Laboratory 8 - Properties of Light and Atomic Spectra

Materials Used: Spectrometers, CLEA software[1].

Objectives: To explore the fundamental nature of light; to become acquainted with *spectroscopy*.

Discussion: From the time of Sir Isaac Newton (1642 - 1727) to the beginning of the 20th century the fundamental nature of light was a topic of debate among scientists. Newton proposed in his book *Opticks* (1704) that light consisted of a stream of particles know as *corpuscles*. With this theory Newton was able to explain phenomena such as reflection and refraction. Newton's corpuscular theory was widely accepted both because it seemed to explain known phenomena and because Newton was its architect.

A contemporary of Newton, Dutch physicist and astronomer Christian Huygens[2] (1629 - 1695), proposed an alternative *wave theory* that not only explained reflection and refraction (more elegantly than Newton's corpuscular theory) but also *diffraction* - the bending of light as it passes around sharp edges or through narrow openings. In spite of its success, Huygen's theory did not receive wide acceptance. All waves known at the time traveled through a physical medium of some sort (air, water, etc.). Light, on the other hand, was known to travel through the vacuum of space – something that seemed inconsistent with the requirements of known waves.

In 1801 Thomas Young conducted an experiment that demonstrated another phenomena, *interference*, which could only be explained by the wave theory of light. Interference occurs when light waves are combined. Although there are many possibilities from such an event Young demonstrated that cancellation of light waves was possible by combining them in just the right way.

Figure 1 depicts both *constructive* and *destructive* interference. In constructive interference identical light waves that are *in phase* (i.e., the crests and troughs of each wave line up) add in such a manner that the combined wave has an *amplitude* (A) that is twice that of either individual wave. In destructive interference waves that are exactly out of phase (i.e., the crest of one wave corresponds to the trough of the other) cancel when combined. Such behavior could not be explained by the corpuscular theory since no mechanism known at the time could explain how two particles could combine so as to cancel.

Half a century later Maxwell, Hertz and others demonstrated definitively that light was a high frequency electromagnetic wave (like radio or television waves) that traveled through free space with a speed of 3×10^8 m/s. By the dawn of the 20th century, the wave theory of light was widely accepted.

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[1] The computerized portions of this lab were provided courtesy of Gettysburg College.

[2] Christian Huygens principal accomplishment as a physicist was the wave theory of light. As an astronomer, Huygens was the first to recognize the rings of Saturn (1655) and discovered Titan, a moon of Saturn.

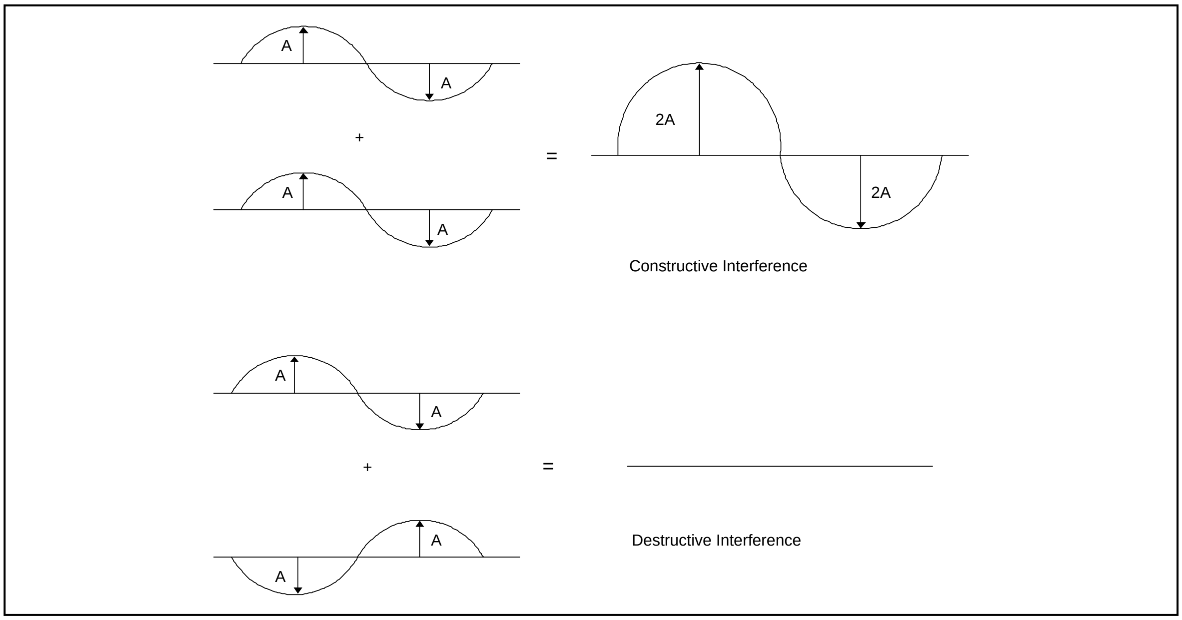

Figure 1. Interference in waves.

As resounding as was the evidence for the wave behavior of light there were still phenomena that could not be explained by the wave theory. One is the *photoelectric effect*. The photoelectric effect is a phenomenon whereby electrons are ejected from a metallic surface that has been exposed to light. This effect cannot be reasonably explained with the wave theory of Huygens and Maxwell.

Albert Einstein proposed an explanation of the photoelectric effect in 1905. Einstein, drawing upon the earlier work of Max Planck (1858 - 1947), proposed that light was composed of discrete bundles of energy called *photons*, and that the energy (E) of each photon was proportional to the frequency (f) of the light wave, i.e.: $E = hf$ ($h = 6.63 \times 10^{-34}$ J · s is *Planck's constant*). Notice that Einstein's explanation of the photoelectric effect contains elements of both the particle (energy of a single photon) and wave (frequency) theories of light.

This is the essential nature of light. At times light exhibits particle-like properties and at other times it exhibits wave-like properties. The best answer to the puzzle "What is light?" is that it is both particles and waves. Sometimes the particle properties dominate and sometimes the wave properties dominate.

For the purposes of this procedure we may assume that the wave properties of light dominate. The wavelength of light (λ) is related to its color. In the visible spectrum, which extends from approximately 400 - 700 *nanometers* (a nanometer is 10^{-9} meters), longer wavelengths correspond to red and orange colors and shorter wavelengths correspond to violet and blue. You have probably heard about *ultraviolet light* and its dangers associated with the depletion of the earth's ozone layer. This is light with wavelengths in the 100 to 400 nanometer range. Wavelengths from 1 millimeter to 10 microns (10^{-3} to 10^{-7} meters) are known as *infrared* light.

The frequency of a light wave (f) is equal to the speed of light (c) divided by its wavelength (λ): $f = c/\lambda$. Since the speed of light in free space is constant ($c = 3 \times 10^8$ m/s) the longer the wavelength the lower the frequency. All visible light waves have frequencies of around 10^{15} Hz.

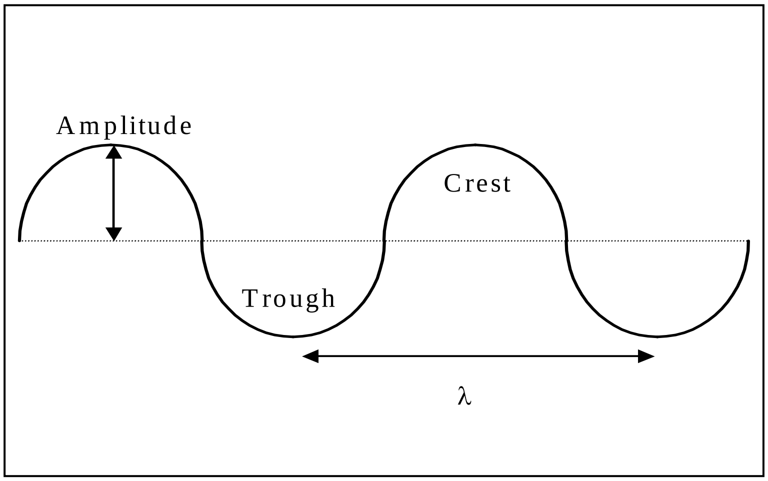

Figure 2. Characteristics of a light wave.

Spectroscopy

All objects emit some form of electromagnetic radiation by virtue of their temperature. Spectroscopy is an extremely useful analytic technique that involves analyzing the light given off by objects that are hot enough to emit visible light. A spectrometer is a device that uses either diffraction or refraction to separate light into its *spectral components*. White light, for instance, is made up of all visible colors in equal balance. A spectrum of white light looks much like a rainbow. Other colors of light have different spectral components.

A single spectral line corresponds to light of a specific wavelength. Spectral lines associated with visible light are created by electrons that jump to excited energy states (related to temperature) then decay back to lower energy states - emitting a photon of light during the decay that is equal to the energy difference between the two states. Every element in the universe has a unique spectral signature.

By carefully analyzing the light spectrum of a star one may gain insight as to not only its composition, but to its temperature, mass, luminosity, magnetic field, translational movement and rotation.

Your lab instructor will direct your attention to a chart illustrating various spectral types. There are three types of visible spectra.

1) Bright line or emission line spectra.
2) Continuous spectra.
3) Dark line or absorption line spectra.

A *bright line or emission spectra* is produced by a hot gas that radiates energy at wavelengths characteristic of the element or elements that make up the gas. An emission spectrum consists of a number of bright lines against a dark background. Each line's color corresponds to a specific wavelength that, in turn, corresponds to a specific energy separation between two atomic states.

A *continuous spectrum* is produced by hot, high-density substances such as solids, liquids or even gasses under certain conditions. Blackbodies (such as stars) produce continuous spectra. A continuous spectrum looks like a smear of color. A continuous spectrum of white light, such as that produced when sunlight is transmitted through a prism, appears as a smooth transition through all colors without any gaps between the colors.

A *dark line or absorption spectrum* is produced when a cool gas absorbs specific wavelengths of light passing through it. The wavelengths absorbed are determined by the elements that compose the gas. Just as atoms promote electrons to excited states at high temperatures, they also promote electrons to excited states by absorbing just the right wavelengths of light. The absorbed light excites an electron that immediately decays back too it's original state - emitting a photon identical to the absorbed photon in the process. The difference is that the new photon is equally likely to be traveling in any direction resulting in the scattering of the light from its original path. An observer behind a gas that is absorbing and scattering certain wavelengths of light notices a diminution of the absorbed colors because much of this light in no longer traveling straight through the gas.

Since no two elements absorb the exact same wavelengths it is possible to determine the elemental composition of the gas by examining its absorption spectrum. An absorption spectrum appears as a sequence of different colors interrupted by dark lines representing the absorbed light. The K and H lines in the solar spectrum, for instance, are absorption lines produced by ionized calcium in the sun's atmosphere.

A spectrometer has been set up in the lab. This spectrometer is accompanied by a Hydrogen arc lamp that uses an electrical current to produce a Hydrogen emission spectrum. You lab instructor will show you how to use this device to observe a Hydrogen emission line spectrum.

Procedure

In this exercise you will examine the absorption spectra of several stars and compare them with standards from an atlas of stellar spectra. By doing so you will be able to classify and identify stars by their spectral lines.

Your lab instructor will instruct you on how to access the CLEA program on your computer. The computer will prompt you for a login but this is unnecessary. Click OK twice. A control bar will appear across the top of the screen. Clicking RUN will open a pop-up menu with two options. Click the TAKE SPECTRA option that takes you into the data-acquisition environment. The computer will display the message "accessing .4 meter telescope." When the computer is ready a set of doors will appear. Click DOME (the computer should respond with "opening") and when the dome has opened click TRACKING (the computer should respond with "on"). The computerized telescope is now tracking a simulated night sky.

The first star that we are interested in has the coordinates R.A. 06h 14m 26s and DEC. 32^0 29' 29". There are two ways to center the telescope on this star. The first is to use the slew controls to move the telescope to the desired coordinates. The second is to enter the coordinates using the SET COORDINATES control and let the telescope align itself. When the star is centered click MONITOR.

This switches the telescope from finder to instrument mode. The star should still be centered within a narrow slit. If everything is OK you are ready to proceed. If not, you should ask your lab instructor for assistance.

Click TAKE READING on the control bar to begin data acquisition. A graph of Intensity vs. Wavelength should appear. You will want to acquire data for at least 30 seconds or until the signal to noise ratio exceeds 300. The higher the signal/noise ratio, the better the data (after a certain point the signal/noise ratio begins to level off). Click STOP COUNT to stop data acquisition. Save the file as number "001" and respond OK to the query to overwrite.

To begin data analysis click RETURN, RUN, CLASSIFY SPECTRA and LOAD. Choose the UNKNOWN SPECTRUM and SAVED SPECTRA. Load NOLOG001 from the list of saved spectra. This is the data you acquired previously. Click LOAD and choose ATLAS of STANDARD SPECTRA. The first thing we'll try is comparing the star you have chosen to main sequence stars. Choose MAIN SEQUENCE from the list of options. This will open another window on the right side of the screen. Click the down arrow in the upper right corner of this new window to reduce it to an icon. This loads the data we need but gets the window out of the way. Click DIFFERENCE to compare the spectrum of your unknown star with the first star in the atlas. The difference between the sample spectrum and your spectrum is displayed on the bottom of the screen. The closer this is to a flat line, the better the two spectra match. Keep scrolling through the spectral atlas by using the DOWN button until you get a good match. What is the spectral classification of your star?

When you have matched your spectrum to one from the atlas load the SPECTRAL LINE TABLE. Use the mouse to place the cursor on some of the absorption features in your spectrum. Click the left mouse button to look up a particular peak in the catalog. Do you recognize any of these lines? Of particular interest are the two deep "wells" near the left end of the spectrum.

Spectral data has been included in the figure below. Each spectral class listed is further subdivided into ten divisions, e.g., K5, F9, etc. Our sun is a spectral class G2 star, i.e., it is two-tenths of the way between G0 and K0. Based on the spectrum you have just analyzed, what are the characteristics of the star being analyzed?

Spectral Class	Color	Temperature (K)	Prominent Examples
O	Violet	>25000 Regor	
B	Blue	11000-25000	Rigel, Spica
A	Blue	7500-11000	Sirius, Vega
F	Blue - White	6000-7500	Procyon
G	White - Yellow	5000-6000	Capella, Sun
K	Orange - Red	3500-5000	Aldebaran, Arcturus
M	Red	<3500	Antares, Betelgeuse

Figure 3

Select another star. Choose BACK from the menu bar and YES to leave the analysis menu. Click MONITOR to return the telescope to finder mode. The star field should reappear. Examine the next star to the left (east) in the field of view. Follow the same steps as before. The spectrum of this star is not as easily matched as the previous one. Acquire a spectrum for about a minute this time. Once you have collected your data scroll through the Main Sequence spectra looking for the spectral type (O - M) that most closely matches your spectrum. When you have found the closest match, load the "Luminosity at XX" data from the spectral atlas and proceed from there.

Exercises

1. Compare the spectra of the two stars you studied in this exercise. What is the difference in their color and temperature? Are there any similarities in the lines in their spectra?

2. What are the two prominent "wells" located at 3933.68Å and 3968.49Å in both of the spectra you acquired (an angstrom, Å, is equal to 10^{-10} meters)? Are these emission or absorption phenomena?

3. Approximately what wavelengths, in nanometers, are associated with colors red, blue and yellow?

4. A light wave has a frequency of 10^{15} Hz. What is its wavelength? It's energy?

8. What is a nanometer? An angstrom? A micron?

9. What is the range of visible light in nanometers, angstroms, and microns?

10. What is 632.8 nm in angstroms (Å)? In microns (μ)?