Astronomy in the Renaissance

Nicolaus Copernicus

The person who began the demolition of the geocentric model and the revolution in astronomical ideas that continues to this day was a Polish physician and lawyer by the name of Nicolaus Copernicus (fig. 2.16). During the early 1500s Copernicus made many attempts to reconcile Ptolemy's geocentric model with the centuries of data on planetary positions that had been collected, but all such attempts failed. Thus, he was led to reconsider Aristarchus's ancient idea that the Earth moves around the Sun.

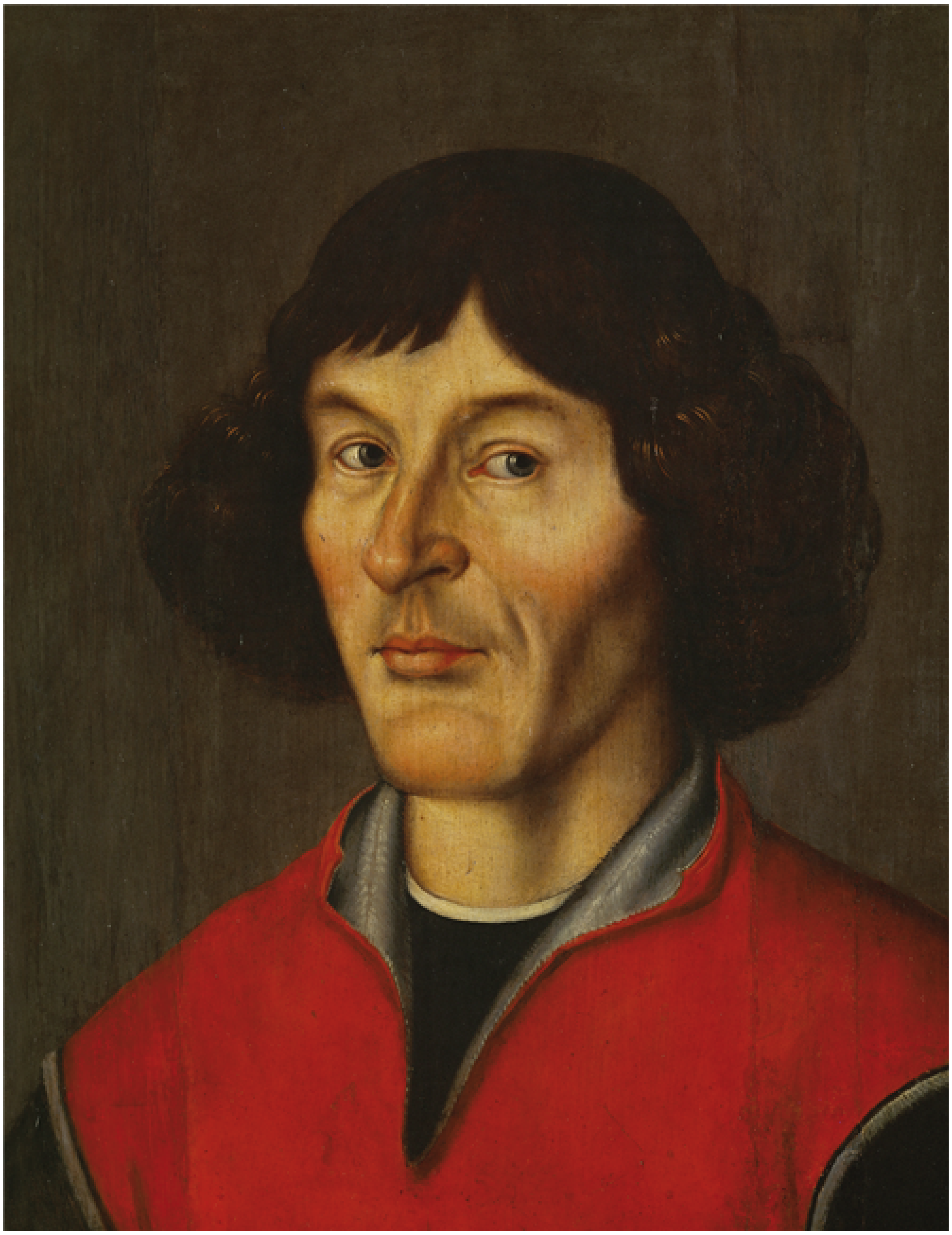

FIGURE 2.16
Nicolaus Copernicus (1473–1543)

A **heliocentric model** in which the Sun (*helios*, in Greek) is the center of the planets' motion had been proposed nearly 2000 years earlier by Aristarchus, but it had been rejected partly because the observational tools available at that time were inadequate to detect stellar parallax. Nevertheless, such models offer an enormously simpler explanation of retrograde motion. In fact, if the planets orbit the Sun, retrograde motion becomes a simple consequence of one planet overtaking and passing another, as Copernicus was able to show.

To see why retrograde motion occurs, examine figure 2.17. Here we see the Earth and Mars moving around the Sun. The Earth completes its orbit around the Sun in 1 year, whereas Mars takes 1.88 years to complete an orbit, with the Earth overtaking and passing Mars every 780 days. If we draw lines from Earth through Mars, we see that Mars appears to change its direction of motion against the background stars as the Earth overtakes and passes it. A similar phenomenon occurs when you drive on a highway and pass a slower car. Both cars are moving in the same direction, but as you pass the slower car, it *looks* as if it shifts backward relative to stationary objects beyond it.

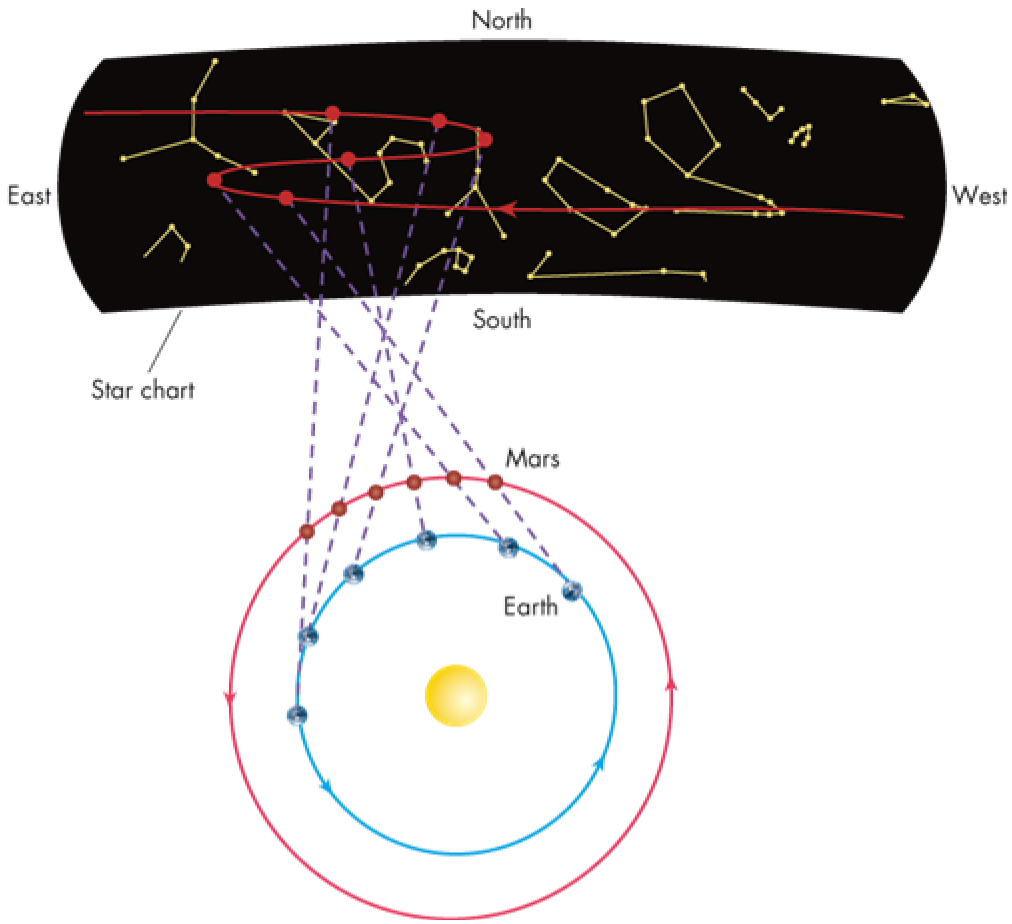

FIGURE 2.17
Why we see retrograde motion. (Object sizes, positions, and distances are exaggerated for clarity.)

The retrograde motion of Mars according to the heliocentric model

Copernicus described his model of a Sun-centered Universe in one of the most influential scientific books of all time, *De revolutionibus orbium coelestium* (*On the Revolutions of the Celestial Spheres*, fig. 2.18). Because his ideas were counter to the teaching of the Catholic Church, they were met with hostility and skepticism. The book itself was not published until shortly before Copernicus's death (which was perhaps just as well for him), and according to legend he saw the first copy while on his deathbed.

FIGURE 2.18
The title page and a diagram showing the heliocentric system of the planets from the first edition of *De revolutionibus orbium coelestium*, published in 1543.
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With his heliocentric model, Copernicus not only could give a simple explanation of retrograde motion but also could also explain why Venus and Mercury never move very far from the Sun. In Ptolemy's geocentric model this was caused by a coincidence in the rotation rates of the planetary cycles and epicycles. In the Copernican model these two planets have orbits smaller than the Earth's, so their angle from the Sun is limited by the size of their orbits (fig. 2.19). As shown in Astronomy by the Numbers: "How Copernicus Calculated the Distances to the Planets," Copernicus was able to use geometery to determine each planet's distance from the Sun. The distances found in this manner must be expressed in terms of the Earth's distance from the Sun, the astronomical unit or AU (whose value was not known accurately until several hundred years later), but table 2.1 illustrates that they agree well with modern values.

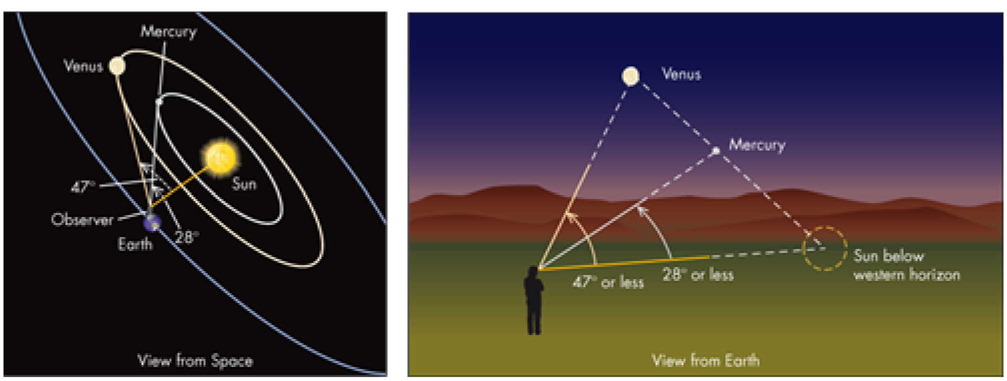

FIGURE 2.19
The greatest elongations of Mercury and Venus and the Evening Star phenomenon. The left-hand diagram also shows that Mercury and Venus can never appear more than 28° and 47°, respectively, from the Sun.

Table 2.1
Planetary Distances According to Copernicus

Planet	**Copernicus's Distance**	**Actual Distance**
Mercury	0.38 AU	0.39 AU
Venus	0.72 AU	0.72 AU

Earth	1.00 AU	1.00 AU
Mars	1.52 AU	1.52 AU
Jupiter	5.22 AU	5.20 AU
Saturn	9.17 AU	9.54 AU

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ASTRONOMY *by the numbers*

HOW COPERNICUS CALCULATED THE DISTANCES TO THE PLANETS

When an inner planet appears farthest from the Sun, the planet's angle on the sky away from the Sun, ***α***, can be measured as illustrated in figure 2.20A. You can see from the figure that the planet makes an angle of 90° with the Sun. The planet's distance from the Sun can then be calculated with geometry, if one knows the value of the angle ***α*** and the fact that the Earth–Sun distance is 1 AU.

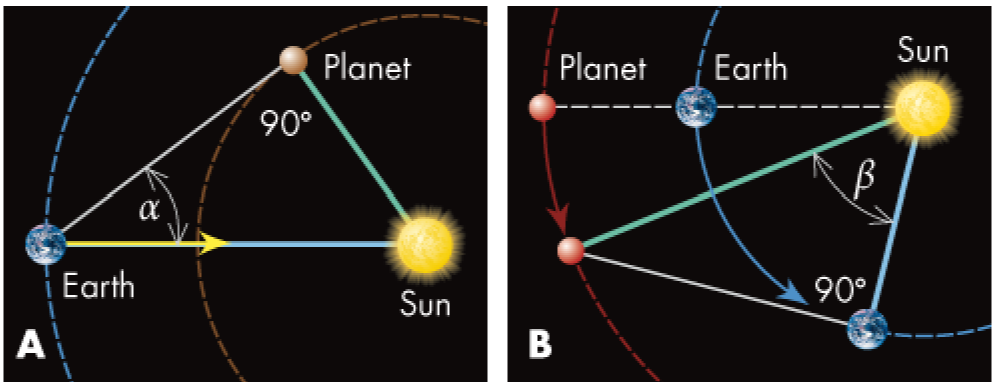

FIGURE 2.20
Finding the size of orbits for (A) planets closer to the Sun than the Earth, and (B) planets farther from the Sun.

Finding the distance to an outer planet is more complicated. First you must determine when the outer planet is directly opposite the Sun (rising when the Sun sets, for example). Then you must count the number of days until the planet is 90° away from the Sun in the sky. From that time interval we can determine the fraction of their orbits that the Earth and planet moved in that time. Multiplying those fractions by 360° gives the angles for those movements; we then take their difference to find the angle ***β*** in figure 2.20B.

For example, in 2012 Mars was opposite the Sun on March 3, and then at right angles from the Sun on June 8. During those 97 days, the Earth moved through approximately (97/365) × 360° ≈ 96°. Because Mars takes 687 days to complete its orbit, it has moved through an angle of about (97/687) × 360° ≈ 51°. The difference between those angles gives the angle ***β*** ≈ 45°. We could then construct a triangle with this shape, and compare the sides, or use trigonometry, to find that Mars is approximately 1.4 AU from the Sun. Mars actually varies between 1.38 and 1.67 AU from the Sun, so many measurements around its orbit are necessary to give the correct mean value.

Ironically, some of the criticism of Copernicus's work was justified. Although his model was basically correct, it did not account for the observed positions of the planets any more accurately than did Ptolemy's more complicated but incorrect model. This lack of complete agreement between model and observation arose at least in part because Copernicus insisted that the planetary orbits were circles. Furthermore, his model again raised the question of why no stellar parallax could be seen. Finally, his views of planetary motion ran counter to the teachings of Aristotle, views supported both by "common sense" and by the Catholic Church at that time. After all, when we observe the sky, it *looks* as if it moves around us. Moreover, we do not detect any sensations caused by the Earth's motion—it feels at rest. This mixture of rational and irrational objections made even scientists slow to accept the Copernican view.

However, by this time there was a growing recognition of the immensity of the Universe. Astronomers such as the Englishman Thomas Digges and the Italian Giordano Bruno went so far as to claim that the stars were other suns, perhaps with other worlds around them. This new scientific open-mindedness, coupled with the aesthetic appeal of the simpler system, led to a growing belief in the Copernican system.

Tycho Brahe

Copernicus's model, although not the only stimulus, marked the opening of a new era in the history of astronomy. Conditions were favorable for new ideas: the cultural renaissance in Europe was at its height; the Protestant Reformation had just begun; the New World was being settled. In such an environment, new ideas found a more receptive climate than in earlier times, at least among scientists.

One scientist whose ideas flourished in this more intellectually open environment was the sixteenth-century Danish astronomer Tycho Brahe (fig. 2.21). Born into the Danish nobility, Tycho utilized his position and wealth to indulge his passion for study of the heavens, a passion based in part on his professed belief that God placed the planets in the heavens to be used as signs to mankind of events on Earth. Driven by this interest in the skies, Tycho designed and had built instruments of far greater accuracy than any yet devised in Europe. Tycho then used these devices to make precise measurements of planetary positions. His meticulous observations turned out to be crucial not only for showing the superiority of the heliocentric over the geocentric system but also for revealing the true shape of planetary orbits.

FIGURE 2.21
Tycho Brahe (1546–1601)
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Tycho did more than just record planetary positions; he recognized opportunity when he saw it. In 1572, when an exploding star (what we today call a supernova) became visible, Tycho demonstrated from its lack of motion with respect to other stars that it was far beyond the supposed spheres on which planets move. Likewise, when a bright comet appeared in 1577, he showed that it lay far beyond the Moon, not within the Earth's atmosphere, as taught by the ancients. These observations suggested that the heavens were both changeable and more complex than was previously believed.

Although Tycho could appreciate the simplicity of the Copernican model, he remained unconvinced of its validity because he could not detect any stellar parallax. Instead, he offered a compromise model in which all of the planets except the Earth went around the Sun, while the Sun, as in earlier models, circled the Earth. Tycho was the last major astronomer to hold that the Earth was at the center of the Universe.

Johannes Kepler

After Tycho Brahe's death, his young assistant, Johannes Kepler (fig. 2.22), was able to derive from Tycho's huge set of precise information a detailed picture of the path of the planet Mars. Whereas all previous investigators had struggled to fit the planetary paths to circles, by using Tycho's superb data Kepler was able to show that the path of Mars was not circular but elliptical.

FIGURE 2.22
Johannes Kepler (1571-1630)

An **ellipse** can be drawn with a pencil inserted in a loop of string that is hooked around two thumbtacks. If you move the pencil while keeping it tight against the string, as shown in figure 2.23A, you will draw an ellipse. Each point marked by a tack is called a **focus** of the ellipse. Not only was Mars's orbit elliptical, Kepler determined that the Sun was located at a spot that was *not* the center of the ellipse but was off center at a focus. Using an elliptical shape for the orbit, he was able to obtain excellent agreement between the calculated and the observed positions of the other planets as well.

Kepler's discovery that planetary orbits are ellipses and not circles was a critical step in understanding planetary motion.

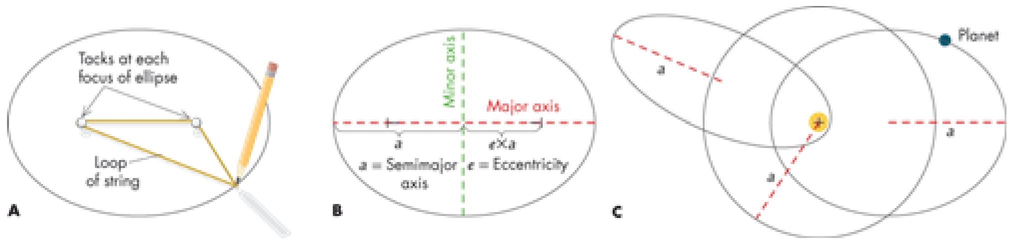

FIGURE 2.23
(A) Drawing an ellipse. (B) The major and minor axes. The semimajor axis, *a*, is half of the major axis. The distance that each focus is off-center in the ellipse determines the eccentricity, *e*, of the ellipse. (C) Three orbits are shown that have the same size semimajor axis but differing eccentricities. The Sun lies at one focus of the ellipse.

Along with discovering the shape of planetary orbits, Kepler also measured the relative sizes of the orbits. Because an orbit is elliptical, its size cannot be described by a single number. The shape of an ellipse is instead given by its long and short dimensions, called its major and minor axes, respectively (fig. 2.23B). Astronomers usually use the orbit's **semimajor axis**—half the major axis, analogous to a circle's radius. To describe the ellipse's shape, astronomers usually report its *eccentricity*, which indicates how far from the center of the ellipse each focus is located. The eccentricity of a circle is 0, but approaches 1 as the ellipse becomes more stretched out. Several ellipses with the same semimajor axis but different eccentricities are displayed in figure 2.23C.

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ANIMATION

Kepler's laws

Based on Tycho's measurements, Kepler could measure not only the shape of a planet's path but also its speed as it changes distance from the Sun. And when Kepler compared the size of a planet's semimajor axes with how long the planet takes to orbit the Sun—its orbital **period**—Kepler discovered the relationship shown in table 2.2: the square of the period is proportional to the cube of the orbital size, as measured by the semimajor axis.

Table 2.2
Table Illustrating Kepler's Third Law for the Planets Known at His Time

Planet	**Distance from Sun (*a*) (in Astronomical Units)**	**Orbital Period (*P*) (in Years)**	a^3	P^2
Mercury	0.387	0.241	0.058	0.058
Venus	0.723	0.615	0.378	0.378
Earth	1.0	1.0	1.0	1.0
Mars	1.524	1.881	3.54	3.54
Jupiter	5.20	11.86	141.0	141.0
Saturn	9.54	29.46	868.0	868.0

Kepler's discoveries of the nature of planetary motions are expressed in what are known today as **Kepler's three laws**:

- I.

  Planets move in *elliptical* orbits with the Sun at one focus of the ellipse (see fig. 2.24-I).

- II.

  The orbital speed of a planet varies so that a line joining the Sun and the planet will sweep over equal areas in equal time intervals (see fig. 2.24-II).

- III.

  The amount of time a planet takes to orbit the Sun is related to its orbit's size, such that the period, P, squared is proportional to the semimajor axis, a, cubed (fig. 2.24-III). Mathematically,

  $$P^2 = a^3$$

  where P is measured in years and a is measured in astronomical units.

These three laws describe the essential features of planetary motion around our Sun.

INTERACTIVE

Kepler's second law

The second law—in its statement that a line from the planet to the Sun sweeps out equal areas in equal times—implies that when a planet is near the Sun, it moves more rapidly than when it is farther away. We can see this by considering the shaded areas in figure 2.24-II. For the areas to be equal, the distance traveled along the orbit in a given time must be larger when the planet is near the Sun. Thus, according to Kepler's second law, as a planet moves along its elliptical orbit, its speed changes, increasing as it nears the Sun and decreasing as it moves away from the Sun.

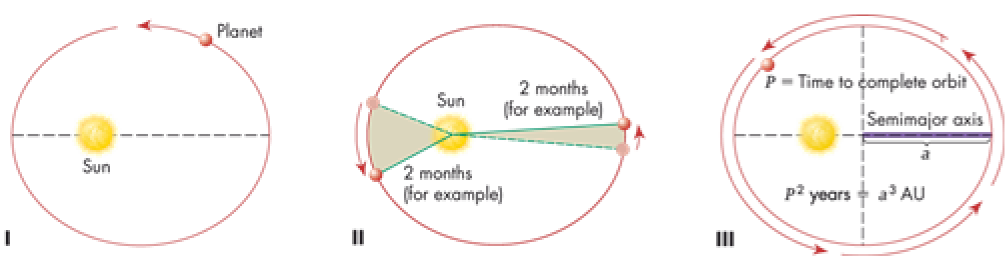

FIGURE 2.24
Kepler's three laws. (I) A planet moves in an elliptical orbit with the Sun at one focus. (II) A planet moves so that a line from it to the Sun sweeps out equal areas in equal times. Thus, the planet moves fastest when nearest the Sun. For purposes of the drawings a two-month interval is chosen. (III) The square of a planet's orbital period (in years) equals the cube of the semimajor axis of its orbit (in AU), the planet's distance from the Sun if the orbit is a circle.

INTERACTIVE

Kepler's third law

The third law also has implications for planetary speeds, but it deals with the relative speeds of planets whose orbits are at different distances from the Sun, not the speed of a given planet. Because the third law states that $P^2 = a^3$, a planet far from the Sun (larger a) has a longer orbital period (P) than one near the Sun (see table 2.2). For example, the Earth takes 1 year to complete its orbit, but Jupiter, whose distance from the Sun is slightly more than 5 times Earth's distance, takes about 12 years. Thus, a planet orbiting near the Sun overtakes and passes a planet orbiting farther out, leading to the phenomenon of retrograde motion, as discussed earlier in this section.

Kepler's third law has other implications. For example, we shall see in chapter 3 that the law gives information about the nature of the force holding the planets in orbit. Also, it implies that a planet close to the Sun moves along its orbit faster than a planet far from the Sun. Finally, the third law allows us to calculate the distance from the Sun of any body orbiting it if we measure the body's orbital period. (See Astronomy by the Numbers: "Using Kepler's Third Law for Orbit Calculations.") The distance we obtain will only be relative to the Earth's distance, but the law thereby gives us at least the relative scale of the Solar System.

ASTRONOMY *by the numbers*
USING KEPLER'S THIRD LAW FOR ORBIT CALCULATIONS

Kepler's third law can be used to calculate the period or size of orbits around the Sun. Here are two examples:

Example 1 – The period of Pluto's orbit. To find how long Pluto takes to orbit, we use its distance from the Sun, which is about 39.5 AU. Putting this into Kepler's third law, we have

$P^2 = a^3 = 39.5^3 = 61630$.

Taking the square root of both sides, we have

$$P = \sqrt{61630} = 248 \text{ yrs.}$$

So, since its discovery in 1930, Pluto has completed only about 1/3rd of an orbit.

Example 2 – Asteroids in resonance with Jupiter. An asteroid with an orbital period half as long as Jupiter's (11.86 years) will suffer repeated gravitational deflections that might send it into a collision course with Earth. At what distance would such an asteroid orbit? Using Kepler's third law, we solve for the semimajor axis of an orbit with $P = 5.93$ years. We set

$a^3 = P^2 = 5.93^2 = 35.2$.

Taking the cube root of each side

$$a = \sqrt[3]{35.2} = 3.28.$$

So these dangerous asteroids orbit at 3.28 AU (chapter 11).

Apart from such astronomical applications, Kepler’s laws have an additional significance. Kepler’s laws are the first mathematical formulas to describe the heavens correctly, and as such they revolutionized our way of thinking about the Universe. Without such mathematical formulations of physical laws, much of our technological society would be impossible. These laws are therefore a major breakthrough in our quest to understand the world around us.

It is perhaps ironic that such mathematical laws should come from Kepler, because so much of his work is tinged with mysticism. For example, as a young man he sought to explain the spacing of the planets as described in Copernicus’s work in terms of nested geometrical figures, the sphere, the cube, and so on. In fact, it was Tycho’s notice of this work that led to his association with Kepler. Moreover, Kepler’s third law evolved from his attempts to link planetary motion to music, using the mathematical relations known to exist between different notes of the musical scale. Kepler even attempted to compose “music of the spheres” based upon such a supposed link. Nevertheless, despite such excursions into these nonastronomical matters, Kepler’s discoveries remain the foundation for our understanding of how planets move. The work of Tycho Brahe and Johannes Kepler was the pinnacle of pre-telescopic astronomy. However, even as Kepler was developing his geometric and mathematical laws describing the motion of the planets, the nature of astronomy was about to change dramatically.