Part II: Key Concepts for Astronomy

Chapter 4. Making Sense of the Universe: Understanding Motion, Energy, and Gravity

This chapter focuses on three major ideas and their astronomical applications: (1) Newton's laws of motion, (2) the laws of conservation of energy and angular momentum, and (3) the law of gravity.

As always, when you prepare to teach this chapter, be sure you are familiar with the online quizzes, interactive figures and tutorials, assignable homework, and other resources available on the MasteringAstronomy website (www.masteringastronomy.com).

Key Changes for the 8th Edition: We have left the basic organization and content of this chapter unchanged from the prior edition. However, we have made numerous edits throughout the chapter to improve clarity for students.

Teaching Notes (by Section)

Section 4.1 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 of 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 Earth and the Moon.
- Also note 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 to use with 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 percentage points smaller in low-Earth orbit than on the ground. Perhaps a better term for the

conditions in orbit would be *microacceleration*, but we think 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 4.2 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.

Section 4.3 Conservation Laws in Astronomy

This section covers conservation of angular momentum and conservation of energy and includes a discussion of the various forms of energy.

- When introducing angular momentum, you may wish to demonstrate conservation of angular momentum using a bicycle wheel and a rotating platform.
- 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. This is 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 Earth. However, you may wish to mention the formula *mgh* in class, particularly if your students are already familiar with it.

Section 4.4 The Force of Gravity

The pieces now are all in place to introduce Newton's universal law of gravitation and use it to explain fundamental ideas in astronomy, including the reasons for Kepler's laws, orbital energy and changes, escape velocity, and tides.

- Note that, as in Chapter 1, we are using average distance to mean a semimajor axis distance.
- Also note that, while we mention parabolas and hyperbolas as allowed orbital paths, the term introduced to include both these cases is *unbound orbits*. Similarly, we refer to elliptical orbits as *bound orbits*. We find that the terms *bound* and *unbound* are far more intuitive for students than precise mathematical shapes.
- 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.

Answers/Discussion Points for Think About It/See It for Yourself Questions

The Think About It and See It for Yourself 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

- (p. 84, SIFY) This activity helps students realize that by crumpling the paper, they make it less subject to air resistance and hence can see the effects of gravity more easily.
- (p. 86, SIFY) This activity asks students to try a small demonstration that will help them understand the difference between mass and weight. Weight changes with acceleration but is not affected at constant speed in the elevator.

Section 4.3

- (p. 91) As the water gets closer to the drain, it moves in a smaller circle and thus must circle the drain faster to conserve its angular momentum.
- (p. 93) 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 to do so.

Section 4.4

- (p. 96) 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 $2^2 = 4$.
- (p. 100) 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 4)

Visual Skills Check

1. b 2. c 3. d 4. d 5. c

Review Questions

1. The term *speed* is used to describe how fast something is moving. *Velocity* carries that same information, but it also tells us in which direction the object is going.

Acceleration is occurring any time an object's velocity is changing; more technically, *acceleration* is the rate of change of velocity over time. The standard units of acceleration are m/s^2, which tell us that the velocity is changing by so many m/s for every second during which the acceleration continues. The acceleration of gravity, *g*, is the acceleration downward due to gravity, which is about 10 m/s^2 (more precisely, 9.8 m/s^2).

2. Momentum is the product of mass and velocity (mass × velocity). A force is something that can change the momentum of an object. However, the object's momentum will respond only to a net force, the force that is left when we add all of the forces together. Even if the individual forces are large, if they cancel out and leave no net force, then there is no change in momentum.
3. Free-fall is the state of falling without any resistance to the fall. Objects in free-fall are weightless because they are not pushing against anything to give them weight. Astronauts in the Space Station are in constant free-fall as they fall around Earth (always missing it), so they are weightless.
4. (i) An object moves at a constant velocity if there is no net force on it. This is why objects that are at rest do not start moving spontaneously. (They remain at constant—zero—velocity.)

   (ii) Force = mass × acceleration. This law tells us that it takes a lot more force to push a car forward than it does a bicycle at the same acceleration.

   (iii) For every force, there is an equal and opposite force. This explains the recoil someone feels when he or she fires a gun: The gun is applying a force to the bullet, but the bullet applies a force back on the gun.
5. The conservation laws say that angular momentum and energy are conserved. That is, in a particular system, the total amount of each of these quantities does not change.

   Conservation of angular momentum is what gives us Kepler's second law. When a planet gets closer to the Sun, it has to move faster to conserve its angular momentum.

   Conservation of energy tells us that as an object falls to Earth's surface, it loses gravitational potential energy. To conserve energy, the object has to move faster as it falls. Eventually, it hits the ground and stops. At this point, its kinetic energy is converted to heat and sound.
6. *Kinetic energy* is the energy an object has due to its motion. Two examples are a car driving down the highway or a cup of hot coffee. (In the latter case, the motion is in the random movement of the molecules, not the overall motion of the liquid.)

   Potential energy is energy that is stored. It could be, for example, chemical, mechanical (e.g., by springs), gravitational, or nuclear. Two examples of potential energy are breakfast cereal, which has chemical potential energy, and a heavy book on the top shelf at the library, which has gravitational potential energy.

   Radiative energy is energy in light. Sunlight carries this form of energy.

7. *Thermal energy* is the amount of energy stored in the random motions of the molecules of some object. *Temperature* is a measurement of the average kinetic energy of these random motions. The two concepts are related because both deal with the energy in the random motions of the particles. However, thermal energy measures the total energy in all of the particles, while temperature measures the average energy per particle. Thus, two objects with the same temperature can have different amounts of thermal energy if they differ in size or density.
8. *Mass-energy* is the potential energy that is stored in the form of matter. All matter can be converted to energy. The amount of energy available is given by Einstein's famous equation, $E = mc^2$: The energy stored is equal to the mass times the speed of light squared.
9. Newton's universal law of gravitation states that every object in the universe attracts every other object. The force of the attraction depends on the product of the masses and declines with the square of the distance between the objects. In mathematical form:

$$F_g = G\frac{M_1 M_2}{d^2}$$

   where F_g is the force of gravity, G is the gravitational constant, M_1 and M_2 are the masses of the objects, and d is the distance separating the centers of the objects.
10. A *bound orbit* is one in which the orbiting object goes around again and again, while in an *unbound orbit* the object makes just one orbit before leaving.
11. We can use Newton's version of Kepler's third law to calculate the mass of an object when one object is orbiting another. If a small object orbits a much more massive one, we can determine the mass of the massive object from the orbital period and orbital distance of the less massive object. If both objects are comparable in mass, we can determine the *sum* of their masses from their mutual orbital period and distance.
12. Because of conservation of energy, objects do not change orbits spontaneously. As long as nothing changes the energy of the object, it must remain in the same orbit, because different orbits have different energies associated with them. However, if two or more objects interact gravitationally, they can exchange orbital energy, causing their orbits to change; if one object gains orbital energy, the other must lose it. If enough energy is added to an orbiting object, it can achieve escape velocity and leave orbit entirely and fly away. Human-made objects can also achieve escape velocity by firing their engines and adding energy to their orbits until they are moving fast enough to leave orbit.
13. The Moon creates tides on Earth by pulling on the different parts of Earth with different forces. The nearest parts of Earth get stronger tugs, according to Newton's law of universal gravitation, so they try to move toward the Moon more than the parts that are farther away. This actually creates two

bulges: The nearest point to the Moon bulges toward the Moon because it is more attracted to the Moon than the average part of the planet, and the farthest point bulges away because it is less attracted to the Moon than the average part of the planet. This leads to two high and two low tides each day as we spin around under the Moon.

14. Tides vary with the phases of the Moon because the Sun also creates tides on Earth. When the Moon is either new or full (in the same direction as the Sun from Earth or on the opposite side of Earth from the Sun), the two tidal bulges combine to create higher, or spring, tides. When the Moon is in first or third quarter, the two tidal bulges tend to cancel each other out somewhat so that we get lower, or neap, tides.

Does It Make Sense?

15. *I've never been to space, so I've never experienced weightlessness.* This statement does not make sense, because you are weightless any time you are in free-fall, and most people experience at least some free-fall frequently, such as every time they jump up and down.
16. *Suppose you could enter a vacuum chamber (a chamber with no air in it) on Earth. Inside this chamber, a feather would fall at the same rate as a rock.* This statement makes sense. Without air resistance, all objects will fall at the same rate under gravity.
17. *If 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.* This statement does not make sense. The astronaut 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).
18. *I used Newton's version of Kepler's third law to calculate Saturn's mass 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.
19. *If the Sun were magically replaced with a giant rock that had precisely the same mass, Earth's orbit would not change.* This statement makes sense because the rock would have the same gravitational effect on Earth as does the Sun.
20. *The fact that the Moon rotates once in precisely the time it takes to orbit Earth once is such an astonishing coincidence that scientists probably never will be able to explain it.* This statement does not make sense because the synchronous rotation is not a coincidence at all, and its cause has been well explained.
21. *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."
22. *If an asteroid passed by Earth at just the right distance,Earth's gravity would capture it and make it 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.

23. *When I drive my car at 30 miles per hour, it has more kinetic energy than it does at 10 miles per hour.* This statement makes sense because kinetic energy depends on the square of the speed. Thus, tripling the speed means an increase in kinetic energy by a factor of $3^2 = 9$.
24. *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.

Quick Quiz

25. c 26. b 27. a 28. a 29. b 30. c 31. b 32. c 33. c 34. a

Process of Science

35. The theory of gravity makes specific predictions about how much a spacecraft should decelerate as it moves away from the Sun. We can therefore test the theory by comparing the observed motions of the spacecraft with the predictions of the theory.
36. The origin of the upward force from the table or your hand is atomic—atoms in your hand or in the table pushing up against the two different balls. Atomic forces are electromagnetic in nature, and we know that like charges repel. The force is self-adjusting because greater weight pushes the atoms closer together, increasing the repulsive force.

Group Work Exercise (no solution provided)

Short Answer/Essay Questions

38. Astronauts are *not* weightless during either launch or return to Earth because they are not in free-fall at those times. Astronauts feel forces due to acceleration as they launch into space and forces due to air resistance when the spacecraft slows as it returns to Earth.
39. 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 1000 grams of hydrogen, fusion results in 993 grams of helium; the remaining 7 grams are 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.

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

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

c. If Earth were moved to one-third of its current distance from the Sun, the gravitational attraction between Earth and Sun would *increase* by a factor of $3^2 = 9$.

41. a. Newton's version of Kepler's third law tells us that a planet's orbit around a star depends on the sum of the masses of the star and the planet. We can generally neglect the planet's mass because a star is usually so much more massive than any planet, which means that the planet's orbit depends on the star's mass but not on its own mass. Thus, Earth's orbit could not stay the same if the Sun were replaced by a more massive star because the orbit *does* depend on the star's mass.

b. Changing Earth's mass would not affect its orbit because, as discussed above, the planet's mass is not important to its orbital properties.

42. The tidal force acting on you depends on the difference between the gravitational force acting on your head and the force acting 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 Earth. Because the length of your body is negligible compared to the radius of 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.)

Quantitative Problems

43. 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:

$$\frac{2.5\times10^{16}\ \cancel{\text{joules}}}{4\times10^{15}\ \cancel{\text{joules}}} = \frac{25\times10^{15}}{4\times10^{15}} = 6.25$$

A major earthquake releases as much energy as six 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

$$\frac{10^{20}\ \cancel{\text{joules}}}{1.2\times10^{7}\ \cancel{\text{joules}}/\text{liter}} = 8\times10^{12}\ \text{liter}$$

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:

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

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.

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

$$\frac{10^{20}\ \text{joules}}{\cancel{\text{yr}}} \times \frac{1\ \cancel{\text{yr}}}{365\ \cancel{\text{days}}} \times \frac{1\ \cancel{\text{day}}}{24\ \cancel{\text{hr}}} \times \frac{1\ \cancel{\text{hr}}}{60\ \text{min}} \approx \frac{1.9\times\ 10^{14}\ \text{joules}}{\text{min}}$$

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):

$$\frac{1.9\times10^{14}\ \frac{\cancel{\text{joules}}}{\text{min}}}{7\times10^{13}\ \frac{\cancel{\text{joules}}}{\text{liter}}} \approx 2.7\frac{\text{liters}}{\text{min}}$$

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.

45. 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 1 year.

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

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

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:

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

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

46. a. Using the Moon's orbital period and distance and following the method given in Cosmic Calculations 4.1, we find the approximate mass of Earth:

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

Making sure that we use appropriate units, we find:

$$M_{\text{Earth}} \approx \frac{4\pi^2\left(384{,}000\ \cancel{\text{km}} \times 1000\,\frac{\cancel{\text{m}}}{\cancel{\text{km}}}\right)^3}{\left(6.67\times10^{-11}\,\frac{\cancel{\text{m}^3}}{\text{kg}\times\cancel{\text{s}^2}}\right)\left(27.3\ \cancel{\text{days}}\times24\,\frac{\cancel{\text{hr}}}{\cancel{\text{day}}}\times3600\,\frac{\cancel{\text{s}}}{\cancel{\text{hr}}}\right)^2} = 6.0\times10^{24}\ \text{kg}$$

b. Using Io's orbital period and distance and following the method given in Cosmic Calculations 4.1, we find the mass of Jupiter to be about

$$M_{\text{Jupiter}} \approx \frac{4\pi^2\left(422{,}000\ \cancel{\text{km}} \times 1000\,\frac{\cancel{\text{m}}}{\cancel{\text{km}}}\right)^3}{\left(6.67\times10^{-11}\,\frac{\cancel{\text{m}^3}}{\text{kg}\times\cancel{\text{s}^2}}\right)\left(42.5\ \cancel{\text{hr}}\times3600\,\frac{\cancel{\text{s}}}{\cancel{\text{hr}}}\right)^2} = 1.9\times10^{27}\ \text{kg}$$

We would 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. We again start with Newton's version of Kepler's third law:

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

We solve for the semimajor axis of the planet with a little algebra:

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

We convert the planet's orbital period of 63 days into seconds:

$$63\ \cancel{\text{days}}\times\frac{24\ \cancel{\text{hr}}}{1\ \cancel{\text{day}}}\times\frac{60\ \cancel{\text{min}}}{1\ \cancel{\text{hr}}}\times\frac{60\ \text{s}}{1\ \cancel{\text{min}}} = 5.44\times10^6\ \text{s}$$

