

CONCEPTS IN DEPTH**● Kepler's Laws**

Prior to the invention of the telescope, Tycho Brahe, a Danish astronomer, devoted his life to making detailed observations of the positions of the stars and planets. Near the end of his life, Tycho hired a German astronomer, Johannes Kepler (1571–1630), as his assistant. Kepler was able to explain Tycho's precise observations in mathematical terms. Kepler developed three laws that explained most aspects of planetary motion.

Law of Ellipses

Kepler's first law states that each planet orbits the sun in a path called an **ellipse**. An ellipse is an oval whose shape is determined by two points within the figure, as shown in Figure 1 below.

Figure 1 An ellipse can be drawn using two pins and a string.



Each of these points is called a **focus** (pl: foci). The sun is at one focus of the orbit of a planet. If you draw a line from any point on the ellipse to each of the two foci, the total length of the lines will always be the same. Some ellipses look almost like circles. In fact, a circle is a special kind of ellipse in which the two foci are at the same point. Other ellipses are more elongated ovals.

Because the orbits of the planets are ellipses, a planet is not always the same distance from the sun. The point where an orbit is closest to the sun is the *perihelion*; the point where it is farthest from the sun is the *aphelion*. Why would a circular orbit have neither a perihelion nor an aphelion?

The distance of a planet from the sun is usually defined as the average of the distances from the sun at its perihelion and its aphelion. For example, the aphelion of the Earth's orbit is about 152 million km from the sun; the perihelion is about 147 million km from the sun. The average of 147 million and 152 million is 149.5 million. This average distance between the Earth and the sun is known as one **astronomical unit**, or AU. The distance between the sun and other planets is usually measured in astronomical units.

CONCEPTS IN DEPTH● **Kepler's Laws** (*continued*)**Law of Equal Areas**

Kepler's second law describes the speed at which planets travel at different points in their orbits. By studying Tycho's data, Kepler found that the orbit of the Earth was a nearly perfect circle, with the sun off-center. He found that the Earth moves fastest when it is closest to the sun. He calculated that a line from the center of the sun to the center of the planet sweeps through equal areas in equal periods of time.

Imagine a line that connects the center of the sun to the center of a planet. When the planet is near the sun, the imaginary line is relatively short. The planet is moving rapidly and in ten days, for example, the imaginary line sweeps through a short, wide triangular sector. When the planet is farther from the sun, the imaginary line is longer. However, the planet is moving more slowly and the imaginary line sweeps through a long, thin triangular sector in ten days.

Kepler's second law states that the area of the long, thin sector is the same as the area of the short, wide sector.

Law of Periods

Kepler's third law describes the relationship between the average distance of a planet from the sun and the **orbit period** of the planet. The orbit period is the time required for the planet to make one revolution around the sun. According to Kepler's third law, the cube of the average distance of a planet from the sun (r) is always proportional to the square of the period (p). The mathematical formula that describes this relationship is

$$K \times r^3 = p^2,$$

where K is a mathematical constant. When distance is measured in AUs and the period is in Earth-years, $K = 1$ and $r^3 = p^2$.

For example, the radius of the Earth's orbit, or its distance from the sun, is 1 AU, and its period is 1 year. Putting these numbers into the formula yields $1 \times 1^3 = 1^2$. This simplifies to $1 = 1$. Jupiter is 5.2 AUs from the sun, and its period is 11.9 years. The cube of 5.2 is 140.6. The square of 11.9 is 141.6. The two results, 140.6 and 141.6, are approximately equal. Apparent errors in the law of periods are caused by rounding off the distance or periods. When the distance and period are calculated with enough precision, the period squared always equals the distance cubed.

CONCEPTS IN DEPTH● **Kepler's Laws** (*continued*)**Newton's Application of Kepler's Laws**

Kepler's laws explained *how* the planets orbit the sun. Isaac Newton asked *why* the planets move in this way. The explanation that Newton eventually gave described both the motion of objects on the Earth and the motion of the planets in space. He hypothesized that a moving body will change its motion only if an outside force causes it to do so. For example, a ball rolling on a smooth surface will continue to move in a straight line unless something causes it to change direction. The tendency of a moving body to move in a straight line at a constant speed until an outside force acts on it is called **inertia**. Inertia also refers to the tendency of an object to remain at rest until an outside force acts on it.

Newton compared a planet to a rolling ball. Because a planet does not follow a straight path, an outside force must cause it to curve. Newton identified this force as *gravity*, the attractive force that exists between all objects in the universe. The gravitational pull of the sun keeps the planets in orbit around the sun.