteroids, comets, and small icy worlds in the outer reaches of the Solar System called Kuiper Belt objects—all revolve around the Sun. The Sun's central role comes from its high mass; it has 99.8 percent of the mass in the Solar System and, therefore, guides the movement of the other objects in the Solar System via gravitational forces. Radiation from the Sun also determines the conditions prevalent at the planets, from making the sunlit side of Mercury bake in 700 K (427°C; 800°F) heat to providing the hospitable environment for life on Earth.

The Sun as a Star

The Sun is a fairly typical star, just one of over 200 billion stars in our Galaxy, the Milky Way. It is not among the brightest or the faintest stars. It is not the most massive star; even though it is more massive than about 96% of the stars in the Milky Way, there are billions of stars more massive than the Sun. The Sun is made up entirely of gas, mostly of hydrogen (91% of the atoms) and helium (8.9%), with heavier elements such as oxygen, carbon, neon and nitrogen mixed in to make up the remaining 0.1%. In the conditions prevalent in the Sun, the gas is almost completely ionized—that is, the atoms have lost one or more of their electrons to become ions. This form of electrically charged gas is called plasma. The electric charge and high temperature make plasma's behavior so different from ordinary gas that some scientists call it a fourth phase of matter, separate from the traditional three (solid, liquid, and gas).

The Sun's radius is about 696,000 km (432,000 miles), roughly 109 times Earth's radius. This is the same ratio as between the height of an NFL linebacker (185 cm) and the size of a honey bee (1.7 cm). The Sun is about 150 million km (93 million miles) away from Earth. The situation is similar to the honey bee hovering about two football fields away from the linebacker. The mass of the Sun is 1.99x10^{30} kg, or about 333,000 times Earth's mass. This is the same ratio as between the linebacker (100 kg) and three honey bees (0.1 g each).

When the Sun is observed with special instruments (e.g., Figure 1), it appears to have a surface. But since the Sun is entirely made of gas, it does not have a solid surface like Earth does. Instead, the apparent surface of the Sun is the region where the light that we see starts its journey toward us and where the visible solar features appear. On top of the basic granular surface appearance of the Sun, striking visible features include sunspots (relatively cool, darker regions), prominences (cool, dense plasma extending outward from the "surface,") and flares (great explosions on the Sun—the most violent eruptions in the Solar System). The behavior of these surface features is largely guided by the Sun's magnetic field.

The Sun's magnetic field is created by the movement of plasma inside the Sun. The number of sunspots on the Sun's surface is a measure of (magnetic) activity in the Sun. The sunspot number changes from a minimum to a maximum and back to a minimum over a sunspot cycle, with an average period of about 11 years. At the end of the sunspot cycle the magnetic field of the Sun quickly changes its polarity (the region that used to be the magnetic north pole becomes the magnetic south pole, and vice versa). A similar change in the polarity of the Earth's magnetic field takes place, but on a much longer timescale—about 500,000 years or so—and not always at regular intervals.

The Sun's Structure

The Sun's internal structure can be described in terms of several zones or layers (Figure 2). At the heart of the Sun is its core, which extends from the center to about one-fourth of the way to the surface. The maximum temperature in the core is over 15 million K, and this is where almost all of the Sun's energy comes from via nuclear fusion. In fusion, nuclear matter is converted to energy by joining hydrogen atoms into helium, with accompanying release of energy. The high temperature in the Sun's core is essential for the operation of the fusion process; otherwise joining hydrogen atoms together would not be possible. Fusion is a very efficient way to make energy, as compared with fission, in which a nucleus of a heavy atom is split to release energy. Fission is the way nuclear energy is produced in nuclear power plants here on Earth. The possibility of being able to produce energy on Earth via fusion is very tantalizing, especially since the by-products of fission can be quite harmful for life, while fusion products are harmless. Unfortunately, we do not yet have the technology to efficiently produce energy via fusion on Earth.

Outside the Sun's core is the radiative zone, which is

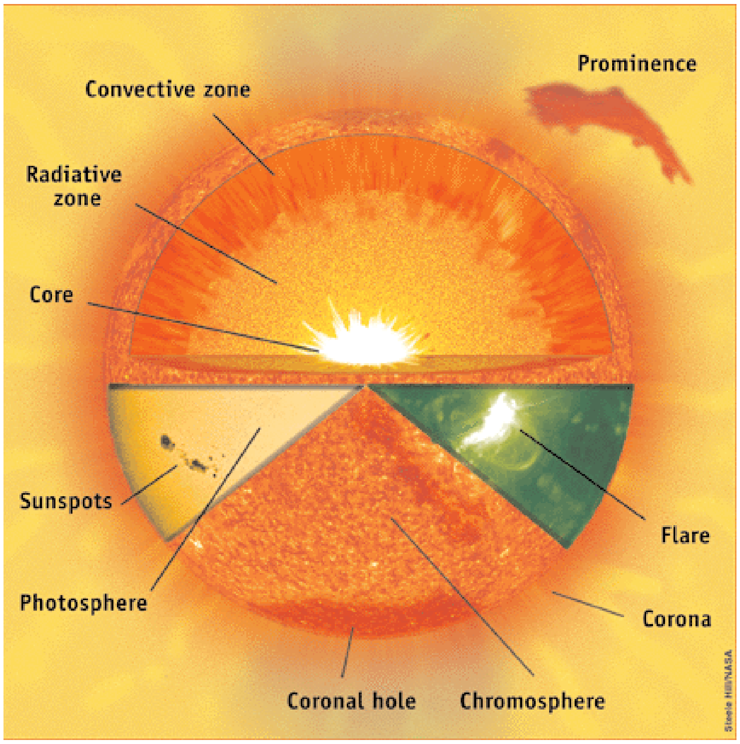

Figure 2. The structure of the Sun. The solar interior consists of the core, the radiative zone, and the convective zone. Above the visible surface, the photosphere, are the chromosphere and the corona. The top half of the picture shows different layers in the interior of the Sun. The bottom half of the picture shows different parts of the Sun as they appear in different wavelengths of light. (Picture credit: NASA/SOHO; http://sohowww.nascom.nasa.gov/explore/images/layers.gif)

named for the way that energy produced in the core travels through the zone—mainly via radiation. The radiative zone extends from the outer edge of the core (at 25% of the solar radius) to about 70% of the solar radius. The outermost layer of the Sun's interior structure is the convection zone, which goes from the outer edge of the radiative zone to the Sun's surface. The name comes from the fact that energy travels through this region via convective motions—hot regions in the bottom rise up while cooler material from above falls down.

The photosphere is the lowest layer of the solar atmosphere. The bottom of this layer is the visible surface of the Sun, which has a temperature of about 5800 K (5500°C; 10,000°F). The next layer is the chromosphere, in which the temperature rises rapidly with increasing altitude. The uppermost level of the solar atmosphere is called the corona, which has temperatures of 500,000 K to 6 million K but is also very tenuous. The coronal gas is so hot that it emits X-rays and expands continuously outward to the rest of the Solar System as the solar wind, a fast outflow of electrons and ions.

Radiation from the Sun

The energy emitted by the Sun is mostly in the form of electromagnetic radiation. To understand this kind of radiation better, we can think of a familiar situation of weather maps. Weather forecasters often show temperature maps of the United States based on the temperature measurements in different parts of the country that day. The maps are created by assigning each temperature a color, and then filling the map with colors corresponding to the temperatures measured at each location. A map created this way shows the temperature field of the United States on that particular day. The temperature field covering the United States, in this sense, is a description of the temperatures at every location across the country.

In a similar fashion, the Universe can be thought of as being permeated by an electric field. All electrically charged particles (such as electrons) have a region of space around them where they influence the behavior of other charged particles wandering there. This region can be described as an electric field around the particle. Just as temperatures in different parts of the country create the temperature field of the United States, the electric charges in the Universe can be thought of as creating an electric field permeating the whole Universe. Magnetic objects behave in a similar fashion: every magnetic object creates a magnetic field around it, and their collective magnetic field permeates the Universe.

Most things in the Universe tend to move around, and electric charges are rarely an exception. If the velocity of an electric charge changes (that is, it accelerates or decelerates), it creates a disturbance in the electric and magnetic fields permeating the Universe. These disturbances move across the Universe as waves in the "fabric" of the electric and magnetic fields. The waves also carry energy from the disturbance with them, in a similar way that the energy of the wind striking a flag is carried across the fabric by the waving of the flag. The waves carrying the energy of the disturbance across the Universe are characterized by their wavelength, which measures the distance between two consecutive wave crests.

A familiar example of this kind of wave is visible light. Different colors of visible light have slightly different wavelengths, and there are waves which have much higher and shorter wavelengths than the light that humans can see. Together, the waves of all different wavelengths are called electromagnetic radiation, and the whole array of different kinds of light, arranged according to their wavelength, is called the electromagnetic spectrum (see Figure 3). Radio waves are in the long-wavelength (low-frequency) and the gamma rays in the short-wavelength (high-frequency) end of the spectrum, with visible light located between infrared and ultraviolet. Electromagnetic radiation travels at the speed of light (300,000 km/s or 186,000 miles/s in a vacuum such as space). The radiation emitted by the surface of the Sun consists of all types of electromagnetic radiation. At the speed of light, it takes about eight minutes for the radiation emitted from the surface of the Sun to reach Earth.

We can see part of the Sun's spectrum in a rainbow, when the visible light is spread out by raindrops in the Earth's atmosphere. We cannot see the other parts of the spectrum beyond visible light (longer wavelength than red or shorter wavelength than blue light), but they can be detected with instruments. The Earth's atmosphere reflects away or absorbs much of the electromagnetic spectrum, so that only part of the radiation reaches the surface. Most of the radio waves come through the atmosphere unimpeded, visible light passes through without much difficulty, while only some infrared radiation, very little of the ultraviolet rays, and none of the X-rays and gamma rays reach the surface. This is actually very fortunate

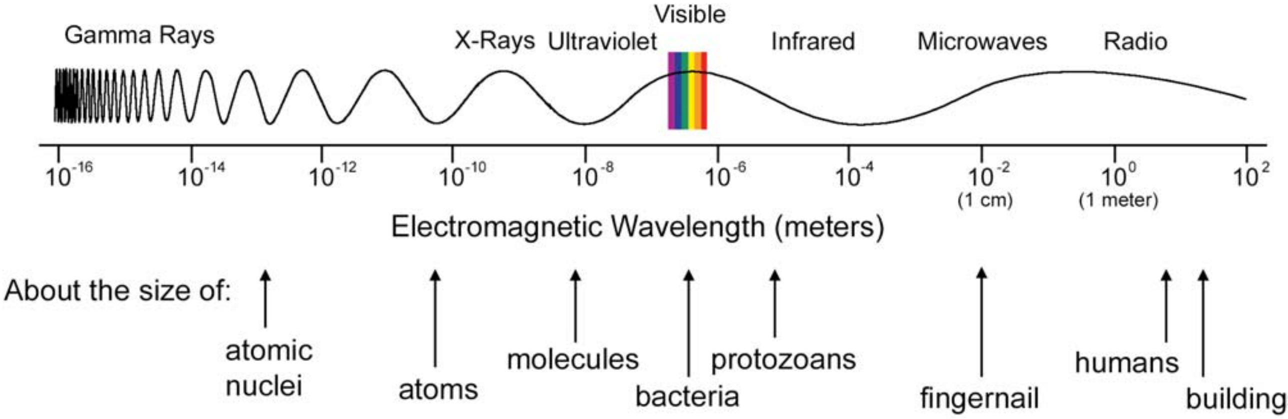

Figure 3. The electromagnetic spectrum. In the picture, different parts of the spectrum are shown as one continuous wave. In reality, a given electromagnetic wave has one particular wavelength. The continuous wave in the picture above is used to better illustrate the difference between wavelengths from one part of the spectrum to another.

for life on Earth, especially with regards to harmful, high-energy radiation (ultraviolet, X-rays and gamma rays).

The Sun emits particle radiation from the corona, made up mostly of protons and electrons, but also of some heavier ions. These spread out to the Solar System as the solar wind. Solar particle radiation can be quite damaging to life, but fortunately Earth's magnetic field prevents the solar wind particles from reaching the surface. Because this protection is less or completely absent in space, the amount of particle radiation to which the astronauts are exposed is carefully monitored to prevent serious health effects. The amount of solar particle radiation arriving at Earth depends on the level of the Sun's activity. When there is an explosion on the Sun (a solar flare), especially large concentrations of particles can arrive at Earth and cause aurorae (commonly known as the Northern and Southern Lights), as the particles collide with atoms in the upper layers of the atmosphere. They can also cause geomagnetic storms, which in turn can disrupt electrical equipment on Earth.

Solar Energy on Earth

The Sun provides most of the energy on Earth. Some heat is generated inside the Earth, but it is a very small effect compared with sunlight. Without the Sun, the Earth would be cold and lifeless. Yet, only a small fraction of the energy produced by the Sun ever actually arrives on Earth; most of it is radiated in other directions toward the far reaches of space.

The total power output of the Sun (the amount of energy radiated per second) is $3.83\text{x}10^{26}$ W (watt; joules per second). Since the radius of the Sun, R_S, is 696,000 km, the power output per square meter of the surface of the Sun is $6.29\text{x}10^{7}\ \text{W/m}^2$ ($3.83\text{x}10^{26}\ \text{W} / (4\pi R_S{}^2)$). But since this energy is radiated in all directions, only a small part of it reaches the top of Earth's atmosphere. The amount of solar radiation arriving on Earth, known as the solar constant, is $1370\ \text{W/m}^2$. This can be calculated by using the total power output of the Sun and spreading it over a sphere with a radius equal to the Earth's distance from the Sun. In this lesson, the students perform an experiment to measure the solar constant. As mentioned above, much of the solar radiation arriving at Earth is reflected away or absorbed by the atmosphere, and only about half of it reaches the surface.

On Earth, the Sun's radiation is absorbed by the ground, the seas, and the atmosphere. It drives air flows in the atmosphere, currents in the oceans, and greatly influences climate and weather. It is the most important source of energy for life on Earth: it provides energy for photosynthesis, and therefore supports the first link in many of the food chains on Earth. It is possible for life to exist in places without sunlight (such as at the bottom of the oceans), but most of the life with which we are familiar uses the energy provided by sunlight in one way or another.

Solar Energy in Human Activities

The Sun's energy can be harnessed to power human activities. Unfortunately, solar energy is spread over a large area and must be collected and concentrated to produce useable power. This is why, at the present time, solar energy is a more expensive power source than fossil fuels in most places and for most applications. Scientific and technological research is underway to make the use of solar power more efficient. But even now, nearly all the energy that we use is actually solar energy, just in a different form. For example, fossil fuels are made of plants that lived millions of years ago and stored solar energy in themselves before dying and becoming the fuels we use today.

One of the most familiar human uses of solar energy is a greenhouse. Windows let the sunlight through, but the heat generated by the sunlight in the greenhouse is trapped in, and it can escape only slowly. This creates a warm environment for plants to grow, making production of fresh vegetables and flowers possible during winter in cold climates.

Solar energy can be converted into electric power in solar cells. They employ the photovoltaic effect, in which energy in the sunlight creates an electric current in a conductive material. For most uses, cells are grouped into modules, and multiple modules may be arranged into arrays to provide sufficient current for the application. Examples of power production by solar cells include spacecraft, satellites, handheld calculators, and wristwatches. Solar cells can also be used for everyday electricity production in areas where there is plenty of sunlight available most of the year.

Another way to take advantage of the power of sunlight is a solar thermal conversion system, which uses reflectors to concentrate solar energy to very high levels. The heat generated in this manner can be used to heat water or to drive a steam turbine to produce electricity. A device called a solar furnace can be used to collect solar radiation to produce temperatures high enough for use in industrial processes, such as processing steel, while smaller-scale versions can be used to cook food. Different variations of this theme are used in different parts of the world to produce power in a manner that is best suited for the region and the application.

Temperature and Heat

In order to understand the interaction of solar radiation with matter here on Earth, we need to understand a few things about temperature and how heat travels.

An object's temperature describes the level of motion and vibration in the atoms and molecules of which it is composed. The higher the temperature of the object, the more its atoms and molecules move around, and the more disorderly is their motion. This means that heat flowing into an object increases the internal energy and disorder in that object, while heat flowing out of it decreases the internal energy and disorder in that object. For example, the water molecules in a snowflake are arranged in an orderly pattern. If you hold a snowflake in your hand, it will melt and become a drop of water. In this case, the orderly pattern of the snowflake changes into the more disorderly form of liquid water.

Heat passes from one substance or object to another by three methods—conduction, convection, and radiation. Although conduction (heat moving through material) and convection (heat transferred by moving material) need media through which to transfer energy, heat can be transmitted via radiation through infrared or other rays, without need for material. The Sun can therefore send its energy through the vacuum of space via radiation. Note that radiation may also work when material is present. For example, after traveling through space, sunlight passes through the Earth's atmosphere to reach the surface. As discussed earlier, both radiation and convection play a role in transferring the energy generated inside the Sun to its surface.

The most common result of heat interacting with matter is a change in the material's temperature. The amount of heat needed to raise the temperature of one gram of a substance one degree Celsius is called the specific heat capacity (or just specific heat) of the substance. Two substances with the same mass but different specific heats require different amounts of heat to reach the same temperature. For example, the specific heat of water is 4186 joules per kilogram per degree Celsius, while the specific heat of air is 1005 J/kg/°C. This means that is takes over four times as much energy to heat 1 kg of water by 1°C that it does to heat 1 kg of air. Heat can also change the size or physical state of the material, but these processes are not important in this lesson.

MESSENGER and the Sun

The Sun has a very important role in the MESSENGER mission to Mercury. Mercury's surface reflects sunlight, and this reflected radiation is used to see features on the planet, in the same way that we see objects here on Earth during the day. The intense solar radiation also heats up Mercury's surface. The heated surface radiates infrared light into space. This infrared radiation can be used to determine the composition and other properties of the planet's surface. The MESSENGER spacecraft relies on solar radiation to produce electricity. Two solar panels, totaling 5.3 m^2 in area, provide sufficient power for the spacecraft during the mission.

In addition to investigating radiation reflected or reradiated by Mercury's surface, MESSENGER will also study radiation coming directly from the Sun. Orbiting Mercury for the duration of one Earth year will offer an excellent opportunity to make long-term observations of the space environment near the Sun, and to investigate the effect of the Sun's activity on the environment. In this manner, the spacecraft will not only help us understand the planet Mercury better, but will also provide invaluable information about the Sun.

The intense radiation from the Sun is also a concern for the mission. While orbiting Mercury, the spacecraft will get within 0.3 AU of the Sun. (Remember: One Astronomical Unit, AU, is the average distance from the Earth to the Sun; about 150 million kilometers, or 93 million miles.) The amount of sunlight to which the spacecraft is exposed depends on its distance from the Sun, R, as $1/R^2$. In other words, the MESSENGER spacecraft will be exposed to up to 11 times more sunlight than it would experience in orbit around Earth ($1/0.3^2 = 11$). Since the Earth's atmosphere allows only about half of solar radiation to pass through, the MESSENGER spacecraft will be exposed to as much as 22 times the amount of solar radiation as it would on the surface of Earth. This means that, unprotected, the spacecraft components could experience temperatures as high as 700 K (427˚C; 800˚F) or more, as happens on the sunlit areas of Mercury's surface.

To make sure that the spacecraft components are not damaged by the intense solar radiation, a variety of solutions will be employed by the MESSENGER design team. For example, heat-resistant materials are used to build the components of the spacecraft, and a sunshade is constructed to protect the sensitive instruments from the Sun. The spacecraft's orbit around Mercury has been designed so that its closest approach to the planet is away from the most sun-baked region of the surface and so that it flies quickly over the sunlit areas. This is achieved by an orbit where the periapsis (the closest point to the surface of Mercury and also the part of the orbit where the spacecraft's speed is at its highest; the distance from the surface is 200 km, or 124 miles) is at a high latitude, and the apoapsis (the farthest point of the orbit and also the part of the orbit where the spacecraft's speed is at its lowest; the distance from the surface is 15,193 km, or 9443 miles) is far away from the surface of Mercury. This orbital design keeps the amount of infrared radiation received from the planet's extremely hot surface at safe levels. The solar panels are constructed from materials that can withstand high temperatures, and the system is designed so that the panels do not face the Sun directly. Using these precautions, the operating temperature at the solar panels is expected to be less than 135˚C, and the instruments are in a thermal environment comparable to room temperature: during Mercury's orbit around the Sun, the temperature on the instrument deck of MESSENGER is expected to vary from a few degrees below 0˚C (32˚F) to 33˚C (91˚F).