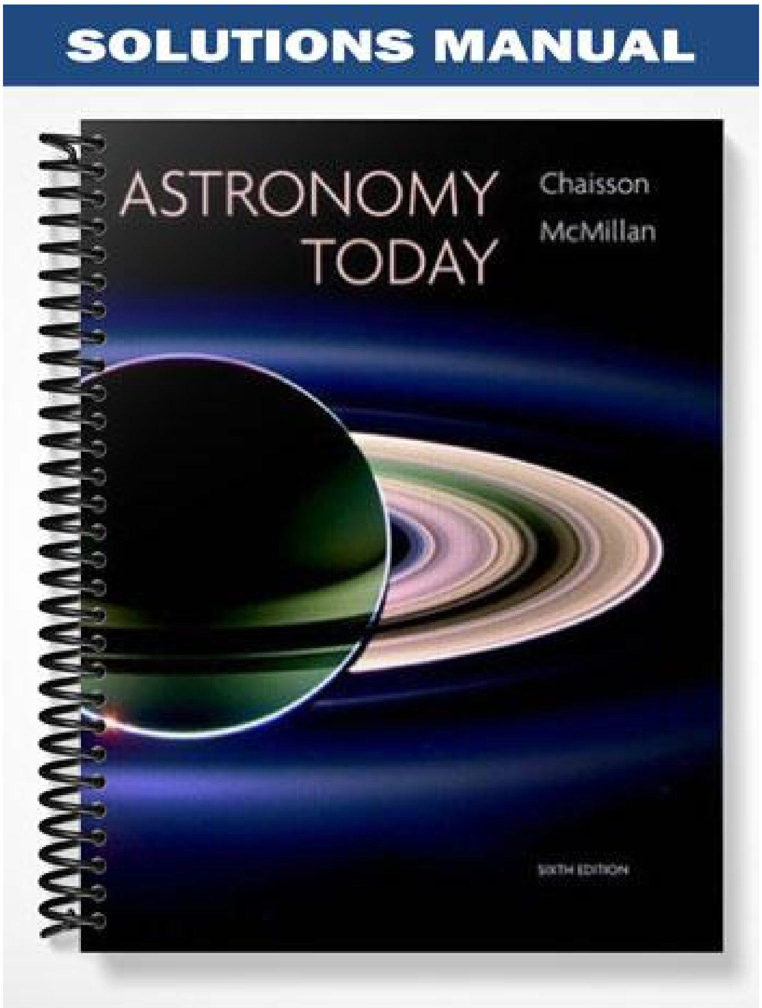

SOLUTIONS MANUAL
ASTRONOMY
TODAY
Chaisson
McMillan
SIXTH EDITION

Chapter 2: The Copernican Revolution

The Birth of Modern Science

Outline

2.1 Ancient Astronomy
2.2 The Geocentric Universe
2.3 The Heliocentric Model of the Solar System
2.4 The Birth of Modern Astronomy
2.5 The Laws of Planetary Motion
2.6 The Dimensions of the Solar System
2.7 Newton's Laws
2.8 Newtonian Mechanics

Summary

Chapter 2 continues the view from Earth started in the previous chapter by discussing the apparent motions of the planets, which leads to two very important concepts that are introduced in this chapter: the historical development of astronomy and the laws of planetary motion and gravity. The historical context in which these concepts are couched provides a framework for demonstrating the scientific process and for portraying that process as a human endeavor. Although the chapter takes a mostly European view, as is traditional, it does speak to the larger issue of contributions from cultures all over the world and throughout history. Modern astronomy is anything but limited to western contributions; it is a truly international science, as will be seen in later chapters.

Chapter 2 is very important, not just for its historical context, but because it describes the ideas of gravity and orbital motion that pervade the rest of the text. There is hardly a chapter that follows that does not make reference to this material and build on it. It is therefore imperative that students understand this material; without this understanding, very little of the following 26 chapters will make sense. The material is also highly relevant to issues of technology and modern life. There are many satellites in orbit that are taken for granted and poorly understood by the students in our classes. These students have been exposed to the process of launches into orbit, yet generally do not understand that process and often have many misconceptions about it. Everything from television cartoons to most science fiction in movies and television programs promotes these misconceptions that become the "lived reality" of our students.

Major Concepts

- Ancient Astronomy
- Motions of the Planets
  - Wanderers Among the Stars
  - Retrograde Motion
- Geocentric Models of the Universe
  - Aristotle
  - Ptolemy
- Heliocentric Models and the Birth of Modern Astronomy
  - Copernicus
  - Brahe
  - Galileo
- Kepler's Laws of Planetary Motion

- Isaac Newton
  - Laws of Motion
  - Gravity
  - Explaining Orbits and Kepler's Laws

Teaching Suggestions and Demonstrations

Section 2.1

Point out to the students that in ancient times, astronomical observations were tightly intertwined with the mythological/spiritual aspects of human life and agricultural factors that were important to the well being of ancient cultures. Food sources, whether animal or vegetable, were found to be dependent on the annual seasonal cycles. Ask the students if they can come up with examples of things in their own lives that are dependent on celestial phenomena, including the Earth's rotation and the cyclical revolution period as we move around the Sun. When modern farmers plan, they simply look at the modern calendar and consult with technologically advanced prediction tools such as Doppler Radar and weather satellites. Ancient cultures lacked these tools and instead relied on other instruments such as Stonehenge or the Caracol Temple as described in the text.

Students may be surprised that even today the spiritual components of society are still intermingled with astronomical phenomenon. For example, the Christian holiday of Easter falls on the first Sunday following the first full Moon after the Vernal Equinox.

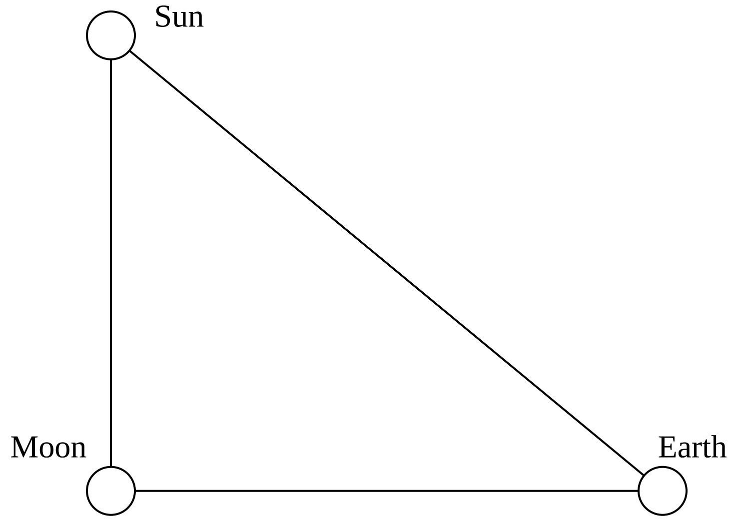
Section 2.2

While some students might be eager to move on to the black holes and string theory, my experience is that most students enjoy hearing about the history of astronomy. Hearing the stories of some of the "big names" in astronomy, the things they got right, and even the things they got wrong, goes a long way toward "humanizing" science for the students. Talking about wrong turns is especially important, because it demonstrates the power of the scientific process. Be sure to emphasize that "bad" theories are brought down by *evidence*, not just by "better" theories. People such as Aristotle and Ptolemy were not wrong because they lacked intelligence, they were wrong because they lacked *information*.

A disturbing number of authors depict ancient astronomers in a bad light; for example, some have said that the ancients clung to an idea of an Earth-centered solar system because they wanted a "special place in the universe." This is not only an arrogant 21st century perspective, it is utterly wrong. Ancient astronomers were rational, mature people who relied on their experiences and information to shape their ideas, just as we do. They could not "feel" the Earth spinning or orbiting, for example, and so believed that it was stationary beneath a rotating sky. Aristotle himself said that if the Earth were moving, then we should feel the wind from its motion. In addition, they could not see the phenomenon of stellar parallax, and thus concluded that our perspective on the stars did not change because we were not moving. Be sure to give credit to ancient astronomers for being rational people. Concerning models to describe the universe, discuss the idea of "Saving the Appearance." Early astronomers were concerned with creating models of the universe that were capable of providing accurate predictions of what they were seeing in the sky without a deep regard for physical explanation or justification. It was simply not part of their tradition, as it is part of ours.

One of the ways that Aristotle tried to justify the geocentric view of the universe was with the five classical elements. Four of these elements were found only on the planet: earth, water, air, and fire. The fifth element (sometimes called the Aether) was found only outside Earth. It was a perfect, glowing, and unchanging material, unlike the chaotic elements of Earth. An object's natural motion (what it did when nothing was exerting a force on it) depended on its composition. An object made mostly of earth or water fell downward, and an object made of air or fire rose upward. The celestial objects did neither, but moved in perfect circles around Earth. These ideas did a pretty good job describing motions in the sky for centuries, until the work of Copernicus, Galileo, and Kepler brought them down.

The text notes that not all Greeks subscribed to the geocentric model, and notes Aristarchus of Samos as an example. Students may be interested to know just how Aristarchus came to believe in a heliocentric system. It began when Aristarchus undertook a project to measure the relative sizes of the Sun and Moon, and thus add to the earlier work of measuring the size of the Earth done by Eratosthenes (see Chapter 1). He reasoned that at certain times, the Sun, Moon, and Earth would form a right triangle with the right angle at the Moon, like so:



To determine exactly when the angle at the Moon was 90 degrees, he built a model of the Earth–Moon–Sun system. He found that when the moon was half-lit as seen from Earth (first and third quarter) the angle was 90 degrees. He then knew when to go out and measure the angle at the Earth—the angle between the Sun and Moon as seen from Earth. He measured that angle to be about 87 degrees; it measured with modern instruments to be over 89 degrees. With so little left over for the angle at the Sun, it became clear that the triangle was of the "long and skinny" variety. The Sun had to be much further away than previously thought. Aristarchus calculated that the Sun was 21-times farther from Earth than was the Moon. This number is actually too small, due to the error in measuring the angle at the Earth, but the implications are what matters here. Since the Sun is much farther than the Moon, it must be proportionately larger, since the two objects have roughly the same angular size (see Chapter 1, Section 1.6). The size of Earth's shadow during a lunar eclipse indicates that Earth is about 3 times larger than the Moon. If the Sun is then 21 times larger (or more!) than the Moon, then the Sun has to be larger than Earth. An elementary school student knows this today, but 2000 years ago, it was by no means obvious. Aristarchus reasoned that it was ludicrous to expect the Earth to command an object so much larger than itself, and so he placed the Sun at the center of motion. The lack of evidence for the Earth's motion, however, proved to be more convincing for many people, including Ptolemy.

The evolution of our understanding of the structure of the Universe is a remarkable story of the scientific process, in which each successive model took care of some problem of the previous model. In many ways, the history of astronomy is the history of the scientific process itself. One common example of the scientific process at work is Ptolemy's geocentric model of the Universe; its epicycles and deferents were ultimately overthrown by the conceptually simpler Copernican heliocentric model. Students are often surprised to learn that aesthetics (simplicity, elegance, etc.) is one metric by which a scientific theory is measured. Although the early Copernican heliocentric model made no significant improvements with regard to predictive power, the scientific community at that time nonetheless accepted it—albeit after some resistance and skepticism. However, since accuracy of predictions is indeed a feature of scientific theories, even the Copernican model had to be modified, as observations revealed more subtle details including the shapes of planetary orbits, which were discovered by Kepler to be ellipses rather than perfect circles.

Section 2.3

Retrograde motion is never obvious to students, and can be hard for them to visualize. Go over Figure 2.9 carefully with students. Emphasize that the foreground of the figure is what's really happening, and the background is what we see from Earth. Ask the students what the faster-moving Earth is doing to Mars at points 5, 6, and 7. Hopefully they will respond that Earth is "lapping" Mars, just as the faster driver in an automobile race does. Then ask the students what a slower car appears to be doing as they are passing it on the highway. Hopefully they will see how the "backward" motion of Mars is explained by Copernicus's model.

DEMO—First, explain to students that the larger the orbit, the slower the planet moves. Draw some stars across the entire board. Ask a student volunteer to play the role of an outer planet. Have the student walk slowly from right to left (from the perspective of the class). You play the role of the observer on Earth. Without moving, note that the outer planet appears to move from west (right) to east (left). However, if you now walk parallel to the student (letting the student start first) and you move at a faster pace, you will appear to overtake and pass the student. This will be obvious. Now, try it again, but stop both your motions before you pass the student and note the position of the student relative to the background stars on the board several times while passing. If the student walks slowly enough and you walk fast enough, you should get a good retrograde effect. (Try this out first before going into the classroom to find an effective pace to use.)

Expand on this idea by showing the roughly circular orbits of the planets and explain how retrograde motion only occurs while Earth is "passing" the outer planet. This will always occur when the outer planet is near opposition. Ask students which planets would have retrograde motion if they were standing on Mercury or Venus. Would other objects appear in retrograde motion or only outer planets? Emphasize that the effect is not unique to viewing from Earth, nor does it only occur in planets.

Section 2.4

Before discussing Galileo's observations with the telescope, go over the prevailing worldview of his time (that is, the view of Aristotle) and emphasize some the period's major characteristics. This background will help students understand just how dramatic Galileo's discoveries were. The Aristotelian view maintained that all astronomical objects were made of a perfect and unchanging substance unknown to Earth, and that these celestial bodies orbited Earth in perfect circles. Earth was flawed and chaotic, but heavenly objects were perfect, unblemished, and unchanging. Furthermore, Aristotle's view had been inextricably linked with Christianity through "medieval scholasticism," so contradicting Aristotle was extremely serious since it was equivalent to contradicting the Roman Catholic Church. Galileo's discoveries gave evidence that objects not only orbited something other than Earth (e.g., Jupiter's moons, phases of Venus) but also that heavenly bodies were blemished (e.g., sunspots, mountains on the Moon). Galileo's experiments with falling bodies also directly contradicted the Aristotelian view, which maintained that heavier objects fall faster than do lighter ones.

If Jupiter is visible at night when you are teaching the course, encourage your students to view Jupiter through binoculars from a reasonably dark site. The four Galilean moons are visible through binoculars, and students can follow their motions over a week or so to recreate Galileo's observations.

Section 2.5

It will probably surprise students that Galileo and Kepler were contemporaries. In terms of conceptual development, it seems that Galileo built on and provided evidence for Copernicus's heliocentric model, and then Kepler refined the heliocentric theory with details about the orbits of the planets. In fact, Galileo and Kepler were working at the same time, and exchanged some correspondence. Galileo was placed under house arrest for promoting the heliocentric model and was forced to declare that it was useful as a mathematical tool only, not as a description of reality. Meanwhile, Kepler was not only assuming that the planets orbit the Sun, but he was describing their actual paths and speeds in those orbits. Point out to students the differences in societies at the time that resulted is these very different climates for scientific research and discussion. In addition, note that there was a radical difference in personalities: Galileo was an opinionated and even antagonistic person who frequently alienated people; Kepler had humility that bordered on low self-esteem. This difference in personality ultimately brought a lot of grief to Galileo, while Kepler's more deferential, "here-are-the-facts" approach may have led to quicker acceptance of his conclusions.

Throughout your discussion of the historical development and final acceptance of the Copernican system, sprinkle in interesting details of the lives of the people involved. Copernicus's theory was not even published until he lay on his deathbed because he feared ridicule. It might never have been published without the efforts of his friend, Georg Rheticus. Brahe wore metal noses after he had his nose cut off in a duel, and represented himself as an astrologer to get funding for his research. Galileo was a flamboyant character who loved to engage in debate, sometimes too much. He published in Italian and often expressed his ideas in dialogue form to make them accessible to both the "common man" and the scholar. He was friends with Pope Urban VIII and the Pope offered to fund the publication of one of Galileo's books. But when Galileo wrote the book, he put some of the Pope's words in the mouth of a buffoonish character, and made his friend look very bad. Kepler rose up from a life of abject poverty to become an accomplished musician and mathematician. He tried for over a decade to make the data that he inherited from Brahe fit traditional ideas; it was when he decided to listen only to the data that he made progress.

Begin your discussion of Kepler's laws of planetary motion by drawing an ellipse on the board or overhead, using the method shown in Figure 2.16 if possible. Define the various parts of an ellipse: perihelion, aphelion, and the semi-major axis. Show how a circle is the special case of an ellipse with an eccentricity of 0. Have students draw ellipses with the same eccentricities as the planets and point out that most of the planetary orbits are nearly circular (see Table 2.1 for data). Extend Kepler's second law to comets, and ask students to describe the relative speeds of a comet with a very elliptical orbit when it is close to the Sun and when it is far away. Finally, for Kepler's third law, pick one or two planets and use the semi-major axes given in Table 2.1 to calculate the periods. Compare to the periods given in the table. Review the mathematical meaning of "squaring" and "cubing." Many students will confuse a^3 with 3a. The students who are more mathematically aware are often concerned that the units of the third law do not work out correctly. Emphasize to them that the equation is tailor-made for specific units, and that there are constant terms with a value of 1 that can cancel the units.

Finally, point out that one of the weaknesses of Kepler's laws is that they are empirical; that is, they have plenty of "proof" or evidence, but no physical explanation. The nature of the motion was clear to Kepler, but the cause was mysterious. The explanations would have to wait for Isaac Newton.

Section 2.6

Students will find it helpful if you review something as basic as similar triangles here. Draw two triangles with one perhaps two times larger than the other but with the same angles. Show that if you know the angles and the length of one of the sides, then you can easily calculate the lengths of the remaining sides. The ratio of lengths for the known side of the similar triangles will be the same as the ratios of the sides where the length is to be determined.

Section 2.7

Newton's laws of motion are extremely important and not necessarily intuitive. Give plenty of examples of each. For instance, ask students to imagine an airplane trip on a beautiful day with no turbulence. If you throw a peanut up in the air, does it hit the person behind you or fall back in your lap? In addition, consider the motion of Earth. If you jump up in the air, does the wall of the classroom slam into you? (Galileo already had a pretty good idea of the notion of inertia when he argued against the geocentric view and used ships at sea as an example.) Emphasize to students that Newton's laws divide objects into the two categories: accelerating and non-accelerating (instead of moving and not moving). An object moving at a constant velocity (that is, in a straight line and at a constant speed) is like an object at rest in that both have no net force acting on them.

Define acceleration carefully and calculate an acceleration with which students are familiar, such as the acceleration of a car merging on the highway. You can use first units that make sense, such as miles per hour per second, and then convert to the more standard meters per second squared to help students gain a feel for the acceleration due to Earth's gravity. Students often confuse acceleration and velocity, so be sure to distinguish carefully between the two.

DEMO—You can demonstrate Newton's second law and the role of mass by attaching a rope to a rolling chair and asking a student to pull it across the floor. Then sit in the chair and repeat. Ask the student to compare (qualitatively) the force used to accelerate the empty chair with the force applied to the chair with an occupant.

DEMO—Use an air track with carts or an air hockey table with pucks to demonstrate Newton's laws, if possible. Seeing the behavior of objects in a nearly frictionless environment will help students overcome Aristotelian misconceptions about motion.

Newton's law of gravitation is explained at the end of this section. Emphasize that gravity is always attractive and (unlike some other forces) is felt by every object in the Universe. To examine the significance of the various terms, ask students what would happen to the force of gravity between Earth and the Sun if the mass of Earth doubled or if the distance between them doubled. Note that while we may understand the dependence of gravity on mass—more "pullers" means more pull—the dependence on the square of the distance remains mysterious.

Section 2.8

This section serves a summative purpose by using Newton's laws to provide a theoretical foundation for understanding the discoveries of Galileo and Kepler. For example, students often confuse the force of gravity with acceleration due to gravity. Derive the expression for acceleration due to gravity and show that it is consistent with Galileo's experiments regarding the motion of falling bodies. In addition, emphasize that Earth alone does not "have" gravity—gravity is a force between two objects. For instance, the weight of an object is the force between it and Earth. Calculate the weight of a 70 kg person on Earth and on the Moon and compare.

Use Figure 2.24 to help explain to students how gravity is responsible for objects falling and orbiting. Ask your students to picture the Moon as constantly falling towards the Earth but missing! Alternatively, students could picture the situation as the Moon's momentum, which wants to carry the Moon off into space, but is prevented from doing so by the "leash" of gravity.

DEMO—Note to the students that Newton's third law states that you are pulling on the Earth just as strongly as it is pulling on you. Then, tell students to brace themselves, and jump in the air, perhaps off a low platform. Ask the students why they did not jerk upwards to meet you, while you certainly fell down to meet the Earth. This can lead to deeper understanding of Newton's second law, and the distinction between cause (force) and effect (acceleration). Follow this up with a discussion of the orbits in Figure 2.26.

DEMO—To demonstrate orbital motion, whirl a ball around on a string in a horizontal circle. In the demonstration, the tension in the string provides the centripetal force. In the case of a planet, gravity is the centripetal force. Ask students to predict what would happen if the force suddenly "turned off," and then demonstrate by letting go of the string. This is also a good time to discuss the fact that an object in a circular orbit is constantly accelerating. Although moving at a constant speed, the object is always changing its direction. Reiterate that the speed may remain constant, but the direction change means a change in velocity nonetheless. Any change in velocity means that the acceleration is not zero.

DEMO—Ask your students whether it is possible to throw an object into orbit around the Earth. If they have read the text before coming to lecture they will probably answer "no." (Orbital velocity is about 18,000 mph around the Earth.) Next, bet them that you can actually throw an object into orbit and will even demonstrate it in class (brag a little about your fast pitch!). After they express their doubts, throw an object up and across the room so they can easily see the curve of the projectile path. Tell them that the object was in orbit but ran into the Earth! Objects orbit around the center of mass; for all practical purposes, this is the center of the Earth in this case. Draw on the chalkboard what the orbit would have been if the object had not run into the Earth, or use Figure 2.27. By throwing the object harder, it goes further. If thrown fast enough (orbital velocity) it will curve (fall) around the Earth at the same rate the Earth's surface curves.

Relevant Lecture-Tutorials

#7 Kepler's Second Law
#8 Kepler's Third Law
#9 Newton's Laws and Gravity
#26 Observing Retrograde Motion

Student Writing Questions

1. Look up one of the historical figures mentioned in this chapter. Find out as much as you can about his or her life and the period of time in which he lived. Describe what his daily life must have been like. In what ways was astronomy a part of his life?

2. Describe what it would be like to live without any gravity. What would be easier? Harder? Impossible? Fun? Annoying? Do you think you would like to live like this for an extended period?

3. Kepler had to fight a legal battle to get access to Tycho Brahe's observations. What if Kepler had been prevented from gaining that access? Speculate how this might have affected Newton's work on gravity. Would he still have been successful and proved his law of gravity? Would he even have worked on this problem? Do you think someone else would have worked on it if Newton had not? Would such a small change in historical events that occurred 400 years ago affect science today?

Chapter Review Answers

REVIEW AND DISCUSSION

1. Astronomers in the Islamic world preserved the writings and discoveries of the ancient Greeks through the Dark Ages in Europe. They translated the works of ancient astronomers such as Ptolemy and expanded on them; many of the proper names of bright stars are Arabic or Persian in origin. They developed many methods in mathematics, including algebra and trigonometry. Chinese astronomers kept careful records of eclipses, comets, and "new" stars, extending back many centuries. They also were likely the first to see sunspots.

2. The geocentric model of Aristotle had the Sun, Moon, planets and stars orbiting a stationary Earth. A modification by Ptolemy had most of the planets moving in small circles called epicycles. The center of these epicycles moved around the Earth in larger circles called deferents. Over the centuries, however, other astronomers further altered the model, and dozens of circles were needed to fully describe the motions of the 7 visible "planets," which included the Moon and the Sun.

3. The most obvious flaw in the Ptolemaic model is in its basic premise, since the Earth is not at the center of the solar system, let alone the entire universe. The unquestioned acceptance of perfectly circular orbits is another problem. However, a deeper flaw is that the Ptolemaic model did not attempt to explain why the motions are the way the model depicts them. The model may *describe* the motions, but it does not *explain* them. Today we would require any such explanation to be based on fundamental physical laws.

4. Copernicus revived the idea that a Sun-centered (heliocentric) model could explain the complex motions of the bodies of the solar system in a simpler way than a geocentric model. However, it was still flawed in that Copernicus clung uncritically to the idea that the orbits of the planets around the Sun had to be "perfect circles."

5. A theory is a framework of ideas and assumptions that represents our best possible explanation for things that happen in the real world. A good theory can be used to make predictions about future events, in addition to explaining things we already know. Theories are always subject to challenge, and thus can never be proven to be true. They can, however, be proven to be false, meaning they no longer explain the phenomenon adequately. As long as a theory survives any attempts at disproving it, it may remain accepted.

6. The ideas of Copernicus were largely ridiculed during his lifetime and he did not wish for them to be published until after his death in 1543. In the early 1600s, astronomers such as Galileo Galilei and Johannes Kepler had fully embraced the Copernican heliocentric theory based on their observations and calculations, although Kepler had to modify it somewhat. However, it is important to remember that we did not have observational evidence of Earth's motion until the mid-19th century, when the phenomena of the aberration of starlight and stellar parallax were finally observed.

7. The Copernican principle, also called the "mediocrity principle," states that Earth does not have a central or special position in the universe. It has been expanded on to include the Sun not having a central position in the Galaxy and the Galaxy not having a central position in the universe.

8. Galileo discovered that the planet Venus exhibits phases that would be impossible in Ptolemy's geocentric model. In addition, the phases of Venus also changed size, indicating that Venus was closer to Earth when a "crescent," and farther away when close to "full." This could be most simply explained by saying that Earth and Venus were both orbiting the Sun. In addition, the moons of Jupiter demonstrated that objects could move around a body other than the Earth.

9. First law: The orbits of planets, including the Earth, are in the shape of an ellipse with the Sun at one focus.

   Second law: A line connecting the Sun and a planet sweeps out equal areas in equal intervals of time; thus, a planet's orbital speed is greatest when it is closest to the Sun.

   Third law: The square of a planet's orbital period (in years) is proportional to the cube of the semimajor axis of its orbit (in astronomical units).

10. Through years of meticulous observations of the motions of the planets among the stars, Tycho provided the huge amount of data that was later analyzed by Kepler to produce the laws of planetary motion.

11. The astronomical unit, defined as the average distance between the Earth and the Sun, was used to provide an estimate of the distances between the planets long before its actual numerical value was known. By reflecting radar waves off the planet Venus and timing how long it takes them to return, we can determine the distance to Venus in kilometers. Comparing this to the distance to Venus in AU, the length in kilometers could be determined, and with it, the distance between the Earth and the Sun.

12. Astronomers used transits of the Sun by Mercury and Venus to calculate distances. When these planets passed in front of the Sun, astronomers at different locations on Earth would observe and time the transits. Using techniques of triangulation (see Chapter 1), they were able to calculate distances.

13. While Kepler's laws do an excellent job of describing how the solar system is structured, they do not explain why the planets move as they do. They are justified purely by observational data with no explanation of basic causes. Explanations would have to wait for Newton's laws.

14. First law of motion: Every object continues in a state of rest or in a state of uniform motion in a straight line unless it is compelled to change that state of motion by an unbalanced force acting on it.

    Second law of motion: When an unbalanced force (F) acts on a body of mass (m), the body experiences an acceleration (a) equal to the force divided by the mass. Thus, $a = F/m$, or $F = ma$.

    Third law of motion: To every action there is reaction equal in size and opposite in direction to the original action.

    Law of gravity: Every particle of matter in the Universe attracts every other particle with a force that is directly proportional to the product of the masses of the particles and inversely proportional to the square of the distance between their centers.

15. Newton modified Kepler's first law by stating that a planet does not really go around the Sun; rather, the planet and the Sun move in elliptical orbits around a common center of mass, located at the focus of the ellipse. The second modification was to Kepler's third law, and incorporated the sum of the masses of the orbiting bodies into the relationship between orbital period and semi-major axis.

16. Earth moves in response to the baseball, but its motion is too small to be noticed, or even measured. The Earth and the baseball pull on each other with equal gravitational force, but because of its greater mass, Earth is harder to accelerate. Thus, by Newton's second law, the acceleration of the baseball toward Earth is much greater than the acceleration of Earth toward the baseball.

17. The height to which a baseball will rise when thrown upward depends on two things: the initial velocity and the gravitational force of the planet pulling it back down. Because the Moon has a much weaker gravitational pull than Earth, a ball thrown upwards with the same velocity will rise to a greater height on the Moon. The Moon's lack of atmosphere (and the resulting absence of air friction), also helps the ball rise higher.

18. The Moon is "falling" toward Earth because of the attractive force of gravity between the two bodies. However, because the Moon has some momentum tangential to that gravitational pull, the two bodies will never collide. The Moon keeps "missing" Earth.

19. The escape speed is the speed you must be traveling to get far away enough from a planet or other large object so that its gravitational influence on you becomes too small to matter. As you rise higher above the surface of the body, its gravitational pull gets weaker. If you are traveling at the escape speed when you leave the surface, gravity cannot reduce the speed quickly enough to stop you. Therefore, you will not fall back down to the object.

20. If the Sun's gravity suddenly stopped affecting Earth, Earth would continue to move, but in a straight line at an angle of 90 degrees to its original orbit. Normally, the Sun's gravity acts like a "tether," compelling Earth to move in a curved orbit.

CONCEPTUAL SELF-TEST

1. F; Aristotle placed Earth at the center of motion.
2. T
3. F; Heliocentric means "Sun-centered."
4. F; Galileo was the first to use a telescope for organized astronomical observations.
5. F; The orbits were originally thought to be circles, until Kepler found otherwise.
6. F; Tycho Brahe provided Kepler with data.
7. F; Newton discovered that the Sun and a planet are both in motion around a common focus.
8. T
9. F; In the absence of outside forces, an object will move at a constant speed in a straight line.
10. T
11. A
12. D
13. B
14. C
15. C
16. A
17. C
18. B
19. C
20. A

PROBLEMS

1. We use the equation for angular size here, with the angular size set to 1/60 of a degree.

$$0.0167 = 57.3 \times \text{diameter/distance}$$

$$\text{diameter} = 0.0167 \times \text{distance}/57.3$$

(a) For the Moon, distance = 384,000 km, so diameter = 110 km.

(b) For the Sun, distance = 150,000,000 km, so diameter = 44,000 km.

(c) Saturn is 9.5 AU from the Sun, and so is 8.5 AU at its closest distance to Earth. This gives a diameter of 370,000 km.

2. In one day, Earth moves along 1/365 of the circumference of its orbit. Assume there is a circular orbit—a distance of $2\pi \times 1$ AU/365 = 0.0172 AU. In that same time, Mars moves a distance of $2\pi \times 1.5$ AU/687 = 0.0137 AU. Earth moves farther, by an amount of 0.0035 AU. Because the Earth moves more than Mars, Mars will appear to move backwards (retrograde) from Earth's perspective. Using the formula for angular diameter above with a distance between Earth and Mars of 0.5 AU, the angular motion of Mars appears to be:

$$57.3 \times 0.0035 \text{ AU}/0.5 \text{ AU} = 0.4 \text{ degrees in 24 hours}$$

3. Mars and Earth will be at their closest possible distance if they should happen to be side-by-side when Mars is at perihelion and Earth is at aphelion. This doesn't happen often, but it does happen. We can use the data in Table 2.1 and the equations from More Precisely 2-1 to find these distances.

$$\text{Earth at aphelion: } a(1 + e) = 1\,(1 + 0.017) = 1.017 \text{ AU}$$
$$\text{Mars at perihelion: } a(1 - e) = 1.524\,(1 - 0.093) = 1.382 \text{ AU}$$

   The difference here is 0.365 AU, which is 54,800,000 km, or almost 34 million miles.

4. The semi-major axis is the average of the perihelion and aphelion distances, which for this object is 3.0 AU. Using the formula in More Precisely 2-1, we can find the eccentricity from the perihelion distance.

$$a(1 - e) = 3\,(1 - e) = 2 \text{ and } e = 0.33$$

   Kepler's third law can tell us the orbital period. $P^2 = 3.0^3$, so P = 5.2 years

5. The satellite's perihelion distance will be 0.72 AU and the aphelion distance will be 1 AU. The semi-major axis will be the average of these two values, or 0.86 AU. Using Kepler's third law, $P^2 = a^3 = (0.86)^3$, we get an orbital period for this satellite of 0.798 years, or 291 days. The satellite will travel from aphelion (Earth) to perihelion (Venus) in half this time, or 146 days.

6. We can use Kepler's third law to calculate the semi-major axis from the period. $76^2 = a^3$, so $a = 17.9$ AU. We double this to get the length of the major axis (35.9 AU) and then subtract the perihelion distance to get the aphelion distance of 35.3 AU, beyond the orbits of all the major planets.

7. During a transit, Mercury is between Earth and the Sun. Assuming an aphelion distance of Mercury from the Sun of 0.47 AU, and that Earth is at its perihelion distance of 0.98 AU. During transit, Mercury is 0.51 AU from Earth, or 76,500,000 km. Using the equation for parallax in Chapter 1 yields:

$$\text{Parallax} = 57.3° \times 3000 \text{ km}/76{,}500{,}000 \text{ km} = 0.0022° = 8.1 \text{ arc seconds}$$

8. Since 1 AU is about 150 million kilometers, 0.7 AU is 105 million kilometers. The round trip of the radar signal would be 1.4 AU = 210,000,000 km, traveling at the speed of light. Therefore, the travel time is:

$$\text{time} = 210{,}000{,}000 \text{ km}/300{,}000 \text{ km/sec} = 700 \text{ seconds} = 11.7 \text{ minutes}$$

9. To use the modified version of Kepler's third law, we must convert the distance of Callisto into AU, and its orbital period into years.

$$a = 1{,}880{,}000 \text{ km}/150{,}000{,}000 \text{ km} = 0.0126 \text{ AU}$$
$$P = 16.7 \text{ days}/365.25 \text{ days} = 0.0457 \text{ years}$$
$$M = a^3/P^2 = 0.000957 \text{ solar masses}$$

   The mass of the Sun is 1.99×10^{30} kg, so the mass of Jupiter should be about 1.9×10^{27} kg.

10. First, we convert the radius of the orbit into kilometers: $26{,}000 \times 9.5 \times 10^{12} = 2.5 \times 10^{17}$ km. Therefore, we can find the centripetal acceleration of the Sun using the formula from More Precisely 2-2.

$$a = v^2/r = (220)^2/2.5 \times 10^{17} = 1.9 \times 10^{-13} \text{ km/s}^2 = 1.9 \times 10^{-10} \text{ m/s}^2$$

Calculate the circumference of the orbit around the Galaxy: C = 2π × 2.5 × 10^{17} km = 1.6 × 10^{18} km. The time to orbit is this distance divided by the orbital speed: P = 1.6 × 10^{18}/220 = 7 × 10^{15}, s = 2.2 × 10^{8} year. Finally, we can estimate the mass of the Galaxy from the formula in More Precisely 2-2.

$$M = rv^2/G = (2.5 \times 10^{20}\text{ m})(220{,}000\text{ m/s})^2/(6.67 \times 10^{-11}) = 1.8 \times 10^{41}\text{ kg}$$

This is an incredible mass, almost 100 billion times the mass of the Sun! Yet, this is a little less than the actual mass of the Galaxy, because we have not accounted for material outside the Sun's orbit.

11. We can use Kepler's third law: $(1{,}000{,}000)^2 = a^3$, so a = 10,000 AU. There are 63,200 AU in a light-year, for the second object, $P^2 = (63{,}200)^3$, and P = 16,000,000 years.

12. The formula for the acceleration due to gravity is $a = GM/r^2$. The mass of Earth is 5.97 × 10^{41} kg, so the only thing that varies is *r*, the distance of the object from the Earth's center.

    (a) r = 6,500,000 m, so a = 9.42 m/s^2.

    (b) r = 7,400,000 m, so a = 7.27 m/s^2.

    (c) r = 16,400,000 m, so a = 1.48 m/s^2

13. From More Precisely 2-2 and 2-3 we have

$$v = \sqrt{\frac{GM}{r}} \qquad \text{and} \qquad a = \frac{v^2}{r}$$

    (a) r = 6,500,000 m, so v = 7830 m/s and a = 9.42 m/s^2.

    (b) r = 7,400,000 m, so v = 7330 m/s and a = 7.27 m/s^2.

    (c) r = 16,400,000 m, so v = 4930 m/s and a = 1.48 m/s^2.

    Note how in every case the centripetal acceleration is equal to the acceleration due to gravity in the previous problem. This is because gravity is the only force causing the acceleration.

14. Assuming a mass of 55 kg for the person, a mass for Earth of 5.97 × 10^{41} kg, and a radius for Earth of 6,400,000 m, the law of gravity gives F = 535 N, or 120 pounds. This force is simply your weight.

15. The speed of the spacecraft in a circular orbit is given by

$$v = \sqrt{\frac{GM}{r}} = 1700\text{ m/s, or 1.7 km/s for the Moon}$$

    As stated in the text, the escape velocity is the square root of two (1.41) times this, or 2.4 km/s.

Student Companion Website Media

Animations/Videos

Retrograde Motion of Mars
Geocentric Solar System
Heliocentric Solar System
Gravity Demonstration on the Moon
Thought-Experiment at Pisa
Earth Captures a Temporary Moon

Transparencies

T-16	Figure 2.4	Planetary Motion
T-17	Figure 2.5	Inferior and Superior Orbits
T-18	Figure 2.6	Geocentric Model
T-19	Figure 2.9	Retrograde Motion
T-20	Figure 2.11	Jupiter's Moons
T-21	Figure 2.12	Venus Phases
T-22	Figure MP 2-1	Properties of an Ellipse
T-23	Figure 2.17	Kepler's Second Law
T-24	Figure 2.23	Gravitational Force
T-25	Figure 2.24	Solar Gravity
T-26	Figure 2.26	Orbits
T-27	Figure 2.27	Escape Speed

Suggested Readings

A number of excellent books are available about the history of astronomy. Here is a sampling:

Hadingham, E. *Early Man and the Cosmos.* Norman: University of Oklahoma Press, 1985. An interesting treatise about ancient astronomy in Britain, Mexico, and southwest America.

Koestler, A. *The Sleepwalkers: A History of Man's Changing Vision of the Universe.* New York: Penguin Books, 1990. More information than you will ever need about Copernicus, Brahe, Kepler, Galileo, and Newton. An exhaustive work.

Kolb, R. *Blind Watchers of the Sky.* Reading, Mass: Addison Wesley, 1999. A lively historical narrative. The first chapter deals with Renaissance astronomy. The title comes from a remark Tycho made about his detractors.

Panek, R. *Seeing and Believing: How the Telescope Opened Our Eyes and Minds to the Heavens.* New York: Penguin Books, 1999. A brief book, but packed with information about a number of astronomers, including Galileo and Kepler.

Walker, C., ed. *Astronomy before the Telescope.* New York: St. Martin's Press, 1997. A series of essays on astronomy from ancient times to the early Renaissance.

Articles:

Berman, B. “The Outsider.” *Astronomy* (October 2003). p. 48. Illuminating article about a modern astronomer. Helpful when discussing the scientific method with students and a good reminder that science is a human endeavor/activity. Relevant to this chapter and to Chapter 1.

Falk, D. “The rise and fall of Tycho Brahe.” *Astronomy* (December 2003). p. 52. A nice overview of Tycho Brahe, his observatories, and details of his eccentric life.

Gettrust, E. “An extraordinary demonstration of Newton’s Third Law.” *The Physics Teacher* (October 2001). p. 392. A description of an apparatus using magnets and force probes to demonstrate that the action and reaction forces are equal in magnitude.

Gould, Stephen Jay. “The sharp-eyed lynx, outfoxed by nature. Part one: Galileo Galilei and the three globes of Saturn.” *Natural History* (May 1998). p. 16. Discusses the life and work of Galileo.

Harwit, Martin. “The growth of astrophysical understanding.” *Physics Today* (November 2003). p. 38. A historical review of almost 3000 years of inquiry about the universe.

Kemp, Martin. “Kepler’s cosmos.” *Nature* (May 14, 1998). p. 123. Describes ancient cultures’ image of the cosmos.

Kemp, Martin. “Maculate moons: Galileo and the lunar mountains.” *Nature* (Sept. 9, 1999). p. 116. Discusses Galileo’s observations of features on the Moon.

Krupp, E. C. “Designated authority.” *Sky & Telescope* (May 1997). p. 66. Discusses the role of the “official” astronomer in ancient cultures.

Krupp, E. C. “From here to eternity: Egyptian astronomy and monuments.” *Sky & Telescope* (February 2000). p. 87. Discusses the depiction of the stars and sky in ancient Egyptian monuments.

Krupp, E. C. “Stairway to the stars: The Jantar Mantar, or ‘House of Instruments,’ in Jaipur, India.” *Sky & Telescope* (September 1995). p. 56. Describes an 18th century Indian monument that was used to track the motions of the Sun.

Nadis, S. “Big science.” *Astronomy* (May 2003). p. 46. Explores the trend toward fewer, but larger research projects and the hope for a trend reversal. This is a good contrast when discussing the projects that occupied Brahe/Kepler and Galileo.

Panek, Richard. “Venusian testimony.” *Natural History* (June 1999). p. 68. Discusses Galileo’s observations of the phases of Venus.

Quinn, Jim. “Stargazing with Galileo.” *Night Sky* (May/June 2006). p. 44. A guide to reproducing Galileo’s observations with a backyard telescope.

Ruiz, Michael J. “Kepler’s Third Law without a calculator.” *The Physics Teacher* (December 2004). p. 530. Describes a simple activity for introducing students to Kepler’s third law.

Stephenson, F. Richard. “Early Chinese observations and modern astronomy.” *Sky & Telescope* (February 1999). p. 48. Discusses ancient Chinese astronomical observations and how they can be connected to modern science.

Sullivant, Rosemary. “An unlikely revolutionary: Nicolas Copernicus.” *Astronomy* (October 1999). p. 52. Discusses the life and scientific works of Copernicus.

Sullivant, Rosemary. “When the apple falls: Sir Isaac Newton.” *Astronomy* (April 1998). p. 54. Discusses Newton, his life, and his scientific works.

Trefil, James. “Rounding the Earth.” *Astronomy* (August 2000). p. 40. Describes some of the astronomical knowledge of ancient Egyptian, Greek, and Near Eastern cultures.

Vogt, E. “Elementary derivation of Kepler’s laws.” *American Journal of Physics* (April 1996). p. 392. For your more advanced students, here is a proof of Kepler’s laws that follows from conservation of energy and angular momentum, with further discussion.

Williams, K. “Inexpensive demonstrator of Newton’s First Law.” *The Physics Teacher* (February 2000). p. 80. Uses a Downy® Ball fabric-softener dispenser!