Part II: Key Concepts for Astronomy

Chapter 4. A Universe of Matter and Energy

The concepts of matter and energy are fundamental to the study of astronomy, but they are unfamiliar to a large fraction of the students entering introductory astronomy courses. This chapter is designed to provide the minimum level of background in the concepts of matter and energy needed for students to succeed in the remainder of their astronomy course. If you happen to have students with a strong background in high school science, this chapter may be review. Otherwise, we recommend that you devote at least one class period to making sure students understand these basic concepts.

As always, when you prepare to teach this chapter, be sure you are familiar with the relevant media resources (see the complete, section-by-section resource grid in Appendix 3 of this Instructor's Guide) and the on-line quizzes and other study resources available on the Astronomy Place website.

Teaching Notes (By Section)

Section 4.1 Matter and Energy in Everyday Life

As with all our "everyday" sections, this first section is part of our pedagogy of beginning with the concrete, since it should show students that they already know something about matter and energy. It should also help alleviate concerns your students might have about learning physics. It introduces units of joules and the three basic categories of kinetic, potential, and radiative energy.

Section 4.2 A Scientific View of Energy

This section formalizes the study of energy by showing students how energy can be quantified. The most important quantification is that of mass-energy, since the formula $E = mc^2$ will be used many times throughout the book. This section also introduces the important concept of conservation of energy, which we also use over and over throughout the book.

- Note that we discuss conservation of energy in a modern sense, with mass-energy included as a form of potential energy.
- Note that we do not introduce a formula for gravitational potential energy, because the general formula would look too complex at this point (coming before the law of gravity) and the formula *mgh* (which will be familiar to some of your students) is a special case that applies only on the surface of the Earth. However, you may wish to mention the formula *mgh* in class, particularly if your students are already familiar with it.
- We also do not introduce a formula for radiative energy here; instead, we give this formula in Chapter 6, after we discuss the properties of light.

Section 4.3 The Material World

With Section 4.2 having discussed energy in some detail, this section turns to matter. There are three key points in this section: (1) We want students to understand the basic concepts and terminology of atoms, including the size scale of atoms, the constituents of atoms (i.e., protons, neutrons, electrons), and the electrical charge of atoms and their constituent particles; (2) we want students to understand how different substances can differ by element (i.e., atomic number), isotope, or ionization; and (3) we want students to understand phase changes.

- Note that we never give the Bohr picture of the atom, instead discussing only the modern picture, albeit in rather vague terms (e.g., stating "electrons in atoms are 'smeared out,' forming a kind of cloud …"). This reflects our belief that the Bohr model, while useful for purposes of calculation, tends only to reinforce misconceptions about atoms that most students bring with them to our courses—namely, the belief that electrons look and act like miniature planets orbiting a miniature Sun. If you have the chance to cover it, our discussion of atomic structure becomes a little less vague in Chapter S4, where we discuss the uncertainty principle and quantum mechanics.
- Note that our discussion of phases is framed in terms of bond breaking, which makes molecular dissociation and ionization part of the phase-change chain. Describing phase changes in these terms should make it easier for students to understand the processes that take place in planets and stars.
- A note on atomic terminology: Astronomers usually refer to the number of protons + neutrons in an atom as its "atomic mass." However, chemists use this term for the actual mass as a weighted average of isotopes found on Earth (i.e., the mass shown on the periodic table). Thus, the formal name for the number of protons + neutrons is "atomic mass number." We use this term so that students will not be confused if they have had chemistry and have used the term "atomic mass" in its chemistry sense.

Section 4.4 Energy in Atoms

This is the section in which we introduce the quantized energy states of atoms.

- Note that while we mention the fact that quantized energy levels are related to emission and absorption processes, we save the details of these processes for Chapter 6. We have found that students understand quantization better by first understanding it simply in terms of energy, then encountering it again in the contexts of emission and absorption.

Answers/Discussion Points for Think About It Questions

The Think About It questions are not numbered in the book, so we list them in the order in which they appear, keyed by section number.

Section 4.1

- Among many possible examples: We buy chemical potential energy in gasoline to fuel our cars; we buy electrical potential energy from the power company for electrical appliances; we buy chemical potential energy in natural gas or heating oil for home heating.

Section 4.2

- Just as a pot of hot water transfers thermal energy to you much more rapidly than hot air of the same temperature, your body will lose some of its thermal energy (meaning you get colder) much more quickly in cold water than in cold air. Thus, falling into a cold lake can cause you to lose heat rapidly, making it very dangerous.
- This question simply asks students to think about the importance of $E = mc^2$ to our lives. As an interesting side note to discussing the formula, you might survey your class to see how many students have previously heard of this formula and how many already knew what it means.

Section 4.3

- ^{3}He represents helium containing 2 protons and 1 neutron.

Section 4.4

- A hydrogen atom in the ground state cannot absorb the photon with 11.1 eV of energy because it does not match any energy-level transition. It can absorb a photon with 10.2 eV of energy, which can cause it to jump to level 2.

Solutions to End-of-Chapter Problems (Chapter 4)

1. The sugar in my soda will provide my body with about a million joules of energy. *This statement makes sense; as shown in Table 4.1, a candy bar can provide you with about a million joules of energy, and a soda with sugar is comparable.*
2. When I drive my car at 30 miles per hour, it has three times as much kinetic energy as it does at 10 miles per hour. *This statement does not make sense, because kinetic energy depends on the square of the speed. Thus, tripling the speed means a factor of* $3^2 = 9$ *increase in kinetic energy.*
3. If you put an ice cube outside the Space Station, it would take a very long time to melt, even though the temperature in the Earth's orbit is several thousand degrees (Celsius). *This statement makes sense; even though the temperature in orbit is quite high, the density is so low that there is little opportunity for the ice cube to absorb thermal energy from other particles.*
4. Someday soon, scientists are likely to build an engine that produces more energy than it consumes. *This statement does not make sense, because such an engine would violate the law of conservation of energy.*
5. Two isotopes of the element rubidium differ not only in their numbers of neutrons, but also in their numbers of protons. *This statement does not make sense, because an element is defined by its number of protons (atomic number); if two atoms have different numbers of protons, then they cannot be the same element.*
6. According to the laws of quantum mechanics, an electron's energy in a hydrogen atom can jump suddenly from 10.2 eV to 12.1 eV without ever having any in-between energy, such as 10.9 eV. *This statement is absolutely true according to the laws of quantum mechanics, though it might be a stretch to say it makes "sense" to our human minds.*
7. Two ions, each carrying a positive charge of +1, will attract each other electrically. *This statement does not make sense, because two positive charges will repel each other.*
8. In particle accelerators, scientists can create particles where none existed previously by converting energy into mass. *This statement makes sense, because it follows from Einstein's formula* $E = mc^2$.

9–14. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

15. a. The bowling ball has more gravitational potential energy than the baseball at the same height because of its greater mass.
    b. The diver has more gravitational potential energy on the higher platform because there is a greater distance to fall to the water.
    c. The satellite has more gravitational potential energy orbiting Jupiter than orbiting Earth at the same distance (from the planet's center) because of the greater strength of Jupiter's gravity.
16. a. In the equation ($E = mc^2$), E is energy, m is mass, and c is the speed of light. (In international units, we measure the energy in *joules*, the mass in *kilograms*, and the speed of light in *meters per second.*) The equation states that mass and energy are equivalent; under certain circumstances it is possible to convert mass into energy, and vice versa.
    b. The Sun, which is necessary for life on Earth, produces energy by nuclear fusion. In nuclear fusion, mass is converted to energy as described by Einstein's formula. (The efficiency of fusion is 0.7%. For every 1,000 g of hydrogen, fusion results in 993 g of helium; the remaining 7 g is converted to energy.)
    c. The formula also explains the operation of nuclear bombs, in which mass is converted to energy during nuclear fission (uranium and plutonium bombs and "triggers") or nuclear

fusion ("H-bombs" or "thermonuclear bombs"). Thus, the equivalence of mass and energy is intimately tied to both our ability to live and our ability to self-destruct.

17. a. The iron has atomic number 26, atomic mass 26 + 30 = 56, and, if it is neutral, 26 electrons to balance the charge of its 26 protons.

b. Atoms 2 and 3 are isotopes of each other, because they have the same number of protons but different numbers of neutrons.

c. An O^{+5} ion is five times ionized and is missing five of its eight electrons; thus, the ion has three electrons.

d. Fluorine with 9 protons and 10 neutrons has atomic number 9 and atomic weight 19. If we added a proton to this nucleus, the result would have a different atomic number and therefore would no longer be fluorine. If we added a neutron to the fluorine nucleus, the atomic number would be unchanged, so the result would still be fluorine. However, because the atomic weight would change, we would have a different isotope of fluorine.

e. Gold with atomic number 79 and atomic weight 197 has nuclei containing 79 protons and 197 – 79 = 118 neutrons. If the gold is electrically neutral, its atoms have 79 electrons to offset the charge of the 79 protons. If the gold is triply ionized, it is missing 3 of its electrons and thus has 76 electrons.

f. Uranium has atomic number 92 and hence 92 protons. Thus, ^{238}U contains 238 – 92 = 146 neutrons and ^{235}U contains 235 – 92 = 143 neutrons.

18. a. Nearly all the matter in the Sun is in the plasma phase because the high temperatures inside the Sun keep nearly all the atoms fully ionized.

b. Most of the ordinary matter (i.e., not dark matter) in the universe is found in stars or in very hot intergalactic gas. Because this matter is in the plasma phase, plasma is the most common phase of matter in the universe.

c. Plasma is rare on Earth because the relatively low temperatures on the Earth's surface are too low for ionization of atoms.

19. a. Transition B could represent an electron that *gains* 10.2 eV of energy because it jumps up from 0 eV to 10.2 eV.

b. Transition C represents the electron that *loses* 10.2 eV of energy because the electron is jumping down.

c. Transition E represents an electron that is breaking free of the atom because the electron has enough energy to be ionized.

d. Transition D is not possible because electrons can jump only from one allowed energy level to another, not to energies in between.

e. Transition A represents an electron falling from level 3 to level 1, emitting 12.1 eV of energy in the process.

20. a. If 2.5×10^{16} joules represents the energy of a major earthquake, the energy of a 1-megaton bomb is *smaller* by a factor of:

$$\frac{2.5 \times 10^{16} \text{ joule}}{5 \times 10^{15} \text{ joule}} = \frac{25 \times 10^{15}}{5 \times 10^{15}} = 5$$

A major earthquake releases as much energy as five 1-megaton bombs.

b. The annual U.S. energy consumption is about 10^{20} joules, and a liter of oil yields about 1.2×10^7 joules. Thus, the amount of oil needed to supply all the U.S. energy for a year would be:

$$\frac{10^{20}\text{ joule}}{1.2\times 10^{7}\,{}^{\text{joule}}\!/\!_{\text{liter}}} = 8\times 10^{12}\text{ liter}$$

or about 8 trillion liters of oil (roughly 2 trillion gallons).

c. We can compare the Sun's annual energy output to that of the supernova by dividing; to be conservative, we use the lower number from the 10^{44}–10^{46} range for supernova energies:

$$\frac{\text{supernova energy}}{\text{Sun's annual energy output}} = \frac{10^{44}\text{ joule}}{10^{34}\text{ joule}} = 10^{10}$$

The supernova puts out about 10 billion times as much energy as the Sun does in an entire year. That is why a supernova can shine nearly as brightly as an entire galaxy, though only for a few weeks.

21. We are seeking the speed at which a 0.2-kg candy bar must move to have a kinetic energy equal to its chemical potential energy of 10^6 joules released by metabolism. We set the formula for the kinetic energy of the candy bar equal to 10^6 joules, then solve for the speed:

$$\frac{1}{2}\times(0.2\text{ kg})\times v^2 = 10^6\,\frac{\text{kg}\times\text{m}^2}{\text{s}^2} \quad\Rightarrow\quad v=\sqrt{\frac{10^6\,\frac{\text{kg}\times\text{m}^2}{\text{s}^2}}{\frac{1}{2}\times(0.2\text{kg})}} = \sqrt{10^7\,\frac{\text{m}^2}{\text{s}^2}} = 3162\,\frac{\text{m}}{\text{s}}$$

We now convert this speed from m/s to km/hr:

$$3162\,\frac{\text{m}}{\text{s}}\times\frac{1\text{ km}}{1000\text{ m}}\times\frac{60\text{ s}}{1\text{ min}}\times\frac{60\text{ min}}{1\text{ hr}} = 11,383\ \frac{\text{km}}{\text{hr}}$$

The candy bar would have to be traveling at a speed of more than 11,000 km/hr to have as much kinetic energy as the energy it will release through metabolism.

22. a. The average density of a rock with a volume of 15 cm^3 and a mass of 0.25 kg is:

$$\frac{0.25\text{ kg}}{15\text{ cm}^3} = \frac{250\text{ g}}{15\text{ cm}^3} = 16.7\,\frac{\text{g}}{\text{cm}^3}$$

b. The Earth has a radius of about 6,400 km, which is equivalent to 6.4×10^8 cm. Thus, the volume of the Earth in cubic centimeters is about:

$$\frac{4}{3}\times\pi\times\left(6.4\times 10^8\text{ cm}\right)^3 = 1.1\times 10^{27}\text{ cm}^3$$

The mass of the Earth is about 6×10^{24} kg, which is the same as 6×10^{27} g.

Dividing this mass by the Earth's volume, we find the Earth's average density to be:

$$\frac{6\times 10^{27}\text{ g}}{1.1\times 10^{27}\text{ cm}^3} = 5.5\,\frac{\text{g}}{\text{cm}^3}$$

c. The mass of the Sun, 2×10^{30} kg, is the same as 2×10^{33} g, and the Sun's radius, 700,000 km, is equivalent to 7×10^{10} cm. Thus, the Sun's average density is:

$$\frac{2\times10^{33}\,\text{g}}{\frac{4}{3}\times\pi\times\left(7\times10^{10}\,\text{cm}\right)^3}=1.4\,\frac{\text{g}}{\text{cm}^3}$$

23. Let's assume that your mass is about 50 kg. Then the potential energy contained in your mass is:

$$E=mc^2=\left(50\text{ kg}\right)\times\left(3\times10^8\,\frac{\text{m}}{\text{s}}\right)^2=4.5\times10^{18}\text{ joule}$$

This is nearly 1,000 times greater than the 5×10^{15} joules released by a 1-megaton bomb.

24. First, we find the U.S. energy consumption per minute by converting the annual energy consumption into units of joules per minute:

$$\frac{10^{20}\text{ joule}}{\text{yr}}\times\frac{1\text{ yr}}{365\text{ day}}\times\frac{1\text{ day}}{24\text{ hr}}\times\frac{1\text{ hr}}{60\text{ min}}\approx\frac{1.9\times10^{14}\text{ joule}}{\text{min}}$$ 0

Next we divide this energy consumption per minute by the amount of energy available through fusion of 1 liter of water (from Table 4.1):

$$\frac{1.9\times10^{14}\ \frac{\text{joule}}{\text{min}}}{7\times10^{13}\ \frac{\text{joule}}{\text{liter}}}\approx2.7\,\frac{\text{liters}}{\text{min}}$$

In other words, it would take less than 3 liters of water per minute—which is less than 1 gallon per minute—to meet all U.S. energy needs through nuclear fusion. This is somewhat less than the rate at which water flows from a typical kitchen faucet. So if we could simply attach a nuclear fusion reactor to your kitchen faucet, we could stop producing and importing oil, remove all the hydroelectric dams, shut down all the coal-burning power plants, and still have energy to spare.

Chapter 5. The Universal Laws of Motion

This chapter continues our overview of basic physical laws, begun in Chapter 4. Here, we focus on the laws of motion: Newton's laws and the universal law of gravitation. We use these laws to "explain" Kepler's laws (covered in Chapter 3), tides, and basic orbital mechanics relevant to astronomy.

As always, when you prepare to teach this chapter, be sure you are familiar with the relevant media resources (see the complete, section-by-section resource grid in Appendix 3 of this Instructor's Guide) and the on-line quizzes and other study resources available on the Astronomy Place website.

What's New in the Third Edition That Will Affect My Lecture Notes?

As everywhere in the book, we have edited to improve the text flow, improved art pieces, and added new illustrations. In addition, those who have taught from previous editions of *The Cosmic Perspective* should be aware of the following organizational or pedagogical changes to this chapter (i.e., changes that will influence the way you teach) in the third edition:

- This chapter in the second edition included discussion of the Copernican revolution, which has now been moved to Chapter 3.
- We have also revised and enhanced the discussion of the "why" of Kepler's laws in Section 5.3.

Teaching Notes (By Section)

Section 5.1 Describing Motion: Examples from Daily Life

Most nonscience majors are unfamiliar with the basic terminology of motion. For example, few students enter our astronomy classes with an understanding of why acceleration is measured in units of length over time squared, of the definitions of force and momentum, or of how mass and weight differ. This section introduces all these ideas in the context of very concrete examples that should be familiar from everyday life.

- Classroom demonstrations can be particularly helpful in this and the next section; for example, demonstrate that all objects accelerate the same under gravity, or use an air track to show conservation of momentum.
- Note that, aside from a footnote, we neglect the distinction between weight (or "true weight") and apparent weight. The former is often defined in physics texts as *mg*, whereas the latter also includes the effects of other accelerations (such as the acceleration due to Earth's rotation or the acceleration in an elevator). While this distinction is sometimes useful in setting up physics problems, it can become very confusing in astronomy, where, for example, it is difficult to decide how to define "true weight" for objects located between the Earth and the Moon. Moreover, the distinction is unimportant from the point of view of general relativity, so our discussion works well to set the stage for the general relativity discussion in Chapter S3.
- Note also that, in stating that astronauts in orbit are weightless, we are neglecting the tiny accelerations, including those due to tidal forces, that affect objects in orbiting spacecraft. Because of these small accelerations, NASA and many space scientists have taken to referring to the conditions in orbiting spacecraft as *microgravity*, rather than weightlessness. In our opinion, the term *microgravity* is a poor one for students and tends to feed the common misconception that gravity is absent in space—when, in fact, the acceleration of gravity is only a few percent smaller in low-Earth orbit than on the ground. Perhaps a better term for the conditions in orbit would be *microacceleration*, but we feel it is pedagogically more useful to simply neglect the small accelerations and refer to the conditions as weightlessness due to free-fall. If you want to be truly accurate, you might refer to the conditions as *near-weightlessness* and explain why small accelerations still are present.

Section 5.2 Newton's Laws of Motion

Having described the terminology of motion, we next discuss Newton's laws of motion. This discussion should solidify students' grasp of how their everyday experiences reflect Newtonian physics.

- Note that this section explains the important concept of conservation of angular momentum, which is used many times throughout the remainder of the book. When introducing angular momentum, you may wish to do a demonstration of conservation of angular momentum using a bicycle wheel and a rotating platform.
- You may omit the discussion of torque if you wish, as we use it only to explain the conditions under which angular momentum is conserved. Otherwise, we will not explicitly use the concept of torque in the rest of the book. However, it is a term that arises in many everyday contexts and as such is useful to discuss for purposes of general education.

Section 5.3 The Force of Gravity

The pieces now are all in place to explain Newton's law of gravitation. This section discusses gravity generally, describes how Newton explained and expanded on Kepler's laws, and discusses the basic characteristics of orbital motion.

- Note that, as in Chapter 1, we are using *average distance* to mean a semimajor axis distance.

- Note also that, while we mention parabolas and hyperbolas as allowed orbital paths, the bold term introduced to include both these cases is *unbound orbits*. Similarly, we refer to elliptical orbits as *bound orbits*. We feel that the terms *bound* and *unbound* are far more intuitive for students than precise mathematical shapes.

Section 5.4 Tides

In this section, we extend the concept of gravity to explain tides and tidal forces. We also explain how tidal forces and conservation of angular momentum gradually slow the Earth's rotation and lead the Moon to move gradually farther from Earth.

- Note that this section also discusses the cause of the Moon's synchronous rotation, as well as other examples of synchronous rotation, including the case of Pluto and Charon and the 3-to-2 ratio for Mercury.

Section 5.5 Orbital Energy and Escape Velocity

Continuing with our overview of gravitational effects, this section covers the concepts of orbital energy and escape velocity.

- Note our emphasis on the idea that orbits cannot change spontaneously—they can change only if there is an exchange of orbital energy. We have found that this is a very important point that students often fail to grasp unless it is made very explicitly. We encourage you to keep reminding them of this point throughout your course whenever you are explaining gravitational capture of any kind—from an asteroid being captured by a planet to the gravitational collapse of a cloud of gas into a star to the infall of material into an accretion disk.

Section 5.6 The Acceleration of Gravity

This final, short section brings closure to the historical aspects of this chapter by explaining why, at least in the context of Newton's law of gravity, all falling objects fall with the same acceleration of gravity. It also mentions the fact that Newton still saw this as an extraordinary coincidence, thus setting the stage for our discussion of general relativity in Chapter S3. This section may be considered optional.

Answers/Discussion Points for Think About It Questions

The Think About It questions are not numbered in the book, so we list them in the order in which they appear, keyed by section number.

Section 5.1

- Students should realize that by crumpling the paper they make it less subject to air resistance and hence can see the effects of gravity more easily.

Section 5.2

- This question essentially asks students to think about the fact that a force can be a torque only if there is a lever arm involved (of course, without mentioning the term "lever arm"). A longer wrench has a longer lever arm and can therefore apply more torque with the same force.

Section 5.3

- If the distance increases to $3d$, the gravitational attraction decreases by a factor of $3^2 = 9$. If the distance decreases to $0.5d$, the gravitational attraction increases by a factor of $2^2 = 4$.

Section 5.4

- Because the tidal force declines rapidly with distance (in fact, as the cube of distance), the other planets would have to be extremely large in mass (e.g., like the Sun) to have any noticeable tidal effect. Because other planets are very low in mass compared to the Sun, their effects are negligible.

Solutions to End-of-Chapter Problems (Chapter 5)

1. If you could go shopping on the Moon to buy a pound of chocolate, you'd get a lot more chocolate than if you bought a pound on Earth. *This statement makes sense, because pounds are a unit of weight and objects weigh less on the Moon than on Earth.*
2. Suppose you could enter a vacuum chamber (on Earth), that is, a chamber with no air in it. Inside this chamber, if you dropped a hammer and a feather from the same height at the same time, both would hit the bottom at the same time. *This statement is true. Without air resistance, all objects will fall under gravity at the same rate.*
3. When an astronaut goes on a space walk outside the Space Station, she will quickly float away from the station unless she has a tether holding her to the station or she constantly fires thrusters on her space suit. *This statement is false. She and the Space Station share the same orbit and will stay together unless they are pushed apart (which could happen, for example, if she pushed off the side).*
4. Newton's version of Kepler's third law allows us to calculate the mass of Saturn from orbital characteristics of its moon Titan. *This statement makes sense, because we can calculate the mass of Saturn by knowing the period and average distance for Titan.*
5. If we could magically replace the Sun by a giant rock with precisely the same mass, the Earth's orbit would not change. *This statement is true, because the rock would have the same gravitational affect on Earth as does the Sun.*
6. The fact that the Moon rotates once in precisely the time it takes to orbit the Earth once is such an astonishing coincidence that scientists probably never will be able to explain it. *This statement is false, because the synchronous rotation is not a coincidence at all and its cause has been well explained.*
7. Venus has no oceans, so it could not have tides even if it had a moon (which it doesn't). *This statement does not make sense, because tides affect an entire planet, not just the oceans. Thus, if Venus had a moon, it could have "land tides."*
8. If an asteroid passed by Earth at just the right distance, it would be captured by the Earth's gravity and become our second moon. *This statement does not make sense, because objects cannot spontaneously change their orbits without having some exchange of energy with another object.*

9–15. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

16. a. Neglecting air resistance, the watermelon falls with an acceleration of 9.8 m/s^2, meaning that its speed increases by 9.8 m/s with each passing second. Thus, after falling for 6 seconds, the watermelon's speed is:

$$6 \text{ s} \times 9.8 \frac{\text{m}}{\text{s}^2} = 58.8 \frac{\text{m}}{\text{s}}$$

We can convert this to both km/hr and mi/hr as follows:

$$58.8 \frac{\text{m}}{\text{s}} \times \frac{1 \text{ km}}{1000 \text{ m}} \times 60 \frac{\text{s}}{\text{min}} \times 60 \frac{\text{min}}{\text{hr}} = 212 \frac{\text{km}}{\text{hr}}$$

$$212 \frac{\text{km}}{\text{hr}} \times \frac{1 \text{ mi}}{1.62 \text{ km}} = 131 \frac{\text{mi}}{\text{hr}}$$

The watermelon hits the ground at a speed of about 212 km/hr, or 131 mi/hr.

b. If you sled down a street with an acceleration of 4 m/s^2, after 5 seconds you will be going at a speed of 5 s × 4 m/s^2 = 20 m/s. This is equivalent to:

$$20\frac{\text{m}}{\text{s}}\times\frac{1\text{ km}}{1000\text{ m}}\times 60\frac{\text{s}}{\text{min}}\times 60\frac{\text{min}}{\text{hr}}=72\frac{\text{km}}{\text{hr}}$$

$$\text{or } 72\frac{\text{km}}{\text{hr}}\times\frac{1\text{ mi}}{1.62\text{ km}}=44\frac{\text{mi}}{\text{hr}}$$

c. The acceleration of –20 mi/hr/s means that your speed slows by 20 mi/hr with each passing second. Thus, it will take you 3.5 seconds to slow from 70 mi/hr to a stop.

17. If a skater wishes to start spinning, she needs to gain some angular momentum by applying a torque on the ice. A torque is a twisting force, so she must apply a force in a way that causes her body to start twisting (turning). Stomping her foot straight down will not give her any twist. In order to start turning, she must use her foot to push off the ice at a point away from the (vertical) center line of her body. This will start her spin, because it represents a twisting force. Once spinning, she can change the rate of her spin by drawing her arms (or legs or torso) in or out to change her effective radius.

18. a. Quadrupling the distance between two objects decreases the gravitational attraction between them by a factor of $4^2 = 16$.

b. From Appendix C, we find that Jupiter's distance from the Sun is about 5.2 times the Earth's distance. Thus, if the mass of Jupiter and the Earth were the same, the gravitational attraction between the Sun and Jupiter would be weaker than that between the Earth and the Sun by a factor of $5.2^2 = 27$. However, because Jupiter is 318 times more massive than Earth, the actual gravitational attraction between the Sun and Jupiter is stronger than that between the Earth and the Sun by a factor of about 318/27 = 11.8.

c. If the Sun were magically replaced by a star with twice as much mass, the gravitational attraction between the Earth and the Sun would double.

19. The tidal force acting on you depends on the *difference* between the gravitational force acting on your head and on your toes. But the gravitational force on any part of your body depends on the distance of the body part from the center of the Earth. Because the length of your body is negligible compared to the radius of the Earth, there's no noticeable difference in gravitational force between your head and your toes. (As discussed in Chapter 18, this would no longer be the case if you could stand on a very compact object, such as a neutron star, or if you were falling into a black hole.)

20. a. The Moon's angular size was larger in the past. Moving an object closer to you *increases* its angular size.

b. The lunar month was shorter in the past. According to Kepler's third law, a smaller average distance means a higher average orbital speed. Thus, it took the Moon less time to orbit the Earth when it was closer to the Earth, meaning that the length of the lunar month was shorter.

c. Eclipses were more common in the past. The shorter lunar month meant more opportunities for eclipses, that is, more frequent new moons and full moons. The larger angular size of the Moon meant a higher probability that the Moon would block the Sun from view during a new moon, and a higher probability that the Earth's shadow would fall on the Moon during a full moon. Both factors made eclipses more common in the past.

21. a. A geostationary satellite must remain above the same point on Earth and hence must orbit with the Earth's actual rotation period. The actual rotation period of the Earth is a sidereal day, not a solar day.

b. Essay question; answers will vary, but the key points should be that a geostationary orbit keeps a satellite above the horizon at all times and eliminates the need for any tracking by ground receivers.

22. a. Because it is at the altitude of geosynchronous orbit, the top of the elevator would be moving with precisely the necessary orbital speed for this altitude. If you placed an object outside the top of the elevator, the object would also be moving with the orbital speed needed for this altitude (assuming that you do not give it any kind of push that gives it a speed relative to the top of the elevator). Thus, the object would simply remain in orbit next to the elevator top, rather than falling.

b. Placing a satellite into geosynchronous orbit would require nothing more than taking it up the elevator. That is, rather than needing a huge rocket to reach orbit, satellites could simply be taken up the elevator shaft, which requires far less energy than a rocket. (In fact, the energy cost of getting a satellite to geosynchronous altitude in the elevator would be only a few dollars, as opposed to millions for a rocket launch.) Once at the top, a small rocket could be used to launch a satellite to a higher orbit, to the Moon, or into deep space.

23. a. As long as a planet's mass is small compared to the Sun, the planet's orbital period is independent of its mass, because only the sum of the planet's mass and the Sun's mass appears in the equation for Newton's version of Kepler's third law. Thus, the orbital period of a planet at Earth's distance but with twice the mass of Earth would still be one year.

b. Newton's version of Kepler's third law has the form:

$$p^2 = \frac{4\pi^2}{G\left(M_1 + M_2\right)} a^3$$

Because the square of the period varies inversely with the sum of the masses, the orbital period itself depends on the *inverse square root* of the object masses:

$$p = \sqrt{\frac{4\pi^2}{G\left(M_1 + M_2\right)} a^3}$$

Thus, if we have a star four times as massive as the Sun, the period of a planet orbiting at 1 AU will be $1/\sqrt{4} = 1/2$ that of the Earth, or 6 months.

24. a. An acceleration of 6 gees means 6×9.8 m/s^2, or 58.8 m/s^2.

b. The force you will feel from this acceleration of 6 gees will be six times your normal weight.

c. It is unlikely that you could survive this acceleration of 6 gees for very long. It would be rather like lying on a table with six times (actually five to six times, since you have your own weight as well) your normal weight in bricks stacked up over you. You could survive fine for a while, but eventually this compression would probably cause serious damage.

25. We are given the period in years, so we can calculate the average distance (semimajor axis) in AU by using Kepler's third law in its original form:

$$p^2 = a^3 \quad \Rightarrow \quad a = p^{2/3} = 1000^{2/3} = 100$$

The average distance of the comet from the Sun is 100 AU.

26. a. Using the Moon's orbital period and distance and following the method given in Mathematical Insight 5.2, we find the mass of the Earth to be about:

$$M_{\text{Earth}} \approx \frac{4\pi^2}{G} \frac{(a_{\text{Moon}})^3}{(p_{\text{Moon}})^2}$$

Making sure that we use appropriate units, we find:

$$M_{\text{Earth}} \approx \frac{4\pi^2 \left(384{,}000 \text{ km} \times 1000 \frac{\text{m}}{\text{km}}\right)^3}{\left(6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right)\left(27.3 \text{ day} \times 24 \frac{\text{hr}}{\text{day}} \times 3600 \frac{\text{s}}{\text{hr}}\right)^2} = 6.0 \times 10^{24} \text{ kg}$$

b. Using Io's orbital period and distance and following the method given in Mathematical Insight 5.2, we find the mass of Jupiter to be about:

$$M_{\text{Jupiter}} \approx \frac{4\pi^2 \left(422{,}000 \text{ km} \times 1000 \frac{\text{m}}{\text{km}}\right)^3}{\left(6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right)\left(42.5 \text{ hr} \times 3600 \frac{\text{s}}{\text{hr}}\right)^2} = 1.9 \times 10^{27} \text{ kg}$$

We find the same answer using Europa's orbital properties; Kepler's third law does not depend on the mass of either moon because neither moon has a significant mass in comparison to the mass of Jupiter.

c. The Space Shuttle is much less massive than the Earth, so we can follow the method of Mathematical Insight 5.2 to write:

$$(p_{\text{shuttle}})^2 = \frac{4\pi^2}{G(M_{\text{Earth}} + M_{\text{shuttle}})}(a_{\text{shuttle}})^3 \approx \frac{4\pi^2}{GM_{\text{Earth}}}(a_{\text{shuttle}})^3$$

Remember that a_{shuttle} represents the shuttle's average distance from the center of the Earth. The radius of the Earth is about 6,400 km, so:

$$a_{\text{shuttle}} = 6400 \text{ km} + 300 \text{ km} = 6700 \text{ km}$$

or 6.7 × 106 m. The mass of the Earth is about $M_{\text{Earth}} \approx$ 6.0 × 1024 kg. Substituting these values and solving the equation for p_{shuttle} by taking the square root of both sides yields:

$$p_{\text{shuttle}} \approx \sqrt{\frac{4\pi^2}{\left(6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right)\left(6.0 \times 10^{24} \text{ kg}\right)}\left(6.7 \times 10^6 \text{ m}\right)^3} \approx 5400 \text{ s}$$

The shuttle orbits the Earth in about 5,400 seconds, or 90 minutes.

d. If we are working with Charon's orbit around Pluto, Newton's version of Kepler's third law takes the form:

$$(p_{\text{Charon}})^2 = \frac{4\pi^2}{G(M_{\text{Pluto}} + M_{\text{Charon}})}(a_{\text{Charon}})^3$$

In this case we are looking for the combined mass of the two worlds, so we do not further simplify the equation. We simply solve for the masses, then plug in the numbers given:

$$\begin{aligned}
M_{\text{Pluto}} + M_{\text{Charon}} &= \frac{4\pi^2 \times \left(a_{\text{Charon}}\right)^3}{G \times \left(p_{\text{Charon}}\right)^2} \\
&= \frac{4\pi^2 \times \left(19{,}700 \text{ km} \times 1000 \frac{\text{m}}{\text{km}}\right)^3}{\left(6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right)\left(6.4 \text{ day} \times 24 \frac{\text{hr}}{\text{day}} \times 3600 \frac{\text{s}}{\text{hr}}\right)^2} \\
&= 1.5 \times 10^{22} \text{ kg}
\end{aligned}$$

Now we compare this mass for Pluto and Charon to the Earth's mass of 6.0×10^{24} kg:

$$\frac{M_{\text{Earth}}}{M_{\text{Pluto}} + M_{\text{Charon}}} = \frac{6.0 \times 10^{24} \text{ kg}}{1.5 \times 10^{22} \text{ kg}} = 400$$

The Earth's mass is about 400 times greater than the combined mass of Pluto and Charon.

27. In parts (a) and (c), the easiest way to find the escape velocities with the given data is by comparison to the escape velocity from Earth:

$$\frac{v_{\text{escape, planet}}}{v_{\text{escape, Earth}}} = \frac{\sqrt{\frac{2GM_{\text{planet}}}{R_{\text{planet}}}}}{\sqrt{\frac{2GM_{\text{Earth}}}{R_{\text{Earth}}}}} = \sqrt{\frac{M_{\text{planet}}}{M_{\text{Earth}}} \times \frac{R_{\text{Earth}}}{R_{\text{planet}}}}$$

Given that the escape velocity from Earth's surface is about 11 km/s, this formula becomes:

$$v_{\text{escape, planet}} = 11 \frac{\text{km}}{\text{s}} \times \sqrt{\frac{M_{\text{planet}}}{M_{\text{Earth}}} \times \frac{R_{\text{Earth}}}{R_{\text{planet}}}}$$

a. From the surface of Mars, the escape velocity is:

$$v_{\text{escape}} = 11 \frac{\text{km}}{\text{s}} \times \sqrt{\frac{M_{\text{Mars}}}{M_{\text{Earth}}} \times \frac{R_{\text{Earth}}}{R_{\text{Mars}}}} = 11 \frac{\text{km}}{\text{s}} \times \sqrt{0.11 \times \frac{1}{0.53}} = 5.0 \frac{\text{km}}{\text{s}}$$

b. From the surface of Phobos, the escape velocity is:

$$v_{\text{escape}} = \sqrt{\frac{2 \times \left(6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right) \times \left(1.1 \times 10^{16} \text{ kg}\right)}{12{,}000 \text{ m}}} = 11 \frac{\text{m}}{\text{s}} = 0.011 \frac{\text{km}}{\text{s}}$$

c. From the surface of Jupiter, the escape velocity is:

$$v_{\text{escape}} = 11 \frac{\text{km}}{\text{s}} \times \sqrt{\frac{M_{\text{Jupiter}}}{M_{\text{Earth}}} \times \frac{R_{\text{Earth}}}{R_{\text{Jupiter}}}} = 11 \frac{\text{km}}{\text{s}} \times \sqrt{317.8 \times \frac{1}{11.2}} = 58.6 \frac{\text{km}}{\text{s}}$$

d. To find the escape velocity from the solar system, starting from the Earth's orbit, we use the mass of the Sun (since that is the mass we are trying to escape) and the Earth's distance from the Sun of 1 AU, or 1.5×10^{11} meters:

$$v_{\text{escape}} = \sqrt{\frac{2 \times \left(6.67 \times 10^{-11} \ \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right) \times \left(2.0 \times 10^{30} \ \text{kg}\right)}{1.5 \times 10^{11} \ \text{m}}} = 42,200 \frac{\text{m}}{\text{s}} = 42.2 \frac{\text{km}}{\text{s}}$$

e. To find the escape velocity from the solar system starting from Saturn's orbit, we use the mass of the Sun (since that is the mass we are trying to escape) and Saturn's distance from the Sun of 1.4×10^{12} meters:

$$v_{\text{escape}} = \sqrt{\frac{2 \times \left(6.67 \times 10^{-11} \ \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right) \times \left(2.0 \times 10^{30} \ \text{kg}\right)}{1.4 \times 10^{12} \ \text{m}}} = 13,800 \frac{\text{m}}{\text{s}} = 13.8 \frac{\text{km}}{\text{s}}$$

28. In parts (a) through (d), the easiest way to find the accelerations with the given data is by comparison to the acceleration of gravity on Earth:

$$\frac{a_{\text{planet}}}{a_{\text{Earth}}} = \frac{G \frac{M_{\text{planet}}}{R_{\text{planet}}^2}}{G \frac{M_{\text{Earth}}}{R_{\text{Earth}}^2}} = \frac{M_{\text{planet}}}{M_{\text{Earth}}} \times \left(\frac{R_{\text{Earth}}}{R_{\text{planet}}}\right)^2$$

a. On the surface of Mars, the acceleration of gravity is:

$$a_{\text{Mars}} = a_{\text{Earth}} \times \frac{M_{\text{Mars}}}{M_{\text{Earth}}} \times \left(\frac{R_{\text{Earth}}}{R_{\text{Mars}}}\right)^2 = 9.8 \frac{\text{m}}{\text{s}^2} \times 0.11 \times \left(\frac{1}{0.53}\right)^2 = 3.8 \frac{\text{m}}{\text{s}^2}$$

b. On the surface of Venus, the acceleration of gravity is:

$$a_{\text{Mars}} = a_{\text{Venus}} \times \frac{M_{\text{Venus}}}{M_{\text{Earth}}} \times \left(\frac{R_{\text{Earth}}}{R_{\text{Venus}}}\right)^2 = 9.8 \frac{\text{m}}{\text{s}^2} \times 0.82 \times \left(\frac{1}{0.95}\right)^2 = 8.9 \frac{\text{m}}{\text{s}^2}$$

c. At Jupiter's cloud tops, the acceleration of gravity is:

$$a_{\text{Jupiter}} = a_{\text{Earth}} \times \frac{M_{\text{Jupiter}}}{M_{\text{Earth}}} \times \left(\frac{R_{\text{Earth}}}{R_{\text{Jupiter}}}\right)^2 = 9.8 \frac{\text{m}}{\text{s}^2} \times 317.8 \times \left(\frac{1}{11.2}\right)^2 = 25 \frac{\text{m}}{\text{s}^2}$$

Because Jupiter has no solid surface, you could weigh yourself only if you were standing on a surface held at a steady altitude in Jupiter's atmosphere, such as on the floor of an airplane or a balloon flying in Jupiter's atmosphere.

d. On the surface of Europa, the acceleration of gravity is:

$$a_{\text{Europa}} = a_{\text{Earth}} \times \frac{M_{\text{Europa}}}{M_{\text{Earth}}} \times \left(\frac{R_{\text{Earth}}}{R_{\text{Europa}}}\right)^2 = 9.8 \frac{\text{m}}{\text{s}^2} \times 0.008 \times \left(\frac{1}{0.25}\right)^2 = 1.3 \frac{\text{m}}{\text{s}^2}$$

e. On the surface of Phobos, the acceleration of gravity is:

$$a_{\text{Phobos}} = G \frac{M_{\text{Phobos}}}{R_{\text{Phobos}}^2} = \left(6.67 \times 10^{-11} \ \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right) \times \frac{1.1 \times 10^{16} \ \text{kg}}{\left(12,000 \ \text{m}\right)^2} = 0.0051 \frac{\text{m}}{\text{s}^2}$$

Chapter 6. Light: The Cosmic Messenger

This chapter concludes our three chapters overviewing basic physical laws (Chapter 4 through 6), this time focusing on the basic properties of light as they apply to astronomy.

- Note that throughout the book we use the term *light* as a synonym for electromagnetic radiation in general, as opposed to meaning only visible light. Thus, we are explicit in saying *visible light* when that is what we mean.

As always, when you prepare to teach this chapter, be sure you are familiar with the relevant media resources (see the complete, section-by-section resource grid in Appendix 3 of this Instructor's Guide) and the on-line quizzes and other study resources available on the Astronomy Place website.

What's New in the Third Edition That Will Affect My Lecture Notes?

As everywhere in the book, we have edited to improve the text flow, improved art pieces, and added new illustrations. In addition, those who have taught from previous editions of *The Cosmic Perspective* should be aware of the following organizational or pedagogical changes to this chapter (i.e., changes that will influence the way you teach) in the third edition:

- We have revised and clarified our discussion of thermal radiation, and eliminated the jargon of "thermal emitter."

Teaching Notes (By Section)

Section 6.1 Light in Everyday Life

Continuing the pattern of the chapters in Part II, we begin with a section on light in everyday life. We use this section to define basic terminology such as power, spectrum, emission, absorption, transmission, and reflection.

Section 6.2 Properties of Light

This section introduces several important concepts: wave properties of wavelength, frequency, and speed; wave-particle duality; the idea that light comes in the form of photons; the concept of a field; and the idea of light as an electromagnetic wave. All of these concepts are probably unfamiliar to your students and therefore warrant some discussion in class.

Section 6.3 The Many Forms of Light

This short section introduces the complete electromagnetic spectrum.

Section 6.4 Light and Matter

This section is probably the most important in the chapter, because it covers the interpretation of astronomical spectra. Note that it begins with Figure 6.7 showing a schematic spectrum and then later shows this spectrum analyzed in Figure 6.15.

- A classroom demonstration of spectroscopy can be very useful if available. We like to hand out inexpensive plastic diffraction gratings, which students can use to see spectra of various discharge tubes with different gases, such as hydrogen, helium, sodium, and neon, along with an incandescent light bulb to serve as a white light source.
- We have found that this material, while somewhat complex, is not difficult for most students to grasp. However, the jargon often used by astronomers tends to confuse students. Therefore we have tried to eliminate jargon. Note in particular:
  - We use the term *thermal radiation* rather than *blackbody radiation.*
  - Although we mention the names Stefan-Boltzmann law and Wien's law in Mathematical Insight 6.2, in the text we simply refer to two "rules" that describe the temperature dependence of a thermally emitting object.

– When discussing atomic transitions in hydrogen, we are explicit in stating the energy levels between which the transitions occur, rather than introducing the jargon of *Lyman* α, etc.
– Aside from a brief note, we do not give a name to Kirchhoff's laws; we do, of course, describe them, both in the text and in Figure 6.14.

Section 6.5 The Doppler Shift

The final section of this chapter describes the Doppler effect and how we can measure it using spectral lines as reference points. We also include a brief discussion of how Doppler line broadening allows us to determine stellar rotation rates.

Answers/Discussion Points for Think About It Questions

The Think About It questions are not numbered in the book, so we list them in the order in which they appear, keyed by section number.

Section 6.1

- This question asks students to try to see the individual red, green, and blue colors from which TV images are constructed on the screen.

Section 6.2

- The material that makes up the rope moves only up and down, while the peak moves transversely. This demonstrates that waves transmit energy without transmitting matter.

Section 6.4

- In a cold cloud of hydrogen gas, nearly all the electrons will be in the ground state and hence cannot fall to a lower energy level. Thus, we do not see emission lines from cold clouds of hydrogen gas. (Note that, at this point in the text, we do not mention the spin–flip transition that creates the 21-cm line; we discuss this line in Chapter 19.)
- The colors we see are reflected light, so it is possible to see only the colors present in the original light. Thus, for example, under low-pressure yellow sodium lights we cannot see the normal colors of objects, because only yellow light is being emitted.

Section 6.5

- A line shifted from a rest wavelength of 121.6 nm to 120.5 nm has actually shifted to a position farther from the blue end of the visible spectrum, which begins around 400 nm. Nevertheless, we call this a blueshift because it is a shift to a shorter (as opposed to a longer) wavelength.

Solutions to End-of-Chapter Problems (Chapter 6)

1. If you could view a spectrum of light reflecting off a blue sweatshirt, you'd find the entire rainbow of color. *This statement does not make sense; the blue sweatshirt reflects only blue visible light, so the spectrum of this reflected light would not contain other colors such as red.*
2. Because of their higher frequency, X rays must travel through space faster than radio waves. *This statement does not make sense; all light travels through space at the same speed of light.*
3. If the Sun's surface became much hotter (while the Sun's size remained the same), the Sun would emit more ultraviolet light but less visible light than it currently emits. *This statement does not make sense; if the Sun's surface were hotter, it would emit more thermal radiation at all wavelengths of light.*
4. A black sheet of paper absorbs all the light that falls on it and emits no radiative energy at all. *This statement is false. If the paper absorbed light without emitting any energy back, it would quickly heat up and spontaneously catch fire! The paper emits thermal radiation that depends only on its temperature.*

5. If you could see infrared light, you would see the backs of your eyelids when you closed your eyes. *This statement makes sense, because your eyelids are warm and emit infrared radiation.*
6. If you had X-ray vision, then you could read this entire book without turning any pages. *This statement does not make sense. The book does not emit X rays, so X-ray vision wouldn't do you any good at all.*
7. If you want to see an object that is too cold to emit visible light, you should try looking at it with an instrument that can detect ultraviolet light. *This statement does not make sense. Hotter objects emit ultraviolet light. If an object is too cool to emit visible light, it won't emit ultraviolet light either.*
8. If a distant galaxy has a substantial redshift (as viewed from our galaxy), then anyone living in that galaxy would see a substantial redshift in a spectrum of the Milky Way Galaxy. *This statement makes sense; the redshift means that we see the galaxy moving away from us, so observers in that galaxy must also see us moving away from them—which means they see us redshifted as well.*

9–13. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

14.
   a. We can determine the chemical composition of an object by identifying the specific spectral lines due to various elements.
   b. If the spectrum is nearly a thermal radiation spectrum, we can determine the object's surface temperature from the peak wavelength of emission. Otherwise, we can determine the surface temperature by studying the ionization states present among the chemicals in the object.
   c. A thin cloud of gas will have a nearly "pure" emission or absorption line spectrum. A more substantial object will have a thermal radiation spectrum with emission or absorption lines superimposed.
   d. An object such as a planet with a hot upper atmosphere will have emission lines in the ultraviolet because atoms in this atmosphere will be in excited states that allow emission.
   e. We can determine the speed at which an object is moving toward or away from us by measuring the Doppler shift of lines in its spectrum.
   f. We can determine the rotation rate of an object by the degree of broadening of its spectral lines, which occurs because different parts of the object have different Doppler shifts due to the rotation.

15. A planet that looks blue to the eye is reflecting blue light from its star, which presumably emits light throughout the visible spectrum. Thus, in a spectrum of the planet, we expect to see the reflected visible light from the star, but with the red light "missing" because it is absorbed by the planet.

16.
   a. From the first rule of thermal radiation, we know that doubling the temperature of an object increases the amount of thermal radiation it emits per unit area by a factor of $2^4 = 16$. Thus, increasing the surface temperature of the Sun from 6,000 K to 12,000 K would increase its thermal radiation by a factor of 16.
   b. The higher temperature of the Sun would shift the peak of its thermal radiation spectrum from its current place in the visible-light region into the ultraviolet. The hotter Sun would emit more energy at all wavelengths, with the greatest output coming in the ultraviolet.
   c. Life on Earth would be difficult (though not necessarily impossible) if the Sun's surface temperature were 12,000 K. Because the Sun would be outputting much more total

radiation, we would expect the Earth to be hotter. We would also expect the additional ultraviolet radiation to have significant effects on our atmosphere.

17. We are considering a spectral line with a rest wavelength of 121.6 nm that appears at 120.5 nm in Star A, 121.2 nm in Star B, 121.9 nm in Star C, and 122.9 nm in Star D. Because the line is shifted to a wavelength shorter than its rest wavelength in Stars A and B, these two stars are moving toward us; Stars C and D are moving away from us. The star showing the greatest shift is Star D, in which the line is redshifted by 1.3 nm; thus, Star D is moving the fastest relative to us of these four stars.

18. We determine that galaxies outside the Local Group are moving away because their spectra all show redshifts. Measuring the redshifts allows us to calculate their speeds, and we find that more distant galaxies are moving away from us faster.

19. a. Converting from calories to joules, we find that the daily energy usage of a typical adult is:

$$2500 \text{ cal} \times 4000 \frac{\text{joule}}{\text{cal}} = 10^7 \text{ joule}$$

b. To find the average power requirement of an adult in watts, we divide the energy usage from part (a) by the number of seconds in a day:

$$\frac{10^7 \text{ joule}}{24 \text{ hr} \times 3600 \frac{\text{s}}{\text{hr}}} = 116 \text{ watts}$$

The average adult runs on about 120 watts of power. Note that this is quite similar to the power needed for a typical light bulb.

20. a. The frequency of a visible-light photon with wavelength 550 nm is:

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8 \frac{\text{m}}{\text{s}}}{550 \times 10^{-9} \text{m}} = 5.45 \times 10^{14} \frac{1}{\text{s}} = 5.45 \times 10^{14} \text{Hz}$$

b. For a frequency of 1,120 kilohertz, the wavelength (λ) and energy (E) are:

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8 \frac{\text{m}}{\text{s}}}{1120 \times 10^3 \frac{1}{\text{s}}} = 268 \text{ m}$$

$$E = h \times f = \left(6.626 \times 10^{-34} \text{joule} \times \text{s}\right) \times 1120 \times 10^3 \frac{1}{\text{s}} = 7.42 \times 10^{-28} \text{ joule}$$

c. For a photon with wavelength 120 nm, the frequency (f) and energy (E) are:

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8 \frac{\text{m}}{\text{s}}}{120 \times 10^{-9} \text{m}} = 2.5 \times 10^{15} \frac{1}{\text{s}} = 2.5 \times 10^{15} \text{Hz}$$

$$E = h \times f = \left(6.626 \times 10^{-34} \text{joule} \times \text{s}\right) \times 2.5 \times 10^{15} \frac{1}{\text{s}} = 1.7 \times 10^{-18} \text{joule}$$

d. A photon energy of 10 keV is equivalent to an energy of:

$$10{,}000 \text{ eV} \times 1.60 \times 10^{-19} \frac{\text{joule}}{\text{eV}} = 1.60 \times 10^{-15} \text{joule}$$

The frequency and wavelength of this photon are:

$$f = \frac{E}{h} = \frac{1.60 \times 10^{-15} \text{ joule}}{6.626 \times 10^{-34} \text{ joule} \times \text{s}} = 2.41 \times 10^{18} \frac{1}{\text{s}} = 2.41 \times 10^{18} \text{ Hz}$$

$$\lambda = \frac{c}{f} = \frac{3 \times 10^{8} \frac{\text{m}}{\text{s}}}{2.41 \times 10^{18} \frac{1}{\text{s}}} = 1.25 \times 10^{-10} \text{ m} = 0.125 \text{ nm}$$

21. a. The energy of a single photon with wavelength 600 nm is:

$$E = \frac{hc}{\lambda} = \frac{\left(6.626 \times 10^{-34} \text{ joule} \times \text{s}\right) \times 3 \times 10^{8} \frac{\text{m}}{\text{s}}}{600 \times 10^{-9} \text{ m}} = 3.31 \times 10^{-19} \text{ joule}$$

b. A 100-watt light bulb emits 100 joules of energy each second. Thus, the number of 600-nm photons it emits each second is:

$$\text{number of photons} = \frac{\text{total energy emitted}}{\text{energy emitted per photon}} = \frac{100 \text{ joule}}{3.31 \times 10^{-19} \frac{\text{joule}}{\text{photon}}} = 3 \times 10^{20} \text{ photons}$$

Because the light bulb emits more than 10^{20} photons each second, there is no chance that we will notice these individual photons acting like particles in our everyday life. Instead, we notice only their collective wave effects.

22. a. We find the average power radiated per square meter on the Sun's surface by dividing the Sun's total power output by its surface area:

$$\text{power per m}^2 = \frac{\text{total power}}{\text{surface area}} = \frac{4 \times 10^{26} \text{ watt}}{4 \times \pi \times \left(7 \times 10^{8} \text{ m}\right)^2} = 6 \times 10^{7} \frac{\text{watt}}{\text{m}^2}$$

b. According to the Stefan-Boltzmann law, the emitted power per unit area is equal to the quantity σT^4. Solving for the surface temperature, we find:

$$\text{power per unit area} = \sigma T^4 \quad \Rightarrow \quad T = \sqrt[4]{\frac{\text{power per unit area}}{\sigma}}$$

We can now calculate the Sun's surface temperature from the power per unit area found in part (a):

$$T = \sqrt[4]{\frac{\text{power per unit area}}{\sigma}} = \sqrt[4]{\frac{6 \times 10^{7} \frac{\text{watt}}{\text{m}^2}}{5.7 \times 10^{-8} \frac{\text{watt}}{\text{m}^2 \times \text{K}^4}}} = 6 \times 10^{3} \text{ K}$$

We have found that the Sun's surface temperature is about 6,000 K.

23. We use the Doppler shift formula to find the speeds of each of the four stars from problem 17:

Star A: $$v = \frac{\Delta\lambda}{\lambda_0} \times c = \frac{120.5 \text{ nm} - 121.6 \text{ nm}}{121.6 \text{ nm}} \times 300{,}000 \frac{\text{km}}{\text{s}} = -2714 \frac{\text{km}}{\text{s}}$$

The negative value indicates that Star A is moving toward us.

Star B: $$v = \frac{\Delta\lambda}{\lambda_0} \times c = \frac{121.2 \text{ nm} - 121.6 \text{ nm}}{121.6 \text{ nm}} \times 300{,}000 \ \frac{\text{km}}{\text{s}} = -987 \ \frac{\text{km}}{\text{s}}$$

The negative value indicates that Star B is moving toward us.

Star C: $$v = \frac{\Delta\lambda}{\lambda_0} \times c = \frac{121.9 \text{ nm} - 121.6 \text{ nm}}{121.6 \text{ nm}} \times 300{,}000 \ \frac{\text{km}}{\text{s}} = 740 \ \frac{\text{km}}{\text{s}}$$

The positive value indicates that Star C is moving away from us.

Star D: $$v = \frac{\Delta\lambda}{\lambda_0} \times c = \frac{122.9 \text{ nm} - 121.6 \text{ nm}}{121.6 \text{ nm}} \times 300{,}000 \ \frac{\text{km}}{\text{s}} = 3207 \ \frac{\text{km}}{\text{s}}$$

The positive value indicates that Star D is moving away from us.

24. a. For a coil with a temperature of 3,000 K, the wavelength of maximum intensity is:

$$\lambda_{max} = \frac{2{,}900{,}000}{3{,}000 \text{ (Kelvin)}} \text{ nm} = 966 \text{ nm}$$

Note that this wavelength is considerably longer than the 500-nm wavelength of maximum emission from the Sun and lies in the infrared portion of the spectrum. Thus, light bulbs with coils at 3,000 K emit much of their energy in the infrared, rather than as visible light.

b. Because light from standard light bulbs has a spectrum that peaks in the infrared, it is generally redder in color than sunlight. Thus, to record "true" colors, film for indoor photography must compensate for the fact that indoor light bulbs emit more red light by having enhanced sensitivity to the less abundant blue light.

c. Because a standard light bulb emits much of its light in the infrared, this light is "wasted" as far as electrical lighting is concerned. In contrast, a fluorescent light bulb that produces emission lines only in the visible portion of the spectrum would have no "wasted" light. Thus, a fluorescent bulb of the same wattage as a standard bulb can actually produce much more visible light.

d. Despite the higher cost of a compact fluorescent light bulb compared to a standard light bulb, the former can save money over the long run for two principle reasons: (1) lower cost for operation because of its lower energy usage, and (2) longer life, so it needs replacement less often. The latter can particularly save money for businesses, since businesses must pay for the labor involved in changing light bulbs; this labor can be substantial if the light bulb is in a hard-to-reach area.

Chapter 7. Telescopes: Portals of Discovery

This chapter focuses on telescopes and their uses. Note that, although these instruments are fundamental to modern astronomy, most of the material in this chapter is not prerequisite to later chapters. Thus, you can consider this chapter to be optional.

As always, when you prepare to teach this chapter, be sure you are familiar with the relevant media resources (see the complete, section-by-section resource grid in Appendix 3 of this Instructor's Guide) and the on-line quizzes and other study resources available on the Astronomy Place website.

What's New in the Third Edition That Will Affect My Lecture Notes?

As everywhere in the book, we have edited to improve the text flow, improved art pieces, and added new illustrations. In addition, those who have taught from previous editions of *The Cosmic Perspective* should be aware of the following organizational or pedagogical changes to this chapter (i.e., changes that will influence the way you teach) in the third edition:

- The final section from the second edition, which was about spacecraft, has been moved to Chapter 8 in this edition.
- We have updated the lists of observatories on the ground and in space.

Teaching Notes (By Section)

Section 7.1 Eyes and Cameras: Everyday Light Sensors

As with all the chapters in Part II, we begin this chapter with a section on "everyday" light collection, discussing the human eye and cameras.

- Note that we also introduce CCDs in this section, because they are now readily available on an "everyday" basis in cameras and camcorders.

Section 7.2 Telescopes: Giant Eyes

This section describes the general design of optical telescopes.

- Note that while we show Cassegrain, Newtonian, and coudé foci in a figure, we do not expect students to learn the names, and we give the names only in parentheses.
- Note our emphasis on two principal properties of telescopes: light-collecting area and angular resolution.

Section 7.3 Uses of Telescopes

This section describes the general types of observations for which telescopes are most commonly used.

- Although different observers tend to categorize observations differently, we have chosen to categorize observations as either imaging, spectroscopy, or timing. We believe that this categorization is pedagogically useful, because it most closely corresponds to the figures that students see in the book and in news reports: photographs (imaging), spectra (spectroscopy), and light curves (timing).

Section 7.4 Atmospheric Effects on Observations

In this section, we turn to the atmospheric effects due to light pollution and turbulence (twinkling), leading to a discussion of how observing sites are chosen and of adaptive optics.

Section 7.5 Telescopes Across the Spectrum

This section covers telescopes designed to collect light of different wavelengths.

- This is where we point out that most wavelengths of light do not penetrate the atmosphere.
- Note that interferometry is also covered in this section.

Answers/Discussion Points for Think About It Questions

The Think About It questions are not numbered in the book, so we list them in the order in which they appear, keyed by section number.

Section 7.1

- The pupil will be wider in the eye exposed to light. Doctors dilate your pupils so that they can see through them into your eye.

Section 7.2

- This question can make for a short discussion, as students state how the total light-collecting area of the eyes of people in their home compares to that of a 10-meter telescope.

Section 7.3

- CAT scans and MRIs use false-color displays to show different types of tissue or different elements within tissue, allowing doctors effectively to "see" inside your body.

Section 7.4

- On warm days the ground heat means added turbulence near the ground, which distorts images, just as upper atmospheric turbulence causes twinkling.

Section 7.5

- If you've never tried this trick for seeing grazing incidence reflections of visible light, you and your students may all be surprised by how it works. Note that this demonstration of visible-light grazing incidence works only with fairly smooth and shiny surfaces. It is impressive if you've never noticed it before.

Solutions to End-of-Chapter Problems (Chapter 7)

1. The image was blurry, because the photographic film was not placed at the focal plane. *This statement makes sense, because light is generally in focus only at the focal plane.*
2. By using a CCD, I can photograph the Andromeda Galaxy with a shorter exposure time than I would need with photographic film. *This statement makes sense, because a CCD is more sensitive than photographic film and hence can record an image in less time.*
3. Thanks to adaptive optics, the telescope on Mount Wilson can now make ultraviolet images of the cosmos. *This statement does not make sense, because ultraviolet light does not reach the ground and there is no technology we can use for a telescope that will change this basic fact.*
4. New technologies will soon allow astronomers to use X-ray telescopes on the Earth's surface. *This statement does not make sense, because X rays do not reach the ground and there is no technology we can use for a telescope that will change this basic fact.*
5. Thanks to interferometry, a properly spaced set of 10-meter radio telescopes can achieve the angular resolution of a single, 100-kilometer radio telescope. *This statement makes sense, because interferometry allows multiple small telescopes to achieve the angular resolution of a larger telescope.*
6. Thanks to interferometry, a properly spaced set of 10-meter radio telescopes can achieve the light-collecting area of a single, 100-kilometer radio telescope. *This statement does not make sense, because interferometry does not affect light-collecting area; it affects only angular resolution.*
7. I have a reflecting telescope in which the secondary mirror is bigger than the primary mirror. *This statement does not make sense. Remember that the secondary mirror is placed in front of the primary mirror in a reflecting telescope. Thus, if the secondary mirror was bigger than the primary mirror, it would block all light from reaching the primary mirror, rendering the telescope useless.*
8. An observatory on the Moon's surface could have telescopes monitoring light from all regions of the electromagnetic spectrum. *This statement makes sense, because the lack of an atmosphere means that all wavelengths of light reach the Moon's surface.*
9.
   a. Smaller angular resolution means that you can distinguish points that are closer together in the sky, which means that you get sharper images.
   b. If two stars are separated by 0.1 arcsecond and you look at them with an angular resolution of 0.01 arcsecond, you will see both stars distinctly. If you view them with an angular resolution of 0.5 arcsecond, they will appear as a single point of light.
10.
    a. The 10-meter Keck telescope has twice the diameter of the 5-meter Hale telescope, so its light-collecting area is $2^2 = 4$ times as much.

b. A 100-meter telescope would have 10 times the diameter of the 10-meter Keck telescope, so its light-collecting area would be $10^2 = 100$ times as much.

11–13. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

14. This is a project that should help students realize that brighter stars tend to twinkle more than dimmer ones and that stars twinkle more when nearer to the horizon then when higher overhead.

15. a. Following the method in Mathematical Insight 7.1, we find the angular separation of the light bulbs by substituting their actual separation $s = 0.2$ m and distance $d = 2$ km = 2,000 m into the angular separation formula:

$$\alpha = \frac{s}{2\pi d} \times 360° = \frac{0.2 \text{ m}}{2\pi \times 2000 \text{ m}} \times 360° = 0.006°$$

We can also convert this to arcminutes:

$$0.006° \times \frac{60'}{1°} = 0.36'$$

Because this is smaller than the 1-arcminute resolution of the human eye, the light bulbs will appear as a single light when seen at a distance of 2 kilometers.

b. We are looking for the angular diameter of a dime with a diameter of $s = 1.8$ cm = 0.018 m at a distance $d = 100$ m. Using the angular separation formula, we find:

$$\alpha = \frac{s}{2\pi d} \times 360° = \frac{0.018 \text{ m}}{2\pi \times 100 \text{ m}} \times 360° = 0.01°$$

The angular diameter of a dime viewed across the length of a football field is about 0.01°.

16. Following the method of Example 2 in Mathematical Insight 7.1, we can use the angular separation formula to find the Sun's actual diameter s from its angular diameter $\alpha = 0.5°$ and its distance $d = 1.5 \times 10^8$ km:

$$s = \frac{2\pi d}{360°} \times \alpha = \frac{2\pi \times 1.5 \times 10^8 \text{ km}}{360°} \times 0.5° = 1.3 \times 10^6 \text{ km}$$

Using this very approximate value of 0.5° for the Sun's angular size, we find that the Sun's diameter is about 1.3 million km—fairly close to the exact value of 1.392 million km.

17. We seek to know how far away we would have to place a dime (actual size $s = 1.8$ cm = 0.018 m) for it to have an angular diameter of 0.05 arcsecond. We begin by converting this angular diameter from arcseconds to degrees:

$$0.05'' \times \frac{1'}{60''} \times \frac{1°}{60'} = \left(1.4 \times 10^{-5}\right)^{\circ}$$

We now use this value as the angular diameter α in the angular separation formula and solve for the distance d:

$$\alpha = \frac{s}{2\pi d} \times 360° \quad \Rightarrow \quad d = \frac{s}{2\pi\alpha} \times 360° = \frac{0.018 \text{ m}}{2\pi \times \left(1.4 \times 10^{-5}\right)^{\circ}} \times 360° = 7.4 \times 10^4 \text{ m}$$

A dime has an angular size of 0.05 arcsecond when seen at a distance of about 74,000 meters, or 74 km. Thus, the Hubble Space Telescope could resolve the disk of a dime (i.e., know that it is a disk and not a point) at a distance of 74 km.

18. We seek the angular separation of two stars with real separation s = 100 million km = 10^8 km at a distance d = 100 light-years. We begin by converting the distance from light-years to kilometers:

$$100 \text{ ly} \times 10^{13} \frac{\text{km}}{\text{ly}} = 10^{15} \text{ km}$$

Now we use the angular separation formula:

$$\alpha = \frac{s}{2\pi d} \times 360° = \frac{10^8 \text{ km}}{2\pi \times 10^{15} \text{ km}} \times 360° \approx \left(6 \times 10^{-6}\right)^\circ$$

Finally, we convert from degrees to arcseconds so that we can compare to the 0.05-arcsecond resolution of the Hubble Space Telescope:

$$\left(6 \times 10^{-6}\right)^\circ \times \frac{60'}{1°} \times \frac{60''}{1'} = 0.02''$$

The angular separation of the two stars in this binary system is below the angular resolution of the Hubble Space Telescope, so they will appear as a single point of light in Hubble Space Telescope images.

19. We use the formula from Mathematical Insight 7.2 to find the diffraction limit of the human eye, but instead of having a telescope diameter we use the lens diameter of the eye, given as 0.8 cm:

$$\text{diffraction limit (arcseconds)} \approx 2.5 \times 10^5 \times \left(\frac{\text{wavelength}}{\text{lens diameter}}\right)$$
$$= 2.5 \times 10^5 \times \left(\frac{500 \times 10^{-9} \text{ m}}{0.008 \text{ m}}\right) = 16''$$

(Note that the actual angular resolution of the human eye, about 1 arcminute, is not as good as the diffraction limit, which is a theoretical limit for a perfect optical system.) For a 10-meter telescope, the diffraction limit resolution is:

$$\text{diffraction limit (arcseconds)} \approx 2.5 \times 10^5 \times \left(\frac{\text{wavelength}}{\text{telescope diameter}}\right)$$
$$= 2.5 \times 10^5 \times \left(\frac{500 \times 10^{-9} \text{ m}}{10 \text{ m}}\right) = 0.0125''$$

The diffraction limit of the 10-meter telescope is smaller than the diffraction limit of the human eye by a factor of about 16/0.0125 = 1,280, or close to 1,300.

20. For a 100-meter (10^4-cm) radio telescope observing radio waves with a wavelength of 21 cm, the diffraction limit is:

$$\text{diffraction limit (arcseconds)} \approx 2.5 \times 10^5 \times \left(\frac{\text{wavelength}}{\text{telescope diameter}}\right)$$
$$= 2.5 \times 10^5 \times \left(\frac{21 \text{ cm}}{10^4 \text{ cm}}\right) = 525''$$

This angular resolution of over 500 arcseconds is about 10,000 times poorer than the Hubble Space Telescope's 0.05-arcsecond resolution for visible light. In order to achieve significantly better angular resolution when observing 21-cm radio waves, a radio telescope must have an effective diameter much larger than 100 meters. Because it would be impractical to build such huge telescopes, radio astronomers use the technique of interferometry to make many small radio telescopes achieve the angular resolution that would be had by a single very large one.

21. a. The angular area of the advanced camera's field of view is about $(0.06°)^2 = 0.0036$ square degree.

b. Given that the angular area of the entire sky is about 41,250 square degrees, taking pictures of the entire sky would require:

$$\frac{41,250 \text{ square degrees}}{0.0036 \text{ square degrees}} = 11.5 \text{ million}$$

separate photographs by the advanced camera.

c. If each of 11.5 million photographs required 1 hour to take, the total time required would be 11.5 million hours, which is the same as:

$$11.5 \text{ million} \times \frac{1 \text{ day}}{24 \text{ hr}} \times \frac{1 \text{ yr}}{365 \text{ day}} = 1310 \text{ yr}$$

That is, it would take more than a thousand years for the Hubble Space Telescope to photograph the entire sky, assuming 1 hour per photograph. Clearly, we'll need many more telescopes in space if we hope to get Hubble Space Telescope–quality photos of the entire sky.