Star Power!

Discovering the Power of Sunlight

Lesson Overview

Lesson Summary

Students estimate the energy output of the Sun using a simple device and discover how much power sunlight provides to Earth; they learn that the Sun is the main source of energy on Earth. Students also evaluate the power of sunlight closer to the Sun—at the distance of Mercury. They also learn that sunlight and the electromagnetic spectrum are the main tools with which we study objects in the Solar System.

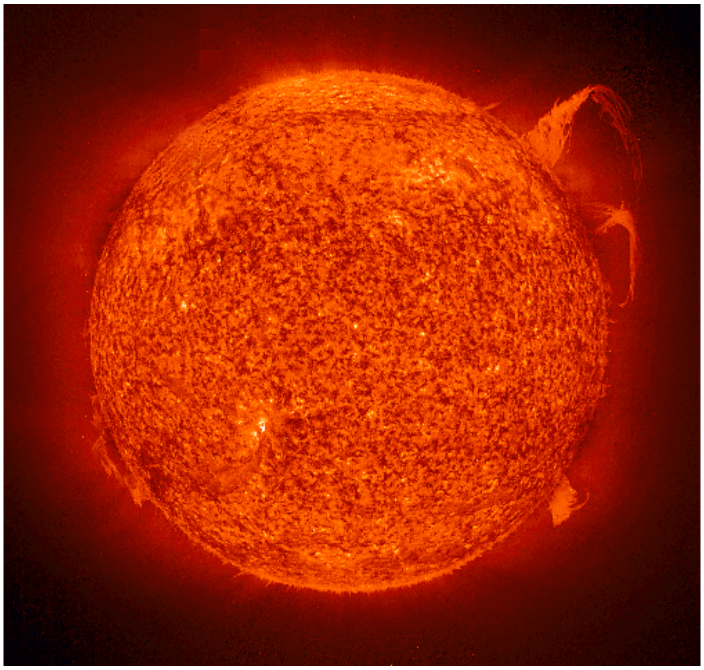


Figure 1. The Sun seen in extreme ultraviolet wavelengths. The surface of the Sun shows the granular structure of convective cells, while a few prominences erupt on the surface at the right-hand side of the picture. (Picture credit: NASA/SOHO; http://sohowww.nascom.nasa.gov/bestofsoho/hooksG.gif)

Grade Level
9 - 12

Duration
Two hours

Essential Question
How much energy does sunlight provide to the Earth and what is its role in the Earth's energy resources?

Lesson 1 of
Grades 9-12 Component
of *Staying Cool*

Objectives

Students will be able to:

- Build a simple device to measure the amount of energy carried by sunlight.
- Calculate the amount of energy arriving at the Earth from the Sun.
- Describe the difference in the amount of solar radiation at Mercury as compared with the Earth.

This lesson was developed by the National Center for Earth and Space Science Education (http://ncesse.org).

Concepts

- Radiation from the Sun is the main source of energy on Earth. It heats the Earth to a temperature at which life is sustainable.
- We can capture the energy from the sunlight and use it to do work on Earth.
- Solar radiation is important for studying objects in the Solar System.

MESSENGER Mission Connection

Sunlight is essential for the MESSENGER mission to Mercury. Many of the instruments study sunlight reflected off Mercury's surface or the infrared radiation emitted by Mercury's surface heated by sunlight. The properties of particle radiation from the Sun around Mercury is also investigated. But because Mercury receives up to 22 times as much sunlight as Earth's surface, mission designers have had to come up with ways to keep the spacecraft and its instruments from heating up significantly.

WARNING

Do *not* look directly at the Sun!

This lesson is about the Sun and sunlight, but be sure to remind students frequently ***never* to look directly at the Sun!** Looking for even a few seconds can cause permanent damage to the eyes, and longer exposure can cause blindness. Note that sunglasses do *not* provide an adequate safeguard against looking directly at the Sun.

Standards & Benchmarks

National Science Education Standards

Standard B6 Interactions of energy and matter

- Electromagnetic waves result when a charged object is accelerated or decelerated. Electromagnetic waves include radio waves (the longest wavelength), microwaves, infrared radiation (radiant heat), visible light, ultraviolet radiation, x-rays, and gamma rays. The energy of electromagnetic waves is carried in packets whose magnitude is inversely proportional to the wavelength.

Standard D1 Energy in the earth system

- Earth systems have internal and external sources of energy, both of which create heat. The sun is the major external source of energy. Two primary sources of internal energy are the decay of radioactive isotopes and the gravitational energy from the earth's original formation.

Related Standards

Standard B5 Conservation of energy and increase in disorder

- Heat consists of random motion and the vibrations of atoms, molecules, and ions. The higher the temperature, the greater the atomic or molecular motion.

- Everything tends to become less organized and less orderly over time. Thus, in all energy transfers, the overall effect is that the energy is spread out uniformly. Examples are the transfer of energy from hotter to cooler objects by conduction, radiation, or convection and the warming of our surroundings when we burn fuels.

American Association for the Advancement of Science, Project 2061

Benchmark 4E3 Transformations of energy usually produce some energy in the form of heat, which spreads around by radiation or conduction into cooler places. Although just as much total energy remains, its being spread out more evenly means less can be done with it.

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 1.99×10^{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

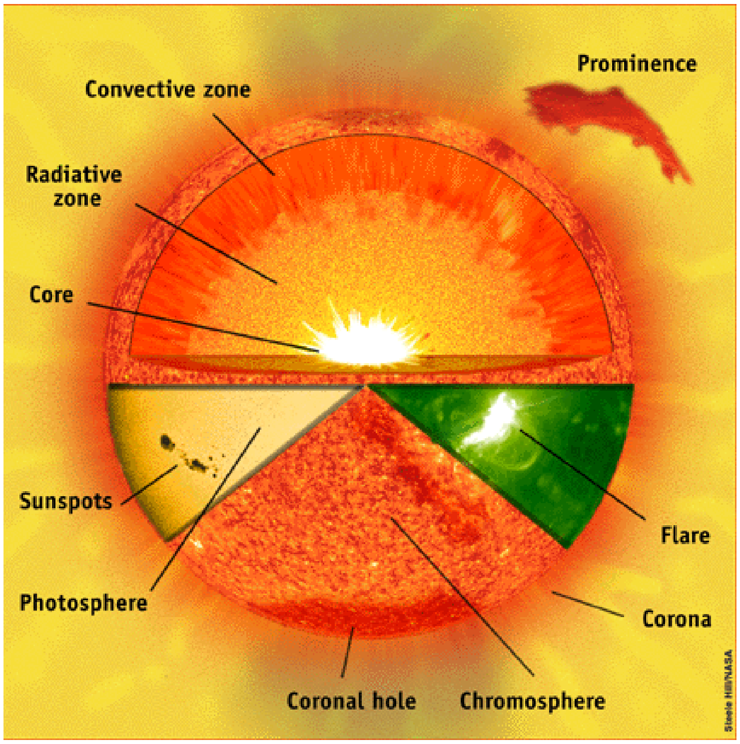


Figure 2. The structure of the Sun. The solar interior consists of the core, the radiative zone, and the convective zone. Above the visible surface, the photosphere, are the chromosphere and the corona. The top half of the picture shows different layers in the interior of the Sun. The bottom half of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

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 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

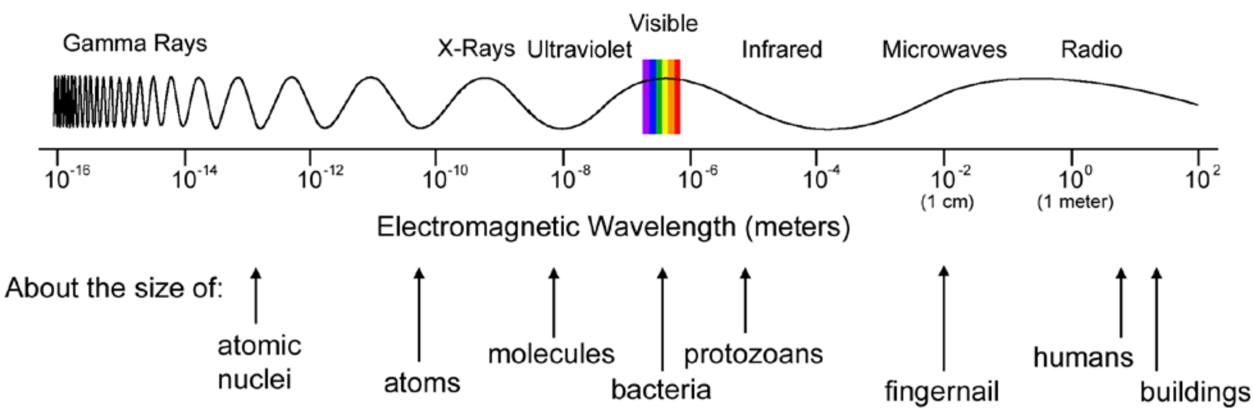


Figure 3. The electromagnetic spectrum. In the picture, different parts of the spectrum are shown as one continuous wave. In reality, a given electromagnetic wave has one particular wavelength. The continuous wave in the picture above is used to better illustrate the difference between wavelengths from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

(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 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 3.83×10^{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 6.29×10^{7} W/m^2 (3.83×10^{26} 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 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 re-radiated 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 9,443 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).

Lesson Plan: Measuring the solar constant

Students will measure the temperature change in a bottle of water as it is exposed to sunlight (see Figure S1 in Student Worksheet 1). Using this data and other parameters of the experiment, they calculate the solar constant, which is the amount of energy the Earth receives from the Sun per square meter per second.

Preparation

- Prepare the cork stoppers by drilling a hole in them large enough to accept the thermometer. You can use the regular cap of the bottle and seal it with silicon or caulk. You can also use masking tape to fasten the thermometer to the side of the bottle (make sure you can read the thermometer scale without moving the bottle), and then seal the top of the bottle. You can also have the students prepare the cork stoppers.

- Try to collect the data as close to noon as possible on a clear, cloudless day.

- If there is not enough time in one class session to complete this lesson, the calculations may be done on a separate day. The collectors may also be prepared and/or water placed in the shade to regulate temperature prior to the class. (These are steps 1 and 2 in the Student Procedures in Student Worksheet 1.)

- Make enough copies of the Student Worksheets and MESSENGER information sheet for each student.

Points to consider in preparation of the experiment to ensure maximum results

- It is best to have a flat-sided bottle with at least 150 ml capacity (a book-shaped glass bottle would be ideal). You can also use larger bottles, but to minimize the amount of measurement errors and sources of "noise" in the experiment, it is good to fill the bottle as full as possible. A noticeable rise in the water temperature in a large, full bottle will take longer to achieve than described here. Since 150 ml of water is ideal for making the calculation, the bottle size should be just a little over that. Important: Each group of students should use the same kind of bottle.

Materials

Per group of three:

- 1 small, flat-sided glass bottle with at least 150 ml capacity
- 1 cork stopper for the bottle
- 1 thermometer with a range up to at least 50ºC
- Books or rocks (to prop up the bottle)

Per class:

- Stopwatch
- Black, water-soluble ink
- Metric measuring cup
- Drill
- Optional: Caulk
- Optional: Masking tape

- Make sure the thermometer fits inside the jar and that the jar can still be properly corked. If possible, do not use a thermometer encased in heavy plastic. The plastic may absorb some of the heat and take away from the accuracy of the experiment.

- If you do not have access to a cork or a metal lid, you can also use masking tape to fasten the thermometer to the side of the bottle (just make sure you can read the thermometer scale without moving the bottle), and then use masking tape to seal the top of the jar.

Warm-up & Pre-assessment

1. Discuss with the students the concepts of temperature and heat.

2. Ask the students to come up with sources of heat and explain how the heat travels from the source. What about sunlight?

3. Talk to the students about sunlight and its role in our life here on Earth. Where do they think the Sun gets its power? How do they think Earth is affected by the amount of power (energy per second) that reaches us? How would other planets be affected?

4. Ask the students how they could calculate the amount of sunlight falling on Earth. Use the concept that light coming from the Sun will end up on the surface of a sphere with a radius equal to the Earth's distance from the Sun.

5. Ask the students how they would go about measuring the power of sunlight. Remind them that we cannot go and take a direct measurement from the Sun, and, therefore, have to design an experiment on Earth to measure indirectly.

6. If it has not already been mentioned, introduce the idea of the solar constant (see Science Overview). Tell the students that they are going to build a device to measure the solar constant, and, therefore, the power of sunlight.

Procedures

1. Put students into groups of three. Give each group the materials necessary to make the experiment, including Student Worksheet 1.
2. If you have not already done so, have the students prepare the collector bottles (see Figure S1 on Student Worksheet 1). A hole should be drilled into the cork or metal top of the jar for the thermometer to fit through.
3. Make sure that the students keep the unit shaded while moving it. Have the students set the collector down so that the flat surface is as perpendicular to the incoming sunlight as possible.

> **Teaching Tip**
> The time it takes for the water to heat up a couple of degrees depends on the time of day (the intensity of sunlight), the amount of water in the bottle, and the surface area of the bottle. Some of the heat will leak away to the environment, so you do not want to have the bottle sit on the ground any longer than necessary.

4. When you return to the classroom, collect data from everyone, and have the students calculate class averages. Create the following chart on the board using the data from each group. Have the students use this information to complete the calculations on Student Worksheet 1.

Group #	Initial Temp (˚C)	Final Temp (˚C)	ΔT (°C)	Elapsed Time (s)	Surface Area (m^2)
1					
2					
3					
…					
Average					

5. Have students use this information to complete the calculations on Student Worksheet 1.

6. Discuss deviations from the average and why these deviations may occur.

   [A: Some possibilities include: errors in reading the temperature accurately, differences in calculating the exposed surface area of the bottle, different responses of the thermometers, and different amounts of ink put in the water.]

Teaching Tip

Have the students read the worksheet while they are waiting for the water to warm up. This will prepare them for what they will be calculating and give them something to occupy their time in-between temperature readings. You may want to discuss what they think will happen, how many degrees they think the thermometers may have changed, etc. Answer any questions that they may have during this time.

Discussion & Reflection

1. It is likely that the values of the solar constant derived by the students differ between groups. Reasons for this may include the amount of ink in the water (since this determines how much sunlight is absorbed by the water instead of reflected or let through), different amounts of heat leaking into the environment from the bottle, and differences in reading the thermometers or recording the time. The values may also differ from the real solar constant, and that may be due to the atmospheric conditions being different from what the correction factor used by the students assumes, the correction factor for the glass bottle being a little different, etc. The correction factors are determined for the specific conditions described, and differences in those (such as the thickness of the glass, or slight coloration in it) may affect the derived values.

   Take this opportunity to discuss with the class the value of the scientific process. Remind them that scientists have to work very hard to be able to calculate the correct values, and that there are many parameters that must be controlled in order for this to be true. Usually scientists want to do the same experiment many times and use averages to calculate what is desired. The repetitions reduce the amount of error from measurements, environment changes, etc. In this case we use the group averages instead of every group repeating their experiment, but the principle is the same—many measurements of the same quantity reduce the effect of errors.

2. Remind students what it is that they have measured and how it relates to the power of sunlight.
3. Ask the class how they think things would change if Earth were closer to the Sun (or more distant).
4. Discuss the Sun as a star (some of its properties). Describe the Sun as one star among billions in our Galaxy. Describe how the Sun receives its power from nuclear fusion processes taking place at its center, and how the power is transmitted to Earth (via electromagnetic radiation). Discuss the importance of solar radiation on Earth.
5. Return to the essential question: what is the Sun's role on Earth? Remind students of the Sun's central role in the Solar System (it provides most of the energy available in the Solar System and guides the movements of the objects in the Solar System via gravity) and without it, none of us would be here. Remind them that it is the source of almost all energy on Earth. Remind them also that too much sunlight can be harmful to people and machines. (Use the example of UV damage to skin in the form of suntan, premature aging, and skin cancer.)
6. Hand out the MESSENGER information sheet and discuss the mission. Tell the students about the important role that the Sun and sunlight have on the mission. Remind them that sunlight is used in all planetary explorations. Most pictures the students have seen of other planets and moons were taken by cameras that capture sunlight reflected by the planets or moons. The engineers working on the MESSENGER mission to Mercury had to work hard to come up with solutions to the problem of protecting the spacecraft against the intense solar radiation at Mercury's close distance to the Sun.
7. Hand out additional worksheets that calculate planetary temperatures (Student Worksheet 2) and the potential of solar power use (Student Challenge Worksheet). You can have the worksheets filled out in class or as homework.

Lesson Adaptations

- For a mathematical challenge, have students complete the Student Challenge Worksheet.
- The Student Worksheets are mathematic in orientation. If you do not think your students can handle the math required, or that they will get discouraged, modify the worksheets for your students. Adapt this lesson to meet the needs of your students as you see fit.

Extensions

You can adapt the experiment described above by making a more accurate, sophisticated measuring device. Use the same ingredients as in the basic activity, but modified:

- Substitute temperature probes from a DMM (Digital Multimeter) or a computer to collect the data; the computer could also provide a more accurate time base.
- Design and build a more sophisticated, insulated collector bottle that minimizes heat loss to the environment.

