Study Guide

21ST CENTURY ASTRONOMY

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STUDY GUIDE for

21st Century Astronomy

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COLUMBIA UNIVERSITY Biosphere 2 Center



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PREFACE

If you're reading this book you've probably attended a few lectures, maybe even completed an assignment, and you might be wondering if you're in the right class. Maybe you were expecting to learn about constellations, mythology, or Stonehenge? While the study of constellations is certainly a part of astronomy, the discipline also draws on physics and math, as well as geology, chemistry, and biology. Even though these sciences may sound difficult, don't panic. Because astronomy is a more-or-less hands-on (or "eyes-on") science, it is easy to break down into small, manageable pieces. This Study Guide will help you do that. The Study Guide (complemented by the 21st Century Astronomy student CD-ROM) will provide you with a review of each chapter, additional practice examples involving the formulas, and questions with which to test your understanding of the material. All of these features will help you organize the information from the textbook and from your lectures into small, manageable pieces. There's nothing to it-trust me!

Each chapter will consist of some or all of the following components.

FUNDAMENTALS AND FORMULAE

Each chapter will begin with an overview of the corresponding textbook chapter. The overview will briefly recap the main points of the chapter. Reading the overview is not intended to take the place of actually reading the textbook. The chapter overview is designed simply to remind you of the main points that were covered in the textbook. If, as you read through the overview, you come across a point that doesn't make sense you should return to the textbook for the detailed explanation of that topic. Definitions of

words or phrases in boldface type can also be found in the glossary of the textbook.

This section will also include a list of any formulae introduced in the chapter.

SELF-TEST

The Self-Test section consists of three types of questions: multiple-choice, fill-in-the-blank, and short-answer. The answers to all of the questions are given in the back of this book. These questions are designed to test your understanding of the concepts laid out in the textbook. For the multiple-choice and fill-in-the-blank questions, only answers and not explanations are given. These questions are based directly on the material in the textbook and you should refer to the section of the textbook referenced with the answers to review any questions you miss. The answers to the short-answer questions are more detailed and provide explanations. These Self-Test questions may or may not be representative of the exams that your instructor gives; However, the Self-Tests do cover all of the main points of each chapter. If you can answer them all correctly you will have made a good start in reviewing for an exam.

GOING FURTHER

The Going Further section contains questions designed to challenge your understanding of the material. These are questions you can't necessarily answer by simply reading the textbook. You'll need to take what you've learned from the textbook and from your lectures and apply this knowledge to a new situation, or look at one of these concepts from a different angle, or perhaps even combine multiple concepts. We suggest that you discuss these questions with your fellow students and possibly your

instructor. The questions are meant to be challenging, so try not to get frustrated if the answers don't come to you right away. You might want to think back to similar problems or analogies that were discussed in this Study Guide, the textbook, or your lectures. Drawing a picture is often helpful, especially if the problem is complex. The answers to the Going Further questions are posted on the 21st Century Astronomy Online Tutor Web Site, http://www.wwnorton.com/astro21 (and not at the end of this book). I strongly encourage you to really think about these questions before you look at the solutions. Don't sell yourself short.

EXAMPLES

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Since math is often the most intimidating part of astronomy for students, we will constantly attempt to reassure you that numbers and equations are your friends. Math is simply a tool that astronomers use, a tool that you will learn to use as well. Every time equations are introduced in the text-book, there will be an Examples section in the Study Guide to explain how to use those equations. We will look at the equations from a variety of angles, take them apart, and then put them back together, all the time using real numbers.

Each Examples section will also include practice problems for you to work through yourself (answers are given at the end of the book). If you think you already understand how to use an equation, move on to the next one.

EXERCISES

Some chapters contain a section suggesting exercises that you can do on your own. These hands-on exercises are designed to help you better understand the concepts presented in the textbook. Doing something yourself (rather than just reading about it in a book) will often help you to better understand a concept. The exercises in this section require only a few items, all easily found around the house. You don't necessarily need to try every exercise, but we hope that you'll find a few of them useful, and maybe even fun. If your astronomy course includes a laboratory component, you may find some of these exercises similar to those you do in the lab.

Just remember, if you get stuck on a concept, try to break it down, draw a picture, or discuss it with your fellow classmates. Above all else, don't panic. Okay, enough talk—let's get going!

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Why Learn Astronomy?

Since the first chapter of the textbook is simply an overview of astronomy, math, and general science, there is no need to specifically address this material in this Study Guide. For this reason, we start the review of the textbook with Chapter 2.

Patterns in the Sky: Motions of Earth

FUNDAMENTALS AND FORMULAE

- The apparent positions and motions of celestial objects depend on our location on Earth.
- The rotation of Earth on its axis is responsible for the apparent daily motions of celestial objects.
- · Motion is only meaningful relative to some frame of reference. We perceive changes in motion or differences in motion between objects.
- The rotation of Earth has many observable consequences even though we do not perceive that rotation directly.
- Aberration of starlight provided the first direct measurement of the motion of Earth around the Sun.
- · Seasonal changes are due to the revolution of Earth around the Sun and to the tilt of Earth's axis relative to the plane of its **orbit**.
- The Moon rotates once per orbit around Earth, always keeping the same face toward Earth.
- The changing phases of the Moon result from the relative positions of Earth, the Moon, and the Sun.
- Eclipses occur when either Earth or the Moon passes through the shadow of the other.
- The altitude of **Polaris** is equal to the **latitude** of the
- The altitude of the **zenith** is equal to 90°.
- The distance between the equator and the pole is 90°.
 - distance = speed × time

SELF-TEST

Multiple-Choice Questions

- 1. If the Moon were twice its present distance from Earth:
 - a. the phases of the Moon would change.

- b. the path of the Moon in the sky (relative to the background stars) would change.
- c. we would never see a total lunar eclipse.
- d. we would never see a total solar eclipse.
- 2. The constellation Orion can be seen in the Northern Hemisphere's winter sky but not in its summer sky. This can be explained by:
 - a. the rotation of Earth on its axis.
 - b. the revolution of Earth around the Sun.
 - c. the different number of daylight hours in winter and summer.
 - d. the tilt of Earth's axis.
- 3. If Earth's axis were not tilted:
 - a. we would always see the same stars.
 - b. we would see solar and lunar eclipses every month.
 - c. we would not have seasons.
 - d. the Sun would always be overhead at noon.
- 4. The daily motion of the Sun across the sky is due to:
 - a. the revolution of the Sun around Earth.
 - b. the rotation of Earth on its axis.
 - c. the revolution of Earth around the Sun.
 - d. the expansion of the Universe.
- 5. If you observe a star at 8 P.M. and again at 11 P.M., the
 - a. be in the exact same position in the sky.
 - b. have moved north.
 - c. have moved west.
 - d. not have moved but will have grown brighter.
- 6. If you observe a star tonight at 8 P.M. and then observe the same star at 8 P.M. two months later, the star will:
 - a. be in the exact same position in the sky.
 - b. have moved west.

c. be located in a different constellation. d. have moved east. 7. A cannonball fired from the North Pole will: a. curve to the west. b. curve to the east. c. not curve at all. d. curve differently depending on the direction toward which it is fired. 8. A cannonball fired from the equator will: a. curve to the west. b. curve to the east. c. not curve at all. d. curve differently depending on the direction toward which it is fired. 9. Which phase of the Moon is visible an hour after sunrise? a. the full Moon b. the first quarter Moon c. the new Moon d. the third quarter Moon 10. Which phase of the Moon is required for a solar eclipse? a. the full Moon b. the first quarter Moon c. the new Moon d. the third quarter Moon 11. The rotation of Earth causes a Foucault pendulum to: a. swing. b. speed up. c. change its swing direction. d. come to a stop. 12. From Mercury you would never see: a. Earth in a full phase.

b. Earth, Venus, and Mars all in the sky at the same

Use a word or phrase to complete the following items.

2. The two points on the celestial sphere that remain

3. When the Sun rises in the Northeast, it will set in the

4. The seasons are caused by the _____ and the

5. The day when the Sun is above the **horizon** for exactly

twelve hours is called the _____

fixed are the and the

c. Venus in a crescent phase.

d. the Jovian planets.

Fill-in-the-Blank Questions

1. The full Moon will rise at ___

6. When viewed from the Northern Hemisphere, a star north of the **celestial equator** will be above the horizon for ______ than a star south of the celestial equator.

Short-Answer Questions

- 1. What season is it in the Southern Hemisphere when it is spring in the Northern Hemisphere? During this season, which city receives more hours of sunlight, Tempe, Arizona (33° north latitude) or Buenos Aires, Argentina (33° south latitude)?
- 2. Does the side of the Moon that faces away from Earth ever receive sunlight? Why or why not?
- 3. The Moon and the Sun are not the same *physical* size, yet they have the same *angular* size in the sky. Why?
- 4. How long is the night at the North Pole on the winter solstice?
- 5. We always see the same side of the Moon. Does the Moon rotate on its axis? Explain.
- 6. If the Moon did not rotate, what would we see from Earth? (Drawing a picture may be helpful.)
- 7. The rotation axes of the terrestrial planets are tilted by the following amounts: Mercury = 0°, Venus = 177.4°, Earth = 23.5°, and Mars = 24°. Which planets have seasons? How do these seasons compare to one another?

GOING FURTHER

- You are sitting on the Moon, looking up at Earth.
 Describe how your view of Earth changes over time (if it does).
- 2. What would change if Earth's axis of rotation were perpendicular to its orbit (so that its tilt was 0° rather than 23.5°)?
- 3. Of the two photos of star trails (Figure 2.7) in the text-book, which one was taken from the more northerly location? What do you notice about Polaris? What does this tell you about the star's location?

EXERCISES

- 1. Sketch the sky every hour for three hours (say, 8 P.M., 9 P.M. and 10 P.M.). Make separate sketches for the northern sky (around Polaris) and the southern sky. What changes take place each hour? Are the changes the same for the northern sky and the southern sky?
- 2. Using your northern sky sketches, find a star that is visible in all three sketches. Using your first sketch as

a baseline, measure how many degrees your star moved over the next two hours. From this information, can you determine how long it will take your star to go once around Polaris (remember, a full circle has 360°)? This is the length of a **sidereal** day.

- 3. Observe the rising or setting Sun from the same location for two to three months. Pick a stationary object on the horizon (i.e., a tree, building, or mountain peak) and note where the Sun rises or sets relative to this object. Is the Sun in the same position each time? If not, how does its position change? Can you estimate how many degrees the Sun moves each day? From your observations, try to predict the day of the **equinox**, when the Sun is on the celestial equator (rising due east and setting due west).
- 4. Measure the altitude of the Sun at local noon (the time of day when the Sun crosses, or transits, the **meridian**) for two to three months. The following Web site can be used to determine the time of local noon anywhere in the world: http://aa.usno.navy.mil/data/docs/RS_One Day.html. Take a ruler and a piece of chalk to a flat,

sunny area at local noon. Hold the ruler perpendicular to the ground and mark the length of its shadow with the chalk. Measure the length of the shadow. The altitude of the Sun can be determined using the following equation:

altitude of the Sun (in degrees) =
$$tan^{-1} \left(\frac{length \ of \ ruler}{length \ of \ shadow} \right)$$
.

Plot the Sun's altitude on a graph as a function of time. Is its rate of change constant? Can you predict when the Sun will cross the celestial equator? (Hint: The altitude of the celestial equator equals 90° minus your latitude.)

5. Use weather records to determine the hottest and coolest times of the **year** where you live. How long after the solstices (when the Sun is at its highest or lowest point in the sky) are these times? What is the average difference in temperature between the hottest and coolest times of year? Compare these times and temperature differences to the same data for a location at a different latitude. Are these times and temperature differences the same everywhere? Why or why not?

Gravity and Orbits: A Celestial Ballet

FUNDAMENTALS AND FORMULAE

- Kepler's laws describe the elliptical orbits of planets around the Sun. These are empirical rules that describe, but do not attempt to explain, natural phenomena.
- Newton's laws describe how objects move in response to forces. These are **theoretical** laws that help us understand a wide range of natural phenomena.
- The concept of inertia states that an object in motion will continue to move in a straight line at a constant speed unless some force acts to change its motion.
- Mass is the property of matter that determines its resistance to changes in motion. Acceleration equals force divided by mass.
- Forces always come in equal and oppositely directed pairs.
- **Gravity** is an attractive force between any two objects which have mass.
- We use mathematics to express physical laws as predictions about and descriptions of the world.
- The gravitational force on an object depends on its mass, but the gravitational acceleration experienced by the object does not.
- An orbit is the path of an object as it "falls around" another object under the influence of gravity.
- Newton's theoretical laws helped explain and corroborate Kepler's empirical laws..
- By successfully applying his laws of terrestrial physics to the motions of the planets, Newton broke down the barrier between our understanding of Earth and our understanding of the heavens.

- Scientific theories make testable predictions about nature, and the validity of scientific knowledge is judged by the success of those predictions.
- The acceleration of an object is equal to the change in its velocity over time.
- · Kepler's laws:
 - 1. The planets follow elliptical orbits with the Sun at one **focus**.
 - 2. The line connecting a planet to the Sun will sweep out equal areas in equal amounts of time.
 - 3. The square of a planet's orbital **period** (measured in years) is equal to the cube of its **semi-major axis** (measure in AU).
- · Newton's laws:
 - 1. An object in motion will remain in motion and an object at rest will remain at rest unless acted on by an outside, unbalanced force.
 - 2. The acceleration of an object is directly proportional to the size of the force acting on it and is inversely proportional to the object's mass.
 - For every action there is an equal and opposite reaction.
 - $(P_{vears})^2 = (A_{AU})^3$
 - a = F/m
 - $F_{grav} = mg$
 - $F = Gm_1m_2/r^2$
 - $v_{circ} = \sqrt{Gm/r}$
 - $v_{esc} = \sqrt{2Gm/r}$

SELF-TEST

Multiple-Choice Questions

- 1. Why do astronauts float around inside the space shuttle?
 - a. There's no gravity in space.
 - b. The force of gravity due to Earth is very weak.
 - c. The gravitational force between Earth and an astronaut is equal to the force between Earth and the space shuttle.
 - d. The acceleration of the astronaut due to Earth is the same as the acceleration of the space shuttle due to Earth.
- 2. What new idea did Kepler introduce into our view of the Solar System?
 - a. retrograde motion
 - b. a Sun-centered Solar System
 - c. elliptical orbits
 - d. epicycles
- 3. According to Newton's first law, an object in motion remains in motion unless acted on by an outside force. What outside force slows down a car when the car is traveling along a road?
 - a. gravity
 - b. friction
 - c. buoyancy
 - d. none, Newton's laws apply only to the planets and not to cars.
- An object whose velocity exceeds the escape velocity of Earth will:
 - a. orbit Earth on a circular path.
 - b. orbit Earth on an elliptical path.
 - c. not stay in orbit around Earth.
 - d. eventually return to the surface of Earth.
- According to Kepler's second law, a planet with a circular orbit would:
 - a. not be able to exist.
 - b. speed up and slow down as it orbited around the Sun.
 - c. have a constant orbital velocity.
 - d. have velocity variations too small to detect.
- 6. When a massive object is pushed upon, it will:
 - a. be more resistant than a less massive object to a change in its motion.
 - b. not move, regardless of the force applied.
 - c. have a greater acceleration than would a less massive object pushed upon with the same amount of force.
 - d. push back with a greater force than was applied to it.
- 7. If you were standing on the Moon with a ball in your hand and you let go of it, the ball would:
 - a. float off into space.
 - b. levitate in place.

- c. fall to the ground.
- d. drift aimlessly.
- 8. While driving down a road you slow to a stop over a distance of 30 ft. If you were to come to a stop over 15 ft instead, the force you would feel would:
 - a. be the same.
 - b. be twice as much.
 - c. be half as much.
 - d. depend on the mass of the car.
- 9. If the mass of Earth were tripled, which of the following statements would be true?
 - a. The force between Earth and the Sun would decrease.
 - The acceleration of Earth due to the Sun would increase.
 - The acceleration of the Sun due to Earth would increase.
 - d. Nothing would change.
- 10. Earth orbits the Sun—rather than the Sun orbiting Earth—because:
 - a. the Sun pulls more on Earth than Earth pulls on the Sun.
 - b. the Sun is larger in size than Earth.
 - c. the Sun is more massive than Earth.
 - d. Earth pulls more on the Sun than the Sun pulls on Earth.
- 11. The *Apollo* astronauts were able to walk on the Moon without floating away because:
 - a. the Moon exerted a force on the astronauts.
 - b. the astronauts moved very slowly.
 - c. the astronauts wore heavy boots.
 - d. of the **centripetal** acceleration produced by the Moon's rotation.

Fill-in-the-Blank Questions

science.

Use a word or phrase to complete the following items.

1.	Compared to your mass on Earth, your mass on the Moon would be
2.	Compared to what your weight is on Earth, your weight on the Moon would be
3.	Copernicus was the first scientist to propose the view of the Solar System.
4.	A more massive object falls than a less massive object.
5.	For an object's orbit to be round its shape must be
6.	Kepler's laws are an example of

Short-Answer Questions

- 1. You and a more massive friend are standing on an ice rink (in ice skates.) If you push your friend, which of you will move (assuming neither of you falls down)? Who will apply the greater force to the other? Who accelerates more? How would your answers change if you and your friend were of equal mass?
- 2. You are unlucky enough to be in an elevator when the cable suddenly snaps. What happens to you while the elevator is falling? (Try not to think about what happens to you when the elevator stops at the bottom!) Not wanting to waste your final moments in this life, you take your trusty ping-pong ball out of your pocket to perform a demonstration. What happens to the ball when you let go of it? Why? What if it's a bowling ball instead?
- 3. When does a spacecraft use its engines? Think of Newton's laws and how they apply to the spacecraft.
- 4. You are an astronaut in a space shuttle orbiting around Earth. You are floating perfectly still in the middle of the shuttle and are unable to reach any of the walls or furniture. How can you get yourself moving?
- 5. A juggler stands on a scale while juggling five balls. Will the scale register the weight of the juggler plus the weight of the five balls? If not, will the scale register more or less weight than this?

GOING FURTHER

- 1. Is it possible to propel a sailboat by mounting a fan on the boat's deck in order to blow air on the sail? Would it be better to mount the fan on the stern in order to blow air toward the rear, away from the sail?
- 2. Galileo's observation that Venus shows phases (from crescent to full) supported the idea of a heliocentric Solar System. Would Venus show phases in a geocentric Solar System? How would these phases be different from those that we actually observe?
- 3. If the Sun suddenly "disappeared," how would the dynamics of the Solar System change? What, if anything, would happen to the planets' orbits? Imagine swinging a ball on a string and then cutting the string. How are the planets different from the ball?
- 4. If there were a massive but invisible planet in our Solar System, how might we be able to find it?

EXAMPLES

Kepler's second law:

Kepler's second law states that, for all bodies orbiting the Sun, the square of the orbital period is equal to the cube of the semi-major axis. We write this as

$$p^2 = p \times p = a^3 = a \times a \times a$$

where the period is measured in years and the semi-major axis in AU. Let's test this on the planet Venus. Venus has an orbital period of 0.615 years and a semi-major axis of 0.723 AU. First square the period.

$$p \times p = 0.615 \times 0.615 = 0.378$$

Now cube the semi-major axis.

$$a \times a \times a = 0.723 \times 0.723 \times 0.723 = 0.378$$

We can see that, in fact, p^2 does equal a^3 . Pretty neat! Now try testing Kepler's second law on Jupiter, where p = 11.86 years and a = 5.2 AU.

The nice thing about Kepler's second law is that it allows us to measure one quantity and then calculate the other. Let's say that we measured the orbital period of a body and wanted to figure out the size of the body's orbit. First we would need to rearrange the equation a bit. If we want to find a, then we have to set up the equation in the form of "a = something." To do so we must reduce a^3 to simply a.

$$\sqrt[3]{p^2} = \sqrt[3]{a^3} = a$$

This works because taking the cube root of a number that is cubed leaves you with just a number. Now we can put in the value for p that we measured (in years), square it, take the cube root, and voila... we know the semi-major axis of the orbit. We can test our result using Venus again. If we put in 0.615 years for p, we find

$$a = \sqrt[3]{p^2} = \sqrt[3]{0.615 \times 0.615} = \sqrt[3]{0.378} = 0.723 \text{ AU}.$$

This is exactly what it should be.

What if instead of measuring p to find a, we try the opposite. If we want to find p then this time we need to write the equation in the form of "p = something." But p is squared, so we need to take the square root to just get p.

$$\sqrt{p^2} = p = \sqrt{a^3}$$

And if we test this equation on, say, Jupiter where a = 5.2 AU, we find

$$p = \sqrt{a^3} = \sqrt{5.2 \times 5.2 \times 5.2} = \sqrt{140.61} = 11.86$$
 years.

Again, this is exactly as it should be.

Here are a couple of problems for you to try.

Problem 1 A new planet is discovered two times as far away from the Sun as Pluto. What is the new planet's orbital period?

Problem 2 Halley's Comet has an orbital period of 86 years. What is the semi-major axis of its orbit?

Newton's second law:

Newton's second law states that the acceleration of an object is directly proportional to the size of the force applied to that object and is inversely proportional to the mass of the object—or F = ma. Let's start with a straightforward example. We have a 10 kg mass and we want to accelerate it at 25 m/s². How much force do we need to apply?

$$F = ma = 10 \text{ kg} \times 25 \text{ m/s}^2 = 250 \text{ kg m/s}^2 = 250 \text{ N}$$

So a force of 250 N is necessary to get our 10 kg mass accelerating at 25 m/s². Now, what if we know both the force we are going to apply and the mass of the object, and we would *like to know* the acceleration that the object will achieve. We would need to write the equation in the form of "a = something."

$$F = ma$$

$$\frac{F}{m} = \frac{ma}{m} = a$$

If our mass is still 10 kg and we push on it with a force of 75 N, what will be the acceleration of the object? Putting these numbers into the equation above we find

$$a = \frac{F}{m} = \frac{75 \text{ N}}{10 \text{ kg}} = 7.5 \text{ m/s}^2.$$

Our mass will be accelerated at 7.5 m/s².

That's all well and good, but what if we don't know the mass of the object? If we push on the object with a certain force, and it accelerates at a certain speed, what is the object's mass? Once again we need to do some rearranging, this time to "m = something."

$$F = ma$$

$$\frac{F}{a} = \frac{ma}{a} = m$$

Say we push with a force of 100 N (we're feeling strong), and the object shoots across the room at a speedy 20 m/s². Knowing these two facts, we can figure out its mass.

$$m = \frac{F}{a} = \frac{100 \text{ N}}{20 \text{ m/s}^2} = 5 \text{ kg}$$

So now, given any two of the variables in the equation F = ma, we can solve for the third.

Here are some more practice problems.

Problem 3 A typical car weighs about 680 kg. If a tow truck tugs on a car with a force of 100 N, how fast will the car accelerate (ignoring friction)?

Problem 4 If you strike a cue ball with a force of 0.5 N and the ball accelerates at 0.5 m/s², how massive is the cue ball?

Universal law of gravitation:

The universal law of gravitation says that the force between two objects is proportional to the product of their masses and is inversely proportional to the square of the distance between them:

$$F = \frac{Gm_1m_2}{R^2}.$$

Just to get started, let's calculate the gravitational force between Earth and the Moon. We need to know each body's mass and the distance between the two. The mass of Earth is 5.79×10^{24} kg, the mass of the Moon is 7.4×10^{22} kg, and the average distance between them is 3.84×10^8 m. The gravitational constant G is 6.67×10^{-11} Nm²/kg². If we plug all of these numbers into our equation, we find that F equals

$$\frac{(6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2) \times (5.79 \times 10^{24} \text{ kg}) \times (7.4 \times 10^{22} \text{ kg})}{(3.84 \times 10^8 \text{ m})^2}$$

$$= \frac{2.86 \times 10^{37} \text{ Nm}^2}{1.47 \times 10^{17} \text{ m}^2} = 1.94 \times 10^{20} \text{ N}.$$

That was pretty straightforward, right? What if we already know the force and instead we want to figure out the mass of one of the objects? You guessed it, we have to do some rearranging. We need to write our equation in the form of " M_1 = something."

$$F = \frac{Gm_1m_2}{R^2}$$

$$FR^2 = GM_1M_2$$

$$\frac{FR^2}{GM_2} = M_1$$

Let's plug in some numbers. If the force between two objects is 1×10^8 N, and the distance between them is 4×10^{12} m, what is the first object's mass given that the second object's mass is 7×10^{18} kg?

$$M_1 = \frac{FR^2}{GM_2} = \frac{(1 \times 10^8 \text{ N}) \times (4 \times 10^{12} \text{ m})^2}{(6.67 \times 10^{-11} \text{ Nm}^2) \times (7 \times 10^{18} \text{ kg})}$$
$$= \frac{1.6 \times 10^{33} \text{ Nm}^2}{4.67 \times 10^8 \text{ Nm}^2/\text{kg}^1} = 3.43 \times 10^2 \text{ kg}$$

Not so hard, right? What if we want to know the distance between two objects, given their mass and the force between them? We need "R = something" this time.

$$F = \frac{Gm_1m_2}{R^2}$$

$$FR^2 = GM_1M_2$$

$$R^2 = \frac{Gm_1m_2}{F}$$

$$\sqrt{R^2} = R = \sqrt{GM_1M_2/F}$$

Now if we have a force of say 3×10^{12} N, and a mass of 2×10^{15} kg for the first object and 9×10^{23} kg for the second object, we will find the distance between them to be

$$R = \sqrt{\frac{Gm_1m_2}{F}}$$

$$= \frac{(6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2) \times (2 \times 10^{15} \text{ kg}) \times (9 \times 10^{23} \text{ kg})}{3 \times 10^{12} \text{ N}}$$

$$= \sqrt{\frac{1.20 \times 10^{29} \text{ Nm}^2}{3 \times 10^{12} \text{ N}}} = \sqrt{4.0 \times 10^{16} \text{ m}^2} = 2.0 \times 10^6 \text{ m}.$$

Try your hand at these next few problems.

Problem 5 Calculate the gravitational force between Earth and Jupiter. Compare this to the force between Earth and the Sun.

Problem 6 If Earth were three times farther away from the Sun than it is now, what would be the gravitational force between Earth and the Sun?

Circular Velocity:

If an object is moving in a stable circular orbit then its velocity is related to the mass it is orbiting, M, and the size of its orbit, r, in a very specific way which is given by the following equation.

$$v_{circ} = \sqrt{\frac{GM}{r}}$$

We can use this formula to determine the velocity of the Moon as it orbits Earth. (Technically, the Moon's orbit isn't exactly circular but it's close enough that we won't worry about it for now.) The Earth's mass is 5.98×10^{24} kg and the Moon orbits Earth at a distance of 3.84×10^8 m. Using these values we find

$$v_{circ} = \sqrt{\frac{GM}{r}} = \sqrt{\frac{(6.67 \times 10^{-11} \text{ m}^3/\text{kgs}^2)(5.98 \times 10^{24} \text{ kg})}{3.84 \times 10^8 \text{ m}}}$$

= 1019 m/s.

Try a few problems on your own.

Problem 7 What is the velocity of the Hubble Space Telescope if it orbits Earth at an altitude of roughly 6×10^5 m?

Problem 8 If an airplane were to orbit Earth at an average cruising altitude of 30,000 ft (9000 m), what would be its velocity?

Escape Velocity:

If a satellite is moving fast enough it can escape the gravity of the planet it is orbiting. The velocity at which this happens is known as the escape velocity and is given by:

$$v_{cesc} = \sqrt{\frac{2GM}{R}}$$

where M is the mass of the object being orbited and R is the size of the satellite's orbit. To find the velocity needed to escape the surface of Earth, M is the mass of Earth and R is the radius of Earth. (In other words, if you are standing on the surface of a planet, the size of your orbit is the radius of the planet.) Putting in the appropriate numbers

$$v_{cesc} = \sqrt{\frac{2GM}{R}} = \sqrt{\frac{2 \times (6.67 \times 10^{-11} \text{ m}^3/\text{kgs}^2)(5.98 \times 10^{24} \text{ kg})}{6.38 \times 10^6 \text{ m}}}$$

= 11.182 m/s = 11.2 km/s.

You can see that quite a bit of speed is needed to launch something from the surface of Earth!

Let's calculate the escape velocities for objects other than Earth.

Problem 9 What is the escape velocity for the Moon?

Problem 10 Would you be able to run fast enough to reach escape velocity on an asteroid with a radius of 10,000 m and a mass of 1.0×10^{16} kg?

EXERCISES

- 1. While in a swimming pool you push on the side of the pool. What happens? What law are you invoking when you do this? How many other situations can you think of where you use this law to your advantage?
- 2. Find an empty gallon jug and punch a small hole in the bottom. Fill the jug halfway with water, keeping your finger over the hole so the water doesn't leak out. Find a high perch from which you can drop the jug (the top of a ladder, a stairwell, or a second floor balcony or window). Make sure no one is standing below and let the jug drop. Does the water leak out while the jug is falling?(You may need some observers standing below, at a safe distance, to help determine this.) Should the water leak out? What do Newton's laws say about this?

Light

FUNDAMENTALS AND FORMULAE

- Light is a traveling electromagnetic wave given off by accelerating electrical charges.
- Visible light is only a small part of the electromagnetic spectrum.
- Light travels at the same speed for all observers regardless of their motion. This idea is the basis of special relativity.
- The equivalence of mass and energy and the dependence of space and time on an observer's frame of reference are consequences of special relativity.
- Light is a particle as well as a wave. The energy of a
 photon is proportional to the frequency of the wave.
- Electrons and other particles of matter are waves as well as particles.
- Electron waves in **atoms** can only exist in certain discrete energy states.
- An atom can only emit or absorb photons with specific, characteristic energies equal to differences between allowed energy states of the atom.
- At the scale of atoms, quantum mechanics replaces Newton's deterministic world with a nondeterministic world governed by laws of probability and random chance.
- Motion of a source of light toward us or away from us causes a shift in the wavelength of light received from the source.
- Temperature measures how energetically the atoms or molecules in a substance are moving about.
- Sufficiently dense materials emit a continuous spectrum of thermal (Planck) radiation, the wavelength and luminosity of which depend on temperature.
- The brightness of light obeys an inverse square law.

- Surface temperatures of planets are determined in part by equilibrium between absorbed sunlight and emitted thermal radiation.
 - f = 1/P
 - $\lambda = c/f$
- $E = hf = hc/\lambda$
- $f = E_2 E_1/h$
- $\lambda = hc/E_2 E_1$
- $\lambda_1 = (1 + v_r/c)\lambda_0$
- $F = \sigma T^4$
- $\lambda_{\text{peak}} = 2900 \ \mu m/T$

SELF-TEST

Multiple-Choice Questions

- 1. Sound waves are different from light waves because:
 - a. all sound waves have the same wavelength.
 - b. sound waves travel faster than light waves.
 - c. sound waves cannot travel through a vacuum.
 - d. all sound waves have the same frequency.
- 2. Our Sun emits most of its radiation at a wavelength of 550 nm. If a star were 10 times cooler than our Sun, it would emit most of its radiation at a wavelength of
 - a. 55 nm.
 - b. 5500 nm.
 - c. 540 nm.
 - d. 560 nm.
- 3. The star in the previous problem would also emit less total energy than the Sun. How much less?

- a. 10 times less
- b. 100 times less
- c. 1000 times less
- d. 10,000 times less
- 4. When a train is passing you, you can hear a Doppler shift in the sound of the whistle but you can't see a Doppler shift in the train's headlights. This is because
 - a. the train isn't traveling directly toward or away from us.
 - b. only sound waves can be Doppler-shifted.
 - c. the train is traveling too slowly for a significant Doppler shift to occur in the lightwaves.
 - d. our eyes cannot detect Doppler shifts.
- 5. The fact that a gas produces an emission line spectrum tells us that the gas is
 - a. rotating.
 - b. hot.
 - c. far away.
 - d. heavy.

- 6. We can tell what kind of gas produced a spectrum by
 - a. how many lines are in the spectrum.
 - b. how strong the spectral lines are.
 - c. at what wavelength the spectral lines appear.
 - d. how wide or narrow the spectral lines are.
- 7. Compared to our Sun, a hotter star would
 - a. be redder.
 - b. have more hydrogen.
 - c. emit more X-rays.
 - d. be in thermal equilibrium.
- 8. When light is red-shifted, what changes?
 - a. the light's wavelength
 - b. the light's speed
 - c. the light's energy
 - d. the light's amplitude

Fill-in-the-Blank Questions

Use a word or phrase to complete the following items.

1. The ripples produced when a p	pebble is dropped into a
pond are examples of	waves, whereas
sound propagates via	waves.

2. As the **period** of a wave increases, the wave frequency

3.	The phenomenon of	results in	time
	passing more slowly in	a moving reference frame	.

4. An X-ray photon has	energy than a radio
photon.	

Short-Answer Questions

- 1. In the movie Superman, Lois Lane asks Superman to demonstrate his X-ray vision be telling her what color her underwear is. Much to Lois' dismay, Superman obliges and announces that she is wearing pink underwear. What is wrong with this scene?
- 2. You are sitting in a dark closet with a white ping-pong ball, a dark blue racquet ball, and a "neon green" tennis ball. Which of these objects, if any, can you see? Why?
- 3. The moon and all of the planets appear to go through phases, meaning that most of the time we see only part of their surface. The Sun never goes through phases. Explain why the Sun is different from the Moon and the planets.
- 4. As you are driving down the road a fire engine passes you, sirens blaring. What do you hear? Even though it's illegal, you decide to follow the engine. Now what do you hear? Eventually the fire engine pulls off the road and you continue on your way. What do you hear now?

GOING FURTHER

- 1. Let's say we double the amount of hydrogen in the Sun. How would its spectrum change, if at all? What if we added some lead (which doesn't currently exist in the Sun)?
- 2. Something extremely hot is often said to be "white hot." You can actually witness this with metal—as metal gets hotter it turns from orange to red to white. Why? What is happening?

EXAMPLES

Wave properties:

The frequency of a wave is given by

$$f = 1/P$$

where P is the wave period. As the period increases, the frequency decreases and vice versa. The wavelength of a wave is given by

$$\lambda = c \times P = c/f$$

where c is the speed of light.

Try a couple of problems using these formulae.

Problem 1 If a wave has a frequency of 1.5 MHz (1.5×10^6) Hz), what is the wave period?