Chapter 3: Radiation
Information from the Cosmos

Outline

Summary

Almost all the information we receive from the universe is in the form of electromagnetic radiation emitted by the objects in it. Without this radiation we would neither be able to study and understand the universe nor even know of its existence. This chapter establishes the relationship between matter and electromagnetic radiation. It provides the first understanding of how astronomers came to study and learn about remote objects by studying the radiation that is emitted.

The material has many connections to everyday life. Students will likely be surprised to learn that various forms of radiation like x-rays, light, and AM radio are all part of the electromagnetic spectrum. Although the wave property of frequency is supposedly not as familiar as wavelength, many students 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.

Possibly the most difficult concept will be blackbody radiation and the relationship of color to temperature. It is contrary to the artistic interpretation of hot and cold colors. Here they must confront a more critical analysis of what they see. The white of the polar caps of Mars, of a white dwarf, and of a white sheet of paper requires an understanding less naïve and concrete than the student has previously experienced.

Major Concepts

- Electromagnetic Radiation
  - Electromagnetic waves
  - Wavelength, frequency, speed
- The electromagnetic spectrum
  - Full range of radiation
  - Visible light
  - Blackbody spectrum
  - Radiation laws
- Spectra and spectral lines
  - Emission
  - Absorption
  - Photons
  - Hydrogen spectrum
  - More complex spectra
  - Analysis of spectral lines

- 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.

Sections 3.1

➲ 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 the propagation of a disturbance, not of the material or medium through which the wave travels.

Section 3.2

Electromagnetic waves do not require a medium in order to propagate. Contrast electromagnetic waves with mechanical waves 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.

Mention that it is one of the ironies in nature that light from distant galaxies travels unperturbed for millions of light years only to be degraded significantly during the last few miles of its journey.

Section 3.3

Spend some time going over Figure 3.9. 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 the wavelengths of electromagnetic radiation. We divide the electromagnetic spectrum into different areas not based on inherent differences in the radiation itself, 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 towards 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 3.11. Help the students relate to each type by identifying everyday examples.

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 them.

ultraviolet: the danger of sunburn increases with elevation because there is decreasing protection from the Earth's atmospheric absorption of ultraviolet.

infrared: although we cannot see it, we do feel it. We have infrared (heat) sensitive cells in our skin that allow us to locate sources of infrared. Notice how warm a light bulb is when it is on. It is producing a lot of infrared, along with visible light.

microwaves: in an oven they are "tuned" to vibrate 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 light to pass through but small enough to block microwaves.

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 m – 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 m – 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 3.10 and 3.11 to discuss **blackbody curves**. Point out that as the temperature of a blackbody increases, two things happen. The glowing body emits more radiation at all wavelengths, so more total energy is emitted (Stefan's law). Also, the peak of the curve shifts to shorter wavelengths or higher frequencies (Wien'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

Students will most likely be familiar with the **Doppler Effect** applied to sound. ➲ **DEMO** 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 towards or away from the observer to produce the Doppler Effect.

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. 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.

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. Choose one of the 92 naturally occurring elements. Conduct library research of this element and give a description of it, where it commonly occurs in nature, any uses it may have, and how it was discovered. In your description include its atomic structure, melting and boiling points, chemical activity, and whether it is common or rare.

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?

5. In everyday life, light seems to travel almost instantaneously to us. What if the speed of light were very slow, maybe slower than even sound? How would this change the way you interact or react to activity around you? Use some simple activities and see what would happen. Would anything be easier? Harder? Dangerous?

Answers to End of Chapter Exercises

Review and Discussion

1. A wave is a way in which energy is transferred from place to place without physical movement of material from one location to another.

2. The wave period is a measurement of the amount of time needed for a wave to repeat itself at some point in space. The wavelength is the distance between any two consecutive positions in the wave, such as from peak to peak. The amplitude is the maximum height or depth of the wave above or below the undisturbed state. The wave frequency is the number of waves that pass a point per unit of time, usually waves per second.

3. The longer the wavelength, the lower the frequency; the shorter the wavelength, the higher the frequency. Wavelength and frequency are inversely related.

4. 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.

5. The speed of light is symbolized by the letter c. The speed of light is actually the speed of all electromagnetic radiation in a vacuum and is a constant.

6. White light is made up of all of the colors (wavelengths) of light between red and violet, a continuous spectrum.

7. Positive and negative charges attract each other. They would tend to move towards each other.

8. The electric force is similar to the gravitational force in that it drops off by the inverse square of the distance. It is different in that it can be either attractive or repulsive; dislike charges attract and like charges repel. If the number of positive and negative charges are equal in an object, it appears to be neutral and has no electric force. Gravity is always present and is never neutralized.

9. A star contains many charged particles that are moving. This motion creates waves in the electric fields of the charged particles and these waves propagate or move outward and away from the star. Traveling at the speed of light, a few of these waves will finally reach a person's eye, which also contains charged particles. The waves make the charged particles move, and this motion is sensed by nerves and transmitted to the brain as an image of the star.

10. Light actually consists of vibrating electric and magnetic fields moving through space.

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. The parts of the electromagnetic spectrum for which the Earth's atmosphere is transparent are the visible (when it isn't cloudy!) parts of the infrared, and radio waves between about one centimeter to ten meters.

13. 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 peaks at a wavelength that depends on the temperature of the blackbody. The hotter the temperature, the shorter the wavelength of the peak 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. Stefan's Law relates the amount of radiation emitted by a blackbody to its temperature. The amount depends upon the fourth power of the temperature.

16. 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.

17. 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, towards or away from each other. If the motion is towards each other, the observed wavelength appears shorter than the wave emitted. If the motion is away from each other, the observed wavelength appears longer than the wave emitted.

18. By measuring the amount of shift in the wavelength of some form of radiation, astronomers can determine whether an object is moving towards or away from us. The shift is proportional to the speed. So by measuring the Doppler shift, the velocity can be determined.

19. The Doppler shift occurs when there is a difference in the speed between a source of radiation and an observer. In this case, both are moving together at the same speed, so no shift occurs.

20. Even with clouds, the day-night cycle is quite evident. The lunar cycle would be evident from the light given off by the Moon, although it might not be clear what the object is that causes the lunar cycle. Radio radiation easily penetrates clouds. Little would be known about stars because their radiation is mostly at visible wavelengths.

Conceptual Self-Test

1. T
2. F
3. F
4. F
5. F
6. T
7. T
8. T
9. T
10. T
11. A
12. C

13. B
14. B
15. D
16. A
17. B
18. D
19. A
20. B

Problems

1. The relationship between frequency, wavelength, and wave velocity is $\lambda f = v$. 5.77 m × 256/s = 1480 m/s.

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

3. For the Earth's diameter, λ = 12,756 km. c = 300,000 km/s = 12,756 km × f. f = 23.5 Hz. This wave would be in the extreme long-wavelength radio.

4. Assume a λ = 0.1 mm dot = 10^{-4} m. $f = 3\times10^8$ m/sec / 10^{-4} m. $f = 3\times10^{12}$ Hz. This is far infrared or microwave.

5. For an 3.2 GHz clock, $f = 3.2\times10^9$ Hz. λ = 3 × 10^8 m/sec / 3.2×10^9 Hz. λ = 9.4 cm (radio).

6. Wien's law states that the peak wavelength is inversely proportional to the temperature. Comparing 200 to 650 nm gives a factor of 3.25; therefore, the object with a peak wavelength of 200 nm must be 3.25 times hotter than the object that peaks at 650 nm.

   Stefan's law states that the energy radiated is proportional to T^4. If the hotter object is 3.25 hotter than the cooler object, it must radiate $(3.25)^4$ = 112 times as much energy as the cooler object.

7. 37 + 273 = 310°K. Using Wien's law, λ_{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.

