1

THE SIZE AND SCALE OF THE UNIVERSE

1. Scientific notation review

Write the following in proper scientific notation, giving the proper number of significant figures.

1.a Thirty-one million, seven hundred thousand

1.b π (the number pi) times 0.2

1.c One fourth

1.d One nanometer (expressed in meters)

2. How long is a year?

Calculate the number of seconds in a year to two significant figures.

3. How fast does light travel?

The speed of light is 3.0×10^8 meters per second. What is the speed of light in units of kilometers per year?

4. Arcseconds in a radian

Calculate the number of arcseconds in a radian, to one significant figure. This is a number we will use throughout this problem book. Hint: *Remember how many degrees, and how many radians, there are in a full circle.*

5. How far is a parsec?

A parsec is the distance at which a star would lie if it has a **par**allax of 1 arc**sec**ond as Earth goes around the Sun. Calculate how far 1 parsec is, in AU and in light-years. Hint: *Remember that the parallax is traditionally defined as* **half** *the angle that the position of a star changes as Earth goes from one side of its orbit around the Sun to the other.*

6. Looking out in space and back in time

The speed of light is 3.0×10^5 km/sec. The distance between Earth and the Sun (1 Astronomical Unit, or AU) is 150 million kilometers. Give all answers to the correct number of significant figures.

6.a You look at your friend, 30 feet (10 meters) away. How far back in time are you seeing her? Express your answer in nanoseconds. The light entering your eyes from your friend is ambient light in the surroundings that reflects off her.

6.b Electrical engineers are always looking for ways to increase the speed of computer chips. One way to allow computers to perform more operations per second is simply to reduce the distance between components, so that the electrical circuits are shorter. The electrons that "flow" from one transistor to the next in your computer travel at close to the speed of light. In modern chips, these distances are impressively small, in 2017 approaching 10 nanometers (one hundredth of a micron). How long, in seconds, does it take the electrons to "flow" from one transistor to the other? Please use scientific notation.

6.c How far back in time are we looking when we observe the Orion Nebula, which is 1,500 light-years away? Express your answer in years.

7. Looking at Neptune

All electromagnetic radiation (including radio waves) travels at the speed of light. In 1989, the Voyager II spacecraft flew by the planet Neptune. Neptune is on a roughly circular orbit around the Sun of radius 30 AU, while Earth is on a circular orbit of radius 1.00 AU (of course!). (For this problem, at the level of precision asked for, the approximation that these planetary orbits are circles lying in the same plane is a good one.)

7.a How far back in time are we seeing Neptune, when Neptune is farthest from Earth in the two planet's orbits? Give your answer in hours and minutes.

7.b How far back in time are we seeing Neptune, when it is *nearest* to Earth in the two planet's orbits? Give your answer in hours and minutes.

8. Far, far away; long, long ago

Problem suggested by Chris Chyba.

Because the speed of light is finite, looking at anything means seeing the thing as it was some time in the past. This usually doesn't matter in daily life on Earth, but it is often important in astronomy and spacecraft engineering, or for communication among galactic civilizations. We'll explore this question here.

8.a Earth started transmitting powerful radio signals in the 1930s, and these signals travel out to space at the speed of light. Consider a radio broadcast sent in 1936. If there were extraterrestrial civilizations listening for radio signals drifting out into the Galaxy, and they were to pick up this broadcast, out to what distance from our solar system could these civilizations have already detected our presence? Give your answer in light-years; round to whole numbers.

8.b The Arecibo radio telescope in Puerto Rico (one of the largest radio telescopes on Earth) can transmit radio signals (as a radar transmitter) as well as receive them. Arecibo is so sensitive that, if there were a duplicate Arecibo on another planet (call it Zyborg) half-way to the center of the Galaxy, and Zyborg's Arecibo were pointed at Earth, it could pick up a transmission from Arecibo, Puerto Rico. The Sun is about 25,000 light-years from the center of the Milky Way. How long would it take a signal sent from Arecibo, Puerto Rico to reach Arecibo, Zyborg? Again, express your answer in years, to the appropriate number of significant figures.

8.c Suppose you were trying to have a conversation with an astronaut on the Moon. The Moon is 384,400 kilometers from Earth. If you sent a radio signal to an astronaut on the Moon, and she replied immediately, how long would be the gap between when you sent the signal and you received your answer? Give an answer to two significant figures.

8.d Now imagine that you are an engineer for the Mars Exploration Rover scooting around on the surface of Mars. Suppose you need to send it an emergency transmission to prevent it from driving into a ditch. Mars is on a roughly circular orbit of radius 1.5 AU around the Sun. Earth is also on a circular orbit in the same plane, of radius 1.0 AU, of course. (For these two planets the approximation of their orbits as circles is a good one at the level of precision asked for in this problem.) About how long would it take your message to reach the rover when Mars is in opposition (i.e., when Earth lies on the line between Mars and the Sun, and is between them)? How long would it take when Mars is farthest from Earth in the two planets' orbits? Give your answers in minutes.

9. Interstellar travel

In *Star Trek* they routinely hop from star to star during the TV commercials.

9.a Apollo 11 astronauts left Earth's atmosphere at a speed of about 40,000 kilometers per hour (7 miles per second) on the Saturn V booster, the most powerful rocket ever launched—before or since. At that speed, how long would it take to travel to the Moon?

9.b If you could travel 30 times that speed, how long would it take you to reach Proxima Centauri (distance ~ 4 light-years), which is the nearest star to the Sun?

9.c If you could travel *another* factor of 30 faster, how long would it take to get to the Andromeda Galaxy, the nearest large galaxy to the Milky Way (distance ~ 2 million light-years)?

You are now traveling 1,000 times faster than the Apollo astronauts, just as they traveled 1,000 times faster than the *Wright Flyer*, the first airplane flown by the Wright Brothers in 1903. And if your calculations are correct, you will notice that you would be dead long before you reached either the stars or Andromeda.

10. Traveling to the stars

In this problem, we examine just how far the stars are from us. The nearest star, Proxima Centauri, is about 4 light-years from Earth. That is a seriously large distance. The spacecraft that we have built to date travel through the solar system at roughly the same speed that Earth travels around the Sun.

10.a Calculate the speed at which Earth travels around the Sun, given that it travels in a circle of radius 1 Astronomical Unit (AU) = 150 million kilometers, in 1 year. Express your answer in kilometers per second.

10.b Knowing that light travels at 300,000 kilometers per second, calculate how many kilometers there are in 4 light-years.

10.c Consider a spacecraft that travels at the speed you calculated in part **a**. Calculate how long it would take for the spacecraft to reach the nearest stars. Express your answer in years.

11. Earth's atmosphere

A cubic meter of air at sea level contains approximately 3×10^{25} molecules. To a fair approximation, all the molecules are N_2 (i.e., a pair of nitrogen atoms bound together into a diatomic molecule). Note that the component of the air that you need to breathe—the oxygen (O_2) molecules—comprises only about 21% of the air by volume; we ignore this O_2 fraction here and pretend that the whole atmosphere is N_2. Each N atom has a mass 14 times that of hydrogen (H).

11.a Calculate the mass density (kilograms per cubic meter) of air on Earth. Do this calculation without a calculator, show your work, and use scientific notation.

11.b Consider the atmosphere to be a spherical shell of thickness 8 kilometers and radius equal to that of Earth itself. Calculate the total volume of Earth's atmosphere.

11.c Combine your work in parts **a** and **b** to calculate the total mass of Earth's atmosphere in kilograms. The mass of all of Earth's oceans is 1.4×10^{21} kg. Compare the mass of the ocean with the mass of the atmosphere by taking the ratio of the two.

11.d Carbon dioxide (CO_2) now comprises about 600 ppm (parts per million, or 10^{-6}) of the atmosphere by mass. What is the total mass of CO_2 in Earth's atmosphere?