You can also:

- Have students do the experiment with substances other than water. The only difference in calculating the solar constant is the number used for specific heat. If there is a discrepancy in the value of the solar constant, discuss why this might be the case.
- Have the students use different colored ink and test their results. Check if the solar constant is the same for various colors, discuss why or why not.
- Have the students repeat the activity without tilting the bottles toward the Sun. Calculate the difference between the solar constants and research why this is the case.
- The Sun is powered by nuclear fusion taking place in its core. On Earth, fission is used as an energy source in nuclear power plants. Have students research both of these processes and their efficiency. Have students discuss what is necessary for each, and why fusion is not used for energy generation on Earth.
- Have students research ways in which the Sun's energy is helpful to human activities and how we use sunlight in our everyday lives. Have students discuss ways in which the Sun's energy is harmful to humans. What are some of the things that we can do to protect ourselves and our planet from harmful rays?
- Have students examine the properties of sunlight further with the help of the Wien displacement law, which states:

  $\lambda_{max} = 2897 / T\ [K]\ \ [\mu m]$

  where λ_{max} is the wavelength of peak emission in micrometers (in μm, or 10^{-6} m), and *T* is the temperature of the radiating body in K. What does this mean? When is it effective? Describe what scientists mean by a "blackbody." Finally, calculate the wavelength of peak emission is for sunlight.

Curriculum Connections

- *History of Science:* Have the students examine the history of the study of the Sun. Have them write a timeline or essay about which scientists made important discoveries about the Sun and when.

- *Social science:* Have the students observe the importance of solar radiation at home and in industry. They can examine how it has affected daily life in modern society.

- *Technology:* Have the students research ways that solar radiation can be captured and applied to advance technology and cut back on the use of fossil fuels. Discuss the practicality, as well as advantages and disadvantages of this technology.

- *Geography/Agricultural Studies:* Have the students consider what effect sunlight has on the farming communities in various parts of the world. Consider locations that receive a lot of sunlight (toward the equator) and compare them to locations that receive varying amounts of sunlight during the year (toward the poles). Discuss how this affects the people of these locations and their contributions to the world. Research SAD (Seasonal Affective Disorder).

- *Environmental Studies:* Solar energy is a growing alternative to other natural resources. Discuss the advantages solar power has with regards to the environment, as well as any disadvantages.

Closing Discussion

Remind the students that they have discovered the central role sunlight plays in our lives here on Earth by calculating the amount of energy the Sun provides to Earth. Discuss other ways that the class could calculate the solar constant. Remind the class of ways they utilize solar radiation every day. Remind them that the solar constant is different for each planet, and ask them what they have learned about how the amount of radiation from the Sun affects conditions on each planet. Discuss the importance of sunlight for planetary exploration, including the MESSENGER mission to Mercury.

Assessment

4 points

- Student accurately calculated the group's solar constant and error, as well as the class average solar constant and error, on page 4 of Student Worksheet 1.
- Student justified the group's error for the solar constant in question 1 of Student Worksheet 1.
- Student set up and calculated questions 2 and 3 correctly in Student Worksheet 1.
- Student accurately filled in the table on Student Worksheet 2.
- Student accurately answered all questions on Student Worksheet 2.

3 points

- Student accurately calculated three of the following: the group's solar constant and error, as well as the class average solar constant and error.
- Student justified the group's error for the solar constant in question 1 of Student Worksheet 1.
- Student set up questions 2 and 3 correctly in Student Worksheet 1, but made errors in one of the calculations.
- Student accurately filled in six of the eight entries in the table on Student Worksheet 2.
- Student accurately answered four of the five questions on Student Worksheet 2.

2 points

- Student accurately calculated two of the following: the group's solar constant and error, as well as the class average solar constant and error.
- Student attempted to justify the group's error for the solar constant in question 1 of Student Worksheet 1.
- Student set up questions 2 and 3 correctly in Student Worksheet 1, but made errors in both of the calculations.
- Student accurately filled in four of the eight entries in the table on Student Worksheet 2.
- Student accurately answered three of the five questions on Student Worksheet 2.

1 point

- Student accurately calculated one of the following: the group's solar constant and error, the class average solar constant and error.
- Student attempted to justify the group's error for the solar constant in question 1 of Student Worksheet 1.
- Student set up either questions 2 or 3 correctly in Student Worksheet 1, and made errors in both of the calculations.
- Student accurately filled in two of the eight entries in the table on Student Worksheet 2.
- Student accurately answered two of the five questions on Student Worksheet 2.

0 points

- No work completed.

Internet Resources & References

MESSENGER website

messenger.jhuapl.edu

American Association for the Advancement of Science, Project 2061, Benchmaeks for Science Literacy

www.project2061.org/tools/benchol/bolintro.htm

NASA Goddard Space Flight Center's "Living with a Star" Website

lws.gsfc.nasa.gov

NASA Goddard Space Flight Center's "Sun-Earth Connection" Website

sec.gsfc.nasa.gov

NASA National Space Science Data Center's Planetary Fact Sheets

nssdc.gsfc.nasa.gov/planetary/planetfact.html

National Science Education Standards

www.nap.edu/html/nses/html/

NOAA Space Environment Center, U.S. Dept. of Commerce

www.sec.noaa.gov

SpaceWeather.com

www.spaceweather.com/

The Solar and Heliospheric Observatory (SOHO)

sohowww.nascom.nasa.gov

U.S. Department of Energy

www.energy.gov

Acknowledgments

This activity has been adapted from the National Oceanic and Atmospheric Administration's "Space Physics and Terrestrial effects" curriculum (www.sec.noaa.gov/Curric_7-12/).

Measuring the Solar Constant

Materials

Per group:

- 1 small, flat-sided glass bottle with at least 150 ml capacity
- 1 cork stopper for the bottle
- 1 thermometer with a range up to at least 50˚C
- Books or rocks (to prop up bottle)

Per class:

- Stopwatch
- Black, water-soluble ink
- Metric measuring cup
- Optional: Drill
- Optional: Caulk
- Optional: Masking tape

In this experiment, you will make a device to measure how much energy sunlight provides to Earth.

Procedures:

1. Prepare the collector bottle by pouring 150 ml of water into the bottle. Add a few drops of the ink to make it black, and place the thermometer through the hole in the cork or lid. Make sure the seal is as tight as possible by using caulk or masking tape, if necessary. You may need to drill a hole into the cork or metal top of the lid. Insert the cork/lid into the bottle with the thermometer in place and sealed (see Figure S1).

2. Place the collector in shade so that it stabilizes to the mean air temperature. This takes about 10 minutes or until the temperature does not change any more while checking every 2-3 minutes.

3. Move the collector to sunlight. Make sure the unit is shaded while moving. Set the collector down so that the flat surface is as perpendicular to the incoming sunlight as possible. You may need to prop up the bottle with books or rocks (see Figure S1).

WARNING

Do *not* look directly at the Sun!

Looking for even a few seconds can cause permanent damage to the eyes! Note that sunglasses do *not* provide an adequate safeguard against looking directly at the Sun.

So remember to *never* look directly at the Sun!

Name ________________________________

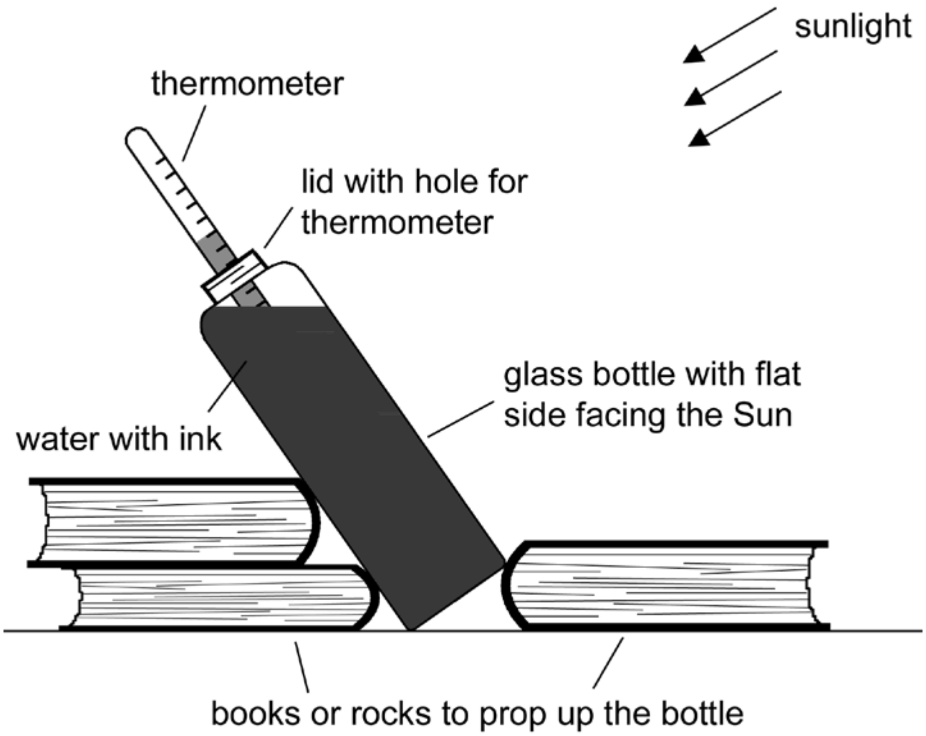


Figure S1. Side view of the experiment setup. Drill a hole to the cork or metal top of a bottle. Insert thermometer in the top and close the bottle. Make sure you can read the thermometer readings without moving the bottle. Place the device in the sunlight so that the flat side of the bottle is facing the Sun and the exposed surface is as perpendicular to the incoming sunlight as possible. You may need books or rocks to help tilt and balance the bottle properly.

4. Begin the experiment by unshading the collector. Start the stopwatch and record the temperature on the Data Table on the next page.

5. Allow the collector to absorb sunlight for 20 minutes or at least enough time to get at least a 3–4 °C temperature rise. Record the elapsed time and temperature rise.

6. Measure the amount of the bottle's surface that is exposed to the Sun and record the area in square meters on the Data Table.

   Think: How can I use my data to find the solar constant (how much energy the Earth is receiving from the Sun per square meter per second)?

Making the measurements:

(Hint: To calculate the mass of the water, keep in mind that water has a density of 1.0 g/cm^3, and that 1 ml = 1 cm^3.)

Volume of water used:_______________ liters

Mass of water used: _______________ kilograms

Data Table

Your Group

Exposed Surface Area (m^2)	Initial Temp (°C)	Final Temp (°C)	ΔT (°C)	Elapsed Time (s)

Average of All Groups

Exposed Surface Area (m^2)	Initial Temp (°C)	Final Temp (°C)	ΔT (°C)	Elapsed Time (s)

Calculate the solar constant for two cases: the values from your own group, and the class average.

Your group's $\Delta T/s$ = ______________

Average $\Delta T/s$ = ______________

The specific heat of a substance or object is defined as the amount of energy needed to raise the temperature of one kilogram of the substance one degree Celsius. The specific heat of water is 4186 J/(kg x ˚C). Therefore the energy absorbed by your water per second is:

Energy/s = 4186 *J/(kg x ˚C) x water's mass(kg) x ΔT (˚C)/sec*

Energy/s = __________________ *J/s* (your group)

Energy/s = __________________ *J/s* (class average)

Energy collected per unit of surface area is:

(Energy/s) / (exposed surface area (m^2)) = _______________ *J/s/m^2* (your group)

(Energy/s) / (exposed surface area (m^2)) = _______________ *J/s/m^2* (class average)

This is your uncorrected solar irradiation for Earth's surface, or how much energy your water is receiving from the Sun per second per square meter. Both Earth's atmosphere and the glass bottle have absorbed or reflected some of the incoming solar radiation, and this "lost" energy will not show up as energy absorbed by the water. If other materials are used for your collector, then these next calculations may not be valid and you may need to find out a proper correction factor.

Multiply your uncorrected solar irradiation by 2 to correct for the glass (determined experimentally) and also by a factor (F_c) to correct for the atmosphere (to determine which factor you should use, look on the Condition Correction Table on Page 6):

solar constant = *irradiation x 2 x* F_c

= _______________ *J/s/m^2* (your group)

= _______________ *J/s/m^2* (class average)

You have now calculated how much energy the Earth is receiving per second per square meter from the Sun. This value is called the solar constant. The accepted value of the solar constant is about 1370 J/s/m^2.

Then your % error is:

(your solar constant–1370)/1370 x 100

= ___________________ % *(include the sign)* (your group)

Questions and Interpretations:

1. Detail as many reasons as possible why your value of the solar constant differs from the accepted value (if it does).

2. The Sun radiates energy in all directions. After traveling a distance, *r*, the energy has spread over an area equal to the surface area of a sphere with radius *r*. Use the formula for surface areas of spheres and the values of the Earth—Sun distance as well as the solar constant to find how much energy is being released per second from the surface of the Sun.

3. Use the formula for the cross-sectional area of Earth (area of a circle with Earth's radius) and the solar constant to approximate how much solar energy is received by the Earth each day. (Note that the cross-sectional area of the Earth is smaller than half of a surface of a sphere exposed to sunlight at any given time. Since sunlight arrives from only one direction—from the Sun—the amount of solar radiation that the Earth intercepts is the cross-sectional area of the Earth, instead of half the surface area of a sphere.)

Condition Correction Table

Conditions	Correction Factor (F_c)
Low humidity, completely clear sky	1.4
High humidity, clear sky	1.5
Some haze	1.6
Some clouds	1.8

Useful Formulae and Constants

Surface Area of Sphere= $4\pi r^2$ (where r is the radius of the sphere)

Cross-sectional Area of Sphere= πr^2 (where r is the radius of the sphere)

Astronomical Unit (1 AU = average Earth-Sun distance) = 1.50×10^{11} m

Solar Constant = 1370 W/m^2 (Remember: 1 W = 1 J/s)

Radius of the Earth = 6.37×10^6 m

Sun's Effect on Planetary Temperatures

The total power (energy per second), P, radiated by objects such as the Sun per square meter is given by the Stefan-Boltzmann law

$$P = \sigma T^4$$

where T is the temperature, and σ is the Stefan-Boltzmann constant and is equal to 5.67×10^{-8} W m^{-2} K^{-4}.

The temperature of the Earth can now be estimated based on the amount of solar radiation it receives.

The luminosity of the Sun (the total power produced) is

$$L_S = 4 \pi R_S^2 \sigma T_S^4$$

where R_S is the radius of the Sun and T_S its surface temperature, 5780 K. This is the amount of energy radiated each second by the Sun in all directions.

The Earth is a globe of radius R_E = 6370 km located an average distance $r_E = 1.50 \times 10^8$ km from the Sun. The amount of radiation emitted by the Sun that the Earth intercepts is determined by the ratio of the cross-sectional area of the Earth to the total area to which the radiation emitted by the Sun has spread at the distance of Earth (that is, the surface area of a sphere with a radius of Earth's distance from the Sun.) The amount of energy per second the Earth receives is therefore

$$P_E = L_S \; (\pi R_E^2 / 4\pi r_E^2).$$

The Earth absorbs this energy and then re-radiates it at longer wavelengths. The luminosity of the Earth is

$$L_E = 4 \pi R_E^2 \sigma T_E^4$$

according to the Stefan-Boltzmann law, where T_E is the average surface temperature of the Earth. If we ssume that the Earth absorbs all the energy that it receives and that it is also a steady-state system ($P_E = L_E$), it emits as much radiation as it receives.

Using the last three equations from Page 1, we can solve for the Earth's surface temperature:

$$T_E = (R_S / 2r_E)^{1/2} T_S$$

That is, the ratio of the Earth's surface temperature to that of the Sun depends only on the solar radius and the Earth-Sun distance.

Now, calculate the surface temperatures for the inner planets in the Solar System (in degrees Kelvin). Find out the distances to the planets from a reference book or online (for example, you can use the charts given in reference (*) below) and fill out the following table using the formulae above:

Planet	Mercury	Venus	Earth	Mars
Distance from the Sun				
Calculated average surface temperature (K)				

* Real average surface temperatures from NASA National Space Science Data Center's Planetary Fact Sheets, nssdc.gsfc.nasa.gov/planetary/planetfact.html

Useful Formulae and Constants

Astronomical Unit (1 AU = average Earth-Sun distance) = 1.50×10^{11} m

Surface temperature of the Sun = 5780 K

Radius of the Sun = 696,000 km

Surface Area of Sphere= $4\pi r^2$ (where r is the radius of the sphere)

Questions:

1. Which planets have their calculated surface temperatures close to the real values? Why do you think this is the case?

2. Which planets have calculated surface temperatures that are way off? Why do you think this is the case? (Hint: Think about the assumptions made in the calculation.)

3. A habitable zone is the range of distances from the Sun (or from the star if we are talking about another star) where liquid water could exist. This is important because life as we know it is thought to be able to survive only in places where there is liquid water. What is the range of distances of the habitable zone around the Sun? (Hint: use the equations in Pages 1-2 to solve for the distance from the Sun at which the calculated average surface temperature is equal to freezing (273 K) or boiling (373 K).) How is Earth situated with regards to the habitable zone?

4. The calculations in this Worksheet assume that the amount of solar radiation is the only source influencing the surface temperature on a planet. Can you think of other sources that might influence the temperature? The calculations also assume that all of the solar radiation received by the planets is later re-radiated. Can you think of circumstances when this might not be the case?

5. During the MESSENGER mission to Mercury, the spacecraft will be exposed to temperatures much higher than those on Earth. You have calculated the difference in the surface temperatures of the two planets already. How much difference is there between the amount of energy experienced by objects at Mercury's distance compared with the situation at Earth's location? [Hint: calculate over how large an area the power of sunlight has spread by the time it reaches Mercury or Earth; what is the ratio?] Can you think of some ways to reduce the amount of heat experienced by the spacecraft?

Potential for Solar Energy Use

1. How far from a 100-W light bulb is the radiation intensity the same as sunlight on Earth (assume that no energy is lost in the atmosphere)? (Hint: Intensity is power per unit area (W/m^2); set intensity from light bulb equal to that from the Sun on Earth.) For the calculation, assume that all the power used by the light bulb is converted into radiation.

2. The electricity consumption in the United States in the year 2003 was about 3650 billion kWh ("kilowatt-hour"), and in the whole world, 14,800 billion kWh (data from "International Energy Annual"; www.eia.doe.gov/pub/international/iealf/table62.xls). A kWh is a measurement of the amount of energy supplied by 1 kW in one hour. For example, if a 100-W light bulb is on for 10 hours, the energy used is 1 kWh of energy.

   a) How does 1 kWh relate to Joules?

   (Hint: kWh and J are both units of energy.

   1 kWh = 1 kilowatt x 1 hour

   How many seconds are there in an hour?

   How does Watt relate to Joule?

   What is the final conversion factor from 1kWh to Joules?)

   b) What is the electricity consumption of the United States and the world in Joules?

c) If we were able to capture all solar radiation arriving on Earth (at the top of the atmosphere) and convert it to electricity with 100% efficiency, how long would we need to capture this energy to satisfy the electricity consumption for the whole year for the United States? The world? (Hint: calculate the cross-sectional area of Earth.)

d) Is it actually possible to capture the Sun's energy with 100% efficiency over the whole Earth (on top of the atmosphere)? Why or why not?

Useful Formulae and Constants

Surface Area of Sphere= $4\pi r^2$ (where r is the radius of the sphere)

Cross-sectional Area of Sphere= πr^2 (where r is the radius of the sphere)

Solar Constant = 1370 W/m^2 (Remember: 1 W = 1 J/s)

Radius of the Earth = 6.37×10^6 m

Power of the Sun = 3.83×10^{26} W.

ANSWER KEY

Student Worksheet 1

Students will have varying answers in their calculations depending on their exposed surface areas. The uncorrected irridation should be around 450 $J/s/m^2$ in order to get the correct solar constant of 1370 $J/s/m^2$.

Questions and Interpretations:

1. Students may come up with any number of reasons, including but not limited to: it may be a partly cloudy day, the correction numbers may not be exactly right for the experiment the students performed (depending on what type of collector they used), the thermometer may not be precise or easy to read, some of the heat is conducted to the environment, reflected from the bottle or the not-perfectly-black water (the amount of ink mixed in influences this), etc.

2. Solar constant x surface area of sphere with radius 1AU = 1.5×10^{11} m.

   $1370\ J/s/m^2 \times 4\pi(1.5 \times 10^{11})^2\ m^2 = 3.87 \times 10^{26}$ J/s (W)

3. Solar constant x cross-sectional area of Earth x the number of seconds in one day

   $1370\ J/s/m^2 \times \pi(6.37 \times 10^{6})^2\ m^2 \times 86400\ s = 1.51 \times 10^{22}$ J

Student Worksheet 2

Planet	Mercury	Venus	Earth	Mars
Distance from the Sun	58×10^6	108×10^6	150×10^6	228×10^6
Calculated average surface temperature (K)	448	328	278	226

1. Planets that have calculated temperatures close to (but not exactly the same as) the real average surface temperatures are Mercury, Earth, and Mars. Answers may vary as to why. Some possibilities include: we assume that there is nothing impeding the radiation on its way through the interplanetary medium, we assume that the planets absorb all of the heat that they receive, (while in reality some of it is reflected away), etc.

2. Venus is the only planet in the group that has a very different calculated surface temperature from the real surface temperature. The reason for this is that Venus's thick atmosphere lets through much of visible light but prevents the infrared radiation emitted by the hot surface from escaping. Venus's atmosphere consists mostly of carbon dioxide (CO_2), which is a significant greenhouse gas and largely responsible for creating this greenhouse effect.

3. If we solve our equation for the distance from the Sun, we get:

   $d = (R_S/2)\,(T_S/T)^2$

   $d\ (T=273) = 156 \times 10^6$ km

   $d\ (T=373) = 84 \times 10^6$ km

   We can now see that Earth is (barely) located within the Sun's habitable zone.

4. Some other sources of heat may include: internal heat from the planet, heat caused by tidal forces from another nearby object (e.g., tidal heating of Jovian moons by Jupiter), etc. Reasons that radiation may not be re-emitted include: absorption of radiation on planet by things like water, plants, etc., atmospheres inhibiting re-emission (i.e., the greenhouse effect), etc.

5. Since the energy received from the Sun is inversely proportional to the square of the distance from the Sun (as the equation for the surface area of the sphere shows), an object at Mercury's distance from the Sun will receive 11 ($1/0.3^2$) times as much energy as it would in space near Earth. (Mercury is 0.3 times the distance from the Sun to the Earth.) Some suggestions for protecting the spacecraft could include: shielding the spacecraft from the Sun, etc. See Science Overview for some of the solutions used in the mission. One might also want to try and stay on the dark side of Mercury, but that isn't feasible for an orbiting spacecraft intended to observe the planet's surface.

Student Challenge Worksheet

1. Intensity = power per unit area

   Power radiated by the light bulb or the Sun is spread over an area $4\pi r^2$, where r is the distance to the light source (light bulb and Sun treated as point sources of light).

   We now match intensity of lamp at distance D from the lamp with the intensity of the Sun at Earth's distance, r_E:

   $$\text{Intensity}_{Sun} = \text{Intensity}_{light}$$
   $$\text{Power}_{Sun} / 4\pi r_E^2 = \text{Power}_{light} / 4\pi r_E^2$$
   $$\longrightarrow D^2 = \text{Power}_{light} \times r_E^2 / \text{Power}_{Sun}$$
   $$\longrightarrow D = (\text{Power}_{light} \times r_E^2 / \text{Power}_{Sun})^{1/2}$$

   For a 100-W light bulb, using the total power of the Sun, 3.83×10^{26} W, and Earth's distance from the Sun, 1.50×10^{11} m, this gives

   $$D = 0.0766 \text{ m}$$

   That is, radiation from a 100-W light bulb at the distance of 8 cm has the same intensity as sunlight arriving on Earth (on top of the atmosphere).

2. a) 1 W = J/s

1 kWh = 1 x 1000 W x 3600 s

= 3.6×10^6 J/s x s = 3.6×10^6 J

b) United States: 3650 billion kWh = 3.65×10^{12} kWh = 1.34×10^{19} J

World: 14800 billion kWh = 1.48×10^{13} kWh = 5.33×10^{19} J

c) Cross-sectional area of Earth facing the Sun at any given time:

$\pi R_E^2 = 1.28 \times 10^{14}$ m^2

where R_E is the radius of the Earth.

The amount of energy received by the Earth in one second:

E = 1370 J/s/m^2 x 1.28×10^{14} m^2 x 1 s = 1.75×10^{17} J

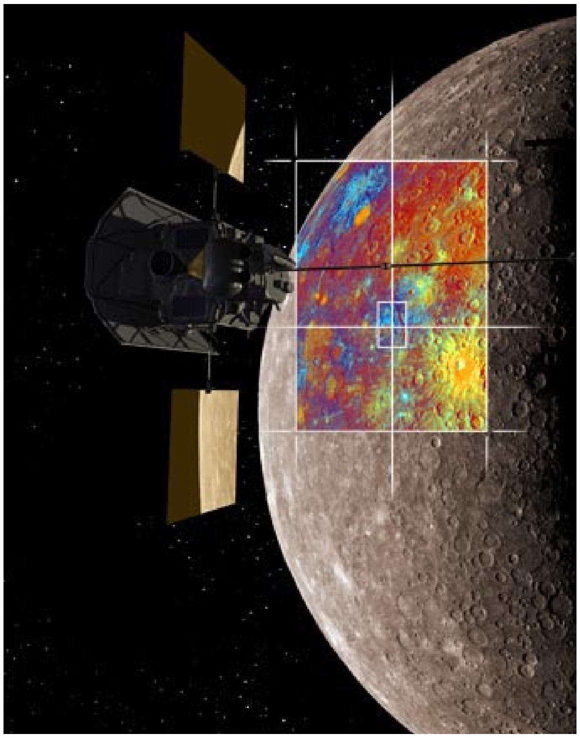
Length of time required to satisfy electricity consumption for one year:

t_{USA} = 1.34×10^{19} J / 1.75×10^{17} J/s = 77 s = 1 min 17 s

t_{world} = 5.33×10^{19} J / 1.75×10^{17} J/s = 305 s = 5 min 5 s

d) This is not possible, at least at present time. In order to do this, we would need to be able to build collectors capable of capturing 100% of the solar energy striking them, hoist them to a configuration above the atmosphere and have them operate reliably there. The technology to do this does not exist at the moment. It probably would not be popular to block out the Sun completely, and it would also have adverse effects on life forms—plants, animals, etc. If this could be done for a brief period of time every now and then, this objection might go away. But the main problem is that the technology to do this does not currently exist.

MESSENGER INFORMATION SHEET



The MESSENGER Mission to Mercury

MESSENGER is an unmanned U.S. spacecraft that was launched in 2004 and will arrive at the planet Mercury in 2011, though it will not land. Instead, it will make its observations of the planet from orbit. MESSENGER will never return to Earth, but will stay in orbit around Mercury to gather data until the end of its mission.

MESSENGER is an acronym that stands for "**ME**rcury **S**urface **S**pace **EN**vironment, **GE**ochemistry and **R**anging," but it is also a reference to the name of the ancient Roman messenger of the gods: Mercury, after whom the planet is named.

MESSENGER will be only the second spacecraft ever to study Mercury: In 1974 and 1975 Mariner 10 flew by the planet three times and took pictures of about half the planet's surface. MESSENGER will stay in orbit around Mercury for one Earth-year; its close-up observations will allow us to see the whole planet for the first time.

Sending a spacecraft to Mercury is extremely complicated. The planet is very close to the Sun; it moves very fast in its orbit, and intense radiation and heat can cause catastrophic consequences. Therefore, engineers and scientists have planned the mission carefully. They have found ways to protect the spacecraft against radiation, and they have built safeguards to make sure it can operate reliably in the difficult Mercurian environment.

During its mission, MESSENGER will attempt to answer many questions about the mysterious planet. How was the planet formed and how has it changed? Mercury is the only rocky planet besides Earth to have a global magnetic field; what are its properties and origin? Does ice really exist near the planet's poles? Answers to these scientific questions are expected to hold keys to many other puzzles, such as the origin and evolution of all rocky planets. As we discover more, we expect that new questions will arise. You could be the one answering these new questions!