16.E: The Sun- A Nuclear Powerhouse (Exercises)

For Further Exploration

Articles

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

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

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

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

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

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

Websites

Albert Einstein Online: http://www.westegg.com/einstein/.

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

GONG Project Site: http://gong.nso.edu/.

Helioseismology: solar-center.stanford.edu/abo...eismology.html.

Princeton Plasma Physics Lab: http://www.pppl.gov/.

Solving the Mystery of the Solar Neutrinos: www.nobelprize.org/nobel_priz...ysics/bahcall/.

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

Videos

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

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

Collaborative Group Activities

1. In this chapter, we learned that meteorites falling into the Sun could not be the source of the Sun’s energy because the necessary increase in the mass of the Sun would lengthen Earth’s orbital period by 2 seconds per year. Have your group discuss what effects this would cause for our planet and for us as the centuries went on.
2. Solar astronomers can learn more about the Sun’s interior if they can observe the Sun’s oscillations 24 hours each day. This means that they cannot have their observations interrupted by the day/night cycle. Such an experiment, called the GONG (Global Oscillation Network Group) project, was first set up in the 1990s. To save money, this experiment was designed to make use of the minimum possible number of telescopes. It turns out that if the sites are selected carefully, the Sun can be observed all but about 10% of the time with only six observing stations. What factors do you think have to be taken into consideration in selecting the observing sites? Can your group suggest six general geographic locations that would optimize the amount of time that the Sun can be observed? Check your answer by looking at the GONG website.
3. What would it be like if we actually manage to get controlled fusion on Earth to be economically feasible? If the hydrogen in *water* becomes the fuel for releasing enormous amounts of energy (instead of fossil fuels), have your group discuss how this affects the world economy and international politics. (Think of the role that oil and natural gas deposits now play on the world scene and in international politics.)
4. Your group is a delegation sent to the city council of a small mining town to explain why the government is putting a swimming-pool-sized vat of commercial cleaning fluid down one of the shafts of an old gold mine. How would you approach this meeting? Assuming that the members of the city council do not have much science background, how would you explain the importance of the project to them? Suggest some visual aids you could use.

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

Review Questions

1. How do we know the age of the Sun?
2. Explain how we know that the Sun's energy is not supplied either by chemical burning, as in fires here on Earth, or by gravitational contraction (shrinking).
3. What is the ultimate source of energy that makes the Sun shine?
4. What are the formulas for the three steps in the proton-proton chain?
5. How is a neutrino different from a neutron? List all the ways you can think of.
6. Describe in your own words what is meant by the statement that the Sun is in hydrostatic equilibrium.
7. Two astronomy students travel to South Dakota. One stands on Earth's surface and enjoys some sunshine. At the same time, the other descends into a gold mine where neutrinos are detected, arriving in time to detect the creation of a new radioactive argon nucleus. Although the photon at the surface and the neutrinos in the mine arrive at the same time, they have had very different histories. Describe the differences.
8. What do measurements of the number of neutrinos emitted by the Sun tell us about conditions deep in the solar interior?
9. Do neutrinos have mass? Describe how the answer to this question has changed over time and why.
10. Neutrinos produced in the core of the Sun carry energy to its exterior. Is the mechanism for this energy transport conduction, convection, or radiation?
11. What conditions are required before proton-proton chain fusion can start in the Sun?
12. Describe the two main ways that energy travels through the Sun.

Thought Questions

1. Someone suggests that astronomers build a special gamma-ray detector to detect gamma rays produced during the proton-proton chain in the core of the Sun, just like they built a neutrino detector. Explain why this would be a fruitless effort.
2. Earth contains radioactive elements whose decay produces neutrinos. How might we use neutrinos to determine how these elements are distributed in Earth's interior?
3. The Sun is much larger and more massive than Earth. Do you think the average density of the Sun is larger or smaller than that of Earth? Write down your answer before you look up the densities. Now find the values of the densities elsewhere in this text. Were you right? Explain clearly the meanings of density and mass.
4. A friend who has not had the benefit of an astronomy course suggests that the Sun must be full of burning coal to shine as brightly as it does. List as many arguments as you can against this hypothesis.
5. Which of the following transformations is (are) fusion and which is (are) fission: helium to carbon, carbon to iron, uranium to lead, boron to carbon, oxygen to neon? (See Appendix K for a list of the elements.)
6. Why is a higher temperature required to fuse hydrogen to helium by means of the CNO cycle than is required by the process that occurs in the Sun, which involves only isotopes of hydrogen and helium?
7. Earth's atmosphere is in hydrostatic equilibrium. What this means is that the pressure at any point in the atmosphere must be high enough to support the weight of air above it. How would you expect the pressure on Mt. Everest to differ from the pressure in your classroom? Explain why.
8. Explain what it means when we say that Earth's oceans are in hydrostatic equilibrium. Now suppose you are a scuba diver. Would you expect the pressure to increase or decrease as you dive below the surface to a depth of 200 feet? Why?
9. What mechanism transfers heat away from the surface of the Moon? If the Moon is losing energy in this way, why does it not simply become colder and colder?
10. Suppose you are standing a few feet away from a bonfire on a cold fall evening. Your face begins to feel hot. What is the mechanism that transfers heat from the fire to your face? (Hint: Is the air between you and the fire hotter or cooler than your face?)
11. Give some everyday examples of the transport of heat by convection and by radiation.
12. Suppose the proton-proton cycle in the Sun were to slow down suddenly and generate energy at only 95% of its current rate. Would an observer on Earth see an immediate decrease in the Sun's brightness? Would she immediately see a decrease in the

number of neutrinos emitted by the Sun?

13. Do you think that nuclear fusion takes place in the atmospheres of stars? Why or why not?
14. Why is fission not an important energy source in the Sun?
15. Why do you suppose so great a fraction of the Sun's energy comes from its central regions? Within what fraction of the Sun's radius does practically all of the Sun's luminosity originate (see Figure $16.3.7$ in Section 16.3)? Within what radius of the Sun has its original hydrogen been partially used up? Discuss what relationship the answers to these questions bear to one another.
16. Explain how mathematical computer models allow us to understand what is going on inside of the Sun.

Figuring for Yourself

1. Estimate the amount of mass that is converted to energy when a proton combines with a deuterium nucleus to form ^{3}He.
2. How much energy is released when a proton combines with a deuterium nucleus to produce ^{3}He?
3. The Sun converts $4 \times 10^{9}\ \text{kg}$ of mass to energy every second. How many years would it take the Sun to convert a mass equal to the mass of Earth to energy?
4. Assume that the mass of the Sun is 75% hydrogen and that all of this mass could be converted to energy according to Einstein's equation $E = mc^{2}$. How much total energy could the Sun generate? If m is in kg and c is in m/s, then E will be expressed in J. (The mass of the Sun is given in Appendix E.)
5. In fact, the conversion of mass to energy in the Sun is not 100% efficient. As we have seen in the text, the conversion of four hydrogen atoms to one helium atom results in the conversion of about 0.02862 times the mass of a proton to energy. How much energy in joules does one such reaction produce? (See Appendix E for the mass of the hydrogen atom, which, for all practical purposes, is the mass of a proton.)
6. Now suppose that all of the hydrogen atoms in the Sun were converted into helium. How much total energy would be produced? (To calculate the answer, you will have to estimate how many hydrogen atoms are in the Sun. This will give you good practice with scientific notation, since the numbers involved are very large! See Appendix C for a review of scientific notation.)
7. Models of the Sun indicate that only about 10% of the total hydrogen in the Sun will participate in nuclear reactions, since it is only the hydrogen in the central regions that is at a high enough temperature. Use the total energy radiated per second by the Sun, 3.8×10^{26} watts, alongside the exercises and information given here to estimate the lifetime of the Sun. (Hint: Make sure you keep track of the units: if the luminosity is the energy radiated per second, your answer will also be in seconds. You should convert the answer to something more meaningful, such as years.)
8. Show that the statement in the text is correct: namely, that roughly 600 million tons of hydrogen must be converted to helium in the Sun each second to explain its energy output. (Hint: Recall Einstein's most famous formula, and remember that for each kg of hydrogen, 0.0071 kg of mass is converted into energy.) How long will it be before 10% of the hydrogen is converted into helium? Does this answer agree with the lifetime you calculated in the previous exercise?
9. Every second, the Sun converts 4 million tons of matter to energy. How long will it take the Sun to reduce its mass by 1% (the mass of the Sun is 2×10^{30})? Compare your answer with the lifetime of the Sun so far.
10. Raymond Davis Jr.'s neutrino detector contained approximately 1030 chlorine atoms. During his experiment, he found that one neutrino reacted with a chlorine atom to produce one argon atom each day.
    1. How many days would he have to run the experiment for 1% of his tank to be filled with argon atoms?
    2. Convert your answer from A. into years.
    3. Compare this answer to the age of the universe, which is approximately 14 billion years (1.4×10^{10} y).
    4. What does this tell you about how frequently neutrinos interact with matter?