Planets are much less massive than their stars are, so we can approximate $M_1 + M_2 \approx M_{\text{star}}$. From Appendix A, the mass of the Sun is about 2×10^{30} kilograms. So we can calculate the semimajor axis:

$$a = \sqrt[3]{\frac{\left(6.67\times10^{-11}\,\frac{\text{m}^3}{\text{kg}\cdot\text{s}^2}\right)(2\times10^{30}\ \text{kg})}{4\pi^2}(5.44\times10^6\text{s})^2}$$
$$= 4.64\times10^{10}\ \text{m}$$

Of course, this number would probably be more useful in astronomical units, so we should convert:

$$4.64\times10^{10}\ \cancel{\text{m}}\times\frac{1\ \text{AU}}{1.5\times10^{11}\ \cancel{\text{m}}} = 0.31\ \text{AU}$$

The new planet is only 0.31 AU from its star, which is closer than Mercury is to the Sun.

d. If we are working with Charon's orbit around Pluto, Newton's version of Kepler's third law takes this 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 simplify the equation further. We simply solve for the masses and then plug in the numbers given:

$$\begin{aligned} M_{\text{Pluto}} + M_{\text{Charon}} &= \frac{4\pi^2 \times (a_{\text{Charon}})^3}{G \times (p_{\text{Charon}})^2} \\ &= \frac{4\pi^2 \times \left(19{,}600\ \cancel{\text{km}} \times 1000 \frac{\text{m}}{\cancel{\text{km}}}\right)^3}{\left(6.67\times10^{-11} \frac{\text{m}^3}{\text{kg}\times \text{s}^2}\right)\left(6.4\ \cancel{\text{days}} \times 24 \frac{\cancel{\text{hr}}}{\cancel{\text{day}}} \times 3600 \frac{\text{s}}{\cancel{\text{hr}}}\right)^2} \\ &= 1.5\times10^{22}\ \text{kg} \end{aligned}$$

We put this in perspective by comparing this mass for Pluto and Charon to Earth's mass of 6.0×10^{24} kilograms:

$$\frac{M_{\text{Earth}}}{M_{\text{Pluto}} + M_{\text{Charon}}} = \frac{6.0 + 10^{24}\ \cancel{\text{kg}}}{1.5\times10^{22}\ \cancel{\text{kg}}} = 400$$

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

e. The spacecraft is much less massive than Earth, so we can follow the method of Cosmic Calculations 4.1 to write

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

Remember that $a_{\text{spacecraft}}$ represents the spacecraft's average distance from the center of Earth. The radius of Earth is about 6400 kilometers, so

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

or 6.7×10^6 meters. The mass of Earth is about $M_{\text{Earth}} \approx 6.0 \times 10^{24}$ kilograms. Substituting these values and solving the equation for $p_{\text{spacecraft}}$ by taking the square root of both sides yields

$$p_{\text{spacecraft}} \approx \sqrt{\frac{4\pi^2}{\left(6.67\times10^{-11} \frac{\cancel{\text{m}^3}}{\cancel{\text{kg}} \times \text{s}^2}\right)(6.0\times10^{24}\ \cancel{\text{kg}})}(6.7\times10^6\ \cancel{\text{m}})^3} \approx 5400\,\text{s}$$

The spacecraft orbits Earth in about 5400 seconds, or 90 minutes.

f. We again begin with Newton's version of Kepler's third law:

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

Since we want the mass of the galaxy, we need to solve for mass. Luckily, the mass of the galaxy is much larger than the mass of the Sun, so $M_1 + M_2 \approx M_{\text{galaxy}}$. Solving for this mass in Newton's version of Kepler's third law gives

$$M_{\text{galaxy}} = \frac{4\pi^2}{Gp^2} a^3$$

We are given that the Sun orbits every 230,000,000 years and its orbital semimajor axis is 27,000 light-years. We need to convert these values to seconds and meters, respectively:

$$230{,}000{,}000\ \cancel{\text{yr}} \times \frac{365\ \cancel{\text{days}}}{1\ \cancel{\text{year}}} \times \frac{24\ \cancel{\text{hr}}}{1\ \cancel{\text{day}}} \times \frac{60\ \cancel{\text{min}}}{1\ \cancel{\text{hr}}} \times \frac{60\ \text{s}}{1\ \cancel{\text{min}}} = 7.25 \times 10^{15}\ \text{s}$$

Using the fact that there are 9.46×10^{12} kilometers in a light-year, as noted in Appendix A, we find

$$27{,}000\ \cancel{\text{light-years}} \times \frac{9.46 \times 10^{12}\ \cancel{\text{km}}}{1\ \cancel{\text{light-year}}} \times \frac{1000\ \text{m}}{1\ \cancel{\text{km}}} = 2.55 \times 10^{20}\ \text{m}$$

Now we can calculate the mass of the galaxy:

$$\begin{aligned} M_{\text{galaxy}} &= \frac{4\pi^2}{\left(6.67 \times 10^{-11} \frac{\cancel{\text{m}^3}}{\text{kg} \times \cancel{\text{s}^2}}\right)(7.25 \times 10^{15}\ \cancel{\text{s}})^2} (2.55 \times 10^{20}\ \cancel{\text{m}})^3 \\ &= 2.08 \times 10^{41}\ \text{kg} \end{aligned}$$

This number is probably easier to understand as multiples of the mass of the Sun, so let's convert:

$$2.08 \times 10^{41}\ \cancel{\text{kg}} \times \frac{1\ \text{solar mass}}{2 \times 10^{30}\ \cancel{\text{kg}}} = 1.04 \times 10^{11}\ \text{solar masses}$$

Based on the given data, the mass of the galaxy is about 100 billion times the mass of the Sun.

Chapter 5. Light: The Cosmic Messenger

This chapter focuses on the nature of light and matter, and also covers basic properties of telescopes.

- 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 online quizzes, interactive figures and tutorials, assignable homework, and other resources available on the MasteringAstronomy website (www.masteringastronomy.com).

Key Changes for the 8th Edition: For those who have used earlier editions of our textbook, please note the following significant changes in this chapter:

- Added emphasis on new and upcoming telescopes, including ALMA, JWST, and LSST, and on non-light observing, including gravitational wave detection with LIGO.
- Revised example in Cosmic Calculations 5.1.
- New Extraordinary Claims feature.

Teaching Notes (by Section)

Section 5.1 Basic Properties of Light and Matter

This section introduces several important concepts, including wave properties of wavelength, frequency, and speed; wave-particle duality; the idea that light comes in the form of photons; the idea of light as an electromagnetic wave; and the basic terminology of atoms.

- 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. For those who wonder why we have chosen to use the term *light* in this way, rather than only for visible light, we can cite at least four reasons:
    1. For our purposes, the goal of a definition of light is to put it in the context of physics, which is why we define light as an electromagnetic wave that comes in individual "pieces" known as photons. This definition does not distinguish between photons based on wavelength, so any distinction between visible light and other forms of light would require changing this definition. Moreover, treating visible light differently from other forms of light does not really have a justification in physics, since it is based on human sensory capabilities, which are not the same as those of other animal species.

2. In many ways, the key idea about light in astronomy is that it encodes information as a result of its interactions with matter, which is why we start this chapter by talking about such interactions. These interactions, which we categorize as emission, absorption, transmission, and reflection/scattering, apply to all parts of the EM spectrum, not just to visible light. So again, using the term *light* only to mean visible light would require complicating this discussion and applying an artificial distinction based on our eyes rather than on physics.
3. Another important concept in astronomy is the speed of light, which we use in defining distances in light-years and in using $E = mc^2$. Since we call it the speed of light, we are already implicitly defining light to include all EM radiation, since all EM radiation travels at this same speed.
4. Finally, many other discussions would be greatly complicated if we did not include all EM radiation under the term *light*. For example, Kirchhoff's laws, the laws of thermal radiation, and even the Doppler shift all require thinking in general terms about emission and absorption, which is easy to do when we use the term *light* as we do but would be much more difficult if we considered only visible light as "light." You can see the problem by thinking about a high redshift case: If infrared is not considered "light," then the shift of a line from the visible part of the spectrum to the infrared would mean that the line had shifted from "light" to "nonlight."

- Note that we never use the Bohr picture of the atom. Instead, in our discussions we use 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.
- 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 5.2 Learning from Light

This section covers the interpretation of astronomical spectra.

- A classroom demonstration of spectroscopy can be very useful if it is possible to arrange one. We like to hand out inexpensive plastic diffraction gratings that 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 the material in this section, 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 such jargon. Note in particular the following:
    - 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 5.8.
    - We use the term *thermal radiation* rather than *blackbody radiation*, since "thermal" more clearly makes the connection to temperature. (Also, students find it really odd to think of a bright star as a "blackbody.")
    - We describe the Stefan-Boltzmann law and Wien's law simply as "Law 1" and "Law 2" of thermal radiation, respectively, rather than expecting students to memorize the names.
    - 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.

Section 5.3 Collecting Light with Telescopes

The final section of this chapter describes telescopes, their design, and their uses.

- This is also where we point out that most wavelengths of light do not penetrate the atmosphere, and introduce the rationale for space telescopes.

Answers/Discussion Points for Think About It/See It for Yourself Questions

The Think About It and See It for Yourself 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

- (p. 108) Shorter wavelength means higher frequency and hence higher energy.
- (p. 110) ^{3}He represents helium containing 2 protons and 1 neutron.

Section 5.2

- (p. 114) Yes, for a jump from level 2 to level 4.
- (p. 115) 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.
- (p. 117, SIFY) Use of the dimmer switch demonstrates the first law (Stefan-Boltzmann) by the fact that as the bulb gets brighter, it gets hotter, and it demonstrates the second law (Wien's) by the fact that the light changes color from reddish to whitish as the bulb gets hotter.

- (p. 119) A line shifted from a rest wavelength of 121.6 nanometers to 120.5 nanometers has actually shifted to a position farther from the blue end of the visible spectrum, which begins around 400 nanometers. Nevertheless, we call this a *blueshift* because it is a shift to a shorter (as opposed to a longer) wavelength.

Section 5.3

- (p. 122) The 10-m telescope has a diameter 2000 times greater than the 5-mm pupil, so the telescope's light-collecting area is greater by a factor of $2000^2 = 4$ million.
- (p. 126, SIFY) The coin appears to move because the water is moving and changing the path of the light as it comes through the water toward our eyes. It's the same reason that air turbulence causes twinkling.
- (p. 128) This question asks students to check the current status of the James Webb Space Telescope, which is scheduled to launch in 2018. Key scientific goals for the telescope include (1) studying the very early universe to learn about the first billion years during which early stars and galaxies were born; (2) learning about the assembly of early galaxies and galaxy evolution over time; (3) studying stars and planetary systems in the process of being born; and (4) assessing the atmospheres of extrasolar planets.

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

Visual Skills Check

1. 1 2. 5 3. b 4. b 5. c

Review Questions

1. *Wavelength*: The distance between two successive peaks in a wave. *Frequency*: The number of wave peaks to pass by a point in a second. *Speed* of a wave: How fast the wave itself travels, equal to wavelength × frequency. Long wavelength means low frequency and vice versa.
2. A *photon* is a particle of light. Unlike an ordinary wave, light has a smallest unit that cannot be subdivided. However, light also has wavelike properties, such as having characteristic wavelengths and frequencies.
3. From lowest to highest energy, the electromagnetic spectrum is radio, infrared, visible, ultraviolet, X rays, and gamma rays. This is the same order we would get if we listed the forms in order of frequency (lowest to highest), because energy is directly proportional to frequency. However, it is the reverse of what we get if we list the forms in order of wavelength, because frequency and wavelength are inversely related.
4. An atom has a tiny nucleus in the center that contains the protons and neutrons. Around the nucleus are clouds of electrons. Atoms are tiny, less than one-millionth the size of the period at the end of this sentence. However, the nuclei are much smaller still.

5. An atom's *atomic number* is the number of protons it has in its nucleus. Its *atomic mass number* is the number of protons plus the number of neutrons. Two atoms can have the same number of protons (have the same atomic number) and have different numbers of neutrons. In this case, we say that these atoms are different *isotopes* of the same element. A molecule is a group of two or more atoms bound together.
6. *Electrical charge* is a measure of how strongly something will interact with electromagnetic fields. We define a proton as having +1 unit of charge and an electron as having –1 unit of charge. Two particles with opposite charge will attract each other, so protons and electrons will attract. Particles with charges of the same sign will repel each other, so two electrons will repel each other.
7. Emission: A light bulb emits light.
   Absorption: A person lying in the summer sun absorbs light.
   Transmission: A window transmits light.
   Reflection/scattering: A mirror reflects light.
8. A continuous spectrum is seen when we observe a hot object emitting light across a broad range of wavelengths. We see an emission line spectrum when we look at a cloud of thin gas because we see only the wavelengths of light that correspond to the atomic transitions allowed in that gas. We see an absorption line spectrum when we look at a hot object (like a star) through a thin cloud of gas. The continuous spectrum of the hot object loses photons of the specific frequencies that the atoms in the thin gas absorb.

   The spectrum on the opening page of the chapter is a continuous spectrum from the Sun's hot "surface." However, before the light reaches us, it passes through the Sun's thin atmosphere, and photons of certain specific wavelengths are absorbed by the gas. This creates the dark lines in the spectrum.
9. Atoms tend to absorb and emit different wavelengths of light because they have different energy levels. Similarly, every molecule absorbs or emits different bands of wavelengths. So when we look at an absorption or emission spectrum, we can see the "fingerprints" of the different atoms (or ions) or molecules. In this way we can learn what an object is made of without ever sampling the object.
10. We know that a hotter object emits more light at every wavelength. Thus, the intensity of light from the 8000 K star will be higher at every wavelength. We also know that the spectrum of the hotter object will peak at shorter wavelengths. So the 8000 K star will show a peak at a shorter wavelength.
11. The *Doppler effect* is the change in frequency in light due to the source's motion toward or away from the observer. When the source is coming toward us, the light we see has a shorter wavelength (higher frequency), and we say that it is blueshifted. If the object is moving away from us, the light has a longer frequency than we would expect, and we say that it is redshifted. Stating that radio waves are blueshifted means there has been a shift toward a shorter wavelength, which means they are coming from an object that is moving toward us.

12. Telescopes have two key properties: light-collecting area and angular resolution. A telescope can collect a lot more light than can the human eye because it is larger. This is important because the objects astronomers want to look at are usually very faint. The other important property of telescopes is angular resolution. Telescopes can make out finer details than can our eyes. This is important because the objects we want to study appear small in our sky.

    The difference between a reflecting telescope and a refracting telescope lies in how the light is focused. In a refracting telescope, a lens is used to focus the light, whereas in a reflecting telescope we use mirrors. Today, we mainly use reflectors because they allow for larger mirrors and less loss of light.
13. The atmosphere has three negative effects on observations. First, it blocks light of most wavelengths from ever reaching the ground. Second, the atmosphere scatters human-generated light and makes it more difficult to make observations. And finally, the constant movement of air in the atmosphere (the source of turbulence when flying) causes stars to appear to twinkle, which effectively blurs telescopic images. Putting a telescope in space overcomes these problems because the telescope no longer has to look through the atmosphere.
14. Adaptive optics is a technology that can essentially undo the blurring caused by twinkling. Interferometry is the process of linking up multiple telescopes so that they combine their observations to make much higher-resolution images than the individual telescopes can.

Does It Make Sense?

15. *If you could view a spectrum of the light reflecting off a blue sweatshirt, you'd find the entire rainbow of color (looking the same as a spectrum of white light)*. 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.
16. *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.
17. *Two isotopes of the element rubidium differ 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.
18. *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.
19. *If you could see infrared light, you would see a glow from the backs of your eyelids when you closed your eyes.* This statement makes sense because your eyelids are warm and emit infrared radiation.

20. *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.
21. *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.
22. *Thanks to adaptive optics, telescopes on the ground 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.
23. *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.
24. *If you lived on the Moon, you'd never see stars twinkle.* This statement makes sense because twinkling is caused by the atmosphere and the Moon doesn't have an atmosphere.

Quick Quiz

25. c	26. a	27. b	28. a	29. c
30. b	31. a	32. a	33. b	34. c

Process of Science

35. Spectra give us confidence that objects throughout the universe are made from the same collection of chemical elements. Each chemical element produces a set of uniquely located spectral lines. To the extent that observations have allowed, distant objects always show lines that match these sets. Given the extremely low probability of such lines randomly appearing for unknown reasons, the only reasonable conclusion is that the same elements are producing the lines.
36. In order to reproduce Newton's experiment, the second prism needs to be placed along the path of the red light emerging from the first prism. You could test where to place the second prism by setting up the white screen behind the first prism and observing where the red light falls. Then you can place the second prism at the location of the red light on the screen, but oriented opposite from the first prism so that it bends the red light in the opposite direction. Placing the screen behind the second prism, you would see that only red light is coming from the second prism, confirming Newton's result. You can make the experiment more precise by making a slit in the screen to allow only the red light through and then placing the second prism on the other side of the screen where the red light hits it.

Group Work Exercise (no solution provided)

Short Answer/Essay Questions

38. a. The iron has atomic number 26, atomic mass number 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 5 of its 8 electrons; thus, the ion has 3 electrons.
39. a. Fluorine with 9 protons and 10 neutrons has atomic number 9 and atomic mass number 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.
    b. Gold with atomic number 79 and atomic mass number 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.
    c. Uranium has atomic number 92 and hence has 92 protons. Thus, ^{238}U contains 238 – 92 = 146 neutrons, and ^{235}U contains 235 – 92 = 143 neutrons.
40. a. Transition B could represent an atom that absorbs a photon with 10.2 eV of energy because the electron jumps up from 0 eV to 10.2 eV.
    b. Transition C could represent an atom that emits a photon with 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 between.
    e. Transition A represents an electron falling from level 3 to level 1, emitting 12.1 eV of energy in the process. This is more energy than emitted in transition C.
41. A glowing cloud of gas will produce an emission line spectrum.
42. We are considering a spectral line with a rest wavelength of 121.6 nanometers that appears at 120.5 nanometers in Star A, 121.2 nanometers in Star B, 121.9 nanometers in Star C, and 122.9 nanometers 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 nanometers; thus, of these four stars, Star D is moving the fastest relative to us.

43. 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. 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.
44. You cannot gain any detail by blowing up a magazine or newspaper photograph beyond the detail that is already there. In much the same way, additional magnification with a telescope cannot provide any more detail than the telescope is capable of obtaining as a result of its size and optical quality.
45. The five telescopes will be much more valuable if linked together for interferometry, because the linkage will improve their angular resolution. Adaptive optics will do nothing at all for telescopes in space, because this technology is designed only to counteract blurring caused by Earth's atmosphere.
46. 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 than when higher overhead.

Quantitative Problems

47. a. We can use the Stefan-Boltzmann law to compute the energy emitted by the object from every square meter:

$$\text{emitted power} = \sigma\, T^4$$

where T is the temperature and $\sigma = 5.7\times10^{-8}\ \dfrac{\text{watt}}{\text{K}^4\ \text{m}^2}$.

For our 3000 K object:

$$\begin{aligned}\text{emitted power} &= \left(5.7\times10^{-8}\,\frac{\text{watt}}{\cancel{\text{K}^4}\,\text{m}^2}\right)(3000\ \cancel{\text{K}})^4\\ &= 4.6\times10^{6}\,\frac{\text{watts}}{\text{m}^2}\end{aligned}$$

We find the wavelength of the peak emission with Wien's law:

$$\lambda_{\text{peak}} = \frac{2{,}900{,}000}{T}\,\text{nm}$$

where T is again the temperature, measured in Kelvins. For a 3000 K object, we get

$$\lambda_{\text{peak}} = \frac{2,900,000}{3000}\text{nm}$$
$$= 967\text{ nm}$$

The object emits 4.6 million watts per square meter and has a spectrum that peaks at 967 nanometers.

b. We can use the Stefan-Boltzmann law to compute the energy emitted by the object from every square meter:

$$\text{emitted power} = \sigma\ T^4$$

where T is the temperature and $\sigma = 5.7\times10^{-8}\ \frac{\text{watt}}{\text{K}^4\text{m}^2}$.

For a 50,000 K object:

$$\text{emitted power} = \left(5.7\times10^{-8}\ \frac{\text{watt}}{\cancel{\text{K}^4}\text{m}^2}\right)\left(50,000\ \cancel{\text{K}}\right)^4$$
$$= 3.6\times10^{11}\ \frac{\text{watts}}{\text{m}^2}$$

We find the wavelength of the peak emission with Wien's law:

$$\lambda_{\text{peak}} = \frac{2,900,000}{T}\text{nm}$$

where T is again the temperature measured in Kelvins. For a 50,000 K object, we get

$$\lambda_{\text{peak}} = \frac{2,900,000}{50,000}\text{nm}$$
$$= 58\text{ nm}$$

The 50,000 K object emits 360 billion watts per square meter and has a spectrum that peaks at 58 nanometers.

48. a. To solve this, we will set up a ratio using the Stefan-Boltzmann law:

$$\frac{\text{energy emitted by hotter Sun}}{\text{energy emitted by the Sun}} = \frac{\sigma T_{\text{hotter}}{}^4}{\sigma T_{\text{Sun}}{}^4}$$
$$= \left(\frac{T_{\text{hotter}}}{T_{\text{Sun}}}\right)^4$$

So if $T_{\text{hotter}} = 2T_{\text{Sun}}$, we get

$$\frac{\text{energy emitted by hotter Sun}}{\text{energy emitted by the Sun}} = \left(\frac{2\,\cancel{T_{\text{Sun}}}}{\cancel{T_{\text{Sun}}}}\right)^4 = (2)^4 = 16$$

If the Sun were twice as hot, it would emit 16 times as much power per square meter in the form of thermal radiation.

b. We will again use a ratio to work this problem, using Wien's law this time:

$$\frac{\text{peak wavelength of hotter Sun}}{\text{peak wavelength of Sun}} = \frac{\dfrac{\cancel{2{,}900{,}000}}{T_{\text{hotter}}}\,\cancel{\text{nm}}}{\dfrac{\cancel{2{,}900{,}000}}{T_{\text{Sun}}}\,\cancel{\text{nm}}} = \frac{T_{\text{Sun}}}{T_{\text{hotter}}}$$

where we have canceled the 2,900,000 in the numerator and denominator and we have used some of the rules for fractions to simplify the expression. Using the fact that $T_{\text{hotter}} = 2T_{\text{Sun}}$, we get

$$\frac{\text{peak wavelength of hotter Sun}}{\text{peak wavelength of Sun}} = \frac{T_{\text{Sun}}}{2T_{\text{Sun}}} = \frac{1}{2}$$

If the Sun were twice as hot, its peak wavelength would be at $\frac{1}{2}$ the peak wavelength of the real Sun.

c. It is doubtful that life could exist on Earth around this star. There would be so much energy coming from the star that our planet would probably be much too hot.

49. a. We use the Doppler shift formula to find the speed of the star:

$$\upsilon = \frac{\lambda_{\text{shift}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}} \times c = \frac{120.5\ \cancel{\text{nm}} - 121.6\ \cancel{\text{nm}}}{121.6\ \cancel{\text{nm}}} \times 300{,}000\,\frac{\text{km}}{\text{s}} = -2714\,\frac{\text{km}}{\text{s}}$$

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

b.

$$\upsilon = \frac{\lambda_{\text{shift}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}} \times c = \frac{121.2\ \cancel{\text{nm}} - 121.6\ \cancel{\text{nm}}}{121.6\ \cancel{\text{nm}}} \times 300{,}000\,\frac{\text{km}}{\text{s}} = -987\,\frac{\text{km}}{\text{s}}$$

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

c.

$$v = \frac{\lambda_{\text{shift}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}} \times c = \frac{121.9\ \cancel{\text{nm}} - 121.6\ \cancel{\text{nm}}}{121.6\ \cancel{\text{nm}}} \times 300{,}000 \frac{\text{km}}{\text{s}} = 740 \frac{\text{km}}{\text{s}}$$

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

d.

$$v = \frac{\lambda_{\text{shift}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}} \times c = \frac{122.9\ \cancel{\text{nm}} - 121.6\ \cancel{\text{nm}}}{121.6\ \cancel{\text{nm}}} \times 300{,}000 \frac{\text{km}}{\text{s}} = 3207 \frac{\text{km}}{\text{s}}$$

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

50. a. The angular area of HST's 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, obtaining a complete picture of the entire sky would require

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

separate photographs by the advanced camera.