The Solar System

Objectives: To investigate the size and shape of the solar system, to study the orbital properties of bodies within the solar system, to gain insight into Kepler's first two laws.

Equipment: Two-meter sticks, models of the planets, flashlights.

Discussion: The solar system consists of the Sun and a number of smaller objects (planets, comets, meteoroids, etc.) in a configuration that resembles a large disk. All of the planets revolve about the Sun in the same counterclockwise direction (as viewed from the north) and, with a couple of exceptions, most of their orbits lie in nearly the same plane. Mercury's orbit is inclined about 7^o relative to the plane of the solar system and Pluto's orbit about 17^o.

Kepler's First Law states that the orbits of the planets are not circular, but elliptical, with the sun at one of the foci of the ellipse. The reason that the orbits are elliptical instead of circular is fairly complex and will not be discussed here (for an excellent treatment of this topic, see *Exploration of the Universe*, 5th edition, by George Abell, pp. 60-61). The term used to describe a deviation from a circular orbit is called *eccentricity*. The orbits of the planets have a very small eccentricity and are therefore very nearly circular. The orbital eccentricity of the Earth, for instance, is only 0.017. This means that at *perihelion* the distance from the Earth to the Sun is 91,000,000 miles and at *aphelion* this distance is 95,000,000 miles. Mercury (e = 0.21) and Pluto (e = 0.25) have somewhat greater eccentricities. Most comets, by contrast, have large orbital eccentricities. Halley's comet (e = 0.967) has a perihelion distance of 55,000,000 miles while its aphelion distance is beyond the orbit of Neptune.

Most of the mass in the solar system (99.85%) is concentrated in the Sun. The planets comprise most of the remaining mass, and their satellites, comets, etc., make up the rest. For the most part, the nine major planets in the solar system may be divided into two sharply contrasting groups. These are:

1. Those having properties roughly similar to those of the Earth are called *terrestrial* planets. Mercury, Venus, Earth, and Mars are in this group. Terrestrial planets are rocky bodies composed mostly of silicates and metals. Venus, Earth and Mars have atmospheres but Mercury is too small to retain an atmosphere.

2. Those having gaseous properties and relatively large diameters are called *Jovian* planets. Jupiter, Uranus, Saturn, and Neptune are in this group. The Jovian planets lack solid surfaces and are composed largely of light elements such as hydrogen, helium, argon, carbon, oxygen, and nitrogen in gaseous or liquid form.

Pluto is neither terrestrial nor Jovian. It is most similar in size and composition to some of the satellites of the Jovian worlds.

Procedure

The average distance from Earth to the Sun is about 1.5×10^{13}cm (in c.g.s. units). The average distance from Pluto to the Sun is 3.58×10^{14}cm. We wish to scale these distances down so that we may construct a *scale model* of the solar system, i.e., a model in which the relative distances between planetary objects remain the same. First we must decide how large our model should be. If we were to build a scale model of, for instance, an aircraft carrier, we would chose a scale such that the model would fit conveniently in the area in which it was to be displayed. An aircraft carrier is on the order of 1000 feet in length. In order for us to have a 20 inch long scale model we would have to use a scale factor of 1 inch = 50 feet. Mathematically, a scale factor (SF) may be expressed:

$$SF = \frac{size\ of\ the\ model}{size\ of\ the\ object}$$

In this particular example (recalling that 1 foot equals 12 inches):

$$SF = \frac{20\ inches}{12000\ inches} = \frac{1\ inch}{600\ inches} = 1.66 \times 10^{-3}$$

Notice that the units cancel in the above calculation. The SF is, therefore, a unitless number. If we wanted to determine the length of a model airplane on our model carrier we would multiply the length of a real airplane by the SF of 1.66×10^{-3}.

Now let's assume that we want our model solar system to have a radius of 1000 cm (i.e., the distance from the Sun to Pluto will be 1000 cm). The SF will be:

$$SF = \frac{1 \times 10^{3}\,cm}{3.58 \times 10^{14}\,cm} = .279 \times 10^{-11} = 2.79 \times 10^{-12}$$

To find the scaled distance between Earth and the Sun we would simply multiply the SF by the actual distance:

$$(2.79 \times 10^{-12}) \times (1.50 \times 10^{13}\,cm) = 4.19 \times 10^{1} = 41.9cm$$

A more convenient scale would result from placing Pluto 4000 cm from the Sun thus allowing us to construct a larger model in the hallway outside the lab. Using Table 1, compute the scale distances to the planets in your model solar system. A set of markers and meter sticks will be provided for your use. When you have computed the scale distances, construct your model solar system in the hall outside the lab.

Notice that the distances given from the Sun to Neptune and Pluto are the same. Drawing upon your knowledge of the eccentricity of Pluto's orbit, what explanation can you give for this?

Table 1. Orbital data (semimajor axis) for the planets.

Planet	Distance to the Sun
Sun	
Mercury	5.79×10^{12} cm
Venus	1.08×10^{13} cm
Earth	1.50×10^{13} cm
Mars	2.28×10^{13} cm
Jupiter	7.78×10^{13} cm
Saturn	1.43×10^{14} cm
Uranus	2.87×10^{14} cm
Neptune	3.58×10^{14} cm †
Pluto	3.58×10^{14} cm †

† Actual distance, not the semimajor axis length

Kepler's second law states that the *radius vector* of each planet sweeps out equal areas in equal times. This is illustrated in Figure 1 below. A planet's motion about the sun is represented by an ellipse with the sun (**S**) at one of the foci. The radius vector is an imaginary line that points from the sun to the planet at any location along the ellipse. The planet is at perihelion at point **A** and aphelion at point **D**. Areas **ASB** and **CSD** are equal. Notice that in order for the radius vector to sweep out equal areas in equal time, the planet must travel more rapidly along the portion of the ellipse from **A** to **B** than from **C** to **D**. Therefore a planet moves more rapidly through space when it is at perihelion than at aphelion.

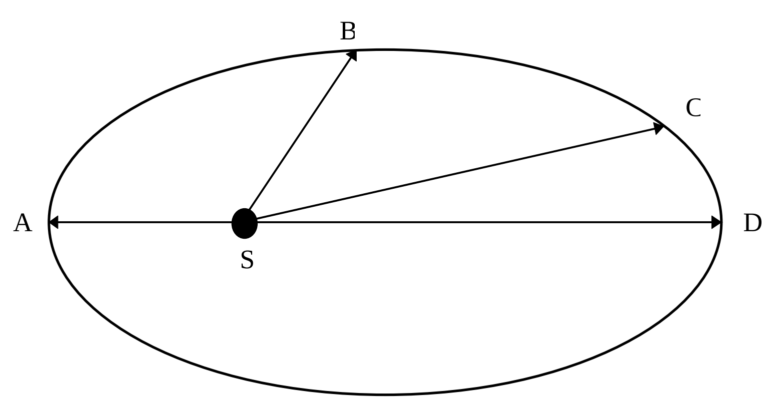
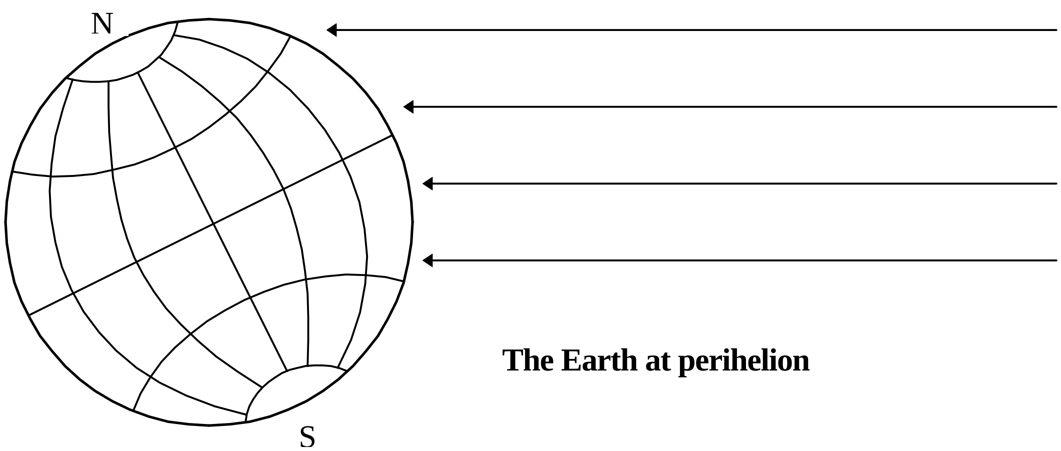


Figure 1. Areas **ASB** and **CSD** are equal. A planet travels more rapidly along the portion of the arc **AB** than in does along **CD**.

The earth is at perihelion in early January each year. This is when its orbital speed is greatest. It gradually slows down until reaching aphelion in July when its orbital speed is at its minimum. *The earth is actually closer to the sun when temperatures are coldest in the northern hemisphere*. This is possible because even though the sun is much closer to the earth during our winter months, the sun's rays travel a greater distance through the atmosphere and strike the earth at a more oblique angle in the northern hemisphere due to the $23\frac{1}{2}^0$ tilt of the earth about its rotational axis.



The Earth at perihelion

Energy from the sun that strikes the earth from directly overhead is more *intense* than energy that strikes the earth at an angle because the light at an angle is spread out over a greater area. You can verify this for yourself with a flashlight. Hold the flashlight about a foot above your lab notebook and shine the beam directly onto the center of a blank page. Trace the outline of the beam and count the number of squares within this circle. The number of squares may be used to give a rough estimate of the area illuminated by the flashlight beam. From the same height shine the beam onto the center of the page at an angle of about 45^0 and trace the outline of the second beam, again counting the squares within the area of the trace. Intensity is defined as power per unit area. Since the power of the flashlight beam is unchanged, in which case is the intensity of the light the lowest?

Even though the difference between the earth's perihelion and aphelion distances is less than 3%. The amount of solar energy striking the earth is 7% greater at perihelion (in January) than at aphelion (in July). This would lead one to conclude that summer in the southern hemisphere, which occurs at perihelion, is warmer than summer in the northern hemisphere. This, however, is not the case. Most of the land mass of the earth is concentrated in the northern hemisphere. The southern hemisphere, by contrast, is 80% covered by water. Water has the ability to absorb large amounts of heat. The additional solar energy supplied by the sun at perihelion is absorbed by the large bodies of water in the southern hemisphere. The result is that temperatures are actually more moderate during summers in the southern hemisphere. On Mars, which does not have any oceans to absorb heat, the temperature fluctuations are much greater due to perihelion and aphelion.

Finally, spring and summer are shorter in the southern hemisphere than in the northern. This is because of the elliptical nature of the earth's orbit and its varying orbital speed. The number of days from the vernal equinox (March 20) to the autumnal equinox (September 22) is about a week longer than from autumnal to vernal.

Exercises

1. What is the definition of perihelion? Aphelion?

2. What two planets have overlapping orbits?

3. What two planets have orbits that are separated by the largest average distance?

4. One wishes to construct a table top model of the moon. If the diameter of the moon is 2.2×10^8 cm and the model is to be 50 cm in diameter, what scaling factor will be used?

5. Why does the distance that sunlight travels through the atmosphere affect the amount of solar energy that reaches the earth's surface?

6. Why are summer temperatures in the southern hemisphere more moderate than temperatures in the northern hemisphere even though the earth is closer to the sun during the southern summer?

7. Define the term *intensity*.

8. Using the same scale factor that you used to construct your scale model of the solar system, what would be the diameter of the sun if the actual diameter of the sun is 1.39×10^{11} cm?

9. What would be the size of Jupiter at the same scale factor if the actual diameter of Jupiter is 1.42×10^{10} cm?