Laboratory 5 - The Solar System

Materials Used: Two-meter sticks, photographs of the planets, flashlight, a sheet of graph paper.

Objectives: To investigate the size, shape and organization of the solar system; to study the motion of bodies within the solar system and to gain insight into Kepler's Laws.

Discussion: As we learned in the last lab, our solar system consists of the Sun, eight planets, and a number of smaller objects that orbit the sun in the same direction (ccl as viewed from above) in the ecliptic plane. Comets are the only notable exception to this arrangement. Mercury's orbit is inclined about 7° relative to the plane of the solar system but it is so close to the sun that it never appears far from the ecliptic.

Kepler's Laws

Kepler's Laws are a masterpiece of *empiricism*. Johannes Kepler (1571 – 1630) inherited an entire career's worth of observational data on the solar system meticulously acquired by his mentor, Tyco Brahe. Kepler lived in an age when the difference between astronomy and astrology was not well-defined - and both were considered disciplines subordinate to mathematics. Curiously, the emerging field of physics was considered philosophic in nature and not an integral part of astronomy/astrology.

As did many scientists of his time, Kepler incorporated elements of mysticism and religion into some of his theories concerning the solar system. His eponymous three laws, however, are the result of a careful and refined scientific evaluation of observational data.

Kepler's conclusions on the movements of planets in our solar system are empirical because they are based not on any extrapolation from physical laws (Newton's *Principia* would not be published for another 75 years), but on a careful study of the positions of the planets over time using Tyco's observations. By carefully plotting the movements of the planets, and studying the relationships between their positions and time, Kepler was able to derive three important relationships involving the orbits of objects in our solar system. Though Newton subsequently offered a more exacting way of describing the mechanics of the solar system, Kepler's Laws are to this day very important in illustrating and understanding the dynamics of our solar system.

Kepler, along with his contemporary Galileo, were among last major figures in the Renaissance era of science. The coming of Isaac Newton and his mathematically rigorous view of celestial mechanics based on fundamental physical laws ushered in the modern era of science and sped the maturation of the field of physics. With the dawn of the modern era astrology was no longer considered a part of astronomy (or even science) and astronomy became a discipline within physics. Most (though certainly not all) modern discoveries in astronomy employ, at some level, Newton's Laws to ascertain the existence of heretofore unknown celestial objects.

Kepler's first observation concerning our solar system was that the orbits of the planets around the sun are not circular (as was the widely held view of his time), but elliptical, with the sun at

one focus of each ellipse. This observation is quantified as Kepler's First Law. Although Kepler studied the orbits of planets his first and all subsequent laws apply to everything in the solar system that orbits the sun.

The geometric term used to describe any deviation from circular orbital symmetry is called *eccentricity*. The orbits of the planets have low eccentricities and are therefore very nearly circular. The orbital eccentricity of the Earth, for instance, is only 0.017. At *perihelion* the distance from the Earth to the Sun is 91,000,000 miles and at *aphelion* the distance is 95,000,000 miles. Mercury (*e* = 0.21) has a somewhat greater eccentricity though still relatively small. Most comets, by contrast, have large orbital eccentricities. Halley's comet (*e* = 0.967) has a perihelion distance of a mere 55,000,000 miles while its aphelion distance is beyond the orbit of Neptune.

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. Orbital speed changes over the course of an orbit.
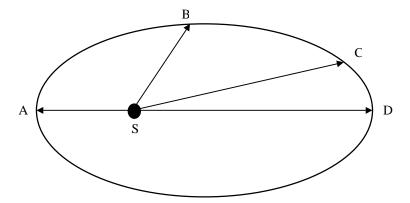

Figure 1. Kepler's second law illustrated. Areas **ASB** and **CSD** are equal. A planet travels more rapidly along the portion of the arc **AB** than in does along **CD**.

Kepler's third law establishes a relationship between the distance of a planet from the sun and its orbital period. The third or "harmonic" law (Kepler labored mightily to explain his third law in terms of musical mysticism) states that the square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit. More succinctly:

$$P^2 \propto a^3$$

A modified form of Kepler's third law is used in conjunction with Newton's Laws to determine the masses of distant objects from measurements of orbital data.

Our Solar System

Most of the mass in the solar system (99.85%) is concentrated in the Sun. The planets and their satellites, comets, asteroids, dust, etc., make up the rest. A rough cross-section of the solar system is described below. All distances from the sun are given in *Astronomical Units*. One astronomical unit (AU) is the mean distance from the Sun to Earth, i.e., about 93 million miles or 150 million kilometers.

Terrestrial Planets: Nearest the sun are a group of planets whose properties are roughly similar to those of the Earth known as *terrestrial* planets. Mercury, Venus, Earth, and Mars are in this group. Terrestrial planets are rocky bodies composed mostly of silicates (silicon and oxygen) and metals. Venus, Earth and Mars have atmospheres but Mercury is too small and hot to retain an atmosphere. The terrestrial planets occupy the region of the solar system from 0.39 AU to 1.52 AU.

Asteroid Belt: Between the orbits of Mars and Jupiter is a region containing numerous small fragments and small rocky *planetesimals* known as the asteroid belt. The asteroid belt is not, as often claimed, the remnant of a planet destroyed in some ancient calamity. It is, rather, material left over from the earliest time of the solar system that failed to condense into a planet due to immense gravitational forces – principally from Jupiter and the Sun. The asteroid belt occupies the region of the solar system from about 1.6 AU to 5.0 AU.

Jovian Planets: Beyond the asteroid belt are a group of gaseous planets with relatively large diameters, violent atmospheres and low average densities know as the Jovian planets. Jupiter, Uranus, Saturn, and Neptune are in this group. The Jovian planets lack solid surfaces (except for small, solid cores) and are composed mostly of light elements such as hydrogen, helium, argon, carbon, oxygen, and nitrogen in gaseous or liquid form. Jupiter, the largest of the Jovian worlds, creates more heat (by gravitationally compressing its immense atmosphere) than it receives from the sun. All of the Jovian worlds are surrounded by networks of satellites (moons) and rings. The Jovian Planets occupy the region of the solar system from about 5.0 AU to about 30 AU.

Kuiper Belt: The Kuiper Belt is a region of the solar system similar to the asteroid belt but located beyond the orbit of Neptune. The Kuiper Belt contains a large number of small bodies (KBO's) composed mostly of icy volatile substances. Pluto, one of the largest of the KBO's, is a dwarf planet most similar in size and composition to some of the satellites of the Jovian worlds. The Kuiper Belt occupies the region of the solar system from about 30 AU to 55 AU.

Oort Cloud: The Oort Cloud is the only large structure in the solar system that does not orbit the sun in the ecliptic plane. The Oort cloud is a spherical cloud of comets that occupies the region of the solar system from 50,000 AU to 100,000 AU. The outer edge of the Oort cloud is thought to be nearly halfway to the nearest star, Proxima Centauri.

In this procedure you will construct a partial model of the solar system – one containing the sun and planets. The purpose of this exercise is to give you some idea of the scale of our solar system and an inkling of the vastness of even our small corner or space.

A Scale Model of Our Solar System

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. These are very large numbers. We wish to scale these down so that we may construct a *scaled down model* of the solar system, i.e., a model in which the relative distances between planetary objects remain the same but is smaller than the original.

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 choose 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:

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

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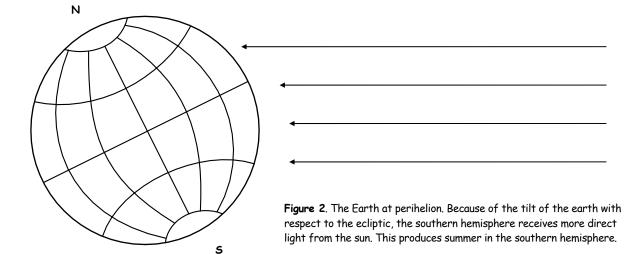
Table 1. Orbital data

Planet	Actual distance from the Sun	SF	Scaled Distance (cm)
Sun	0 cm		
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		

Effects of Earth's Orbital Motion on Our Climate

The earth is at perihelion in early January each year. This is when Earth's orbital speed is greatest. Earth's orbital speed gradually slows until reaching aphelion in July when our orbital speed is at its minimum.

The earth is actually closer to the sun when temperatures are coldest in the northern hemisphere. Even though the sun is 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.

Figure 2. The Earth at perihelion. Because of the tilt of the earth with respect to the ecliptic, the southern hemisphere receives more direct light from the sun. This produces summer in the southern hemisphere.

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 a sheet of graph paper and shine the beam directly onto its center. Trace the outline of the beam and count the number of squares within this area. The number of squares may be used to give a rough estimate of the area illuminated by the flashlight beam. Then from the same height shine the beam onto the center of the opposite side of the same sheet of graph paper at an angle of about 45^0 and trace the outline of the 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 the same in both measurements you made, in which case is the intensity of the light the lowest, when the beam is perpendicular to the surface or at an oblique angle?

This change in intensity, along with other factors such as the path length of light rays through the atmosphere (which increases at more oblique angles) – all related to the tilt of the earth with respect to the ecliptic plane - account for the change of seasons.

Many erroneously think that the elliptical nature of Earth's orbit around the sun, and our changing distance from the sun during the course of a year, is responsible for the change of seasons. 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). At first blush this would lead one to conclude that, at the very least, summer in the southern hemisphere, which occurs at perihelion, is warmer than summer in the northern hemisphere. This 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 because of its great *specific heat capacity*. 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.

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

Exercises

1. What is the definition of perihelion? Aphelion?

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

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

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

5. 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?

6. Which, if any, of Kepler's Laws influences the change of seasons on Earth?

7. Using the same scale factor that you used to construct our 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?

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

9. What is the largest region of the solar system – that occupied by the terrestrial planets, the asteroid belt, the Jovian planets, the Kuiper Belt, or the Oort Cloud?

10. What is the difference between empiricism, as practiced by Kepler, and modern methods in astronomy?