Chapter 1: The Copernican Revolution

The Birth of Modern Science

Outline

Summary

Chapter 1 continues the view from Earth begun in Chapter 0 by discussing the apparent motions of the planets. The historical development of astronomy from Copernicus through Newton is considered next. This chapter ends with a thorough discussion of Kepler's laws of planetary motion and Newton's laws of motion and gravity. The development of models of the universe from Ptolemy through Newton is discussed as an example of the scientific method at work.

Major Concepts

- The planets' motions
  - Wanderers among the stars
  - Retrograde motion
- Geocentric models of the universe
  - Aristotle
  - Ptolemy
- History of modern astronomy and heliocentric models
  - Copernicus
  - Brahe
  - Galileo
  - Kepler
- Kepler's laws of planetary motion
- Isaac Newton
  - Laws of motion
  - Gravity

Teaching Suggestions and Demonstrations

At the beginning of this chapter, give your students a copy of a current star chart showing positions of any visible planets. Encourage them to observe the planets over the course of the semester and the Moon over the course of a month and notice how these move with respect to the stars.

Sections 1.1 and 1.2

Humans have looked at the sky and tried to unravel the motions of the stars and planets since early times. *Discovery 1-1* on ancient astronomy describes several intriguing examples of artifacts and structures with astronomical significance that have survived from ancient societies. The evolution of our understanding of the structure of the universe is a remarkable story of **scientific process**, where each successive model took care of some problem of the previous model. Ptolemy, for instance, introduced epicycles to account for retrograde motion that could not be explained by the Aristotelian universe. Kepler changed the shape of the orbits from circles, as shown in Copernicus' model, to ellipses.

Starry Night College can be used to demonstrate the **retrograde motion** of the superior planets. Mars will be the best planet to use because the retrograde motion happens over just a few months. Jupiter and Saturn will both work since they are visible as they move through the constellations. The trick with this simulation is that you should center on the planet and then change the time intervals to multiple days. It takes some practice, but will make for a good demo in class and will likely be more effective than showing a static image. You should have the students mark the relative positions of both Earth and Mars in their orbits during the retrograde interval. Students should understand that the retrograde motion is associated with the Earth overtaking Mars in its orbit.

Students accept the **heliocentric model** without question, and they tend to forget just how hard it was for people to give up the **geocentric model**. The reason is obvious; go outside at night and observe the sky over a period of time. It sure *looks* like the stars are going around Earth, and it certainly does not *feel* like Earth is moving! Reluctance to demote Earth from its position at the center of the universe resulted in Ptolemy's complicated and intricate model, which still failed after a long time to accurately predict the positions of the planets. Moving to a heliocentric system and changing the orbits from circles to ellipses greatly simplified the model. As discussed in the text, simplicity is a desirable characteristic in scientific models; ask students to think of other examples of scientific advancement where successive models increased simplicity.

Tycho Brahe actually had a model of his own that combined aspects of the heliocentric model with geocentrism. He kept Earth in its central position, but placed the other planets in orbit around the Sun, which itself orbited Earth. Brahe's model was largely ignored, and he is remembered today for his contributions in the form of vast quantities of observational data (that predated the telescope), which laid the foundation for Kepler's work. Interestingly, Brahe's main argument for keeping Earth at the center was the lack of observed stellar parallax. Brahe had a good point; he just could not conceive of stellar distances so great that the corresponding parallaxes would be too small to be observed without precise instruments. In fact, the first successful parallax measurements were made in 1838 by Wilhelm Bessel.

Before discussing **Galileo's observations with the telescope**, go over the prevailing worldview of his time and emphasize some of its major characteristics. This background will just help students understand how dramatic Galileo's discoveries were. The Aristotelian view maintained not only that all astronomical objects orbited Earth but also that they did so in perfect circles. Earth was flawed, but heavenly objects were perfect, unblemished, and unchanging. Further, Aristotle's view had been inextricably linked with Christianity through "medieval scholasticism," so contradicting Aristotle was extremely serious as it was equivalent to contradicting the Roman Catholic Church. Galileo's discoveries provided evidence that objects not only orbited something other than Earth (Jupiter's moons, phases of Venus) but also that heavenly bodies were not unblemished (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 in binoculars, and students can follow their motions over the course of a week or so to recreate Galileo's observations. The orbital motion of the Galilean moons can be demonstrated using **Starry Night Pro**. You will need to zoom in on Jupiter until the moons are visible. Then you can advance through time and watch the moons orbit. When you initially see the moons it is not necessarily apparent which moon is which, so **Starry Night Pro** can be used to identify them.

It will probably surprise students that Galileo and **Kepler** were contemporaries. In terms of conceptual development, it seems that Galileo built upon and provided evidence for Copernicus' 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. 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, at the same time, Kepler was not only assuming that the planets orbit the Sun, but he was also describing their actual paths and speeds in those orbits. Point out to students the differences in societies at the time that resulted in these very different climates for debate and discussion.

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' theory was not even published until he lay on his deathbed. Brahe wore metal noses after he had his nose cut off in a duel. Galileo was a flamboyant character who loved to engage in debate. He published in Italian and often expressed his ideas in dialogue form, to make them accessible to both the common man and the scholar.

Sections 1.3 and 1.4

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 1.11. Define the various parts of an ellipse and 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 1.1 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 semimajor axes given in Table 1.1 to calculate the periods. Compare the periods given in the Appendix on planetary orbital properties. Review the mathematical meaning of "squaring" and "cubing." Many students will confuse a^3 with $3a$. The more mathematically aware students are often concerned that the units of the third law do not work out correctly. When it is said that the constant of proportionality is one, it does not imply that there are no units associated with the constant. In fact, the constant is 1 yr^2/AU^3, but for convenience we rarely show it.

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"; demonstrate by letting go of the string. Note that if you shorten the string then the period will also shorten, much like **Kepler's third law**. For instructors that might be skilled with a yo-yo, the trick "around the world" can be used instead of the ball and string for this demo. To shorten the string, simply have a second yo-yo that already has a shorter string prepared.

Try using "Observing Retrograde Motion" from the book *Lecture-Tutorials for Introductory Astronomy*. This exercise is particularly good and helps to reinforce material that you have covered in lecture. Be sure to consider how much time to devote to this exercise because it normally takes more class time than you would estimate.

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? Also 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 of *accelerating* and *nonaccelerating* 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 onto 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 between the two carefully. You can demonstrate Newton's third 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 occupant.

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.

Gravitational force is an extremely important concept in astronomy so it is worth spending some time on **Newton's law of gravity**. Refer to the explanation in the text as well as to Figure 1.18, which gives both a mathematical expression of the law and a graph depicting its inverse-square nature. 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. 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. Also 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 when the two are in contact. Calculate the weight of a 70-kg person on Earth and on the Moon and compare. It is important to distinguish the difference between weight and mass of an object. The mass of an object is expressed in kilograms, but the weight is a force and is calculated by the mass times the acceleration due to gravity. The weight of a 70-kg person is 686 N (or $kg \times m/s^2$). The weight varies from planet to planet because the acceleration due to gravity is a function of the mass and size of the planet. Use Figure 1.19 to help explain how gravity is responsible for objects falling as well as objects orbiting. Ask your students to picture the Moon as constantly falling toward the Earth and missing!

The final section of this chapter refers back to the scientific method introduction in Chapter 0. Use the development of ever-improving models of the universe as an illustration of the cyclic nature of the scientific process.

Student Writing Questions

1. Try to identify at least one star that you can see at night. Look up information on it such as its distance and how its properties compare to the Sun. What would it be like to live on a planet orbiting this star?

2. Mars is a planet with several similarities to Earth: its day is about the same length and it is tilted in a way that causes seasons to occur. But its orbital period is significantly longer. Imagine people born and raised on Mars. They might use the Martian year rather than an Earth year to measure time. How long are the seasons on Mars, as measured in Earth units? How old would you currently be in Martian years? Do you think time would actually pass differently for you if you lived on Mars? There are 669.5 Martian days in a Martian year. What kind of calendar would you design? How would you define months and weeks and how many would you want to make?

3. Kepler’s accomplishments, with his three laws of orbital motion, cannot be overstated. What is more amazing is the way in which he had to make all calculations by hand without the aid of the modern instruments we usually take for granted. How did he do this? Go to the library and look up a biography of Kepler and investigate how Kepler went about this monumental task of taking Tycho Brahe’s observations and turning them into these three laws. Did he use mathematical tricks and shortcuts?

4. 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 of time?

Answers to End of Chapter Exercises

Review and Discussion

1. The geocentric model of the universe placed Earth at the center with all the other astronomical bodies orbiting it. Ptolemy’s model also included epicycles to explain retrograde motion. The advantage of this model was that it made sense to people at the time. With no direct experiential evidence for the Earth movement, it was reasonable to place the Earth at the center. However, its disadvantage was that as observations of the motions of stars and planets became more detailed, the model could no longer explain them without adding more complications.

2. The Ptolemaic model was extremely complicated and intricate. It was missing simplicity, a quality often taken to be an indicator of truth. The geocentric insistence that Earth was at the center of the universe was the major flaw in the model.

3. Copernicus “rediscovered” and refined the heliocentric model of the universe, in which the Sun is at the center and Earth spins on its axis while orbiting the Sun.

4. In the heliocentric model, the Earth as well as the other planets orbit the Sun. Retrograde motion is easily explained by this model since an outer planet appears to move backward when the Earth overtakes and passes it on an inside orbit. Brightness variations are explained by the fact that the distance between the Earth and another planet will change significantly as the two orbit the Sun. If planets orbited the Earth in a circular path, their distance and therefore brightness would not be expected to change as much.

5. Four of Galileo’s discoveries are considered the most important in terms of refuting Aristotelian philosophy and therefore supporting Copernicus. These are: (1) the discovery of mountains and valleys on the Moon, (2) the discovery of sunspots, (3) the discovery of the moons of Jupiter, and (4) the discovery that Venus goes through phases that can only be explained by its motion around the Sun. Discoveries (1) and (2) both refuted the belief that all celestial objects were pure and unblemished. Discovery (3) gave proof that objects (in this case, moons of Jupiter) could orbit something other than the Earth.

6. Galileo performed experiments to test his ideas rather than using logic alone. For instance, Aristotelians argued that heavier objects would fall faster. After all, it was “logical.” Galileo actually performed experiments on falling bodies to investigate them.

7. Kepler’s first law: The planets travel along orbits that are elliptical, with the Sun at one focus.
   Kepler’s second law: A planet sweeps out equal areas of the ellipse in equal time intervals.
   Kepler’s third law: The square of a planet’s period is proportional to the cube of its semimajor axis.

8. Tycho Brahe made the most accurate positional measurements in astronomy prior to the invention of the telescope. These positional observations of the planets were used by Kepler to devise his three laws of planetary motion.

9. His laws were based on observations.

10. Radar can be used to find the distance from Earth to Venus. Also, Kepler's laws can be used to find the distance from Venus to the Sun in terms of Earth's distance, that is, in astronomical units. Combining these pieces of information yields the distance of Earth to the Sun. (See Figure 1.14.)

11. Newton modified Kepler's first law to state that each planet orbits the Sun in an ellipse, with the *center of mass of the Sun–planet system* (instead of the center of the Sun) at one focus of the ellipse. Newton modified Kepler's third law to state that the period squared is proportional to the semimajor axis cubed *divided by the total mass of the system*.

12. Even though the force between the baseball and Earth is equal, the acceleration of the baseball is much greater than the acceleration of the Earth, so the baseball moves more.

13. The acceleration due to gravity on the Moon is about one-sixth what it is on the Earth. When a ball is thrown upward on the Moon, the force pulling it down is less, so the ball goes higher.

14. According to Newton, the Earth is in orbit around the Sun because the Sun–Earth gravitational force is causing the Earth to accelerate toward the Sun, but the Earth has a sufficient tangential velocity that Earth is continually "falling around" the Sun.

15. If the Sun's gravity were somehow "turned off," Earth would move in a straight line, tangential to its orbital path, through space instead of orbiting the Sun.

Conceptual Self-Test

True or False? 1. F; 2. F; 3. F; 4. F; 5. F; 6. F; 7. F; 8. T

Multiple Choice: 9. D; 10. c; 11. c; 12. a; 13. c; 14. b; 15. b

Problems

1. The ratio of 1 arcmin to 360° will be the same as the ratio of the corresponding distance to the circumference of the whole circle:

$$\frac{(1/60)^\circ}{360^\circ} = \frac{x}{2\pi(\text{dist.})}.$$

(a) At the distance of the Moon, $x = \dfrac{(1/60)^\circ \times 2\pi(384{,}000 \text{ km})}{360^\circ} = 110 \text{ km}.$

(b) Using the distance of the Sun (1.5×10^8 km), the result becomes 44,000 km.

(c) At closest approach, Saturn and Earth are (9.5 − 1.0 AU) = 8.5 AU apart. Converting to km and substituting this distance into the equation in part (a) results in

$$x = \frac{(1/60)° \times 2\pi(8.5\text{ AU})(1.5\times10^8\text{ km/AU})}{360°} = 3.7\times10^5\text{ km.}$$

2. Use $d = vt$ and remember that the radar travels at the speed of light and is making a round trip:

$$t = d / v = \frac{2\times0.7\text{ AU}\times1.50\times10^8\text{ km/AU}}{3\times10^5\text{ km/s}} = 700\text{ s.}$$

3. The Earth has an average orbital speed of 29.79 km/s = 2,573,856 km/day. Mars has an average orbital speed of 24.1 km/s or 2,082,240 km/day. The separation is 0.5 AU or 7.45×10^7 km. Let's assume that the motion during 1 day can be approximated as linear motion, then in 1 day the Earth moves 2,573,856 km and Mars moves 2,082,240 km. The difference is 491,616 km. We can treat the parallax angle as if it is the angular diameter of 491,616 km as seen from 7.45×10^7 km:

$$\frac{\text{Parallax}°}{360°} = \frac{491{,}616\text{ km}}{2\times3.14\times\ 7.45\times10^7\text{ km}} \Rightarrow \text{ Parallax}° = 0.37° = 23'\text{ Mars moves in retrograde.}$$

4. (a) The semimajor axis will be half the major axis, which is the sum of the perihelion and aphelion distances: $a = \frac{(2.0\text{ AU } + \text{ 4.0 AU})}{2} = 3.0\text{ AU}$

(b) From Figure 1.12, the eccentricity can be calculated from the perihelion (or aphelion) distance and the semimajor axis:

$$\text{perihelion} = a(1-e), \text{so } e = 1 - p/a = 1 - 2/3 = 1/3 = 0.33.$$

(c) Finally, use Kepler's third law, $P^2 = a^3$ to calculate the period:

$$P = \sqrt{a^3} = \sqrt{(3.0)^3} = 5.2\text{ years.}$$

5. From Kepler's third law, $P^2 = a^3$, so $a = \sqrt[3]{P^2} = \sqrt[3]{76^2} = 17.9\text{ AU}$.

The major axis is therefore $2\times17.9\text{ AU} = 35.8\text{ AU}$. Theaphelion distance plus the perihelion distance is the major axis, so the aphelion distance is the major axis minus the perihelion distance:

$$\text{aphelion} = 35.8\text{ AU} - 0.6\text{ AU} = 35\text{ AU.}$$

6. The perihelion distance of any planet is given by $\text{perihelion} = a(1-e)$. The aphelion distance is given by aphelion = $a(1 + e)$. Use the data from Table 1.1 to calculate the difference in distance for Mercury at aphelion compared to perihelion:

Mercury: $\text{perihelion} = a(1-e) = 0.31\text{ AU.}$

$\text{aphelion} = a(1+e) = 0.47\text{ AU.}$

difference = 0.16 AU.

7. Use the modified version of Kepler's third law, $P^2 = a^3 / M_{\text{total}}$, where the period is in Earth years, the semimajor axis is in AU, and the mass is in solar masses. Because Callisto's mass is negligible, the total mass of the Jupiter/Callisto system is just the mass of Jupiter: $M_{\text{Jupiter}} = a^3 / P^2$

$$= \frac{[(1.88\times10^6\text{ km})/(1.50\times10^8\text{ km/AU})]^3}{[(16.7\text{ days})/(365\text{ days/yr})]^2} = 9.40\times10^{-4}\text{ solar masses } = 1.87\times10^{27}\text{ kg.}$$

8. The acceleration due to gravity is inversely proportional to the square of the distance from the center of the Earth. Therefore, $\frac{g_h}{9.80\text{ m/s}^2} = \frac{(r)^2}{(r+h)^2}$, or $g_h = \frac{(r)^2}{(r+h)^2}(9.80\text{ m/s}^2)$, where r is the radius of the Earth, h is the altitude, and g_h is the acceleration due to gravity at that altitude:

(a) $g_h = \frac{(6.40\times10^6\text{ m})^2}{(6.40\times10^6\text{ m}+100{,}000\text{ m})^2}(9.80\text{ m/s}^2) = 9.50\text{ m/s}^2.$

(b) $g_h = \frac{(6.40\times10^6\text{ m})^2}{(6.40\times10^6\text{ m}+1{,}000{,}000\text{ m})^2}(9.80\text{ m/s}^2) = 7.33\text{ m/s}^2.$

(c) $g_h = \frac{(6.40\times10^6\text{ m})^2}{(6.40\times10^6\text{ m}+10{,}000{,}000\text{ m})^2}(9.80\text{ m/s}^2) = 1.49\text{ m/s}^2.$

9. For a 70.0-kg person:

$$F = \frac{GMm}{r^2} = \frac{(6.67\times10^{-11}\text{ N m}^2/\text{kg}^2)(5.97\times10^{24}\text{ kg})(70\text{ kg})}{(6.40\times10^6\text{ m})^2} = 681\text{ N}\times(1\text{ lb}/4.45\text{ N}) = 153\text{ lb}.$$

We typically call this force the person's *weight*.

10. Use the formula on p. 39: $P^2(\text{in Earth years}) = \frac{a^3(\text{in astronomical units})}{M_{\text{total}}(\text{in solar units})}$

The mass of the moon in solar units is $(7.4\times10^{22}\text{ kg})/(1.99\times10^{30}\text{ kg}) = 3.72\times10^{-8}$.

The distance of the satellite is approximately the radius of the moon. In astronomical units, this is $(1700\text{ km})/(150{,}000{,}000\text{ km}) = 1.13\times10^{-5}$ AU.

$P^2 = (1.13\times10^{-5})^3/(3.72\times10^{-8})$ or $P = 1.97\times10^{-4}$ years = 1.7 hours.

speed = distance/time = $2\pi r/P = (2\pi\times1.7\times10^6\text{ m})/(1.7\text{ hours}\times3600\text{ s/h}) = 1.7\times10^3\text{ m/s} = 1.7\text{ km/s}$.

Resource Information

Mastering Astronomy Media Resources

Self-Guided Tutorials for Students
None

Animations/Videos
Gravity Demonstration on the Moon

Interactive Figures
Figure 1.3 Ptolemaic Model
Figure 1.5 Retrograde Motion
Figure 1.8 Venus Phases
Figure 1.11 Ellipse

Figure 1.12 Orbital Properties
Figure 1.13 Kepler's Second Law
Figure 1.14 Astronomical Unit
Figure 1.18 Center of Mass of a Binary Star

Materials

The *Sky Calendar* from Abrams Planetarium is a very helpful resource for keeping up with interesting events to watch in the sky. It can be found online.

Balls and string are helpful in demonstrating orbital motion.

Air track systems or low-friction cart systems are available from physics equipment suppliers.

Suggested Readings

Bernhard, K. and Bernhard, J. "Mechanics in a wheelchair." *The Physics Teacher* (Dec 1999), p. 555. Describes a kinesthetic experience of Newton's laws.

Christianson, J. R. *On Tycho's Island: Tycho and His Assistants, 1570-1601.*Cambridge University Press, 1999. This is a scholarly work of the life and times of Tycho Brahe. Not only his relationship to Kepleris highlighted, but other collaborations that Tycho fostered.

Ehgamberdiev, S. "The astronomical school of Ulugh Beg." *Sky & Telescope* (Nov 1995). p. 38. Describes astronomical observations made by a 15th-century Mongol prince.

Ferrguson, K. *Tycho&Kepler*.Walker & Company, New York, 2002. A lively account of the tumultuous collaboration between two great astronomers who together would change our view of the solar system.

Gettrust, E. "An extraordinary demonstration of Newton's third law." *The Physics Teacher* (Oct 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, S. J. "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.

Graney, C. M. "Teaching Galileo? Get to know Riccioli! What a forgotten Italian astronomer can teach students about how science works." *The Physics Teacher* (Jan 2012). p. 18. Interesting profile of a lesser known Italian astronomer.

Kemp, M. "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* (Sep 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* (Feb 2000). p. 87. Discusses the depiction of the stars and sky in ancient Egyptian monuments.

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

Manos, H. “ Tycho Brahe’s Stjerneborg.” *The Physics Teacher* (Nov 2003). p. 469. Describes Brahes’s scientific inventions used for astronomy and his castles, Stjerneborg and Uraniborg.

Maran, S. and Marschall, L.*Galileo’s New Universe: The Revolution in Our Understanding of the Cosmos*. Benbella Books, Inc., Dallas, TX, 2009. A short book about Galileo which also compares his major discoveries with the telescope with our understanding of the same astronomical objects and phenonema today.

Morris, R. *Dismantling the Universe: The Nature of Scientific Discovery.* Simon and Schuster, New York, 1983. Chapter 4 covers the story of Brahe, Kepler, and Galileo.

Munns, D. “The challenge of variations: The observational traditions of Ptolemy and Aristotle, and Copernicus’ heliocentric solution.” *Nuncius: Journal of the History of Science* (2007). p. 223. Detailed article about the conflicts between the cosmologies of Ptolemy and Aristotle.

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

Ruiz, M J. “Kepler’s third law without a calculator.” *The Physics Teacher* (Dec 2004). p. 530. Discusses Kepler’s third law and applications, including estimating frequency of Halley’s comet.

Sobel, D. *Galileo’s Daughter.* Walker & Company, New York, 1999. A very readable, detailed account of Galileo’s work, with fascinating details about his personal life, his scientific contributions, and the interactions between them.

Stephenson, F. R. “Early Chinese observations and modern astronomy.” *Sky & Telescope* (Feb 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* (Oct 1999). p. 52. Discusses the life and scientific works of Copernicus.

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

Thomas, B. C. and Quick, M. “Getting the swing of surface gravity.” *The Physics Teacher* (Apr 2012). p. 232. Presents a science experiment for an introductory college astronomy class in which students find and compare values for acceleration due to gravity.

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

Vogt, E. “Elementary derivation of Kepler’slaws.” *American Journal of Physics* (Apr 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.

Westfall, R. S. *The Life of Isaac Newton.* Cambridge University Press, Reprint edition, 1994. This is a condensed version of a larger biography of Newton from the same author. This work is very scholarly and highlights Newton's experimental approach to understanding the universe.

Williams, K. "Inexpensive demonstrator of Newton's first law." *The Physics Teacher* (Feb 2000). p. 80. Uses a Downy® Ball fabric-softener dispenser!

Notes and Ideas

*Class time spent on material: Estimated:*_______ *Actual:*______________

Demonstration and activity materials:

Notes for next time: