

OpenStax Astronomy, Ch.16: WS Solutions (Apr-2021)

Solutions

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

Through radioactive dating, we can determine the age of Earth, the Moon, and meteorites to be about 4.5 billion years. Our models of the formation of the solar system and observations of the formation of other stars with planets tell us that the Sun formed at the same time as the other members of our solar system.

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).

The vast amount of energy produced by the Sun over the past 4.5 billion years exceeds the amount that could be supplied by burning or shrinking of the Sun by a significant factor. Chemical burning would only last a few thousand years, whereas gravitational contraction would provide energy for only about a hundred million years.

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

Matter that is converted into energy through the fusion of hydrogen into helium.

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

First, the neutrino's mass is much, much smaller; second, it hardly interacts with matter at all, where as a neutron interacts with other particles; third, it isn't one of the particles to make up an atom; fourth, it can "oscillate" (change from one type of neutrino to another between the Sun's core and Earth).

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

The pressure and gravity are in balance throughout the Sun, from the very center to the surface. This means the gas pressure at any depth within the Sun can support the weight of all of the gas pressing down upon it, due to gravity. So the Sun neither expands nor contracts but remains as it is; this is true at every point within the Sun as well as for the Sun overall.

6. 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.

The neutrino was generated in a fusion reaction in the Sun's core and made it out of the Sun in about 2 seconds and then continued through space until it arrived at Earth about 500 seconds later. Since this neutrino was detected by this process, we know it avoided oscillating and changing into a different kind of neutrino. The photon, which left the Sun's photosphere as sunshine, is "descended" from a gamma-ray photon that was created 100,000 to 1,000,000 years ago by fusion. That gamma ray was absorbed by a particle that reemitted a photon in a totally random direction. That process repeated itself over and over again until some of that energy emerged from the Sun's surface as a photon of visible light. That photon then also arrived at Earth a little more than 8 minutes later.

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



The neutrinos are being produced in the solar core by fusion reactions, and measuring their number gives us a sensitive probe into what is happening in the Sun's core. It helps confirm that there are enough proton-proton chain reactions (each of which produces a neutrino) going on in the Sun's core to explain the energy output of the Sun.



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

Yes, they do have mass, and they have always had mass. Human just didn't know that at first. When neutrinos were first proposed by Pauli, physicists thought they were massless particles (all energy).

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

Since the majority of neutrinos produced inside the Sun do not interact with other particles as they leave the Sun, the energy they carry is transported as radiation.

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

The Sun must be dense and hot enough in the center for the motion of the protons to overcome their mutual repulsion, with a temperature of at least 12 million K.

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

Energy is created through fusion of hydrogen into helium at the center of the Sun. This energy first enters the radiative region of the Sun, where photons are absorbed and reemitted in random directions until they make it about 2/3 of the way to the surface. Once the energy has traveled 2/3 of the way to the surface, it reaches the convection zone where the hot gas flows up and down (like water boiling in a pot) carrying the energy to the solar surface.

12. 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.

There is less air between the top of Mt. Everest and the outer edge of Earth's atmosphere than there is, say, between a location at sea level and the outer edge of the atmosphere. It takes less pressure to hold up the smaller mass above Mt. Everest. Since the altitude of your classroom is lower than that of Mt. Everest, the pressure in your classroom is higher. The summit of Mt. Everest is above about 70% of the molecules in Earth's atmosphere, and the pressure at the summit is only about 30% the pressure at sea level.

13. 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?

Radiation is the mechanism that transports heat away from the surface of the Moon. Since space is nearly a vacuum, the alternative mechanisms of conduction and convection cannot work. The Moon does become colder at night. It also becomes hotter and hotter during the day. Any location on the surface of the Moon is heated by the radiation from the Sun, which raises its temperature. When that location faces away from the Sun, it radiates heat away from the Moon's surface. Overall, the total amount of heat received from the Sun during the day equals the total amount of heat radiated away into space.

14. 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?)

The heat from the fire is transported by radiation. The air itself remains cold, as you can easily tell if you turn your back to the fire. Therefore, the heat is not transported by the air, as would be the case for convection or conduction.





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

A floor heater spreads heat throughout a room by convection. Ironically, the style of heater called a radiator doesn't really radiate much energy. Most of its heat is transported by convection of the air which it heats (you can test this easily by comparing how well it warms your hand if you place it 12 inches off to the side to how well it warms your hand if it is 12 inches above it). Absorption of sunlight and subsequent radiation of infrared energy by Earth in its daily cycle is an example of radiation. (Heat from a light bulb or from a fire also are examples of radiation.)

16. 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?

The observer would see a decrease in the number of neutrinos almost immediately since neutrinos take only about 2 seconds to travel from the center of the Sun to its surface and another 8 minutes to reach Earth. Light, on the other hand, takes about 10^5 to 10^6 years to traverse the distance from the center of the Sun to its surface, so 10^5 to 10^6 years would elapse before an observer on Earth saw a decrease in the brightness of the Sun.

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

Each year, the Sun converts $(4 \times 10^9 \text{ kg}) \times (3 \times 10^7 \text{ s/y})$, or $1.2 \times 10^{16} \text{ kg/y}$. Divide the mass of Earth ($6 \times 10^{24} \text{ kg}$) by this to get 5×10^7 , or 50 million y.

18. 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.

If the mass of the Sun is 2×10^{30} , then 1% of the mass of the Sun is $2 \times 10^{28} \text{ kg}$. If the Sun fuses $4 \times 10^6 \text{ tons/s} \times 2000 \text{ lb/ton} \times 1 \text{ kg}/2.2 \text{ lb} = 3.6 \times 10^9 \text{ kg/s}$, then it will take $5.6 \times 10^{18} \text{ s}$ to destroy 1% of the Sun's mass. Since there are about $3.15 \times 10^7 \text{ s/y}$, it will take about 1.8×10^{11} or about 180 billion years to destroy 1% of the Sun's mass. Since the Sun is only about 5 billion years old, the decrease in mass so far is negligible.

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

- How many days would he have to run the experiment for 1% of his tank to be filled with argon atoms?
- Convert your answer from A. into years.
- Compare this answer to the age of the universe, which is approximately 14 billion years (1.4×10^{10} years).
- What does this tell you about how frequently neutrinos interact with matter?

A. 1% of 10^{30} atoms is $0.01 \times 10^{30} = 10^{28}$; B. $10^{28} \text{ day} \times 1 \text{ year}/365 \text{ days} = 1.37 \times 10^{25} \text{ years}$; C. For 1% of the tank to be converted to argon atoms, it would take many orders of magnitude longer than the age of the universe; D. Neutrinos interact so infrequently that you would have to wait much longer than the age of the universe for



the neutrinos to create a substantial amount of argon in Davis's experiment. Thus, they truly don't interact with matter all that often.

