Orbits and distances

During a recent class discussion about the announcement that planets were discovered orbiting a star other than our Sun, students questioned, not so much how they were discovered, but how astronomers could tell so much about them. This led to a discussion of how astronomers determine a planet's orbit and its distance from its sun.

Extra-solar planets, those outside of our solar system orbiting different stars, do not reflect enough light to be easily seen. However, their presence around a star may be detected by variations in the star's brightness as the planet periodically eclipses it. Extra-solar planets are also detected through measurements of the subtle, yet regular, motions of the star caused by the gravitational interaction of unseen orbiting companions. These cyclical events are timed and then used to calculate an orbital period. Once an orbital period can be determined, it is just a matter of further calculations to determine the distance an object must be in order to orbit at the calculated rate. This is done through what are now known as Kepler's Laws.

Johannes Kepler (1571–1630) was a mathematician who worked as an assistant to the great observer Tycho Brahe (1546–1601). Kepler used Brahe's accurate observational data as he studied the Copernican model of a Sun-centered solar system, in particular the curious orbital data collected by Brahe's years of meticulous observation of Mars. Using the Copernican model, with the planets following circular paths around the Sun, Kepler applied the data to the model to calculate the positions of Mars. He noticed that the data from Tycho Brahe did not fit the circular orbit model. Kepler then deduced what we now know as his three laws of planetary motion.

Elliptical orbits

Kepler's first law describes the shape of orbits as being elliptical rather than circular. While a circle has one focus, the center point, an ellipse has two, called *foci*. The Sun is at one focus of a planet's elliptical orbit, while empty space is the other. The distance between the center point of a circle and the circle line surrounding it is known as the *radius*. A planet with an elliptical orbit has an average distance from the focus (sun) known as the *semimajor axis*. The semimajor axis is one half the length of the long axis of an ellipse. When describing these shapes the term *eccentricity* is used. The greater the eccentricity, the more elliptical the orbit. A scale of 0 to 1 is used where a circle has an eccentricity of 0. The Earth's orbit is slightly elliptical with an eccentricity of only 0.017.

Equal areas

The second law came from his observations that a planet moves at different speeds at different places along its orbital path. When a planet is closest to the Sun it is moving more rapidly than when it is at a greater distance from the Sun. The description of this motion involves an imaginary line connecting the planet to the Sun. As a planet moves along its orbital path the line sweeps across equal areas no matter where the planet is along its orbit.

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A harmonic law

While the first two laws describe the shape of a planet's orbit and its speed variation, Kepler's third law determines how long it takes a planet to complete an orbit and how its distance from the Sun affects this speed. A planet closer to the Sun has less distance to travel than a distant planet. Also, the more distant planet travels at a slower rate thereby taking longer to complete an orbit. In other words, the further away a planet is from the Sun, the slower it travels.

In studying orbital period and distance, Kepler came up with a simple formula that applied to all of the planets called the *harmonic law*. Using the Earth year and astronomical units, Kepler's third law states that the period of a planet in Earth years squared is equal to its distance in astronomical units (semimajor axis) cubed, or $P^2=A^3$.

For example, a planet twice the distance from the Sun as the Earth has a distance of 2 AU. However, the planet does not take twice as long to complete its orbit. Using Kepler's third law, we determine that this planet takes nearly three years to complete one orbit compared to the Earth's one year:

$P^2 = A^3$

$P^2 = 2^3$ the orbital period squared equals 2 cubed

$P^2 = 8$ orbital period squared equals 8 (or the square root of 8 equals the orbital period)

$2.8284^2 = 8$

$8 = 8$

When calculated as a ratio, with the period squared over the distance cubed, the resulting answer will always be one, or nearly so, depending on how values are rounded:

$P^2/ A^3 = 1$

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FIGURE 1 **Planetary orbital data**

Planet	Eccentricity	Period in years	Semimajor axis in AU	P^2 / A^3
Mercury	0.2056	0.240	0.387	= 0.057 / 0.057
Venus	0.0067	0.615	0.723	=
Earth	0.0167	1.000	1.000	=
Mars	0.0935	1.880	1.524	=
Jupiter	0.0489	11.861	5.204	=
Saturn	0.0565	29.456	9.582	=
Uranus	0.0457	84.010	19.201	=
Neptune	0.0113	164.785	30.047	=
Pluto	0.2444	247.675	39.236	=

With the information provided in Figure 1, a graph can be constructed with the period as the independent variable to show that, as the orbital period increases, the distance increases. With this information and the orbital period based on observations of the changes in a star's motion, the distance an extra-solar planet lies from its star can also be determined.

Daniel Kirkwood, an astronomer, used this information to explain the gaps in the asteroid belt between Mars and Jupiter in our solar system. At the time, there was an assumption that the distribution of asteroids would be uniform. However, it was discovered that, at certain distances from the Sun, there were virtually no asteroids. Kirkwood found that the distances corresponded to certain fractions of the orbital period of Jupiter. He concluded that Jupiter's gravitational field repeatedly tugged on the asteroids at certain distances and points and gradually pulled them away from the Sun, thus leaving gaps in the belt. This deduction, like the answer to the students' question, is simply a straightforward application of Kepler's planetary motion laws.

Interestingly, while Kepler could describe the motions of the planets, he could not tell why they moved this way. We now know, thanks to the later work of Sir Isaac Newton, that it is the force of gravity that keeps a planet in orbit around the Sun.

Visible planets

- Mercury is visible low over the eastern horizon before sunrise during the first half of the month.
- Jupiter rises after midnight and is over the northeast horizon before sunrise.
- Saturn rises before midnight and is visible all night.

Moon phases

October

New Moon	10/06
First quarter Moon	10/13
Full Moon	10/21
Third quarter Moon	10/29

Celestial events

- 10/27 Daylight Saving Time ends (set clock back 1 hour)

Resources

- Kepler—*www.kepler.arc.nasa.gov/johannes.html#anchor784359*
- Kepler's laws—*home.cvc.org/science/kepler.htm*
- Asteroid distribution histogram—*ssd.jpl.nasa.gov/a_histo.html*
- Daniel Kirkwood—*www.astro.indiana.edu/daniel_kirkwood.html*
- Asteroids—*www.seds.org/nineplanets/nineplanets/asteroids.html*
- The Extra-solar Planets Catalog—*cfa-www.harvard.edu/planets*
- Daylight Saving Time—*www.webexhibits.org/daylightsaving/b.html*