Chapter 16: The Sun
Our Parent Star

Outline

16.1 Physical Properties of the Sun
16.2 The Heart of the Sun
16.3 The Solar Interior
16.4 The Solar Atmosphere
16.5 The Active Sun
16.6 Observations of Solar Neutrinos

Summary

This chapter marks the beginning of the next major areas of study, namely the stars. The Sun is the first star considered in the text so Chapter 16 can be considered as a transitional chapter. It completes the solar system with its most dominant inhabitant, our own star. The Sun, being the closest star, allows us to take a close up view of stellar activity. Features of the solar surface are discussed as well as observational evidence of activity within the interior. The chapter examines how the Sun, as a typical star, produces its energy, which naturally leads into the study of stars in the following chapters.

Major Concepts

- Solar properties
- Energy
  - Production: proton–proton chain
  - Transport
- Structure of the Sun
  - Interior: core, radiation zone, convection zone
  - Surface: photosphere
  - Atmosphere: chromosphere, transition zone, corona
  - Solar wind
- Activity and magnetic fields
  - Sunspots and the solar cycle
  - Flares
  - Prominences

Teaching Suggestions and Demonstrations

At the beginning of class, set a timer for 8 minutes. When it goes off, briefly stop what you are doing and announce to the class that the light that left the Sun as they were entering class has just arrived. Students are familiar with kilometers and astronomical units. This exercise gives them an idea of another way to characterize distances; the Sun is about 8 light-minutes from Earth. (You can also point out that light from the Sun will not have reached Pluto for another 5 hours, or the nearest star for over 4 years!)

Section 16.1

For the rest of the text, many characteristics of astronomical objects will be given in terms of how they compare to the Sun. For instance, the masses, radii, and luminosities of stars and clusters of stars are usually given in "solar masses," "solar radii," and "solar luminosities." Thus it is important that students have a good feel for the basic **properties of the Sun**. Go over the solar properties in Table 16.1 in some detail. Have students calculate how these compare to the corresponding properties of Earth. For instance, the Sun's mass is about 330,000 times the mass of Earth.

How do we know the mass of the Sun? Review the method for determining the mass of celestial objects by measuring a few properties of the objects orbiting them and applying Newton's laws. Once the Earth-Sun distance is known, the period of the Earth's orbit gives the mass of the Sun directly from Newton's form of Kepler's third law. However, in previous chapters we have used solar and Earth units in the third law. Now it is important to see the third law as Newton derived it. The advantage is that we will calculate the mass of the Sun in kilograms, not solar masses. The disadvantage is the inconvenience of the units and the need to know G, the universal gravitational constant. In mks units, $G = 6.67\times10^{-11}$.

Assuming the mass of the Earth is insignificant relative to the Sun's mass we have

$$MP^2 = \frac{4\pi^2}{G}a^3$$

Using P = 1 year = 365 × 24 × 60 × 60 = 31,536,000 s and a = 1 A.U. = 1.496×10^{11} m gives $M = 1.99\times10^{30}$ kg. The mass of the Sun is an extremely important number in astronomy. Astronomers often measure mass in solar masses. The mass of the Sun gives us the equivalent in a standard mass unit, kilograms.

Now, as large and massive as the Sun is compared to the planets, when compared to the other stars, we see that it really is rather average or typical. However, the term "typical" must be used with some caution when referring to the Sun. As explained at the start of this chapter, the Sun is in the middle of the range of mass, radius, and other properties for stars. Does this necessarily mean it is truly average among stars? The lightest and heaviest adult humans weighed 45 and 1400 pounds. The "average" of this range is 723 pounds. Certainly the average human adult does not weigh this much! In the same way, the average star does not have the mass, radius, and other properties of the Sun. As will be seen later, the average star is an M-type star that is much smaller than the Sun. However, much of what we know about the Sun makes it typical of many stars. If we were able to pick any star to study, as typical of most stars, the Sun would still be a good choice.

To continue your introduction to the overall structure of the Sun, project a cross-sectional view of the Sun, such as Figure 16.2, and give an overview of the **structure** before discussing each layer in detail. Planets are described in terms of "interior," "surface," and "atmosphere." So is the Sun, although the meaning of these terms is slightly modified. The "surface" is the photosphere, which is the layer we see. Those layers above (chromosphere, transition zone, and corona) comprise the atmosphere, and those below (convection zone, radiation zone, and core) make up the interior.

➲ **DEMO** Bring a light meter or solar cell to class to demonstrate how light can be measured. Hold it near a bulb radiating in all directions and then move it farther away to show how a lower light level is measured at greater distances. Convince students that from the reading at a known distance and a little geometry, the **total energy output of the Sun** can be calculated. Then go through the calculation of the Sun's luminosity as shown in the end of Section 16.1.

A quantitative measure of the amount of energy Earth receives from the Sun is known as the **solar constant**. It is not difficult to measure the solar constant to within a factor of 2 accuracy. It can be done on any sunny day during a lecture. ➲ **DEMO** Take a Styrofoam coffee cup and fill almost to the top with water. Add a little India ink to make the water very black. Weigh the cup before and after this to determine the mass of water in grams (cgs units are much easier to use in this experiment than mks units. The result can always be converted to mks). Measure the temperature of the water (in centigrade or Celsius units) and set it in direct sunlight for about half an hour (time it exactly). Cover the top of the cup with a transparent plastic wrap to reduce evaporative losses. Align the cup in the sunlight so that the cup's sides do not shadow any of the water. Measure the diameter of the circle made by the surface of the water and calculate the area in square centimeters. At the end of the half hour, measure the temperature again. Using the specific heat of water as 4.186×10^7 ergs/gm/°C, calculate the amount of energy gained by the water by multiplying by the change in the temperature and the mass of the water. Dividing this energy by the area of the circle and the time will give the solar constant. Again, this will give a result that is about half the true value (which is 1.4×10^6 erg/cm^2/s); the other half is lost due to absorption of visible and infrared light by the atmosphere of the Earth. If it is not convenient to do this as a demo, try having the students do it as part of a lab exercise.

The amount of energy received by the Earth via the solar constant is often not appreciated. An area 10 feet on a side receives in one day the equivalent energy of one gallon of gasoline (assuming only half the solar energy reaches the ground). (Since this area is larger than cars, a completely solar car may not be practical.) The typical roof of a house receives tens of thousands of watts of power from the Sun. Little wonder that attics get so hot during the summer! Even at a conversion efficiency of 10%, there is sufficient power to meet most of the power needs of a house. What are some of the limitations and complications in actually using this power? It is a good question to ask students. Typical answers are: no power at night, cloudy weather, roofs facing the wrong direction, variable angle of the Sun during the day, seasonal changes in the position of the Sun, cost of solar power cells, cost of retrofitting houses, apartment buildings with low roof area per capita. It is equally informative to challenge students to suggest solutions to these same problems.

Using the above example of only half the solar constant and a 10% efficiency, every one of the Earth's 5 billion people could be provided with 1000 watts of power by using a square area of land about 160 miles on a side. Although that amount of power is much less than the per capita use in the USA, it is much more than most people in the world have available to them now!

Section 16.2

The equation $E = mc^2$ is very familiar to most students. But the energy equivalence of mass is rarely appreciated. Show the students a paperclip and let them know that if all of the mass in that paperclip could be converted to energy, it would be sufficient to place an aircraft carrier into Earth orbit!

How can mass be converted to energy? This is where you can introduce the **proton–proton chain,** which is ultimately the source of most of the energy we receive from the Sun, so it is worth spending some time discussing it. If you wish, you can discuss conservation of charge and show how it applies at each step. You can also point out that the total number of nucleons (protons and neutrons) is the same before and after each reaction. Go through the calculation of the amount of energy produced in the sequence of reactions and the corresponding rate at which hydrogen is being fused. The numbers are impressive!

When lecturing on the proton-proton chain, you will want to have a periodic table of elements located somewhere in the lecture room. To summarize the process, 4 hydrogens go into making 1 helium plus some energy. Note from the table that the mass of hydrogen is given as 1.0080 atomic mass units (although it is not important for students to understand the units being used). Four hydrogens have a mass of 4.0320. But the mass of helium is given as 4.0026, which is less. The difference, 0.0294, is converted into energy. Comparing this amount to the amount of hydrogen gives 0.7%. So, 0.7% of the mass is converted into energy. This is equivalent to 4 billion kilograms (4 million tons) of hydrogen being *converted into energy* each second; 4 million tons lost from the Sun each second! Does the Sun lose a significant amount of its mass over its lifetime? No! If it converted all of its hydrogen into helium, which it will not, it would only lose 0.7% of its mass. This is like a 150-pound person losing one pound. It is a common misconception that this mass loss somehow forces the Sun or other stars to evolve. It is important to establish the fact that this mass loss is rather insignificant.

Section 16.3

Figure 16.8 shows the **temperature and density** as a function of radius for the solar interior. There are no sharp edges on the graphs; ask students what determines the boundaries between the different layers. The **core** is the area where temperatures are high enough for the energy production to occur. In the **radiation zone**, the temperatures are lower, but still high enough that all the atoms are ionized and the radiation travels freely. In the **convection zone**, the temperatures are even lower, and electrons are now bound to nuclei; atoms absorb the photons so the energy can no longer be transported through radiation. Remind students of the convection demonstration from a previous chapter. Contrast energy transport by radiation and by convection.

The **photosphere** ("sphere of light") is the visible surface of the Sun and is actually very thin. Make a scale drawing or model of the layers of the Sun to emphasize the comparative thicknesses. (Remind your students to never stare directly at the Sun and never look at the Sun through a telescope without proper filters.)

The **chromosphere** ("sphere of color") is only visible during a solar eclipse, as it is dimmer than the photosphere. The "color" is produced by the Hα line, and the layer looks slightly pink. Show the solar spectrum (Figure 16.11 or Figure 4.4) and point out the complexity of it! It is also fun to bring in a prism and go outside or use sunlight coming in a window to look at the solar spectrum, minus the details.

The **corona** ("crown") is the wide layer that extends out into space, eventually turning into the **solar wind**. It is also only visible during a total solar eclipse. One reason astronomers get so excited about solar eclipses is that they provide a rare opportunity to view and study these layers of the Sun.

If possible, set up a telescope outside the classroom so that students can view the Sun as they come to class. Obviously you will need to use some type of solar filter such as the Solar Skreen filter (available from Roger W. Tuthill, http://www.tuthillscopes.com). It is a very safe way of showing sunspots, limb darkening, and solar granulation.

An even more spectacular view of the Sun is with an H-alpha filter. These filters are commercially available, although rather pricey; they can cost as much as an 8-inch telescope, but the view is worth it. The filter is a very narrow-band interference filter that is tunable around the hydrogen 3→2 transition, better known as the first line in the Balmer series or Hα as discussed in Chapter 4. Rather than viewing the photosphere, as is the case with the common solar filters, this filter shows the chromosphere.

Although **solar granulation** shows up quite nicely, as do other active regions on the Sun, the real prizes are solar prominences seen along the limb of the Sun. The sky appears black; the Sun, red. Two hints in using these filters. First, once plugged in, give them time to stabilize, about 10 to 15 minutes. Second, the quality of the images depends strongly on the positioning of the prefilter, which fits loosely over the front of the telescope. Slowly turn this filter until the solar granulation becomes apparent. All features, including large prominences, disappear when this filter is turned into the incorrect position, so make sure you have had a chance to work with it on your own before demonstrating to the class.

Section 16.4

As stated in the text, the Sun loses about a million tons of matter each second due to the solar wind. This is 1×10^9 kg/s. (This sounds like a lot of matter but in fact a billion kg would be equivalent to the mass of a large hill on Earth.) How much of this material does the Earth intercept? Is it a significant amount? Compare the circular area of the Earth, $\pi r^2 = \pi\,(6\times10^6\text{ m})^2 = 1\times10^{14}\text{ m}^2$, to the area of a sphere at 1 A.U. from the Sun, $4\pi r^2 = 4\pi(1.5\times10^{11}\text{ m})^2 = 2.8\times10^{23}\text{ m}^2$. Taking the ratio of these two areas and multiplying by 1×10^9 kg/s gives about 0.4 kg/s. Over the 4.6-billion-year lifetime of the Earth this accounts for less than 1% of the hydrogen of the Earth. It sounds like a lot of material but in fact does not amount to much as far as the Earth is concerned! This is equivalent to 12 million kilograms per year of mostly hydrogen and some helium!

Section 16.5

From our view on Earth, the Sun seems like a fairly stable, uneventful place. Section 16.5 details several active events that take place on the Sun. **Flares, prominences,** and **sunspots** are all related somehow to magnetic fields. Repeat the earlier demonstration of magnetic fields by placing a bar magnet under a piece of paper and sprinkling iron filings on top. Show students how the filings align with the magnetic field lines. Emphasize the loop structure of the magnetic field lines, and compare to the shapes of prominences.

If you have not been able to obtain a telescope and filters as discussed above, an alternative is to find a Web site with daily pictures of the Sun and compare the positions of the sunspots on the images from day to day. The site SpaceWeather.com has daily images for both sunspots and **coronal holes**, as well as predictions of **solar flares**.

Section 16.6

Neutrinos are both fascinating and important to our overall understanding of the processes that take place in the core of the Sun. Describe some of the neutrino detection experiments that have been attempted and discuss the discrepancies between theory and observation.

Student Writing Questions

1. Throughout human history, the Sun has been recognized as the "giver of life." Humans have feared losing the Sun, whether during an eclipse, at night, or as it moves southerly during the Fall season. From what you have learned of the Sun and the processes that occur in it, describe why it is that we should no longer have these fears. On human time scales, the Sun will always shine; it cannot suddenly, and permanently, disappear.

2. Solar flares put out only a fraction of the total energy of the Sun when they occur. For some types of stars, this is not the case. What if the Sun suddenly had a flare that emitted energy equal to the entire output of the Sun. Considering the lifetime of a typical flare and the radiation given off (electromagnetic and particulate), what would be the effects on life and the general environment of the Earth? How would different parts of the Earth be affected?

3. Controlled nuclear (hydrogen) fusion has been attempted for years with very little success. It still may be feasible, and, if so, would give humans an enormous supply of energy. But this is the same process the Sun does every second and on a huge scale. Discuss the pros and cons of developing a fusion program versus developing solar energy use. What are the difficulties and the advantages of each? Which might be more economical for developing countries?

4. During the Maunder minimum, weather in Europe was severe, below average in temperature. It has been referred to as a mini ice age. What if solar astronomers were able to predict such an occurrence again; a 70 year period of time during which the Earth would experience very cold temperatures that would affect crop yields and energy use? How would we react to this? How should preparations be made? Who would most be affected? Can humans really prepare for such a lengthy event?

5. Although Question 1 has you consider the fact that the Sun will last a very long time, you also are now aware that the Sun cannot last forever. Knowing what you now do about the energy source of the Sun and the fact that it will run out of hydrogen in its core in another 5 billion years, what do you think will happen to the Sun? How will it die out? Predict what it will look like as it goes through this process. Save what you have written until you have completed Chapter 20. Then compare what you predicted would happen to what actually will happen. Are there differences? What most surprises you about how the Sun will die out?

Answers to End of Chapter Exercises

Review and Discussion

1. Refer to Figure 16.2 for help in answering this question. The regions are: core, interior, convective zone, photosphere, chromosphere, and corona. You may also want to include the solar wind, although it is really not a part of the Sun because it is material being lost by the Sun. The radius of the core is 200,000 km, the interior is 300,000 km thick, convective zone is 200,000 km thick, photosphere is 300 km thick, chromosphere is 3,000 km thick, and the corona extends about a few million km above the chromosphere.

2. The Sun has 330,000 times the mass of the Earth.

3. The solar surface is 5800°K and the interior is about 15 million °K.

4. Luminosity is a measure of the true brightness or energy output of the Sun. It can be measured by experimentally determining how much energy is received from the Sun per square meter, at the distance of the Earth from the Sun. This is then multiplied by the surface area of a sphere the size of the Earth's orbit.

5. The Sun's energy output is fueled by the fusion of hydrogen into helium. In this process that takes place in the core of the Sun, 4 hydrogen atoms (really just protons) come together and fuse to form a heavier element, helium. In this process, a small amount of matter is lost; it has been converted into energy.

6. Only hydrogen goes into the proton-proton chain. What comes out is helium, two neutrinos, and energy in the form of gamma rays. The mass of helium produced is 0.7% less than the mass of the hydrogen that was fused to make it. This small amount of mass was converted into energy. The amount of energy is easily calculated from $E = mc^2$.

7. The helium formed has slightly less mass than the hydrogen that went into making it. The "lost" mass is actually converted into energy.

8. Knowing basic facts about the Sun, such as its mass and composition, and physical processes allow astronomers to predict the entire structure of the Sun. This is known as a model. The model is correct if it successfully predicts observed properties of the Sun, such as its luminosity, radius, and temperature. Some of the input information to the model is uncertain but the results suggest how correct this input data is. By making slight adjustments in the input parameters, the model is adjusted until its predictions are in agreement with all the observed properties. Once the model "works," astronomers are then able to learn from the model about the properties in the interior of the Sun. Models are used as a test to see whether we fully understand the structure and processes of objects. They are also then used to predict properties that may not be directly observable. Models also make predictions of observables that help us further test the validity of the model.

9. Helioseismology is the study of waves that occur on the surface of the Sun. Some of these waves travel from deep inside the Sun. Their appearance on the surface provides information about the interior of the Sun that cannot otherwise be observed.

10. The oscillations observed on the solar surface are equivalent to seismic waves observed on Earth. The waves depend on the internal structure of the Sun. Models of the solar interior predict the waves that should be observed; observed waves suggest how the models need to be modified until there is agreement between observations and models.

11. The solar radiation is first produced in the core of the Sun. Because the gas is totally ionized, it is transparent to radiation and so the radiation passes through it freely. But farther out, the temperature drops and more and more of the gas is not ionized or only partially ionized. Such a gas is opaque to radiation. At the outer edge of the radiation zone, all of the radiation has been absorbed by the gas. This heats the gas and it physically rises, while cooler gas from the surface falls. This is the region of convection. The energy is transported by convection to the photosphere. Here, the density of the gas is so low that radiation can freely escape into space.

12. Virtually all the visible radiation we receive from the Sun comes from a thin layer called the photosphere. It is only 500 km thick; a small fraction of the Sun's radius. So what we see is a sharply defined region of the Sun, below which radiation cannot escape and above which the gas is too thin to emit significant quantities of light.

13. "Coronium" was first discovered in the 1920s when spectra of the corona during a solar eclipse showed emission lines never before seen. These lines were at first thought to indicate the presence of a new element, "coronium." Further investigation showed that these lines were actually due to highly ionized elements. The high ionization was due to the corona's very high temperature, about one million °K.

14. Because the corona of the Sun is hot, some of the gas can escape into space; it escapes the gravity of the Sun. The gas is mostly composed of ionized hydrogen, that is, protons and electrons. The rush of particles away from the Sun is known as the solar wind.

15. The Sun's magnetic field reverses every 11 years, so it takes 22 years to go through an entire cycle of magnetic reversals.

16. All of these objects are caused by magnetic fields of the Sun. Sunspots are caused by kinks or loops of magnetic field extending through the lower atmosphere. Flares are not well understood but are the result of magnetic instabilities. They produce large quantities of energy in just a matter of minutes. Prominences are caused by very large loops of magnetic field that carry luminous gas far above the solar surface.

17. A coronal mass ejection, really a cloud of ionized gas, will be mostly captured by the Earth's magnetic field. Some of it gets through and ionizes the upper atmosphere, which alters radio communication. The magnetic field is swept along by the particles and can induce large currents in electrical power grids, knocking them out. Earth satellites are particularly vulnerable to these electrical and magnetic storms because of their delicate electronics.

18. The detection of solar neutrinos is very important to the complete understanding of the Sun's interior. Neutrinos are produced in the proton-proton chain, which occurs in the core of the Sun. The neutrinos pass unimpeded through the Sun. So neutrinos, in a sense, allow astronomers to directly observe the core of the Sun and the processes that occur there. At this time, the number of neutrinos observed is about half that predicted by the standard model.

19. Very simply, either the Sun is not producing the number of neutrinos we predict or something happens to the neutrinos on their way to the Earth. In order to produce fewer neutrinos, the Sun's core would have to be 10% cooler than we predict. But that would also drop the luminosity of the Sun below what is predicted and observed. It is more likely that we do not fully understand the properties of the neutrino. If they have a little mass, they might change properties during the time they move from the Sun to the Earth. Whether this occurs or not is still not known.

20. If the Sun's internal energy source suddenly shut down, nothing would be immediately observed from Earth other than a stop in the emission of neutrinos. The Sun would continue to shine for possibly millions of years before it would noticeably dim.

Conceptual Self-Test

1. T
2. T
3. F
4. T
5. F
6. F
7. F

8. F
9. T
10. F
11. C
12. B
13. C
14. A
15. A
16. B
17. B
18. C
19. C
20. B

Problems

1. (a) Mercury's distance from the Sun at perihelion is 0.31 A.U., i.e., 0.31 times closer than Earth is from the Sun. Since light varies by the inverse square law, it will receive $1 / (0.31)^2$ more light per square meter than do we. This is 10.4 times more or $1400 \times 10.4 = 14{,}600$ watts/m^2.

   (b) Jupiter's distance from the Sun is 5.20 A.U., i.e., 5.20 times farther than Earth is from the Sun. It will receive $(5.20)^2$ less light per square meter than do we. This is 27 times less or $1400 / 27 = 52$ watts/m^2.

2. From Chapter 3, Wien's law is the following. $\lambda_{max} = 0.29 / T$. T is the temperature in Kelvins and λ is the wavelength measured in centimeters.

   (a) For a core temperature of 10^7 °K the $\lambda_{max} = 2.9\times10^{-8}$ cm = 2.9 Å. X-rays

   (b) For the 10^5 °K temperature of the convection zone $\lambda_{max} = 2.9\times10^{-6}$ = 290 Å. Extreme UV.

   (c) For the 10^4 °K of the lower photosphere $\lambda_{max} = 2.9\times10^{-5}$ = 2900 Å. UV.

3. The Sun's luminosity is 3.86×10^{26} J/sec. How much matter must be processed in order to produce this energy for one second? The proton-proton chain produces 4.3×10^{-12} J when 6.7×10^{-27} kg of matter (4 protons) are fused. By dividing the Sun's luminosity by the energy of one proton-proton chain we will get the number of these reactions needed to produce the Sun's luminosity for one second. 4×10^{26} J / 4.3×10^{-12} J = 9.3×10^{37}. How much hydrogen is fused in order to produce this many reactions? Multiply this number times the mass of 4 protons. $9.3\times10^{37} \times 6.7\times10^{-27}$ kg = 6.2×10^{11} kg/s. (Note this is equivalent to about 600 million tons per second as stated in the text.)

   Finally, we need to compare the mass of hydrogen fused each second to the mass of the Earth and find how many seconds that amount of fuel would last for the Sun. The mass of the Earth is 5.98×10^{24} kg. 5.98×10^{24} kg / 6.2×10^{11} kg/sec = 9.6×10^{12} s. Since a year is about 30 million seconds, 9.6×10^{12} sec / 3×10^7 sec/yr = 320,000 years.

4. (a) Convert the solar luminosity into mass using $E = mc^2$. $3.86\times10^{26} = m(3\times10^8)^2$, $m = 4.3\times10^9$ kg/s. In 4.6 billion years this will amount to $4.6\times10^9 \times 3.2\times10^7 \times 4.3\times10^9 = 6.3\times10^{26}$ kg which is 0.03% of the Sun's mass.

   Since 0.7% of the mass is converted into energy, divide the mass lost by 0.007 to get 8.6×10^{28} kg of hydrogen has been used. This is 4.3% of the Sun's total mass.

   (b) First, convert one solar mass into the equivalent amount of energy. $E = 1.99\times10^{30} \times (3\times10^8)^2$. $E = 1.8\times10^{47}$ J. Divide this by the solar luminosity; the time will be in seconds. Convert the time to years. 1.8×10^{47} J / 3.86×10^{26} W = 4.86×10^{20} s. Dividing by 3.16×10^7 s/yr gives 1.5×10^{13} yr or 15 trillion years.

5. The Sun converts 4.3×10^9 kg/s of mass into energy. Dividing by 0.007, the total mass of hydrogen processed is 6.1×10^{11} kg/s. The Sun is 71% *by mass* hydrogen. Its total hydrogen is $0.71 \times 2\times10^{30}$ kg = 1.4×10^{30} kg. Dividing this by the rate at which hydrogen is being used gives 1.4×10^{30} kg / 6.1×10^{11} kg/s = 2.3×10^{18} s or 73.7 billion years. (The Sun will not last this long because it will use up its hydrogen in its core first and then evolve.)

6. Dividing the energy per reaction into the solar luminosity will give how many reactions occur each second. $3.86\times10^{26} / 4.3\times10^{-12} = 9.0\times10^{37}$ reactions per second. Two neutrinos are produced but only one gets to Earth. The cross-sectional area of the Earth is $\pi(6.4\times10^6)^2 = 1.3\times10^{14}$ m^2. The area of a sphere with radius of 1 A.U. is given in the text to be 2.8×10^{23} m^2. Dividing the Earth cross-sectional area by the total area of this sphere at 1 A.U. and multiplying by the number of reactions per second will give the number of neutrinos passing through the Earth each second. (1.3×10^{14} m^2 / 2.8×10^{23} m^2) $\times$ 9.0×10^{37} reactions/s = 4.1×10^{28} neutrinos/s

7. (a) Five minutes is 300 s, times 10 km/s gives 3,000 km.

   (b) The circumference is $2\pi r = 2\pi(696{,}000 \text{ km}) = 4.37\times10^6$ km. Dividing this by 3,000 gives 1458 wavelengths.

   (c) Converting the equatorial radius to A.U. gives 696,000 / 150,000,000 = 0.00464 A.U. (This gives the well-known result that the Sun's radius is about 1/200 of an A.U.) Use Kepler's third law to calculate the orbital period at this distance. $P^2 = (0.00464)^3$. P = 0.000316 yr = 2.77 hrs. = 166 minutes. Wave period is 33 times shorter.

8. The granule material will move 1000 km in 1000 s, which is 16.7 minutes. The granule should be disrupted faster than this because 1000 km is its diameter; the material does not have to flow completely across it for the granule to disappear. So the 10-minute lifetime observed sounds about right.

9. Use the ratio form of Stefan's law to find the fractional amount of light emitted by a sunspot. Flux = $(4500 / 5800)^4$. Flux = 0.36, so a sunspot emits about one third as much light as the photosphere.

10. This problem is equivalent to calculating the synodic period. 1 / S = 1 / 25.1 - 1 / 34.4, S = 93 days.

11. The temperature given in the text is 3 million °K. From *More Precisely 8–1*, equating escape speed to average molecular speed, and knowing the Sun's mass is 333,300 Earth masses gives

$$0.157\sqrt{\frac{3{,}000{,}000}{1}} = 11.2\sqrt{\frac{333{,}300}{R}}$$

$$R = 565 \text{ Earth radii} = 5.2 \text{ solar radii}$$

12. Divide the 2 billion kg into the mass of the Sun, $2\times10^{30} / 2\times10^{9} = 10^{21}$ s = 3.2×10^{13} yr. = 32 trillion years.

13. One Earth mass is $5.98\times10^{24} / 2\times10^{9} = 3\times10^{15}$ s = 9.5×10^{7} yr. = 95 million years.

14. $1.5\times10^{8} / (36 \times 3600) = 1200$ km/s. 3×10^{12} kg is lost in one week (which equals 604,800 s) or 5×10^{6} kg/s. But from Problem 8, the solar wind carries 2×10^{9} kg/s, which is 400 times more (or the flares produce 0.25% as much).

15. Convert the solar luminosity into mass using $E = mc^2$. 3.86×10^{26} W = $m \times (3\times10^{8})^2$. $m = 4.3\times10^{9}$ kg. This is about two times more mass lost than from the solar wind.

Resource Information

Student CD Media

Movies/Animations
May 12, 1997 Solar Flare Event
Coronal Mass Ejection

Interactive Student Tutorials
SuperSpaceship-Voyage to the Sun

Physlet Illustrations
Rotation by Sunspots
Random Walk

Transparencies

T-140	Figure 16.1	The Sun	p. 407
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Materials

A bar magnet and iron filings can be used to demonstrate magnetic field lines.

A light meter and a solar spectrum chart suitable for hanging on a wall are available from Edmund Scientific.

It is helpful to have a large periodic chart available when discussing the proton–proton chain.

The Astronomical Society of the Pacific sells the Sunspotter® solar telescope, solar eclipse glasses, and various other daytime astronomy materials.

Suggested Readings

Bahcall, J. “How the Sun Shines.” *Mercury* (September/October 2001). p. 30. Historical development of the Solar research and Solar theory. Discussions of the proton-proton chain and traces the path of a photon from the fusion core to the photosphere.

Bartusiak, Marcia. “Underground astronomer.” *Astronomy* (Jan 2000). p. 64. Talks about the life and work of Raymond Davis, the inventor of neutrino astronomy.

Burtnyk, Kimberly. “Anatomy of an aurora.” *Sky & Telescope* (Mar 2000). p. 34. Describes the formation of the aurora.

di-Cicco, Dennis. “Photographing the analemma.” *Sky & Telescope* (Mar 2000). p. 135. Discusses methods and techniques used to photograph the analemma.

Eather, Robert H. “An aurora watcher's guide.” *Sky & Telescope* (Mar 2000). p. 42. Offers advice on how to observe the aurora.

Franklin, A. “The Road to the Neutrino.” *Physics Today* (February 2000). p. 22. Historical description of the discovery and subsequent study of the neutrino.

Harrington, Phil. “The sunny side of stargazing.” *Astronomy* (Jan 2000). p. 100. Offers advice on how to observe the Sun.

Haxton, W.; Holstein, B. “Neutrino Physics.” *American Journal of Physics* (January 2000). p. 15. Technical and thorough treatment of the basic concepts of neutrino physics.

Hayden, Thomas. “Curtain call.” *Astronomy* (Jan 2000). p. 44. Describes the distant future of the Earth and Sun.

Lang, Kenneth R. “Unsolved mysteries of the Sun - part 2.” *Sky & Telescope* (Sept 1996). p. 24. Discusses helioseismology (the study of solar oscillations) and the results of the SOHO mission.

Medkeff, Jeff. “A beginner's guide to solar observing.” *Sky & Telescope* (June 1999). p. 122. A guide to observing sunspots and other features on the Sun.

Newton, J. “Imaging the Sun in Hα.” *Astronomy* (June 2003). p. 78. Many excellent photographs and tips on imaging the Sun through an Hα filter.

Odenwald, Sten. "Solar storms: the silent menace." *Sky & Telescope* (Mar 2000). p. 50. Discusses effects felt on Earth from solar storms.

Plait, P.; Cook, L "Under Alien Skies." *Astronomy* (January 2003). p. 37. Provocative discussion and images of what the night sky might look like for inhabitants of extrasolar planets.

Semeniuk, Ivan. "Catching cosmic ghosts." *Astronomy* (June 1999). p. 38. Discusses neutrinos and neutrino astronomy.

Soon, W.; Yaskell, H. "Year Without a Summer." *Mercury* (May/June 2003). p. 13. Detailed discussion of the interaction between solar activity and Earth's climate. Focuses on events on Earth and on the Sun in the year 1816.

Tyson, Neil De Grasse. "Journey from the center of the sun." *Natural History* (Apr 1996). p. 68. Describes how a photon of light travels from its place of origin in the core to the surface of the Sun.

Notes and Ideas

*Class time spent on material: Estimated:*_______ *Actual:*______________

Demonstration and activity materials:

Notes for next time: