Chapter 3: Radiation
Information from the Cosmos

Outline

3.1 Information from the Skies
3.2 Waves in What?
3.3 Electromagnetic Spectrum
3.4 Thermal Radiation
3.5 The Doppler Effect

Summary

Astronomers face a challenge that few other scientists do. The objects that astronomers study are so staggeringly far away that traditional experimentation—except for the occasional Moon rock or meteorite—is impossible. Thus, astronomers rely almost exclusively on observations to gather data. An understanding of electromagnetic radiation and what information it can convey is therefore essential to the study of astronomy.

This chapter deals primarily with the wave nature of light; its particle nature will be discussed in Chapter 4. Emphasis is on the properties of a wave, and how we experience those properties. The chapter frequently compares and contrasts light with other wave phenomena, and offers a brief explanation of the unique nature of electromagnetic waves.

The chapter introduces students to the many different types of electromagnetic radiation, visible and invisible. Students will likely be surprised to learn that radiation we don't traditionally consider "light," like X-rays and AM radio, are all part of the electromagnetic spectrum. Although the wave property of frequency is not as easily visualized as wavelength, students may recognize kHz and MHz units used for the AM and FM radio. They may not know the Doppler effect by name but they certainly have all experienced it with sound, water waves, and radar guns.

The idea of "color" is introduced in this chapter, and students will have to think critically about what that concept really means. An apple, the star Betelgeuse, and the Orion Nebula are all red, but they look that way for very different reasons. This chapter starts to explain how those colors come to be.

Major Concepts

- Electromagnetic Radiation
  - Properties of Waves
  - The Speed of Light
  - Electromagnetic Nature of Light
  - Evidence for Light as a Wave
- The Electromagnetic Spectrum
  - Visible and Invisible Radiation
  - Atmospheric Opacity
  - The Blackbody Spectrum
  - Wien's Law and Stefan's Law
- The Doppler Effect

Teaching Suggestions and Demonstrations

The first section of this chapter makes the excellent point that "virtually all we know about the universe beyond Earth's atmosphere has been gleaned from the analysis of electromagnetic radiation received from afar." Contrast the work of an astronomer to the work of a biologist, chemist, or environmental scientist. Astronomers can rarely touch, manipulate, or experiment directly upon their objects of interest. (An exception, of course, is the study of solar system material such as Moon rocks or meteorites.) Impress upon students the fundamental importance of light (or rather, all forms of electromagnetic radiation) to astronomers. This chapter will help students learn how to analyze the information contained in light.

Section 3.1

It is important to remember that most of your students will know next to nothing about the properties of a light wave, so go over the concepts of wavelength and frequency carefully.

DEMO—Demonstrate wave motion with a long Slinky®. Give the Slinky a quick shake at one end and have students watch the pulse travel to the other end. Tie a bit of red yarn to a coil in the Slinky and ask students to compare the motion of the pulse with the motion of the yarn. The pulse moves from one end to the other; the yarn just moves up and down. A wave is energy; it is the propagation of a disturbance through a material, not the material (or medium) itself.

Section 3.2

Electromagnetic waves do not require a medium in order to propagate. Contrast electromagnetic waves with mechanical and sound waves. Emphasize that the speed of electromagnetic waves in a vacuum is constant and is equal to wavelength times frequency. Try some examples. Students can calculate the wavelength of an FM radio wave and compare it to the wavelength of, say, red light.

Make the point that light from distant galaxies travels unperturbed (except for dimming as it spreads out) for millions of light-years only to be degraded significantly during the last few miles of its journey by the Earth's atmosphere. This is also a good place to re-visit the idea of the light-year in the context of light's fast but limited speed. Emphasize that the light coming to us from stars is "old news" by the time it reaches us; even information from the Sun arrives 8 minutes out of date. Ask students if they have experienced a "lag" while making a long-distance phone call or seeing a "live via satellite" interview on television. Students may be surprised to learn that radio waves are light waves, and thus travel at the fast but finite speed of light. While this is annoying for cell phone calls, it is an opportunity for astronomers. Since we see the stars and galaxies not "as they are" but "as they were" when the light left them, as we look out in space, we virtually look back in time. This idea will be very important in later chapters, so plant the seed here.

Section 3.3

Spend some time going over Figure 3.8. It is an excellent representation of the full range of the electromagnetic spectrum. Students will tend to think that visible light is somehow special or different. Point out that it is just one range of wavelengths for electromagnetic radiation, and a small range at that. We divide the electromagnetic spectrum into different areas based not on inherent differences in the radiation itself—the wavelength "borders" between regions can be ill-defined—but rather by differences in how we perceive it. We detect visible light with our eyes. Infrared is felt as heat, and ultraviolet gives us sunburns. Discuss the opacity of Earth's atmosphere and the major windows in the atmosphere that allow us to observe in certain wavelength ranges.

DEMO—To demonstrate the visible continuous spectrum, use a slide projector or any strong source of light. Place a slit in front of it and direct toward a screen. (Do not tape a slit to the front of the projector. The heat build-up can easily crack the lens or otherwise damage the projector.) Use a good prism or diffraction grating that is slightly larger than the slit to form the visible spectrum. If a prism is used, a second prism may be used to reverse the spectrum back into white light.

Review the various major types of radiation as given in Figure 3.8. Help the students relate to each type by identifying everyday examples.

Gamma rays: Thankfully, we encounter few gamma rays in everyday life. But students may be familiar with cancer radiation therapy, which sadly can kill healthy cells as well as cancerous ones.

X-rays: Most of us have had an X-ray during a visit to the dentist or doctor. We see and feel nothing when exposed to X-rays but they can be very damaging in high doses. It is recommended that people keep track of the number and types of X-rays they have had during the year so that their doctors can be made aware of their total exposure to the radiation.

Ultraviolet: The danger of sunburn increases with elevation because there is decreasing protection from the Earth’s atmospheric absorption of ultraviolet. The cornea of our eye protects the eye from UV rays, but the eye can detect some wavelengths of ultraviolet. Astronomers who have had their corneas removed report that some of the hotter stars, which give off lots of ultraviolet radiation, look different to them after the surgery.

Visible: Students may have seen street signs, roadside-worker vests, and even ambulances painted a particular shade of yellow called “high-visibility yellow.” This is close to the peak wavelength emitted by the Sun. Most clothing that is considered “black” some people might consider a deep shade of purple or red, shades that most eyes are not sensitive to.

Infrared: Although we cannot see infrared radiation, we do feel it. We have infrared (heat) sensitive cells in our skin that allow us to locate sources of infrared. Notice how warm an incandescent light bulb is when it is on. It is producing a lot of infrared, along with visible light. William Herschel discovered infrared radiation accidentally in 1800. He wanted to see if different colors of the visible spectrum had different temperatures, and noted that the thermometer showed an elevated temperature even when the visible spectrum was to the side.

Microwaves: In a microwave oven these radio waves are “tuned” to excite water molecules. Water, which makes up at least 80% of most foods, becomes hot and heats the other molecules. Notice the screen in the front of the oven. Its holes are large enough to allow visible light to pass through but small enough to block most microwaves. The application of microwaves for cooking was discovered accidentally in 1945, when an engineer experimenting with microwaves for communication purposes discovered that his chocolate bar had melted in his pocket!

FM radio: 88–108 MHz on the radio dial. Choose a popular station listened to by your students and convert the frequency into wavelength (they will be in the range of 3.4–2.8 m). These wavelengths are sufficiently short to be blocked by buildings and hills. Diffraction helps some, but you get the best reception with a direct line-of-sight to the transmitter.

AM radio: 540–1600 kHz on the radio dial. Convert these frequencies into wavelengths (556–188 m). Because of their long wavelengths, few objects, like buildings and hills, are large enough to block them.

Section 3.4

Ask students to estimate the classroom temperature in degrees Fahrenheit. Check with a thermometer if you have one available. Then ask them to quickly estimate the temperature in degrees Celsius and in Kelvin. Chances are they will have a harder time with these estimations! Convert the room temperature and a couple of other familiar temperatures to both Celsius and Kelvin to help students get a feel for these scales.

Use Figures 3.9 and 3.10 to discuss blackbody curves. Point out that as the temperature of a blackbody increases, two things happen. First, note that the peak of the curve shifts to shorter wavelengths or higher frequencies (Wien's law). Also, the glowing body emits more radiation at all wavelengths, so more total energy is emitted (Stefan's law). Students may be surprised that therefore a blue star actually emits more radiation at red wavelengths than a red star does!

DEMO—Connect a filament light bulb to a variable power supply. Allow students to observe the light produced at various levels of power. Relate this qualitatively to temperature. As power is increased, the filament first glows a dull red, then orange, yellow, and white. Have a student hold a hand up to the bulb and comment on the amount of infrared coming from the bulb as well. At low temperatures, most of the energy comes out in the form of infrared and very little as visible light.

Section 3.5

DEMO—Students will most likely be familiar with the Doppler effect applied to sound. An easy demonstration of the Doppler effect is tying a toy whistle or buzzer (battery operated) to the end of a string and twirling it overhead. A Nerf® ball with a beeper or bell embedded inside it makes a nice demonstration. Students throw the ball back and forth while the class listens to the sound and compares it to the sound they hear when the ball is stationary. The variation in frequency is easily heard. Play "catch" with someone in the back of the room and listen for the pitch to change. (Remember, what you hear is the opposite of what the students will hear.) Play catch again, but now do so across the front of the classroom and stand fairly close to each other. Since the motion is transverse to the students, there should be little if any variation in pitch. Thus, you have demonstrated that the motion must be toward or away from the observer to produce the Doppler effect. For more information on constructing and using a "Doppler football" see an article by Michael Ruiz and Jeremy Abee in *The Physics Teacher* (October 2006, p. 44).

Make recordings of race cars as they rush by the microphone (easily done from a televised race) or from a friend driving by the recorder and blowing the car's horn. First record the car's horn when it is stationary, then again as it approaches and moves away. Be sure to point out that the driver does not hear a change, because the driver and the source of sound are moving together. From the moving car, record a friend (who is stationary) blowing a horn or whistle. It does not matter whether it is the object or the observer who is moving; the Doppler effect still occurs.

The Doppler effect applies to light waves as well as to sound waves. Use the equation introduced in this section to try a few examples with students. Point out that the shift in wavelength or frequency can only determine the velocity of the object *toward* or *away from* the observer, not the transverse velocity.

Relevant Lecture Tutorials

Electromagnetic Spectrum of Light, p. 47
Luminoisty, Temperature, and Size, p. 55
Blackbody Radiation, p. 59

Student Writing Questions

1. You are on a team of experts who are proposing the launching of a space telescope. With regard to the atmospheric blockage of parts of the spectrum, in what ways can you justify making astronomical observations from space?

2. Pick an item that is colorful. Describe in detail why it appears colorful; which colors are being reflected and which absorbed? When we say "the shirt is red," is the shirt really red?

3. What types of electromagnetic waves do you use on a regular basis? Think carefully about this because there may be hidden uses that you are not immediately aware of. How is your long-distance telephone call transmitted? How does your cable TV service receive its signals? How many of these uses would not have existed 25 years ago? 50 years ago? 100 years ago?

4. Imagine being able to see in a different part of the spectrum than the visible. What would it be like? How would your perception of your world be different from what it is now? Would there be advantages and/or disadvantages?

Chapter Review Answers

REVIEW AND DISCUSSION

1. A wave is a vibration, a way in which energy is transferred from place to place without large-scale physical movement of material from one location to another. The material is just disturbed a small amount from its resting position, in a rhythmic and predictable manner.

2. The wavelength is the distance between any two consecutive positions in the wave, such as from peak to peak. The wave frequency is the number of waves that pass a point per unit of time, usually measured in waves per second. The wave velocity is the speed of the disturbance (*not* the speed of the vibrating medium, which varies). If speed is constant, the longer the wavelength, the lower the frequency; the shorter the wavelength, the higher the frequency. Thus, wavelength and frequency are inversely related. The product of the wavelength and frequency is the velocity of the wave.

3. Diffraction is the ability of waves to bend around corners. A sharp-edged gap in a wall produces a fuzzy shadow due to diffraction. Diffraction would not occur if light were strictly made of particles—the shadows would be very sharp. Inference occurs when waves interact, when they try to act on the same material at the same time. If two waves try to do the same thing to the same material at the same time, they add together, a phenomenon called constructive interference. In such a situation, light waves become brighter and sound waves become louder. If they try to do the opposite thing to the same material at the same time, they subtract from each other, which is called destructive interference. Light waves become darker, and sound waves become fainter.

4. Light is actually a combination of vibrating electric and magnetic fields moving through space. This is why we call light an electromagnetic wave.

5. Positive and negative charges attract each other. They would tend to move toward each other. By contrast two positively charged particles (or two negatively charged particles) repel each other, and would be pushed apart by the repulsive force.

6. The speed of light is symbolized by the letter *c*. The speed of light is actually the speed of all electromagnetic radiation and is a constant in a particular medium. All forms of light travel at the same speed in a given material. All theory and evidence currently indicate it is the fastest possible speed.

7. If the speed of light were only a little faster or slower, we probably would not notice a difference, especially over short distances. Altering the speed of light would change the range of frequencies we consider "visible," since light needs to have certain wavelengths to interact with our eyes. If the speed were many orders of magnitude slower, so that visual information from nearby traveled in a time longer than our reaction time, we would have to use another source of information to interact with our environment. If light were many orders of magnitude faster, we might not even notice, since we rarely notice light travel time as it is. If the speed were not constant—if, for example, it changed as frequency changed—then different colors of light would arrive at our eye at slightly different times. This would definitely affect how we perceive color.

8. Since the overwhelming majority of celestial objects are too far away from us to gather information about them by any means other than sight, light is our only source of information for most objects. Light can reveal a variety of things about celestial objects, such as temperature, chemical composition, and space motion. For very distant objects, the finite speed of light means that we see them as they were in the distant past, allowing us to "look back in time."

9. Even with clouds, the day-night cycle would be quite evident. The lunar cycle would be evident from the light given off by the Moon, although it might not be clear what object is causing the changing illumination. Radio radiation easily penetrates clouds, so we would know about the unusual objects that give off radio waves. Little would be known about stars because their radiation is mostly at visible wavelengths, and would not be bright enough to penetrate the clouds.

10. White light is made up of all of the colors (wavelengths) of light between red and violet, a continuous spectrum. Each color is unique because of its wavelength or, alternatively, its frequency, but they all travel at the same speed.

11. Radio waves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays are all electromagnetic radiation and move at the speed of light in a vacuum. They differ only by their wavelengths (or frequencies), from longest wavelength (radio waves) to shortest wavelength (gamma rays).

12. A blackbody is an idealized object that absorbs all radiation falling on it. It also re-emits all this radiation. The radiation emitted occurs at all wavelengths but has its peak intensity at a wavelength that depends on the temperature of the blackbody. The hotter the temperature, the shorter the wavelength of the peak radiation.

13. As the coal cools off, its temperature decreases. According to Wien's law, more and more of its radiation will be emitted at longer and longer wavelengths. According to Stefan's law, it will emit less and less radiation as it cools. The net result is that it gets fainter and redder with time, before finally "fading to black." At that point it is primarily giving off invisible infrared radiation.

14. Wien's law states that the wavelength at which a body emits the peak amount of radiation in its blackbody curve depends inversely on the temperature of the body; no other factors are involved. By observing the wavelength at which this peak radiation occurs, the temperature of a star can be determined.

15. The Doppler effect is the observed change in the wavelength (or frequency) of a wave due to the motion of the emitter, observer, or both, as they move toward or away from each other. Thus the Doppler Effect can make the radiation we receive from objects display a different wavelength than what we expect. By measuring the amount of this "shift" in the wavelength, astronomers can determine whether an object is moving toward or away from us. The greater the shift appears, the greater the relative speed. So by measuring the Doppler shift, the size, and direction of the relative velocity along the line of sight can be determined. However, only the line of sight velocity can be determined; finding any velocity perpendicular to the line of sight is much more challenging.

CONCEPTUAL SELF-TEST

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

PROBLEMS

1. The relationship between frequency, wavelength, and wave velocity is $\lambda f = v$.
   5.77 m × 256/s = 1480 m/s. Thus, the speed of sound in water is 1480 m/s.

2. The relationship between frequency, wavelength, and wave velocity is $\lambda f = v$, or
   $\lambda = v/f$. The frequency is 100 MHz or 10^8/s and $v = 3\times10^8$ m/s. Therefore, λ = 3 m.

3. Using the Celsius to Kelvin conversion, 37 + 273 = 310 K. Using Wien's law, $\lambda_{max} = 0.29/T$, with T in Kelvins and the wavelength in centimeters. For 310 K, this gives λ_{max} = 0.00094 cm = 9.4 μm. This is in the infrared portion of the spectrum.

4. Estimate your skin temperature to be 20°C or 293 K and your surface area to be about 2 m^2. Stefan's law gives L = Flux × Surface Area = $5.67 \times 10^{-8} \times (293)^4 \times 2$ = 835 W.

5. Using Wien's law, λ_{max}= 0.29 cm/T (1000 K) = 0.00029 cm or 2.9 μm, which is in the infrared.

6. According to Stefan's law, the hotter of the two produces more energy. Since the hotter object is 5 times hotter, it will emit 5^4 times as much energy, or 625 times.

