Kepler's Laws of Planetary Motion

Unit: Gravitation

NGSS Standards/MA Curriculum Frameworks (2016): N/A

AP® Physics 1 Learning Objectives/Essential Knowledge (2024): 2.9.B, 2.9.B.1

Mastery Objective(s): (Students will be able to…)

- Set up and solve problems involving Kepler's Laws.

Success Criteria:

- All variables are identified and substituted correctly.
- Algebra is correct and rounding to appropriate number of significant figures is reasonable.

Language Objectives:

- Explain how the speed that a planet is moving changes as it revolves around the sun.

Tier 2 Vocabulary: focus

Notes:

Danish astronomer Tyco Brahe had become interested in astronomy when as a child, he observed a solar eclipse that occurred exactly at the time it was predicted. He built an observatory on an island off the coast of Denmark in 1571, from which he recorded accurate data for the positions of celestial bodies, including the planets and stars.

German mathematician and astronomer Johannes Kepler was appointed to be Brahe's assistant in 1600, just one year before Brahe died. From Brahe's data, Kepler derived three laws and equations that govern planetary motion, which were published in three volumes between 1617 and 1621.

Kepler's First Law

The orbit of a planet is an ***ellipse***, with the sun at one focus.

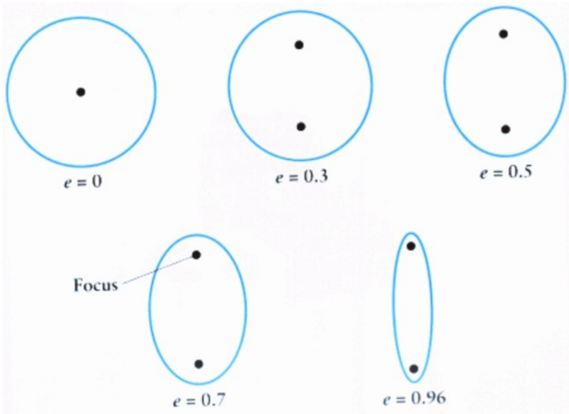
<u>ellipse</u>: a regular oval shape, traced by a point moving in a plane so that the sum of its distances from two other points (the foci*) is constant.

<u>eccentricity</u>: the extent to which an ellipse approaches a straight line. An ellipse with an eccentricity of 0 is a circle; an ellipse with an eccentricity of 1 is a straight line. Notice that as an ellipse becomes more and more eccentric, the foci move farther and farther apart.

* Foci is the plural of focus.

Use this space for summary and/or additional notes:

The following diagram shows ellipses with different eccentricities. The table to the right lists the eccentricities of the orbits of the planets in the Solar System:

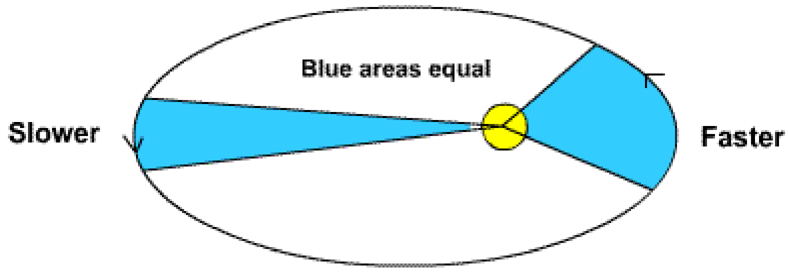


Planet	Orbital Eccentricity
Mercury	0.206
Venus	0.007
Earth	0.017
Mars	0.055
Jupiter	0.049
Saturn	0.052
Uranus	0.047
Neptune	0.010

Pluto, which is not a planet because it was captured by the Solar System rather than having formed with it, has an orbital eccentricity of 0.244. While that may not look like much in the above diagram, its eccentricity is enough to take its orbit inside that of Neptune for more than 10 % of its journey around the Sun.

Kepler's Second Law

A line that joins the sun with a planet* will sweep out equal areas in equal amounts of time.



I.e., the planet moves faster as it moves closer to the sun and slows down as it gets farther away. If the planet takes exactly 30 days to sweep out one of the blue areas above, then it will take exactly 30 days to sweep out the other blue area, and any other such area in its orbit.

While we now know that the planet's change in speed is caused by the force of gravity, Kepler's Laws were published fifty years before Isaac Newton published his theory of gravity.

* Or any other entity that is orbiting the sun, such as a comet.

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Kepler's Third Law

If T is the period of time that a planet takes to revolve around a sun and $r_{ave.}$ is the average radius of the planet from the sun (the length of the semi-major axis of its elliptical orbit) then:

$$\frac{T^2}{r_{ave.}^3} = \text{constant} \text{ for every planet in that solar system}$$

We now know that, $\frac{T^2}{r_{ave.}^3} = \frac{4\pi^2}{GM}$, where G is the universal gravitational constant and M is the mass of the star in question, which means this ratio is different for every planetary system. For our solar system, the value of $\frac{T^2}{r_{ave.}^3}$ is approximately $9.5\times10^{-27}\ \frac{\text{s}^2}{\text{m}^3}$ or $3\times10^{-34}\ \frac{\text{years}^2}{\text{m}^3}$.

Kepler's third law allows us to estimate the mass of a planet in some distant solar system, based on the mass of its sun and the time it takes for the planet to make one revolution.

Use this space for summary and/or additional notes: