

Using Spectroscopy to Find Life on Other Planets

Introduction

Scientists can study the structure of a substance by looking at how it absorbs and releases light. This method is called **spectroscopy**. To understand spectroscopy, it is important to understand the properties of light. Light acts as both a particle and a wave and spectroscopy makes use of both properties of light. In spectroscopy, light's wave nature is demonstrated when white light is sent through an instrument that uses something like a prism to break white light into all of its different wavelengths as modeled in **Figure 1**. The separation of light into a spectrum of wavelengths is called **dispersion** and the device that separates the light into its individual wavelengths and analyzes this data is called a **spectrometer**. Dispersion is evidence of light's wave nature. Dispersion occurs when different wavelengths of light travel through a medium at different speeds causing them to be bent (refracted) by different amounts. In this lesson, we'll examine the wave and particle nature of light and how they are both important to spectroscopy.



Figure 1. Dispersion via a Simple Prism. This diagram shows a basic prism leading to the dispersion of light—splitting white light into its different components. *Source: Wikimedia Commons*

What To Do

Answer the analysis questions below, reading the Bite when instructed.

Analysis Questions

1. In a vacuum, all light travels at a speed of 3×10^8 m/s. The speed of light through a given medium is slower. How much slower depends on the properties of the medium and the wavelength of light. Moving from one medium into another, light bends in proportion to its change in speed. The greater the change in the wave's speed as it enters a medium, the more the light will bend. Examine **Figure 1**.
 - a. Based on the diagram, which color of light, red or violet, bends more as it enters the prism?
 - b. Based on how it bends, which color of light, red or violet, must travel slower through the prism? Explain your answer.

The frequencies, wavelengths, and energies associated with different colors of visible light are shown in **Table 1**.


Color	Frequency (THz)	Wavelength (nm)	Energy
red	435–495	685–605	Lowest  highest
orange	495–515	605–585	
yellow	515–535	585–560	
green	535–630	560–475	
blue	630–660	475–455	
indigo	660–680	455–40	
violet	680–740	440–405	

Table 1. The Frequency, Wavelength, and Relative Energies of Different Colors of Light. Frequency is reported in terahertz (THz). 1 THz is 1 billion billion hertz or a billion billion complete wavelengths passing by a point per second. Wavelength is given in nanometers (nm). 1 nm is 1 billionth of a meter (1 billion nm = 1 m).

2. According to **Table 1**, how does frequency of light relate to its wavelength? Is the relationship direct or inverse? Explain how you know.

Astronomers use light from outside our solar system to learn about the universe. Some researchers use a technique called transmission spectroscopy. **Transmission spectroscopy** gathers information about an object by analyzing the wavelengths of light that are **absorbed** (taken in by the object) and **transmitted** (pass through the object) as light hits that object.

3. Describe an object in your everyday life that allows a lot of light to be transmitted through it. How do you know light is being transmitted?
4. Describe an object in your everyday life that absorbs most of the light that hits it. How do you know light is being absorbed?

Transmission spectroscopy provides a useful tool for studying phenomena and structures in the universe. For example, when an **exoplanet** (a planet outside of our solar system) passes in front of the star it orbits (its host star) it blocks some of that star's light. At that time, transmission spectroscopy can be used to gather information about the planet, such as its radius and the composition of its atmosphere. **Figure 2** shows an example of how scientists gather data about exoplanets using transmission spectroscopy. In this example, transmission spectroscopy confirms that the exoplanet has a lot of sodium in its atmosphere.

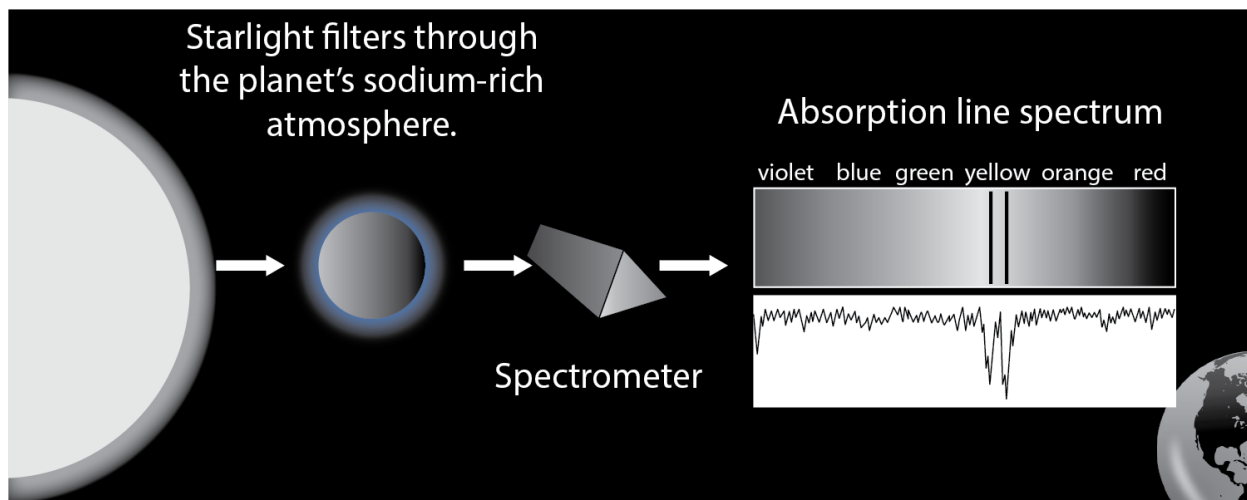


Figure 2. Planetary Absorption Lines. A planet with an atmosphere that contains sodium passes in front of the star it is orbiting. Particular wavelengths are absorbed by the sodium atoms in the planet's atmosphere. The rest of the light is transmitted through the planet's atmosphere. This light reaches a telescope orbiting Earth. Scientists observe the light and use a spectrometer to figure out which wavelengths have been absorbed by the planet's atmosphere. From there, they can infer the atmosphere's composition. *Source: [Wikimedia Commons](#)*

5. **Figure 2** shows an absorption line spectrum for a planet with an atmosphere rich in sodium.
 - a. What color of light is absorbed the most in the absorption line spectrum of the planet shown in **Figure 2**?
 - b. Look back at **Table 1**. What wavelength does this color closely correspond to? What frequency?
 - c. Look back at **Table 1**. Is the energy associated with this wavelength of light relatively high, medium, or low?

As incredible as it is that we can infer the composition of an exoplanet's atmosphere, that isn't all we do! The radius of the exoplanet can be precisely determined by looking at the light curve collected when the planet is between Earth and its host star. A **light curve** is a plot of the change in brightness of an object (such as a star) over time. Modern telescopes continually collect data about a star's brightness as its exoplanet passes between the star and the telescope. From the resulting light curve, scientists can determine how much light the exoplanet blocks as it passes by. There is a direct relationship between the exoplanet's radius and the dip in brightness picked up by the telescope: Planets with larger radii block more light than planets with smaller radii. **Figure 3** shows how the observed light curve of a star is impacted when a planet orbiting that star moves between the star and Earth.

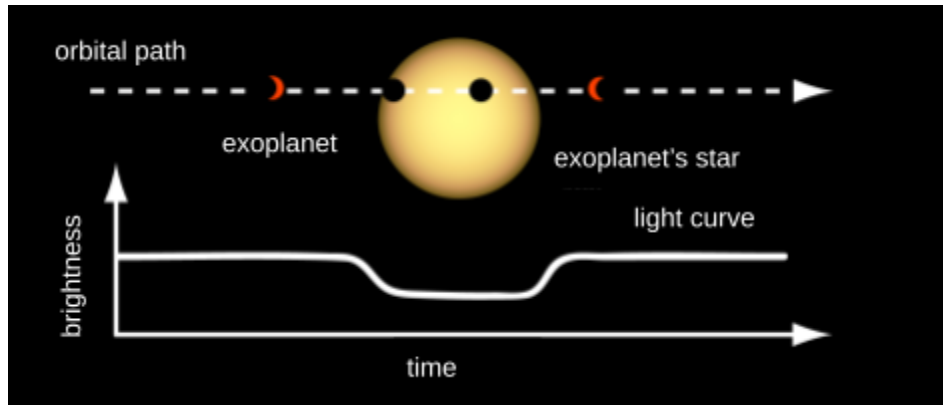
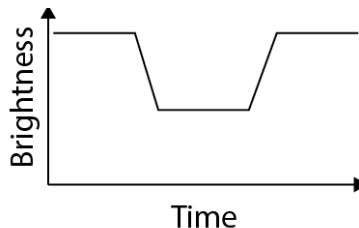


Figure 3. Light Curve as a Planet Moves Between a Star and the Earth. This picture models how the brightness of the light detected by human telescopes is affected by an exoplanet passing in front of its star. If a planet with a larger radius were to pass in front of the same star, the dip in brightness observed would be proportionally larger. By understanding the properties of the host star and analyzing this dip in brightness, we can precisely determine the planet's radius. *Source: NASA*

- Suppose two exoplanets (Planet A and Planet B) are orbiting the same star. The planets are identical, except that Planet A is much larger than Planet B. A student sketched the light curve of the star when just Planet B is in front of the star. On the same graph, sketch what the light curve of the star would look like when just Planet A is in front of the star.



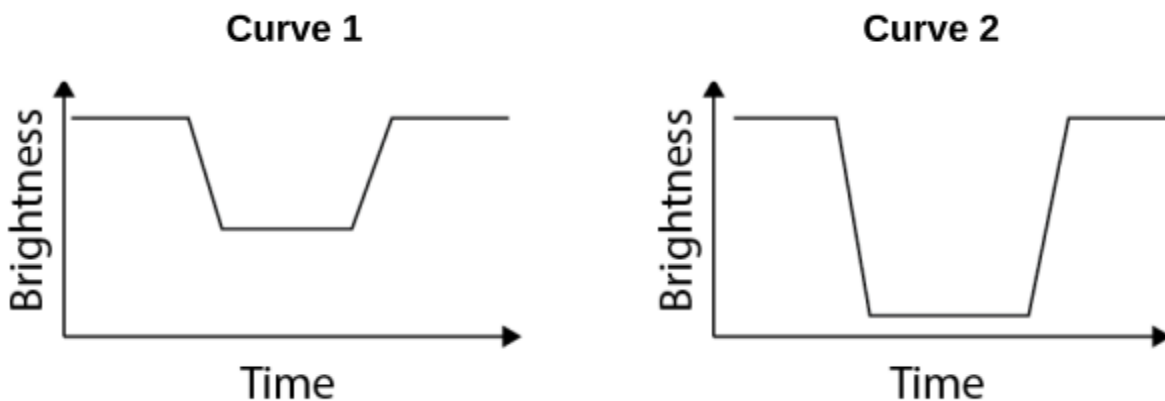
STOP & read Science Bite:
Are We Alone?

7. Examine **Figure 1** in the Bite.

- a. Based on the data, which line (solid, dashed, dot) represents the type of light that is absorbed the most by the planet's atmosphere? Justify your response.

- b. If the dashed line represents a wavelength of light absorbed by sodium, the dotted line represents a wavelength of light absorbed by oxygen, and the solid line represents a wavelength of light absorbed by hydrogen, which element do you expect to be the most abundant in this planet's atmosphere? Justify your response.

8. Suppose that two planets, both the same size, are orbiting the same star. One planet (Planet A) has molecular oxygen (O₂) in its atmosphere, while the other (Planet B) does not. Molecular oxygen best absorbs light with a wavelength of 687 nm. A diagram of two possible light curves captured at 687 nm for Planet A and Planet B are shown below.



- a. Which light curve belongs to Planet B? Justify your response.

- b. Based only on these curves at 687 nm, which planet would scientists expect to have a larger diameter? Explain your answer.

9. What do you think makes it difficult for scientists to measure the size of exoplanets directly? Why do we need new innovations in techniques such as transmission spectroscopy?

In addition to making use of light's wave properties to study the atmosphere of distant planets, digital spectrometers use light's particle nature to determine the intensity of light at each wavelength. After a spectrometer separates light into its different wavelengths, **photons**, which are individual particles of light, land on a detector. An example of a detector is a Charge-Coupled Device (CCD) detector. In a CCD detector, photons with high enough energy cause an electron to be released from the silicon plate of the CCD detector. The greater the intensity of light, the more electrons will be released. The greater the energy of the light (as determined by the light's frequency), the more kinetic energy the electrons will have once they are released. As electrons are released, they generate an electric charge that can be quantified by the CCD detector into a measurement of the amount of light present at a particular wavelength. In sum: Photons hit the instrument causing electrons to be released. The properties (quantity and kinetic energy) of the released electrons enable the instrument to determine the intensity and frequency of the photons.

The process of photons striking a surface, such as a CCD detector's silicon plate, and causing electrons to be released is known as the **photoelectric effect**. The photoelectric effect demonstrates the particle nature of light, because only particles with high enough energies can cause the ejection of electrons. This idea was first suggested by Albert Einstein in 1905, for which he was later awarded the Nobel Prize. **Figures 4 and 5** show how the energy and intensity of light hitting a metal surface impacts the electrons ejected from the surface.

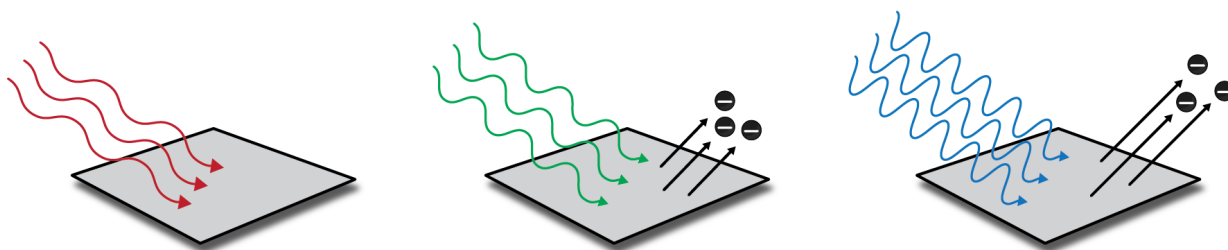


Figure 4. The Effects of Wavelength and Intensity on the Ejection of Electrons from a Metal Surface. Light needs to have enough energy (have a high enough frequency) to cause electrons to be ejected from a surface. Once the light's energy exceeds the threshold needed to release electrons, the higher the energy of the light, the greater the kinetic energy of the electrons ejected. In this example, red light does not have enough energy to eject electrons, but green and blue light do. The blue light has more energy, so the electrons ejected have more kinetic energy.

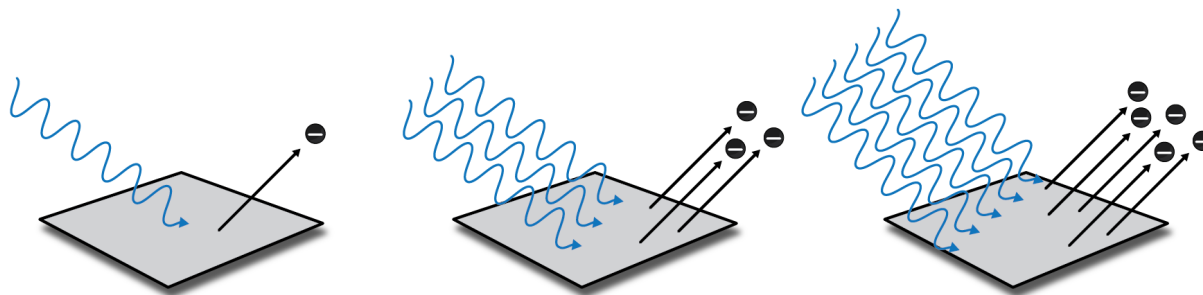


Figure 5. If a particular wavelength of light has enough energy to eject electrons, as the intensity of the light increases, the number of electrons ejected from the surface increases. As the intensity of the blue light increases, the number of electrons ejected increases, but the kinetic energy of each electron being ejected is the same because the frequency of the light is the same.

Similar to a CCD, a sample of solid cesium metal will eject electrons in response to both yellow and violet light. A student states, “The electrons ejected by the yellow light will have a higher kinetic energy than those ejected by the violet light. No matter which light is used, as the intensity of the light increases the number of electrons ejected and the kinetic energy of the electrons will increase.”

- a. What is correct about the student's statement? Explain your answer.

- b. What is incorrect about the student's statement? Explain your answer.

10. A student decides to model the photoelectric effect. They place ping pong balls in a shallow tray. Then they throw large beads at the ping pong balls. First they throw the beads lightly and the ping pong balls don't move. Next, they throw the beads harder and when a bead hits a ping pong ball, the ping pong ball jumps from the tray as shown in **Figure 6**.

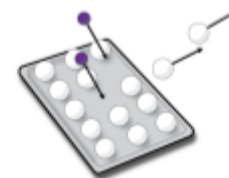


Figure 6. A student's model of the photoelectric effect using ping pong balls and beads

- a. Describe what each of the following items in the model represented:
 - i. Ping pong balls

 - ii. Beads thrown softly

 - iii. Beads thrown harder

- b. The harder the beads are thrown, the faster the ping pong balls are when they leave the tray. What does this represent in terms of the photoelectric effect?
- c. If the student wanted to use their ping pong ball and bead model to describe how the intensity of the light impacts the electrons that are released from a surface, how would they do so? Include a picture or series of pictures in your explanation.
11. Without a basic understanding of the wave-particle duality of light, scientists would not be able to develop the technology needed in order to study exoplanets. Briefly describe how the wave nature and particle nature of light allows us to make these observations.
12. **Connect to the Big Question.** You see a newspaper headline that reads “WE ARE NOT ALONE” and implies that life has been found on a distant planet. When you start reading the article you realize that the authors are discussing a scientific paper that used transmission spectroscopy to find evidence of water and oxygen on this planet. Do you think the headline is justified? Why or why not?