7. Since the shift is to a lower frequency, the wavelength is shifted to a longer wavelength. Thus, the motion of the spacecraft must be away from the transmitter. We can use the formula for the Doppler effect that involves frequency. Thus we have 100 Hz/99.9 Hz = 1 + v/c. Solving for v gives $v = 3\times10^5$ m/s or 300 km/s.

8. The ratio between the apparent wavelength and the true wavelength is 0.999933. Thus 0.999933 = 1 + v/c. Solving for v gives −20100 m/s or −20.1 km/s. The negative sign means that Alpha Centauri is heading toward us, making the wavelength shorter ("blueshift").

Suggested Readings

Web Sites

The "Crash Course" channel on YouTube has a series about astronomy:
https://www.youtube.com/playlist?list=PL8dPuuaLjXtPAJr1ysd5yGIyiSFuh0mIL
Video #24 is especially relevant to this chapter

https://www.youtube.com/watch?v=m4t7gTmBK3g is a short video touring the electromagnetic spectrum, titled "What is the Electromagnetic Spectrum?"

"Wien's Law" (https://www.youtube.com/watch?v=__x4IjPQnro) is a narrated run-through of a Wien's law simulation

Magazines and Publications

Ambrose, B.; Heron, P.; Vokos, S.; and McDermott, L. "Student understanding of light as an electromagnetic wave: Relating the formalism to physical phenomena." *American Journal of Physics* (October 1999). p. 891. Development and modification of tutorials to address student difficulty with the wave nature of light.

Berman, Bob. "Light speed follies." *Astronomy* (September 2000). p. 100. Describes the strange effects predicted by special relatively for objects traveling near the speed of light.

Deans, Paul. "2MASS treasure hunt." *Sky & Telescope* (December 2000). p. 54. Showcases results from the near-infrared sky survey conducted by twin 1.3-m telescopes in Arizona and Chile (2MASS).

Dibble, W. "A pedagogical note on the Doppler-effect formulas." *The Physics Teacher* (September 2000). p. 362. A quick and simple derivation for the Doppler-effect formulas useful at the introductory level.

Doherty, M., V. L. Fish and M. Needles. "Revealing the hidden wave: Using the very small radio telescope to teach high school physics." *Physics Teacher* 49:9 (2011). p. 546. Describes the process of constructing an inexpensive radio receiver/transmitter and using it to demonstrate the properties of light.

Gale, T. "Chasing light speed." *Sky & Telescope* (August 2012). p. 34. A review of early efforts to measure the speed of light.

Helfand, David J. "Seeing the whole symphony." *Natural History* (February 2000). p. 84. Discusses the electromagnetic spectrum and astronomy at wavelengths other than the visible.

Kaler, James B. "Beyond the rainbow." *Astronomy* (September 2000). p. 38. Gives a nice overview of the different parts of the electromagnetic spectrum, and talks about the relation between the temperature of an object and the type of radiation it emits.

Keeports, D. "Estimating the speed of light from a satellite echo." *The Physics Teacher* (March 2004). p. 154. Discusses a method to measure the speed of electromagnetic radiation based on long-distant satellite phone conversations.

Kruesi, L and R. Kelly. "Illustrated: Light's dual personality." *Astronomy* (July 2009). Visualizing the dual nature of light.

Marangos, Jon. "Faster than a speeding photon." *Nature* (July 2000). p. 243. Describes how parts of a wave pulse can seem to travel faster than the speed of light.

"Millimeter wavelengths saved for astronomers." *Sky & Telescope.* (November 2000). p. 32. A short description of the conflict between radio astronomy and radio communications.

Thomsen, Volker. "Signals from communications satellites." *The Physics Teacher* (April 1996). p. 218. Discusses the Doppler shift observed in signals from satellites.

Van Dyk, S. "The Ultimate Infrared Sky Survey." *Mercury* (March–April 2003). p. 23. Discusses an IR research program and includes short overview of some of the advantages of working in the IR part of the spectrum.

Western, Arthur B. "Star colors for relativistic space travelers." *The Physics Teacher* (March 1997). p. 160. Discusses how stars would appear to an observer traveling near the speed of light.

Wyrembeck, E. "A Student Centered Interactive Color Quiz." *The Physics Teacher* (December 2003). p. 531. A fun and simple way to engage students in the concepts of color and color combination as well as touching on reflection and atomic emission and absorption of light. Applicable to Chapter 4 as well.