

CHAPTER 8

ELECTROMAGNETIC RADIATION AND SPECTROSCOPY

A. Introduction

All objects that have a temperature greater than absolute zero contain thermal energy. Therefore, automatically and spontaneously every object emits some type and amount of electromagnetic radiation. That is, the energy source for emitted radiation is the heat or thermal energy in the body. The emission process occurs at the atomic level and involves electrons in the atoms undergoing transitions from high energy states to lower energy states.

If an object is sufficiently hot that it gives off visible light, it is said to be incandescent. Incandescence is a state of thermal emission. Stars are incandescent bodies but generally, planets are not.

Mid-nineteenth century science found that temperature was related to the apparent color of a radiating source of light: blue = hot, red = cooler. This is because very hot objects give off or emit much more blue light than red light, while cooler objects emit more red light than blue light. In order to understand this, we now turn to a discussion of the laws of radiation for incandescent bodies.

B. The Laws of Radiation

1. Stefan-Boltzmann Law:

The type and amount of electromagnetic radiation emitted by an object depends only on its surface temperature. The higher the temperature, the greater the total amount of radiation emitted per unit area per second. This latter quantity is called the flux, F , or surface brightness B_s , and is given quantitatively by the Stefan-Boltzmann Law,

$$B_s = \sigma T^4,$$

where sigma, σ , is a known number or constant of proportionality between B_s and T , the absolute temperature.

The light emitted by a star consists of a mixture of many different wavelengths or colors so that we essentially see white light. The starlight may be tinted slightly red or slightly blue, depending on which color dominates. Which color dominates depends again on the surface temperature of an incandescent body.

Sir Isaac Newton was the first to demonstrate that white light was a mixture of all visible colors, and that each of these colors could not be further separated into any other colors. He did this by using a glass prism to disperse a beam of sunlight into a spectrum.

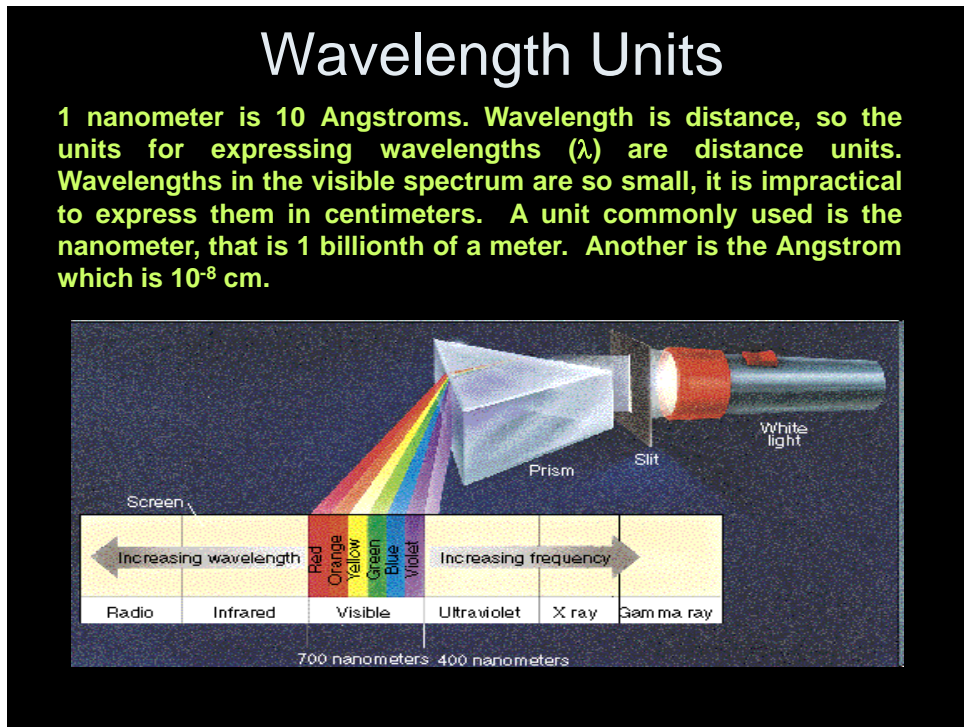
A spectrum is lateral display of the different wavelengths comprising a polychromatic beam of light.

The study of spectra is called spectroscopy.

Newton carried out the first experiments in spectroscopy by studying sunlight. He is considered the father of spectroscopy.

An example of a spectrum in nature is the rainbow. For this phenomenon, raindrops in the Earth's atmosphere act in unison to spatially separate the different colors in sunlight to form a spectrum of the Sun's light. Rainbow halos may also be seen around the Moon. These lunar halos are produced by a thin layer of clouds made of ice crystals. The ice crystals produce these halos much the same way raindrops produce a rainbow of sunlight.

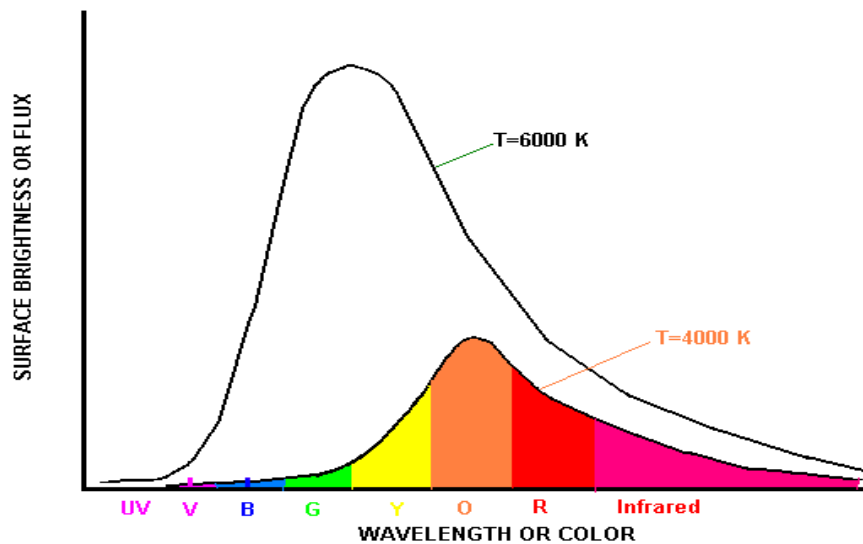
A beam of white light, such as that from a flashlight, may be dispersed into a spectrum by means of a prism, as shown in the diagram below. In addition to the colors of the visible spectrum, there are other electromagnetic waves that have both shorter and longer wavelengths than the wavelengths of visible light. The total electromagnetic spectrum is also shown in the diagram below. The main groups of EM radiation are radio (which includes microwaves), infrared, visible, ultraviolet, X-rays, and gamma rays.



The wavelengths of visible light range from 700 nm (nanometers) in the red to 400 nm in the violet, or 7000 Å (Angstroms) to 4000 Å.

2. Planck's Law:

We can produce the spectrum of the radiation we receive from other stars by attaching an instrument to a telescope called a spectrograph or a spectrophotometer. These devices use either a prism or a mirror ruled with thousands of very closely spaced lines to form a spectrum of the star's light. With the spectrophotometer, one directly measures the relative brightness of the spectrum at different wavelengths. The distribution of brightness with wavelength is given theoretically by Planck's Law. In 1901, Max Planck was the first to successfully derive an equation that characterizes the distribution of brightness for different wavelengths in agreement with laboratory studies by introducing quantum theory. This equation is too complex to present here. However, the diagram below schematically shows the results of Planck's law:



The above diagram depicts a plot of Planck's Law for two different temperatures. It shows how the brightness varies with wavelength over the spectrum for an incandescent body, such as stars.

Each curve in the above diagram is given by Planck's Law for a given temperature. These curves are called "Planckian or Black Body Curves". That is, for a given temperature, Planck's Law enables one to compute the intensity or surface brightness for any wavelength. The term "Black Body" is used, since at $T = 0\text{K}$, a body emits no EM radiation and would look completely black. The surface brightness or flux at a given wavelength is also called the monochromatic (one color) surface brightness.

The total area under each curve represents the total flux or surface brightness of the star as given by the Stefan-Boltzmann Law. It is the sum of the amount of radiant energy that the star emits at each wavelength integrated over the entire spectrum. Note that the star at 6000K emits more green, blue, and violet light than the star at 4000K. Therefore, it will look bluer to the eye. Also note that the area under the curve for 6000K is far greater than the area under the curve for 4000K. This is a visualization of the Stefan-Boltzmann Law.

3. Wien's Law

When one examines the Planckian radiation curves for different temperatures, it is apparent that the wavelength of maximum brightness or flux decreases with increasing temperature. For example, in the above diagram, the maximum brightness for the body with a surface temperature of 6000K is in the yellow-green part of the visible spectrum. For the body with a surface temperature of 4000K, the maximum brightness or flux occurs in the orange part of the visible spectrum. This was known from laboratory studies before Planck introduced quantum theory to successfully derive his equation that describes the way incandescent bodies radiate. The relationship between temperature and the wavelength of maximum brightness was developed by Wien. It is a very simple relationship, namely:

$$T = a/\lambda_{\text{max}}$$

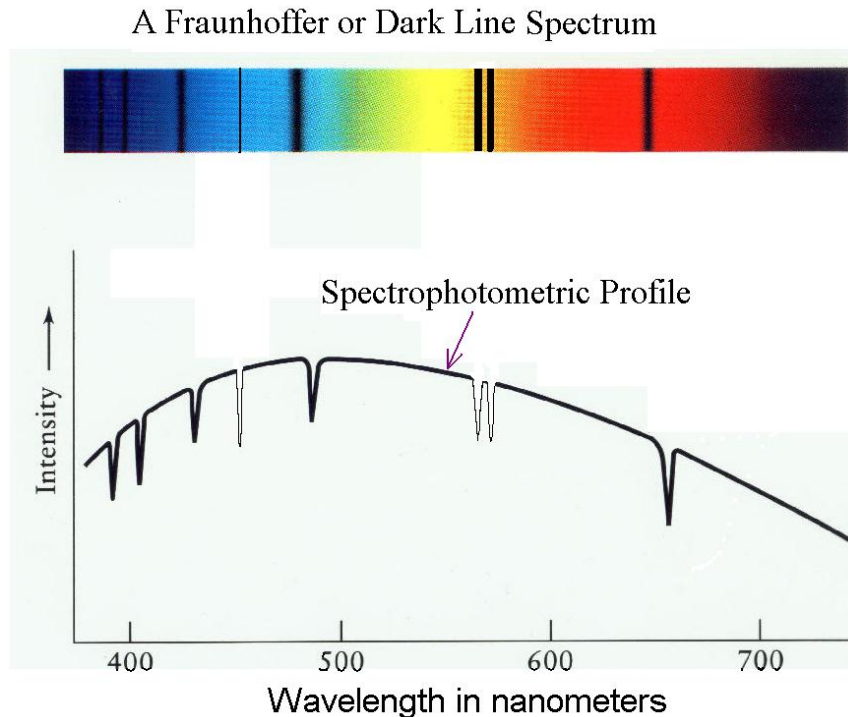
Here, "a" is a measured constant. This is Wien's Law. So the temperature of a star may be found by examining the spectrum of a star and determining the wavelength of maximum brightness, λ_{max} , and then applying Wien's Law. However, as we shall see, stellar spectra are very complex and it is difficult to determine exactly what the value of λ_{max} is.

C. The Appearance of Stellar Spectra

In 1802, Wollaston was the first to note that there were dark lines in the Sun's spectrum.

In 1812, Joseph Fraunhofer studied the Sun's spectrum in more detail and cataloged many of the dark lines in the Sun's spectrum, but he did not know what they meant.

For this reason, stellar spectra are also called Fraunhofer spectra, or dark line spectra, or absorption line spectra. The latter name implies how the lines are formed.



Most stars exhibit a dark line or absorption spectrum. That is, a continuous spectrum with discrete wavelengths weakened by atoms absorbing radiation at these wavelengths. Such a spectrum is also called a Fraunhofer spectrum. An example is shown in the diagram above.

The convex curvature in the spectrophotometric profile of the spectrum is what would be expected from Planck's Law as shown in the previous diagram. If there were no absorption features or lines, the spectrum would be a continuous one.

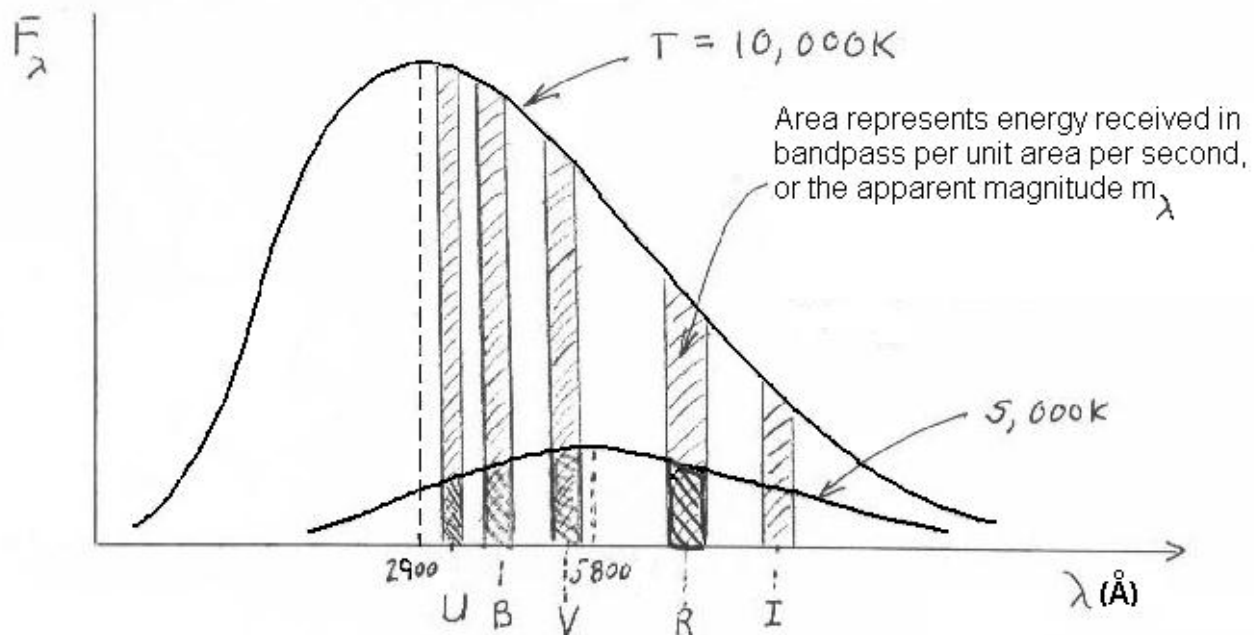
D. Color Magnitudes and Color Index (CI)

(This topic is also covered in Exercise 18.0 in the Course Manual)

A color magnitude expresses the brightness of a star within a specific wavelength interval (bandpass) of its spectrum. Examples of color magnitudes are U, B, V, R, and I. Color magnitudes may also be denoted by a subscript on the symbol for apparent magnitude, e. g., m_V or m_B . For absolute magnitudes we use the same notation, e. g., M_V or M_B .

A color index is the difference between 2 color magnitudes. A color index that is frequently used by astronomers is B - V. The hotter the star, the smaller the value of B-V is. For example very hot stars have B-V values that are negative, whereas cool have B-V values that are positive. The range is -0.40 to +2.2.

The diagram below shows schematically how the color magnitudes represent the brightness of a star in different parts of its spectrum and how the color magnitudes compare depending on the surface temperature of the star. The letter F, with a Greek letter lambda, λ , subscript, along the vertical axis of the diagram represents monochromatic flux or brightness.



For a hotter star : $F_{\lambda B} > F_{\lambda R}$ > 50 $\left\{ \begin{array}{l} B < R \\ B > R \end{array} \right.$

For a cooler star: $F_{\lambda R} > F_{\lambda B}$

COLOR INDEX (CI): Difference of 2 color mags
 E.G. B-V, U-B, V-I, etc.

The B-V color index is the one most frequently used.

When properly calibrated, color index indicates temperature as listed below:

B-V	Temp (K)
-0.30	33,000
-0.15	14,800
0.00	9,600
+0.50	6,500
+1.00	4,800
+1.52	3,600

E.G. 1
 $B = 9.10, V = 8.50$
 Hence:
 $B - V = 9.10 - 8.50 = +0.60$
 Hence $T \approx 5500 \text{ K}$

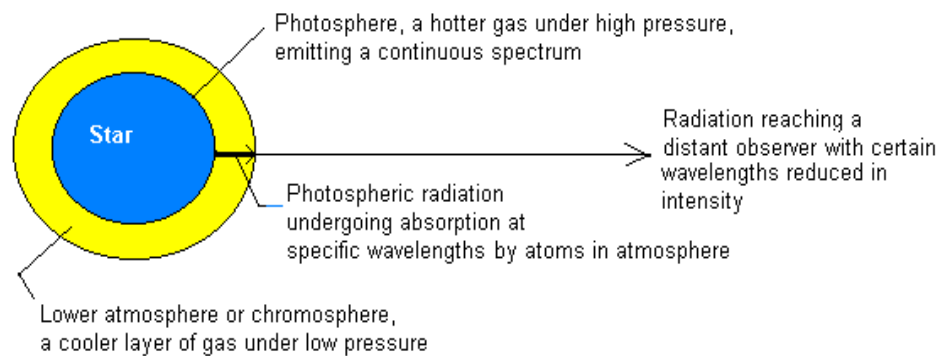
E.G. 2
 If $B = 4.40$ & $V = 4.60$
 Then $B - V = 4.40 - 4.60 = -0.20$
 Hence. $T = 20,000 \text{ K}$

E. The Formation of Stellar Spectra

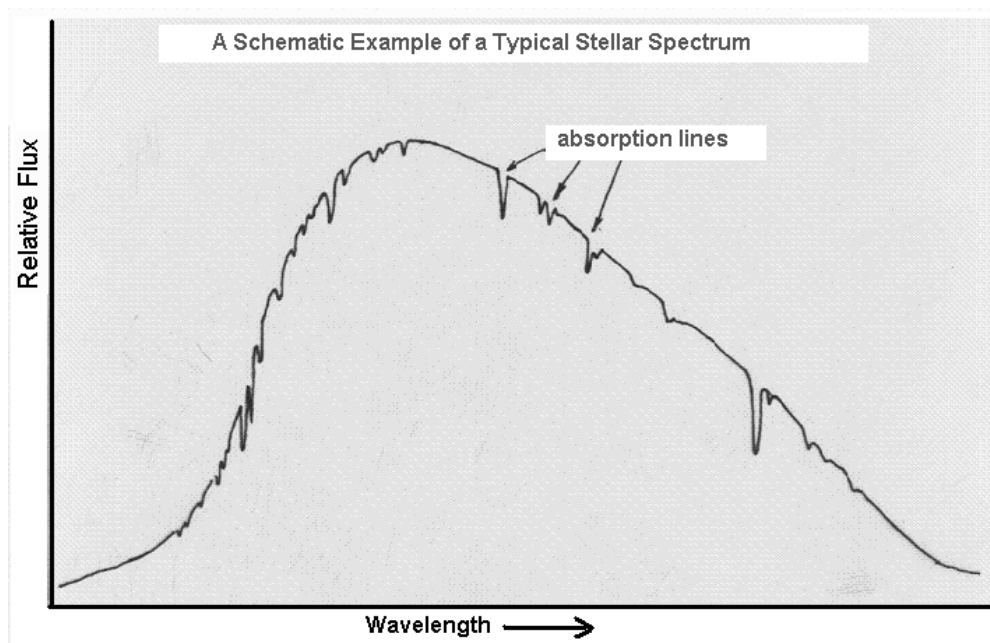
Radiation leaving the surface or photosphere of a star must travel through the star's atmosphere before getting into space. The atmosphere of a star selectively absorbs radiation at specific wavelengths that

correspond to energy levels in the atoms comprising the star's atmosphere. Therefore, a star's spectrum has dips in the intensity at many wavelengths, corresponding to the light absorbed by the atoms in a star's atmosphere.

The adjacent diagram schematically illustrates how such a spectrum is formed in a star. The surface or **photosphere** of a star is a hot gas under high pressure. According to Kirchhoff's 1st Law of Spectroscopy, the photosphere of a star should emit a continuous spectrum, as described by Planck's Law. However, this radiation must pass through the star's atmosphere, the lower part of which is called the **chromosphere**, before reaching the observer. The chromosphere is a cooler gas under low pressure. Hence, the atoms in the chromosphere absorb some of the photospheric radiation at the same wavelengths the atmospheric gas would radiate if it were hotter. Therefore, the light from the photosphere that emerges from the atmosphere will have discrete wavelengths weakened by this absorption. These places in the spectrum will then appear as dark lines in accordance with Kirchhoff's 3rd Law of spectroscopy. The term "strength of a spectral line" refers to the total amount of radiation that is absorbed from the spectrum. This is related to the total area within the spectral line profile. **The strength of a spectral line depends mainly on the temperature of the chromosphere but it is also related to the abundance of the element producing the line.**



In reality, stellar spectra are very complex and contain thousands of spectral lines, many of which overlap one another. The diagram below shows a more realistic depiction of a stellar spectrum, but even it is a bit simplified. Note that there are many lines, some of which are stronger than others.



F. Spectrochemical Analysis

The absorption or dark lines in a star's spectrum make it possible to identify what atoms are present causing the absorption. That is, the absorption lines act like finger-prints for determining the chemical composition of a

star's atmosphere. Since there is evidence that the composition of the atmosphere is very nearly the same as the interior of the star, one has determined the chemical composition of the entire star.

The determination of the chemical composition of a star is based on the following, which is called the Principle of Spectrochemical Analysis:

Every element consists of atoms that absorb or radiate energy at a unique set of wavelengths that are characteristic of the atom's structure.

(Memorize this principle.) Hence, these wavelengths serve as a means of identification of the presence of a given atom in the source of the radiation. The spectrochemical analyses of the stars have resulted in the following abundances by number of atoms:

H 75%
He 22%

The elements Ne, O, N, C, Mg, Ar, Si, etc. together amount to about 2 to 3% and are categorically referred to as "metals" by astrophysicists. The abundances for a planet such as the Earth are much different.

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