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

9. λ_{max}=2900 nm/T(1000°K) = 2900 nm or 2.9 μm, which is in the infrared.

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

11. The Sun's temperature is 5778°K. Using this in Stefan's Law gives $5.67\times10^{-8} \times (5778)^4$ = 6.32×10^7 J. Its radius of 6.96×10^8 m will give a surface area of $4\pi\,(6.96\times10^8)^2 = 6.09 \times 10^{18}$ m^2. Multiplying these two results gives the total solar luminosity of 3.85×10^{26} W.

12. Use the Doppler formula. v = 300,000 km/s × (1–0.999933), v = 20 km/s.

13. 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. To solve for the speed, the frequencies must be converted to wavelengths. The wavelengths are, respectively, 3.00m and 3.003m. Using the formula for the Doppler Effect gives 300.3/300 = 1 + v/c. Solving for v gives $v = 3\times10^5$ m/s or 300 km/s.

14. The Earth orbits the Sun with an average speed of 30 km/s so the 700 nm laser beam will be shifted by amounts proportional to speeds of 70 and 130 km/s. λ = 700 nm (1 - 70/300,000) = 699.84 nm. λ = 700 nm (1 - 130/300,000) = 699.70 nm

15. The true wavelength must be exactly 3.00000 m. Using the Doppler formula

$$\frac{3.00036}{3.00000} = 1 + \frac{v}{300,000}$$

$$v = 36 \text{ km/s}$$

The spacecraft is moving a distance equal to one circumference in this speed. The period of the orbit can therefore be determined. Using velocity = distance / time, time = distance / velocity. $2\pi \times$ (100,000 km) / 36 km/s = 17,450 s. To use Kepler's third law, change units to years and A.U. There are 3.15×10^7 seconds in a year, so this period is 0.000553 yr. The orbital radius is 100,000 / 150,000,000 = 0.000667 A.U. Kepler's third law gives:

$$0.000553^2 = \frac{0.000667^3}{M}$$

M = 0.000969 solar masses or

$M = 1.93 \times 10^{27}$ kg or

323 Earth masses or about 1 Jupiter mass.

Resource Information

Student CD Media

Movies/Animations
The Planck Spectrum

Interactive Student Tutorials
Doppler Effect
Continuous Spectra and Blackbody Radiation

Physlet Illustrations
Basic Wave Properties
Electromagnetic Waves
Doppler Effect

Transparencies

T-22	Figure 3.2/3	Water Waves and Wave Properties	p. 63
T-23	Figure 3.4	Visible Spectrum	p. 64
T-24	Figure 3.5	Charged Particles and Wave Propagation	p. 65
T-25	Figure 3.7	Electromagnetic Wave	p. 66
T-26	Figure 3.9	Electromagnetic Spectrum	p. 70
T-27	Figure 3.11	Blackbody Spectrum	p. 73
T-28	Figure 3.15	Doppler Effect	p. 78

Suggested Readings

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* (Sept 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* (Dec 2000). p. 54. Showcases results from the near-infrared sky survey conducted by twin 1.3-meter 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.

Elvis, Martin. "NASA's Chandra X-ray Observatory: a revolution through resolution." *Sky & Telescope* (Aug 1999). p. 44. Gives a detailed overview of X-ray astronomy and the characteristics and capabilities of the Chandra X-ray Observatory.

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

Kaler, James B. "Beyond the rainbow." *Astronomy* (Sept 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.

Leonard, Peter J.T.; Wanjek, Christopher. "Compton's legacy." *Sky & Telescope* (July 2000). p. 48. Reviews results of the high energy gamma ray sky obtained during the nine-year mission of the Compton Gamma Ray Observatory.

Marangos, Jon. "Faster than a speeding photon." *Nature* (July 20, 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 and Telescope.* (Nov 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.

Watson, Andrew. "Physicists trap photons and count them one by one." *Science* (April 5 1996). p. 34. Describes an experiment which directly measures individual photons.

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.

Notes and Ideas

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

Demonstration and activity materials:

Notes for next time: