

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. For example, students often take the many satellites that serve us in orbit for granted, and may have a poor understanding (and some misconceptions) about what it takes to get them in orbit and keep them there. Cartoons as well as some science fiction movies and television programs can promote these misconceptions that have become the “lived reality” of our students.

Major Concepts

- Ancient Astronomy
 - Early Uses of the Sky
 - Astronomy During the “Dark Ages”
- 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 as well as agricultural practices 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 meteorological 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. It is worth noting that we have only deduced after the fact that these ancient monuments had astronomical applications; it's not as if they came with instruction manuals! There are also instances where an ancient site was thought to have astronomical significance that later proved to be spurious, such as the Nazca Lines in South America.

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

Section 2.2

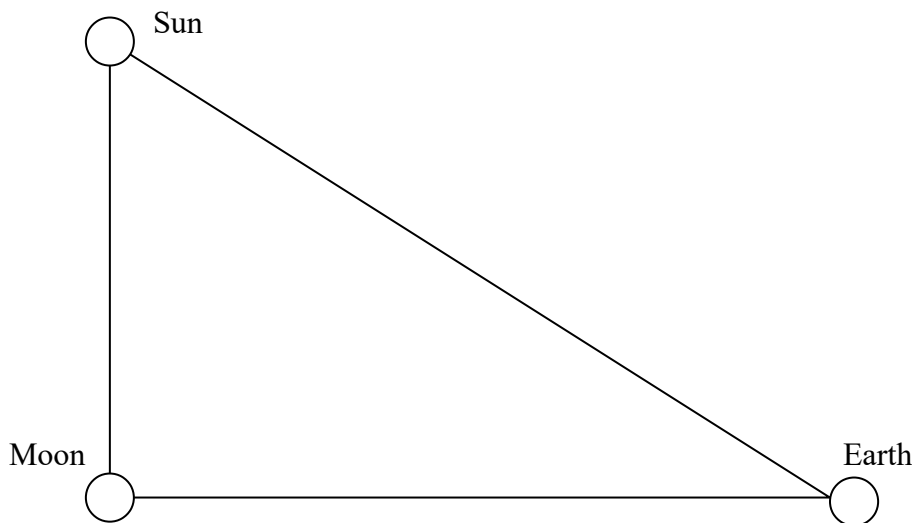
While a few students might be eager to move on to the black holes and string theory, my experience is that most students enjoy hearing about the history of astronomy. Hearing the stories of some of the "big names" in astronomy, the things they got right, and even the things they got wrong, goes a long 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 patronizing manner; 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. When talking about the ancient practice of using 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 reproductions of what they were seeing in the sky without a deep regard for

physical explanation or justification. The need for such justification 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 in our world: 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 seemed reasonable for 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 mentions Aristarchus of Samos as an example. Students may be interested to know just how Aristarchus came to the conclusion that the Sun is at the center. 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° , 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° . 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° ; it is measured with modern instruments to be over 89° . 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 about 19 times farther from Earth than was the Moon. In modern terms we would use the sine function, and say that since $\sin 3^\circ \approx 1/19$, the hypotenuse (Earth–Sun distance) is about 19 times the side opposite the 3° angle (Earth–Moon distance). 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 Section 1.5). 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 19 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.) are 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 eventually 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. The process of refinement continued when Isaac Newton revealed that the Earth does not technically orbit the Sun, but the Sun and Earth both orbit around a common focus.

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, give a little background on the prevailing worldview of the time, to 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 that heavier objects fall faster than do lighter ones.

You may want to mention that Galileo did not actually invent the telescope, nor was he actually the first to use it to observe the heavens. A Dutch optician named Hans Lippershy first got the idea to look through two lenses at once, allegedly from his children. An Englishman named Thomas Harriot mapped out the surface of the Moon with a telescope a few months before Galileo built one in 1609. It is still amazing that Galileo was able to build his own telescope purely from a physical description, and that he made such meticulous observations that literally revolutionized the discipline of astronomy and helped make it a science.

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.

Anyone wishing to experience the sky as Galileo did may wish to purchase a “Galileoscope” (at www.galileoscope.org) or similar small telescope kit. Even a moderately priced pair of binoculars have optics as good as, or superior to, Galileo’s. However, the man himself had one huge advantage that we cannot match, sadly: four centuries ago the world had incredibly dark skies, even in urban areas!

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. Why were the results of these two men so differently received? Point out to students the differences in their societies and situations that resulted in these very different climates for scientific research and discussion. Kepler was essentially an agent of the Holy Roman Empire at the time he published his work, while Galileo was mostly supported by private patrons like the Medici family. In addition, note that there was a radical difference in personalities: Galileo was an opinionated and even antagonistic person who frequently alienated the people he was trying to educate; 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 prosthetic 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.
- Galileo published in Italian, as opposed to Latin, and often expressed his ideas in dialogue form to make them accessible to both the scholar and the “common man.”

- Galileo 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.
- Kepler tried for almost 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. In some ways, Kepler can be seen as the first person to fully employ the "Scientific Method."

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 2.15 if possible. Define the various parameters of an ellipse: perihelion, aphelion, semi-major axis, and eccentricity. 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. Reassure 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 as far as Newton's laws are concerned, an object moving at a constant velocity (i.e., in a straight line and at a constant speed) is pretty much the same as an object at rest: both have no net force acting on them, and thus neither is accelerating, or changing velocity.

Define acceleration carefully and calculate an acceleration that students can relate to, such as the acceleration of a car merging on the highway. You can use more familiar units at first, 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 can 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 forces such as the electromagnetic force) is felt by every object in the Universe. Also, note that it is proper to speak of the gravitational force *between two* objects, not the gravitational force *of* an object. 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.

To help drive home the factors that influence the gravitational force, I present the students with the following fanciful thought experiment. Imagine that malevolent aliens come to Earth and demand that we capitulate, or else they will turn their “shrink ray” on the Sun and reduce its radius to 1 kilometer. That is enough to turn the Sun into a black hole! Three things could then happen: the Earth could get sucked into the black hole Sun, Earth could go flying off into the void of space, or the Earth could stay in its orbit. Have students briefly weigh the options with a neighbor, then take a poll to see which outcome is most likely, according to the class. Students will probably be surprised that the gravitational force will not change, since none of the important factors—the masses of the Sun and Earth and the distance between their centers—have changed. Black holes are not “cosmic vacuum cleaners” as popular fiction depicts them. You can recall this example later in the semester during your discussion on black holes.

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. Use the gravitational formula to compare the weight of a 70-kg person on Earth and the weight of that same person on the Moon.

Use Figure 2.23 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 because it has velocity! Alternatively, students could picture the situation as the Moon wanting to head off into space in a straight line, but being prevented from doing so by the “leash” of gravity.

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—Point out 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 as you jump in the air, perhaps off a step or 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 2.25. To better understand the orbits of objects with different masses, ask the students to imagine a parent whirling a child around. The child makes a big circle, while the parent moves in a much smaller circle. This will be important when discussing the discovery of new “exoplanets” later on.

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 2.26. 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

Kepler’s Second Law, p. 21

Kepler’s Third Law, p. 25

Newton’s Laws and Gravity, p.29

Observing Retrograde Motion, p. 99

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 or she lived. Describe what the scientist’s daily life must have been like. In what ways was astronomy a part of the person’s 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 in formulating 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, many years before Galileo.

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. Scholars clung to this model for reasons that had nothing to do with religion or needing a “special place in the Universe.” They had two very rational reasons for thinking the Earth was stationary at the center. First, there was no sensation of motion, no “wind” as the Earth moved through space. Second, there was no observed change in position of the stars (parallax) as the Earth moved around the Sun. This change in position occurs, but it was not measurable until the mid-1800s.
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, backed up by hard data. 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. It is notable that theories are refuted by data, not by other theories. As long as a theory survives any attempts at disproving it, it will likely continue to be accepted.
6. 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, with Venus’ orbit entirely inside the Earth’s. In addition, the moons of Jupiter demonstrated that objects could move around a body other than the Earth, that there was more than one “center” of motion.
7. Through years of meticulous observations of the motions of the planets among the stars, Tycho Brahe provided the huge amount of data that was later analyzed by Kepler to produce the laws of planetary motion.
8. First law: The orbits of the 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 semi-major axis of its orbit (in astronomical units).

9. 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 from Venus to Earth in kilometers. Comparing this to the distance from Venus to Earth in AU, the size of the AU in kilometers could be determined, and with it, the distance between the Earth and the Sun.
10. 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.
11. First law of motion: Every object continues in a state of rest or in a state of uniform motion (constant 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.

12. Newton explained Kepler's First Law by saying that a planet and the Sun have an attraction for each other. They do not crash into each other because they have been moving from the beginning. You can say that the Earth is indeed "falling" toward the Sun, but keeps missing the Sun due to its motion. Alternatively, you can say that the Earth wants to go flying off in a straight line (Newton's First Law) but its motion is changed by the unbalanced force of the Sun's gravity (Newton's Second Law). Kepler's Second Law can be explained as follows: as a planet approaches the Sun from aphelion to perihelion, it is moving in the direction of the force of gravity (toward the Sun) and thus it speeds up. From perihelion to aphelion, the planet is moving away from the Sun, in the opposite direction of the gravitational force, and the planet slows down. Kepler's Third Law is a relationship between the average distance of a planet from the Sun, and the amount of time for the planet to orbit the Sun. Distance from the Sun is an important factor determining the strength of the gravitational force between a planet and the Sun, which in turn controls orbital speed.
13. Earth does move 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.
14. The Moon is "falling" toward Earth because of the attractive force of gravity between the two bodies. However, because the Moon has a sufficiently large velocity tangential to that gravitational pull, the two bodies will never collide. The Moon keeps "missing" Earth. By measuring the speed the Moon is traveling to maintain its orbit, we can calculate the strength of the gravitational pull between the Moon and Earth, and then find the Earth's mass.
15. 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.

CONCEPTUAL SELF-TEST

1. A
2. D
3. B
4. C
5. C
6. A
7. C
8. B
9. C
10. A

PROBLEMS

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

$$0.0167^\circ = 57.3^\circ \times \frac{\text{actual diameter}}{\text{distance}}$$
$$\text{actual diameter} = 0.0167^\circ \times \frac{\text{distance}}{57.3^\circ}$$

- (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. Since that is bigger than Saturn itself is, Saturn just looks like a point to the unaided eye.

2. 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.
3. 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.
4. 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:

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

5. During a transit, Mercury is between Earth and the Sun. The aphelion distance of Mercury from the Sun is 0.47 AU, and the perihelion distance of Earth is 0.98 AU. Thus, during transit, the closest Mercury can be to Earth is 0.51 AU, or 76,500,000 km. Using the equation for parallax in Chapter 1 yields:

$$\text{parallax} = 57.3^\circ \times \frac{\text{baseline}}{\text{distance}} = 57.3^\circ \times \frac{3000 \text{ km}}{76,500,000 \text{ km}} = 0.0022^\circ$$

This is about 8.1 arc seconds

6. The formula for the acceleration due to gravity is $a = \frac{GM}{r^2}$. The mass of Earth is 5.97×10^{24} 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 $a = 9.43 \text{ m/s}^2$.
- (b) $r = 7,400,000$ m, so $a = 7.28 \text{ m/s}^2$.
- (c) $r = 16,400,000$ m, so $a = 1.48 \text{ m/s}^2$

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

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

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

8. Assuming a mass of 55 kg for the person, a mass for Earth of 5.97×10^{24} 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.

Suggested Readings

Web Resources

<http://www.jpl.nasa.gov/video/index.cfm?id=888> NASA video on the discovery of Jupiter's moons. The site also offers current information about making observations of Jupiter's moons.

<https://solarsystem.nasa.gov/basics/index.php>. A series of videos from NASA that can help students better understand the force of gravity and orbits.

<http://www.wam.umd.edu/~tlaloc/archastro> . The Center for Archaeoastronomy.

The "Crash Course" channel on YouTube has a series about astronomy:

<https://www.youtube.com/playlist?list=PL8dPuuaLjXtPAJr1ysd5yGlyiSFuh0mIL>
Video # 7 is especially relevant to this chapter

You can purchase a modern replica of Galileo's telescope at <http://galileoscope.org/>.

Books

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

Aveni, A., *Sky Watchers of Ancient Mexico*. Austin: University of Texas Press, 1980. A discussion of astronomy in ancient Mesoamerica.

Aveni, A. *Between the Lines*. Austin: University of Texas Press, 2000. Although the Andean Nazca Lines are generally regarded as having no astronomical significance, they are still an interesting study in modern interpretations of ancient monuments.

Gribbin, J. *The Scientists*. New York: Random House, 2002. A 500-year-plus tour of the history of science, featuring many prominent astronomers, to whet the appetite for deeper study.

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.

Hawking, S., ed. *On the Shoulders of Giants: The Great Works of Physics and Astronomy*. Philadelphia: Running Press, 2002. This immense omnibus features the seminal works of Copernicus, Galileo, Kepler, Newton, and Einstein, with commentary by Dr. Hawking.

Johnson, A. *Solving Stonehenge*. London: Thames and Hudson, Ltd., 2008. A recent attempt to reconstruct the various stages of the construction of Stonehenge, and gain insight as to the site's intended purpose.

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, MA: Addison Wesley, 1999. A lively historical narrative. The first chapter deals with Renaissance astronomy. The title comes from a remark Tycho Brahe made about his detractors.

North, J. *Stonehenge: A New Interpretation of Prehistoric Man and the Cosmos*. New York: The Free Press, 1996. Further investigation of the ancient megalithic site and its environs.

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.

Magazine 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.

Falk, D. "Did ancient astronomers build Stonehenge?" *Astronomy* (July 2009). Proposes that the astronomical uses of Stonehenge were not its primary function.

Falk, D. "Who was Thomas Harriot?" *Astronomy* (April 2010). The career of one of the early users of the telescope.

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.

Gingerich, O. "The great Martian catastrophe and how Kepler fixed it." *Physics Today* 64:9 (2011). p. 50. How Kepler dealt with the problems resulting from Mars' eccentric orbit.

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

Hudon, D. "How Johannes Kepler revolutionized astronomy." *Astronomy* (January 2009). A summary of the German astronomer's outstanding body of work.

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

Kemp, M. "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, R. "Venusian testimony." *Natural History* (June 1999). p. 68. Discusses Galileo's observations of the phases of Venus.

Quinn, J. "Stargazing with Galileo." *Night Sky* (May/June 2006). p. 44. A guide to reproducing Galileo's observations with a backyard telescope.

Ruiz, M. "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.

Schilling, G. "Gravitational waves hit prime time." *Sky & Telescope* (December 2015). p. 26. Recent potential detections of gravitational waves may change the way we view gravity.

Sherwood, S. "Science controversies past and present." *Physics Today* 64:10 (2011). p. 39. A comparison between the heliocentric controversy and the modern controversy of global warming.

Shubinski, R. "How the telescope remade the Universe." *Astronomy* (May 2009). The invention of the telescope and the transformation it caused in science.

Stephenson, F. "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, R. "An unlikely revolutionary: Nicolas Copernicus." *Astronomy* (October 1999). p. 52. Discusses the life and scientific works of Copernicus.

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

Trefil, J. "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!