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Catalog No. AP7326
Publication No. 7326

Planetary Orbits

Student Laboratory Kit

Introduction

Johannes Kepler (1571–1630) determined that orbits of the planets around the Sun are not circles as originally thought, but "stretched out circles" called ellipses. Explore the shape of a planet's orbit and investigate Kepler's laws of planetary motion.

Concepts

- Elliptical orbits
- Eccentricity
- Kepler's laws of planetary motion

Background

Before Isaac Newton (1642–1727) developed his laws of gravity and motion, Johannes Kepler observed the planets and formulated his own laws of planetary motion. In 1543, just before he died, Nicolaus Copernicus (1473–1543) published a book in which he proposed that the Sun, not the Earth, was the center of the solar system and the planets orbited the Sun in circular paths. Although placing the Sun at the center of the solar system explained many observations of planetary motion, certain observations did not fit with the proposed circular orbits. In 1609, Kepler published a book entitled *New Astronomy*. In his manuscript, Kepler presented detailed observations made by the well-respected astronomer Tycho Brahe (1546–1601), as well as his own observations and calculations, to show that the planets do not travel in perfect circular orbits. Instead, they travel in oblong paths known as ellipses. An *ellipse* is an elongated circle that has two separate points of rotation, or *foci* (singular *focus*), instead of one central point (see Figure 1). The longest distance from end to end through the center of the ellipse is the *major axis* and the shortest distance through the center is the *minor axis*.

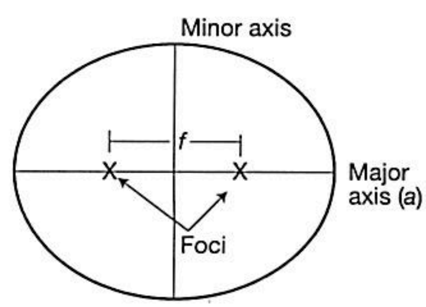

Figure 1.

The "oblongness" of the ellipse is known as its *eccentricity*. The eccentricity (e) is calculated as the ratio of the distance between the foci (f) to the length of the major axis (a) of the ellipse (Equation 1).

$$e = f/a \qquad \textit{Equation 1}$$

An ellipse with an eccentricity of zero (both foci at the same point) is a circle. The larger the eccentricity, the more flattened the ellipse (see Figure 2). Elliptical orbits have an eccentricity between zero and one. The eccentricities of most of the planets are very close to zero; therefore, on a small classroom-scale model, the difference between a circular orbit and an elliptical orbit of a planet is difficult to discern. Mercury, Pluto, and Halley's Comet are exceptions (see Table 1 on the following page). These orbiting bodies have larger eccentricities and therefore follow more elongated paths.

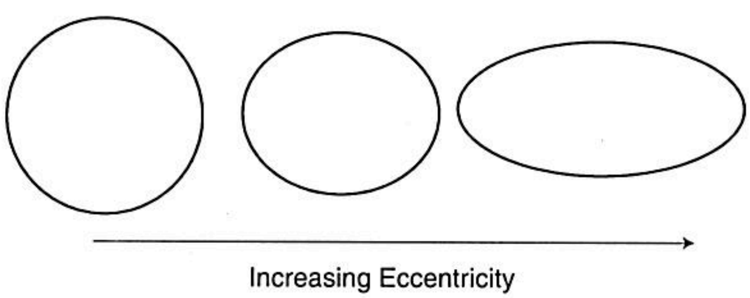

Figure 2.

Orbiting Body	Semimajor Axis Distance (AU*)	Eccentricity
Mercury	0.387	0.206
Venus	0.723	0.007
Earth	1.000	0.017
Mars	1.524	0.094
Jupiter	5.203	0.049
Saturn	9.537	0.057
Uranus	19.19	0.046
Neptune	30.07	0.011
Pluto	39.48	0.249
Halley's Comet	17.9	0.967

Table 1.

*AU is an abbreviation for the Astronomical Unit which is equal to the Earth's average distance to the Sun (1.50×10^{11} m).

Kepler's *first law of planetary motion* states that the orbits of the planets are ellipses and the center of the Sun is one focus of the ellipse. As a result, a planet's distance to the Sun is constantly changing. When a planet crosses the major axis of its orbit, the planet will be either at its farthest distance from the Sun or at its closest distance. The farthest distance is known as the *aphelion* and the closest distance a planet is to the Sun is the *perihelion* (see Figure 3). As a consequence of the conservation of angular momentum, the orbital speed of a planet is inversely proportional to its distance from the Sun. In other words, as a planet's distance from the Sun increases, its orbital speed decreases. The closer a planet is to the Sun, the faster it orbits. Kepler noticed this change in the orbiting speed of the planets and discovered that the area of space swept by a planet in a given amount of time is always the same, no matter where the planet is in its orbit. Kepler called this second law the *Law of Equal Areas* (Figure 3). If the time a planet takes to travel along arc A in Figure 3 is the same as the time traveled along arc B, then the area of space produced by arc A is equal to the area of space produced by arc B.

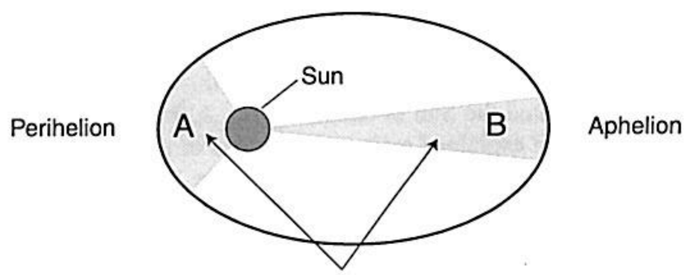

Figure 3.

Kepler's observations also allowed him to formulate an equation to show the relationship between the period of revolution and the major axis of the planets; this relationship is known as the *Law of Planetary Periods*. Years later, Newton validated this third law of planetary motion when he derived Kepler's equation from his own equations of universal gravitation.

Experiment Overview

The purpose of this activity is to investigate the shape of planetary orbits by constructing three different ellipses. Data will be collected and the eccentricity of each ellipse will be calculated. The factors that affect the eccentricity of an ellipse will also be determined.

Pre-Lab Questions *(Answer on a separate sheet of paper.)*

1. What is the eccentricity of an ellipse if the foci separation (f) is 1.2 cm and the major axis length (a) is 5.8 cm?
2. Why does the distance from a planet to the Sun change as the planet travels around its orbit?
3. Where in a planet's orbit will it be traveling the fastest? The slowest?
4. Which of the orbiting bodies listed in Table 1 of the *Background* section has an orbit that most closely resembles a circle? How can you tell?

Materials

Bolts, 2

Hexagonal nuts, 6

Pencil, wood (not mechanical)

Planetary Orbits platform with holes

Planetary Orbits paper templates, 3

Ruler, metric

Scissors

String, 53 cm

Tape, transparent

Washer

Safety Precautions

Please follow all laboratory safety guidelines.

Procedure

Part 1. Drawing the Ellipses

1. Measure and cut two lengths of string—one 28 cm long and one 25 cm long.
2. Form a loop of string with the 28-cm piece by tying the string's ends together with a knot as shown in Figure 4. Tie the knot close to the ends of the string to make the loop as large as possible.

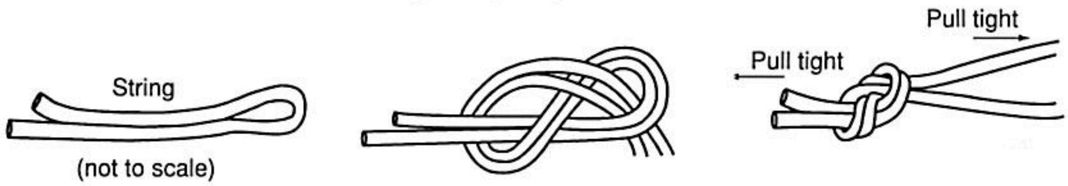

Figure 4.

3. Repeat step 2 with the 25-cm piece of string.
4. Obtain a Planetary Orbits platform and one Planetary Orbits template.
5. Center the template on the platform (on the side without the bumpers) and line up the numbered dots with the holes in the platform.
6. Place a piece of tape on each short side of the template to hold the paper in place on the platform (see Figure 5).

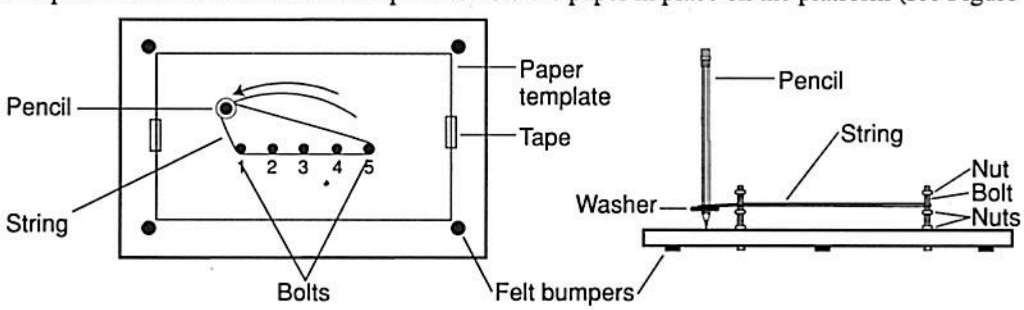

Figure 5.

7. Using a sharpened wood pencil, poke a hole through dot number 1 of the template and through the corresponding hole in the platform.
8. Repeat step 7 with dot number 5.
9. Obtain six nuts and two bolts.
10. Insert the bolts through the outermost holes (1 and 5) of the platform from the bottom and up through the holes in the template. Be careful not to tear the paper around the holes.
11. Thread one nut onto each bolt and tighten securely (see Figure 5). *Note:* The nuts must be as tight as possible so the bolts will not move with gentle pressure from the side. Too much "play" in the bolts will affect the results.

12. Thread two more nuts part way onto each bolt leaving small spaces between each set of nuts. These nuts will serve as a guide to keep the string at the same height when drawing the ellipse.
13. Loop the 28-cm string around both bolts.
14. Obtain the washer and insert a wood pencil through the hole. Press the washer firmly onto the pencil so the washer stays on the pencil. The washer will help keep the string at the same height as the ellipse is drawn.
15. Adjust the two upper nuts on each bolt so the gap between them is the same height as the washer on the pencil when the pencil is held vertically and the pencil tip touches the template (see Figure 5). This will help keep the string level.
16. Place the pencil with the washer inside the loop of string that is around the bolts. Hold the pencil vertically and perpendicular to the platform.
17. Pull the string taut so it rests between the gaps in the nuts and just above the washer (see Figure 5).
18. Draw an ellipse by allowing the string to act as the guide for the pencil. Keep the pencil vertical and the string taut, but not so taut as to stretch the string or shift the bolts from a vertical position.
19. Label the template "Ellipse 1."
20. Remove the nuts from the bolts and gently pull the bolts out of the holes, being careful not to tear the paper or make the holes bigger.
21. Remove the paper template from the platform and set it aside for Part 2.
22. Repeat steps 4–21 with the 25-cm string. Label this template "Ellipse 2."
23. Repeat steps 4–21 with the 25-cm string, this time using dots 1 and 4 instead of dots 1 and 5. Label this template "Ellipse 3."

Part 2. Investigating the Ellipses

24. Using a metric ruler, draw a line the length of Ellipse 1 intersecting the center of the two holes (foci) and the center dot to represent the major axis (see Figure 1).
25. Measure the distance between the two foci (from the center of one hole to the center of the other hole) to the nearest tenth of a centimeter and record in Data Table 1 for Ellipse 1 of the Planetary Orbits worksheet.
26. Measure the length of the major axis and record in Data Table 1 of the worksheet.
27. Repeat steps 24–26 for Ellipse 2 and Ellipse 3, respectively.
28. Using Ellipse 1, mark two points anywhere on the ellipse with a pencil. Label one point "A" and the other "B."
29. Using a ruler, draw a straight line from point A to one focus of the ellipse. *Note:* Since each focus is a hole, draw the line so it would intersect the major axis at the center of the hole (see Figure 6). Label this line A1.
30. Repeat step 29, drawing a line from point A to the second focus. Label this line A2.
31. Repeat steps 29 and 30, drawing a line from point B to each of the foci. Label these lines B1 and B2, respectively (see Figure 6).
32. Measure the length of each line segment to the nearest tenth of a centimeter and record these measurements in Data Table 2 of the worksheet for Ellipse 1.
33. Repeat steps 28–32 for Ellipse 2 and Ellipse 3, respectively.

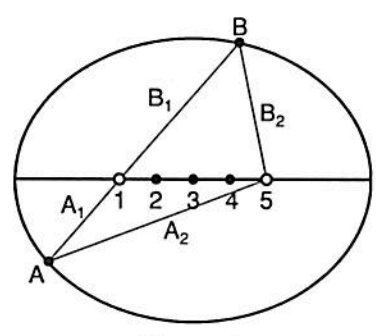

Figure 6.

Name: ______________________________

Planetary Orbits Worksheet

Data Table 1

Ellipse	String Length	Foci Separation, *f* (cm)	Major Axis, *a* (cm)	Eccentricity *f/a*
1	28 cm			
2	25 cm			
3	25 cm			

Data Table 2

Ellipse	A_1 (cm)	A_2 (cm)	$A_1 + A_2$ (cm)	B_1 (cm)	B_2 (cm)	$B_1 + B_2$ (cm)
1						
2						
3						

Post-Lab Calculations and Analysis

1. Calculate the eccentricity of each ellipse and record these values in Data Table 1.
2. Which ellipse has the greatest eccentricity? Which has the least eccentricity?
3. How do the orbits of the bodies listed in Table 1 of the *Background* section compare to the three ellipses constructed in this activity?
4. In terms of the definition of eccentricity, what property of the ellipse is changed when the length of the string is changed?
5. Describe the difference in eccentricity between Ellipse 2 and Ellipse 3. Note the perihelion of each "orbit." How might this explain why Pluto is sometimes closer to the Sun than Neptune?
6. Add the length of line segments A_1 and A_2 for Ellipse 1. Record the sum in Data Table 2. Do the same for line segments B_1 and B_2.
7. Complete Data Table 2 for Ellipse 2 and Ellipse 3, respectively.
8. How does the sum of line segments A_1 and A_2 compare to the sum of line segments B_1 and B_2 for each ellipse?
9. Write a definition of an ellipse that includes the results from question 8.