CHAPTER 7

Electromagnetic Radiation and Spectroscopy

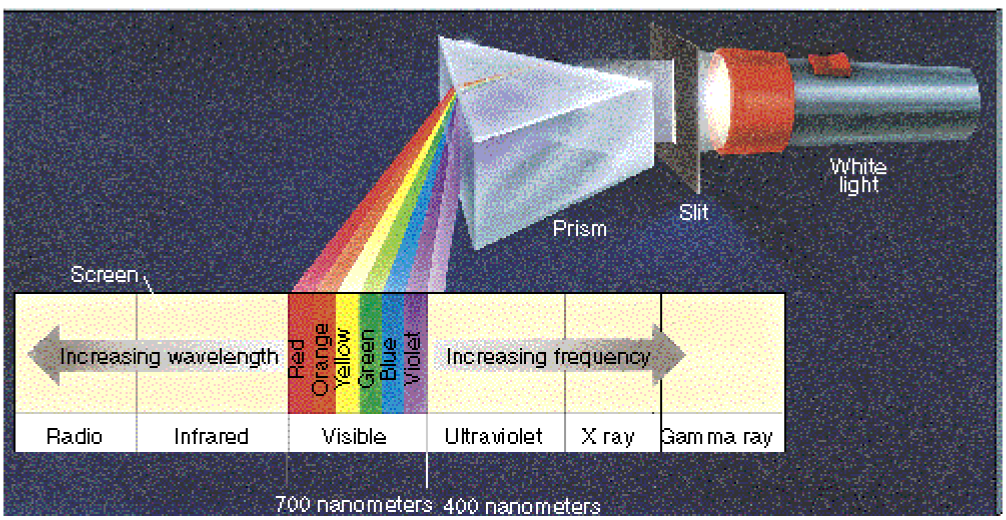
7-A. Properties of Light

Light is a phenomenon, which we may imagine consists of electromagnetic waves. The wavelength of an electromagnetic wave, λ, is the distance between adjacent crests of a wave. Wavelength is distance, so the units for expressing wavelengths are distance units. Wavelengths in the visible spectrum are so small, it is impractical to express them in meters or even centimeters. A unit commonly used is the nanometer (nm), that is 1 billionth of a meter. Another unit is the Angstrom (Å) which is 10^{-8} cm; 10 Angstroms equals 1 nanometer.

All electromagnetic waves, regardless the wavelength, travel with the same speed in a vacuum. This is called the speed of light, c, and has been measured very precisely to be 2.998×10^{8} m/s. Another property of EMR is the frequency, ν or f. These three properties of EMR are related by the expression:

$$c = \lambda\nu$$

It is the wavelength or frequency of radiation that determines what color the human eye perceives amongst the visible radiations. Red light consists of much longer wavelengths than violet. Orange, yellow, green and blue light have increasingly shorter wavelength waves than red until we reach violet. Radiation with wavelengths shorter than violet wavelengths are radiations we call ultraviolet, x-rays, and finally gamma rays. Wavelengths longer than those of red light are infrared, microwaves, and radio waves. Infrared radiation was discovered by Sir William Herschel in 1800, by placing thermometers in different parts of the spectrum of sunlight. Johann Ritter discovered ultraviolet light by placing silver chloride in that region of the spectrum.



All of these groups of EM waves comprise what is called the total electromagnetic spectrum. The total EM spectrum is a continuous, lateral display of all the different possible wavelengths of EM radiation. White light, like sunlight, is actually a mixture of all the visible colors. This is illustrated in the diagram above, which depicts a beam of white light from a flashlight being dispersed by a prism into a spectrum. In reality, the flashlight does not generate any radiation short of violet or longer than the short infrared radiation. Radiation consisting of a unique wavelength is referred to as **monochromatic** (one color) radiation, whereas a beam of radiation that consists of many different wavelengths is called **polychromatic** radiation.

It is the amplitude of the wave that is related to the amount of energy carried by the wave. In the quantum theory of radiation, light is composed of photons. Each photon carries a distinct amount of energy given by the equation $E = h\nu$, where h is Planck's constant and has value equal to 6.623×10^{-34} J·s.

A clear distinction must be made between emission and reflection. We see things around us by reflection when they are cool (<1000K). In this case, the source of the light (the illuminating source) is external to the object we see. The Sun and light bulbs are illuminating sources of white light. The walls of a room at room temperature, you, the Moon, and the planets are seen by reflected light.

If we see an object by reflection, it may absorb certain wavelengths and reflect certain others. Whenever radiation is absorbed, the absorbed radiation is converted into heat or thermal energy within the absorber. This energy is quickly shared by all the atoms making up the absorber. The greater the amount of kinetic energy there is per atom, the higher the temperature.

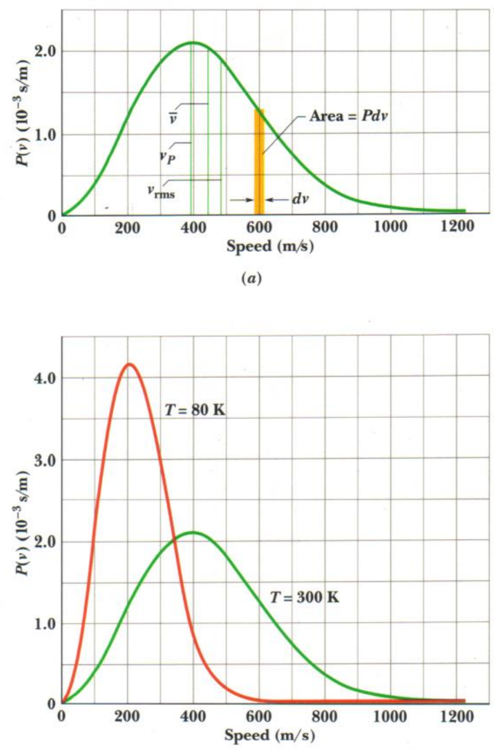
7-B. Kinetic Theory

Temperature is an index of the amount of kinetic energy there is per atom within a material. The expression relating the average kinetic energy per molecule or atom to temperature is:

$$\frac{1}{2}mv^2 = \frac{3}{2}kT.$$

In this equation, m is the mass of the particle, v is the speed of the particle, k is the Boltzmann constant and has a value equal to 1.38×10^{-23} J/K.

The higher the temperature, the greater the speed of the atoms in a gas or liquid or the faster the atoms vibrate in a solid. The relationship between the speed of molecular motion and temperature was derived by Maxwell and Boltzmann and is now known as the Maxwell-Boltzmann velocity distribution function.



(a)

(b)

$$dN_v = N[(4/\pi^{1/2})(m/2kT)^{3/2}v^2\exp(-mv^2/2kT)]dv$$

N is the total number of particles in the system. We may write $dN_v = NP(v)dv$, where P(v) is the red factor enclosed in the square brackets. P(v) is the probability of finding a particle or molecule with speed between v and v+dv. Now the argument of the exponential is dimensionless and the factor $(m/2kT)^{3/2}v^2$ has units of reciprocal speed, and hence, so does P(v). It therefore follows that P(v)dv is dimensionless. It must be then that $\int_0^\infty P(v)dv = 1$, which is the area under the curves shown to the right. Furthermore, it follows that,

$$\int_0^\infty \frac{dN_v}{dv}\, dv = N.$$

Assignment 7-B1:

Write a program that numerically integrates P(v)dv from 0 to 2000 m/s for nitrogen gas at T = 100K and see how close this comes to being 1.00. Take dv to be 10 m/s.

7-C. Laws of Radiation

Emitted light comes from an internal source of energy. Things that emit light are the Sun, stars, light bulbs, and fires. In other words, incandescent things are hot and obey the Stefan-Boltzmann Law. Actually, all objects obey the Stefan-Boltzmann Law, but if an object's temperature is <1000K, it is not hot enough to emit discernable visible light. However, it may emit weak infrared radiation.

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. That is, the energy source for emitted radiation is the heat or thermal energy in the body.

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. Bodies that radiate this way are called incandescent bodies. Stars are incandescent bodies. In order to understand this, and be able to apply these concepts to the stars, we now turn to a discussion of the laws of radiation for incandescent bodies.

The type and amount of electromagnetic radiation emitted per unit area by an object depends only on that body's surface temperature. The higher the temperature, the greater the total amount of radiation emitted per unit area per second, or flux, F. This is given quantitatively by the Stefan-Boltzmann Law,

Stefan-Boltzmann Law: $B = \sigma T^4$,

where σ (or sigma) is a known number or constant of proportionality between B and T. B is the intensity of the radiation and, in astronomy, is defined as the energy radiated per unit area per second per steradian over the entire EM spectrum . T must be the absolute temperature expressed in Kelvins.

Also the higher the temperature the greater the amount of short wavelength radiation emitted. Which color or wavelength is the most intense is given by Wien's Law. Wien's Law gives the wavelength emitted with maximum intensity (WL_{max}) for a given temperature, T as:

Wien's Law: $WL_{max} = a/T$,

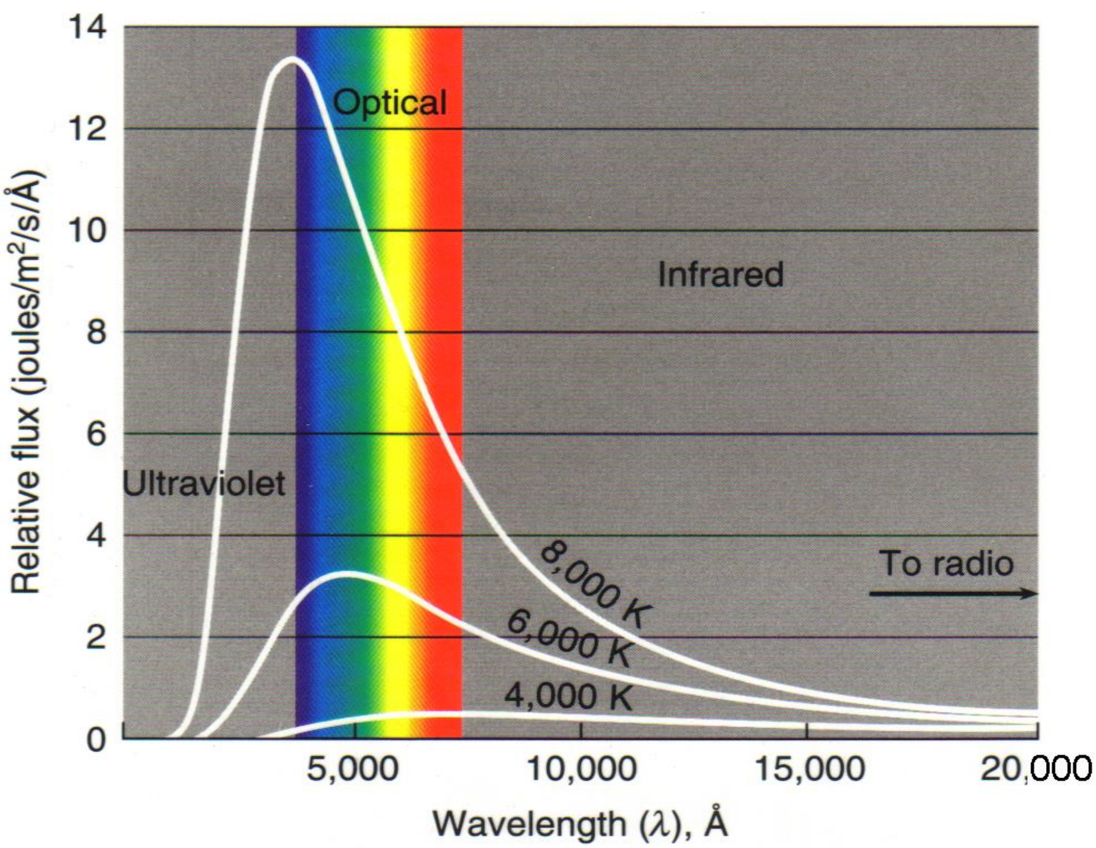
where "a" is a constant of proportionality.

In 1901 Planck was able to theoretically derive an expression that related the temperature, wavelength and monochromatic intensity, B_λ, of thermal radiation. To accomplish this, Planck introduced quantum theory.

Planck's Law is:

$$B_\lambda = \frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT}-1}\right]$$

When B_λ is integrated over all wavelengths, one gets what is called the ***bolometric*** intensity, which is what is given by the Stefan-Boltzmann Law. When B_λ is multiplied by π, we get monochromatic flux, F_λ, in units of Joules/m^2/s/wavelength unit. The latter may be Angstroms (Å) or nanometers (nm). Flux is the result of integrating the Planck function over all directions (4π steradians). B_λ or F_λ is also known as black body radiation. The diagram below shows how F_λ varies with



wavelength for several different temperatures. Integrating F_λ over all wavelengths yields what is called the ***bolometric*** flux, F_{bol}, or bolometric surface brightness of the star. Remember we have suppressed any time dependency for these expressions.

Inverse Square Law:

The above expression for monochromatic flux, F_λ, is only valid at the surface of a star of radius R_*. But radiation suffers and inverse square dilution factor, so that at some distance r, the observed flux, $F_\lambda(r)$, is:

$$F_\lambda(r) = F_\lambda(R)[R_*/r]^2$$

7-D. Spectroscopy, the Study of Spectra

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.

One way to determine the temperature of a star is to study how bright the component colors are in the star's light and then apply Wien's Law. To accomplish this, we must spatially separate the different wavelengths and form what is called a spectrum. Studying spectra is called spectroscopy.

Sir Isaac Newton was the first to demonstrate that sunlight, or white light is polychromatic radiation. That is, white light it is a mixture of all the wavelengths that make up the visible spectrum. By means of further experiments, Newton demonstrated that each of these colors could not be further separated into any other colors. These were the first experiments in spectroscopy and therefore, Newton is considered the father of spectroscopy.

An example of a spectrum in nature is the rainbow. Here raindrops in the Earth's atmosphere sometimes 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 way raindrops produce a rainbow of sunlight.

To produce a star’s spectrum, an instrument is attached 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. As discussed previously, the distribution of brightness with wavelength for incandescent bodies is given theoretically by Planck's Law. Stars are incandescent bodies. A graph of spectral brightness distribution (Flux versus wavelength) was shown above. 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=0K, 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 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 along the 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.

It has been found that the surface temperatures of stars range from 50,000K to about 2500K for the coolest stars. The Sun has a surface temperature of about 5800K.

Upon closer examination, stellar spectra are somewhat different than the Planckian curves shown in the diagram above. A star's spectrum has dips in the intensity at many wavelengths. These dips are very narrow and are called "dark lines or absorption lines". To understand why this is so we first turn to Kirchhoff's Laws of Spectroscopy

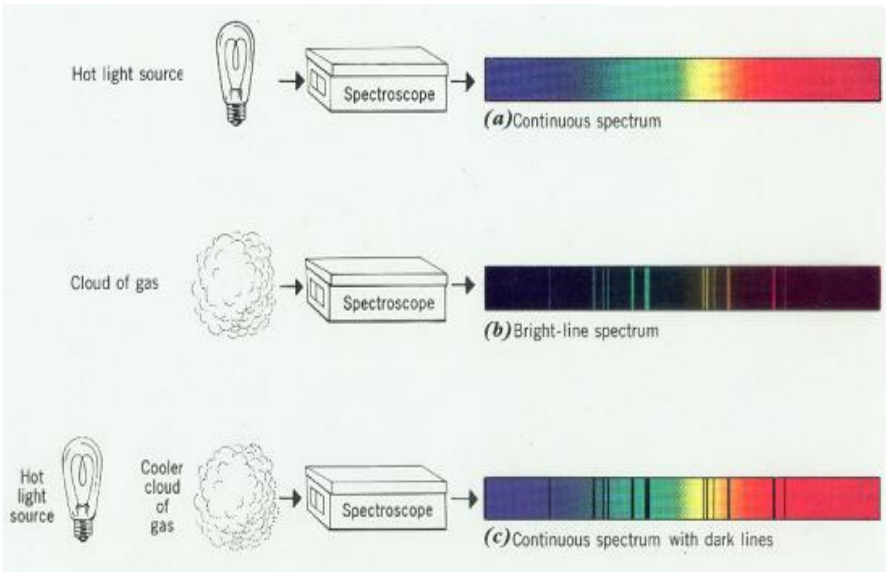
From laboratory studies, it is known that there are different kinds of spectra. In 1859, Kirchhoff studied this and made 3 conclusions regarding the type of spectrum observed and the physical properties of the body

1. **A hot or incandescent solid, liquid, or gas under high pressure radiates a continuous spectrum.**

2 **A hot or incandescent gas under low pressure radiates a bright line or emission spectrum.**

3. **When a source radiating a continuous spectrum is viewed through a layer of cooler gas under low pressure, one sees a dark line, Fraunhoffer, or absorption line spectrum.**

The three laws are schematically illustrated below:



The appearance of stellar spectra is in accordance with Kirchhoff's 3rd Law. We know discuss the physics underwriting Kirchhoff's Laws?

Emission is an atomic process that converts thermal energy to EM energy. Thermal energy, or heat, is related to temperature in some way. As discussed in section 7-2, temperature is an index of the average KE per atom in a substance. Kinetic energy is the energy an atom in gas has by virtue of its motion or speed. The faster the speeds of the atoms in a gas, the greater their KE is and hence the higher the temperature of the gas.

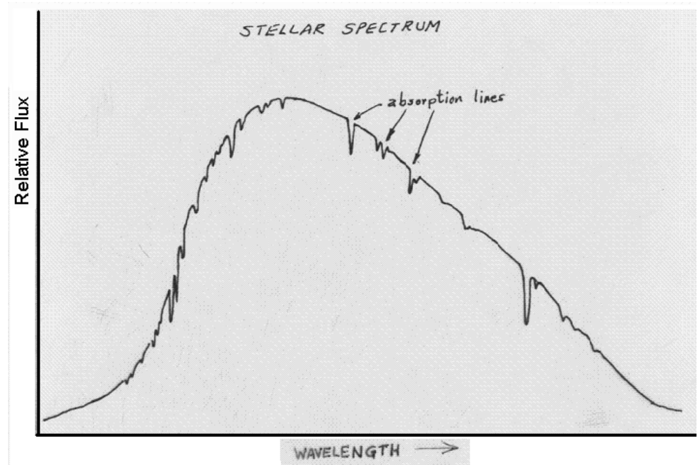
The atoms in a hot gas are constantly colliding with one another. The higher T, the more intense are their collisions with one another. During a collision, some of the KE they carry is imparted to the outer electrons in the atoms. This causes the electrons to jump into higher energy states within the atoms. This is called **collisional excitation**. The electrons are then said to be in excited states. However, the natural tendency of a system is to spontaneously go to a lower energy state. This is the second law of thermodynamics. Therefore, electrons jump down or undergo a transition to their original level almost spontaneously in a time approximately equal to 10^{-8} seconds. To do so, they must give up the energy imparted to them by collision of the atoms. This happens automatically by the electrons emitting a photon of EM energy or emitting a specific WL of EM radiation. The wavelength of radiation emitted is determined by the energy difference between the two transition energy levels of an electron. The greater the energy difference between the 2 energy states, the shorter the WL of the emitted radiation

In general, EM radiation is produced by electrons undergoing a transition from a higher energy state to a lower energy state. In any one given type of atom, such as H, there are many different excited energy states or levels available to the electron. Also, the energy states available to the electrons in an atom varies from one type of atom to another. So, uniquely different wavelengths of radiation are emitted by different atoms in a hot gas, if it is under low pressure. This is the physics behind Kirchhoff's 2nd Law.

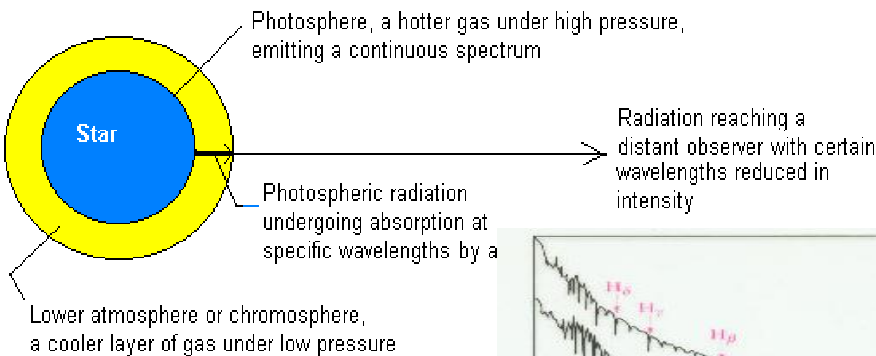
If the gas is under high pressure the atoms collide with one another very frequently and with great intensity. This disturbs the energy states in an atom and blurs them out over a wide range of energy differences from one atom to another. In this case, all the atoms, of a given type, are no longer emitting the same unique wavelengths. This is the physics behind the 1st Law.

The 3rd law is more complex and involves another physical aspect about electron transitions, called **photoexcitation.** If an electron is struck by a photon of exactly the right wavelength, it will absorb that photon and undergo a transition to a higher energy state. In a relatively cool gas, most electrons are in their lowest energy states or ground states. This makes it more probable that the electrons will absorb photons rather than emit them. But the photon must have exactly the energy difference between the two states. This requires that the photon carry an amount of energy = hc / WL, where h is called Planck's constant. This is the key point for understanding Kirchhoff's 3rd Law. The dark lines in a dark line spectra indicate the specific wavelengths of light that have been weakened by absorption as the light passes through a relatively cool cloud of gas under low pressure.

Stellar spectra are predominantly absorption line or dark line spectra as schematically depicted to the right. There is an overall trend in the spectroscopic flux that is similar to a Planckian curve, but this trend in interrupted by numerous absorption lines. In most cases, the absorption is not total and there is usually a large amount of flux remaining at the center of the line.

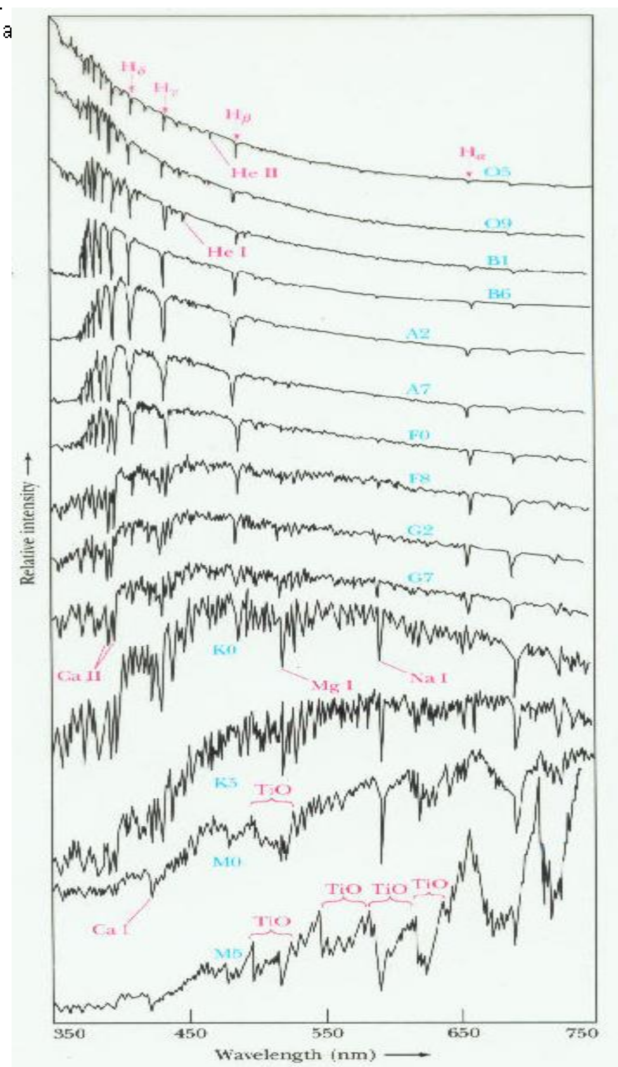


The adjacent diagram schematically illustrates how such a spectrum is formed in a star. The surface or **photosphere** of a star is a hot gas under high pressure. According to Kirchhoff's 1st Law of Spectroscopy, the photosphere of a star should emit a continuous spectrum, as described by Planck's Law. 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 adjacent diagram shows a more realistic depiction of various stellar spectra. Note that there are many lines, some of which are stronger than others.



7-E. The Quantum Theory of Radiation

In 1915**,** Niels Bohr, a Danish physicist, developed a new model of the atom based on E. Rutherford's scattering experiments, Planck's concept of the quantization of energy and momentum, and experimental spectroscopy. This model successfully predicted the measured wavelengths that were emitted or absorbed by an atom. In the Bohr model, the electrons in an atom occupy orbits or states that are associated with a definite energy and they cannot have any other energy. The energy of the nth state is given by:

$$E_n = - 2\pi^2 m_e Z^2 e^4 / n^2 h^2 = -13.6(Z^2/ n^2). \quad (7\text{-}5.1)$$

The values for the constants in the above equation are such that the energy units are electron volts (ev), where 1 ev = 1.60 x 10^{-12} ergs = 1.60 x 10^{-19} Joules.

For hydrogen, Z=1, in which case $E_n = -R' /n^2$, where R' = -13.6 ev = 2.18 x 10^{-11} erg. Now, the difference between two electron energy states *a* and *b*, where *b* is the lower energy state and *a* is a higher energy state is

$$\Delta E_{ab} = h\nu = hc/\lambda \quad (7\text{-}5.2)$$

Here the difference in energy corresponds to an absorbed or emitted photon with a corresponding wavelength λ. We now define wave number to be $1/\lambda$. Combining (7-5.1) and (7-5.2) for any two electron states of hydrogen we have:

$$1/\lambda_{ab} = (R'/ch)[1/n_b^2 - 1/n_a^2] =R[1/n_b^2 - 1/n_a^2] \quad (7\text{-}5.3)$$

State b is the lower energy state and R =109,737.31 cm^{-1}, is called the Rydberg constant. Equation (7-5.3) is called the Balmer Equation, since Balmer empirically devised it from spectroscopic studies.

For each value of n_b and different values of n_a, a series of spectral lines is produced

n_b	SERIES NAME	
1	Lyman	UV; All transitions to ground state from higher energy states
2	Balmer	VISIBLE; All transitions to 1st excited state from higher states
3	Paschen	IR
4	Brackett	IR
5	Pfund	IR
6	Ritz	IR

Consider the Balmer series of spectral lines, most of which are in the visible portion of the spectrum but merge to the **Balmer limit** in the UV. The first line of the series is referred to as the H_α line and represents the transition from $n_a = 3$ to $n_b = 2$. Let us compute the wavelength of this line. From (7-5.3) we have:

$$1/\lambda_{H\alpha} = R[1/n_b^2 - 1/n_a^2] = R[1/2^2 - 1/3^2] = 15{,}241.3 \text{ cm}^{-1}$$

$$\lambda_{H\alpha} = 6.5611 \times 10^{-5} \text{ cm} = 6561.1\text{Å, since 1Å is } 10^{-8} \text{ cm.}$$

The actual laboratory measured value is 6562.85Å. The difference results from not taking into account what is called the reduced mass. That is, in the derivation of (7-5.1), the assumption was that the electron orbited around the center of the nucleus rather than a common barycenter. In addition, Sommerfeld added a relativistic correction for the electron, thereby getting better agreement between theory and measurement.

As n gets larger, the energy states get closer together until they finally merge into a continuum as n goes to infinity. The wavelength for $n_a = \infty$ is called the series limit, which is given by:

$$\frac{1}{\lambda_{lim}} = R\left(\frac{1}{n_b^2} - \frac{1}{\infty}\right) = \frac{R}{n_b^2} \qquad (7\text{-}5.4)$$

For the Balmer Series:

$$\frac{1}{\lambda_{lim}} = \frac{R}{2^2} = \frac{R}{4} = \frac{109737.31}{4}$$

$$\lambda_{lim} = \frac{4}{109737.31}\ cm = 3.64510 \times 10^{-5}\ cm$$

$$\lambda_{lim} = 3645.10\ \mathring{A}, \text{ which is in the UV.}$$

The Balmer limit is the beginning of what is called the Balmer continuum or Balmer confluence of spectral lines. Similar terms are used for the other spectral series. The electron states and transitions are depicted schematically in Fig. 5 and Fig. 6 schematically depicts the spectrum of the Balmer lines. The wavelength for the Balmer limit is indicated in Fig. 6 by H∞.

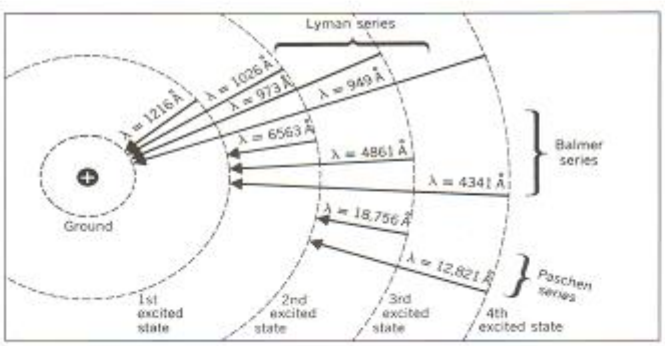


Fig. 5. Energy transitions for Hydrogen

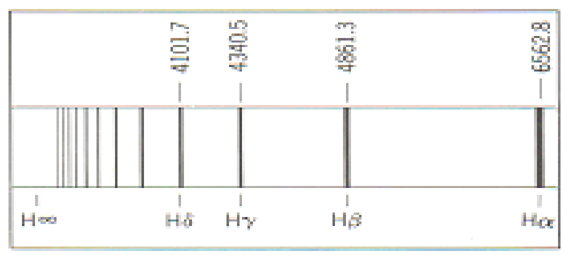
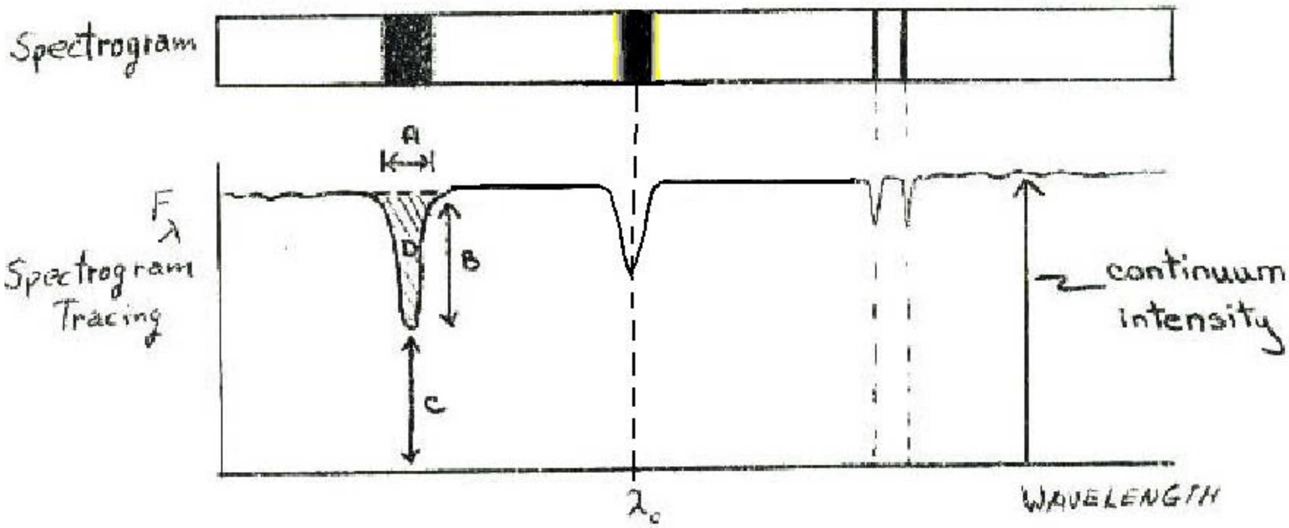


Fig. 6. A schematic spectrogram for the first few spectral lines of the Balmer Series.

7-F. Spectral Line Characteristics

Much information about stars may be gleaned by studying there spectra. Before we can begin to discuss how to decipher stellar spectra, we must first become acquainted with the terminology that spectroscopists use in describing the measurable properties of spectral lines. A schematic spectrogram and its spectrophotometric scan are depicted in the diagram below. Several different spectral absorption lines of different properties are drawn. The term "line profile" is used to refer to the actual shape of the conical dip in brightness of the continuum for the representation of a line in a spectrophotometric tracing or scan. The geometric properties of the profile for the leftmost absorption line are labeled A, B, etc., which are defined as follows:



A. The full width of the line in Angstroms. Sometimes spectral line widths at half the maximum depth of the line are quoted and are referred to as "FWHM" values. The minimum width of a line depends on the Heisenberg uncertainty principle. This is called the natural width, which is a very small fraction of an Angstrom. If the width of the line is broader than the natural width, the line is said to be broadened. One broadening mechanism is the pressure in the gas. This mechanism is called Stark broadening. Lines are also broadened by several Doppler effects:

1. The star's rotation. Rotational broadening usually dominates in stellar spectra.
2. Thermal motions in the gas.
3. Turbulence in the gas.
4. Convective motions in the atmosphere.

Doppler motions do not affect the strength of a line.

B. The depth of the line. This is sometimes given as a fraction of the continuum flux level or intensity. E.G., 0.48. A line's depth is sometimes given in place of line strength but is otherwise not very useful.

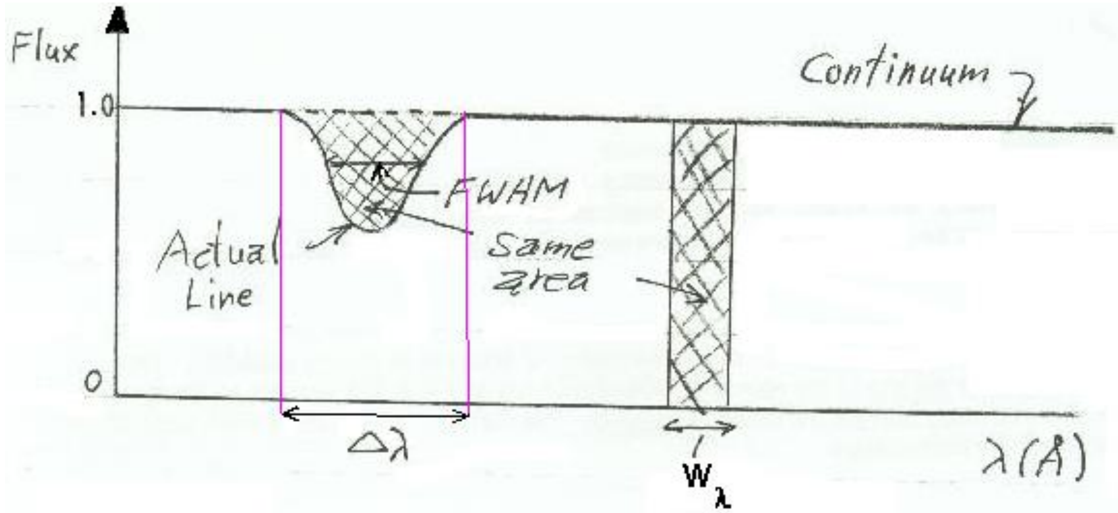
C. The flux level at the bottom of the line. This is usually given as a fraction of the continuum level. E. G., 0.52. This parameter has limited use also.

D. Line strength, which is the total area within the line profile and represents the total amount of flux or energy absorbed by the atoms in the gas. Line strength depends on the total number of photons that have been absorbed or emitted along the line of sight. This in turn depends on:

1. The temperature of the atmosphere of the star *vis a vis* the mechanisms of excitation and ionization of the element.
2. The "oscillator strength" or transition probability for a line. This comes from quantum mechanical considerations.
3. The number density of atoms in the atmosphere and, hence, the abundance of the element.

Also λ_c indicates the central wavelength of a line. This is the quoted wavelength of a line or the value that is computed from the Balmer equation (7-5.3). A line profile may or may not be symmetrical about the central wavelength depending on several complex matters.

Line strength is often given in terms of its "equivalent width", W_λ, which is used in conjunction with a normalized continuum level. The diagram below shows a representative absorption line on the left with its strength indicated by the shaded area in the line's profile and its total width $\Delta\lambda$. The FWHM of the line is also indicated. The rectangular absorption feature on the right has the same profile area as the actual line on the left but with a total line width



of W_λ. Notice that W_λ is less than $\Delta\lambda$. Equivalent widths, W_λ, are given in Angstroms and defined by:

$$W_\lambda = \int_{\Delta\lambda} (I_c - I_\lambda)/I_c \, d\lambda \qquad (3\text{–}14)$$

Here the integration is over the full width of the line, $\Delta\lambda$. Equivalent widths are determined and studied in stellar spectra in order to determine the temperature of the star and its chemical composition.

7-G. Spectrochemical Analysis

Studying the spectrum of an object, such as a star, makes it possible to determine the chemical composition of that object. To accomplish this in general, one applies the Principle of Spectrochemical Analysis:

Every element consists of atoms that emit or absorb radiation at a unique set of wavelengths that are characteristic of the structure of that atom.

By matching the absorption lines in a star's spectrum with known emission lines for the different elements, we identify what elements are present in the atmosphere of the star. By studying the equivalent widths of the lines, we determine the abundance or how much of a specific element is present in the star. More specifically, one measures the equivalent widths of many spectral lines that are the result of electron transitions taking place in a specific atom. One then plots the measured equivalent widths versus theoretically computed abundances to determine the abundance. This method is called the **Curve of Growth Method**.

Results: Stars are approximately 75% H, 22%He, and 2 to 3% metals, which is all other elements, Li thru U.

7-H. Spectroscopic Radial Velocities

7-H.1 The Doppler Effect

In 1842, C. Doppler discovered that:

Any wave phenomenon, emitted by a source that is moving relative to an observer, is found to have wavelengths, λ, different than what would be observed if there were no relative motion.

This is known as the **Doppler Effect**. It does not matter if the source is moving and the observer is at rest, the observer is moving and the source is at rest, or whether both are moving. Furthermore, only the component of the relative velocity or speed along a line connecting the observer and the source (the radial direction or line of sight) is significant and is called the **radial velocity.** Any component of the relative velocity that is perpendicular to the radial direction does not produce a Doppler effect. **The Doppler Effect applies to both light and sound waves.**

The wavelength observed or measured when there is relative motion is called λ_{meas}. The wavelength observed when there is no relative motion, that is, when the source is at rest with respect to the observer, is called the rest wavelength, λ_{rest}. The difference between these two wavelengths is called the **Doppler shift,** □□, which is defined by:

$$\Delta\lambda = \lambda_{meas} - \lambda_{rest}$$

The greater the relative motion or velocity, the greater the Doppler shift. Hence, the Doppler shift

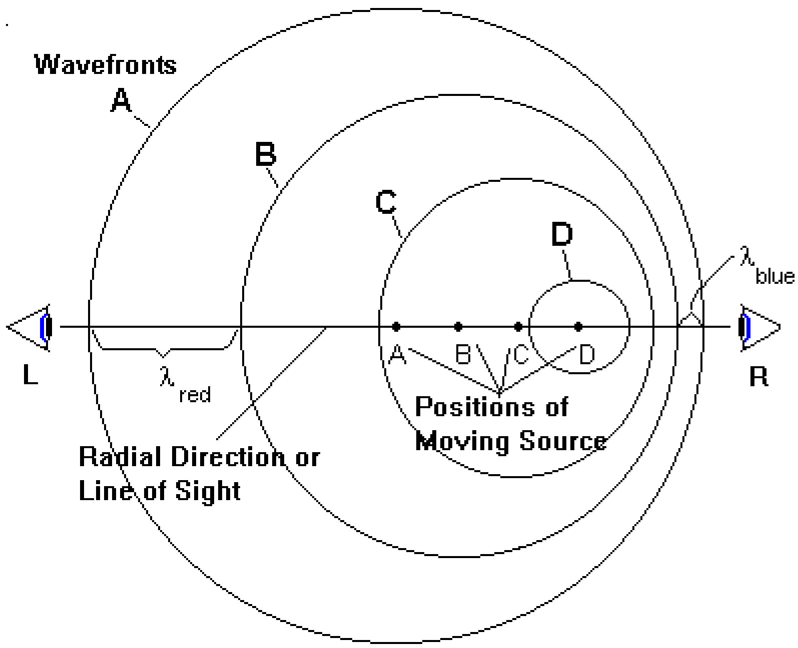


Figure 7H1. The Doppler Effect

is a direct indication of the relative speed of the source of the waves along an observer's line of sight to the source.

When we study the spectra of atoms in the laboratory, we assume that there is no relative motion of the source with respect to the observer. Hence, wavelengths measured in the laboratory are considered rest wavelengths. Therefore, rest wavelengths are also called laboratory wavelengths or λ_{lab}.

Let us discuss the Doppler effect in terms of the light or radiation we observe coming from stars. In Fig. 1, a star is moving along a line between two different observers labeled as L and R, for left and right. When the star was at position A, it emitted a wavefront, which has now expanded to the position shown as **A**. When the star was at position B it emitted a wavefront which has now expanded to position **B**. Similarly for C and D. The star's motion compresses the wavefronts in the direction the star is moving and stretches the distance between the wavefronts in the opposite direction. Hence, for the observer on the right, any spectral line will be measured to have a wavelength that is shorter than the wavelength measured in the laboratory for the atomic species producing that line. In this case, λ_{rest} is greater than λ_{meas} and the Doppler shift is a negative number. Since in the visible spectrum, the shorter wavelengths are blue ones, a negative Doppler shift is called a "blueshift". In astrophysical parlance, when an object is said to have a "blueshift", it means that that object is moving towards the Earth or the Sun.

On the other hand, if a star is moving away or receding from us, as for the observer on the left in the diagram, a specific wavelength of radiation will be measured to have a longer wavelength than that measured in the laboratory. In this case, the Doppler shift will be a positive number and it is said that the Doppler shift is a "redshift." Hence, when astronomers say a star, planet, or galaxy has a redshift, it means that object is moving away from us. Furthermore, the speed of recession or approach is proportional to the amount of the Doppler shift.

Examine the diagram below (Fig. 2) which shows schematic spectra for three different cases of relative motion. The top spectrum shows the spectrum of a star that is approaching us and, therefore, the various spectral lines are blueshifted. The middle spectrum is an emission spectrum emitted by a mixture of gases producing the same spectral lines in the laboratory. The spectral lines in this spectrum have wavelengths that are considered to be rest wavelengths. The values of these rest wavelengths in Angstroms (Å) are written at the top of the diagram The bottom spectrum is one for a star that is receding from us. Its spectral lines are redshifted with respect to the laboratory wavelengths. In the diagram, the Doppler shifts are exaggerated for clarity.

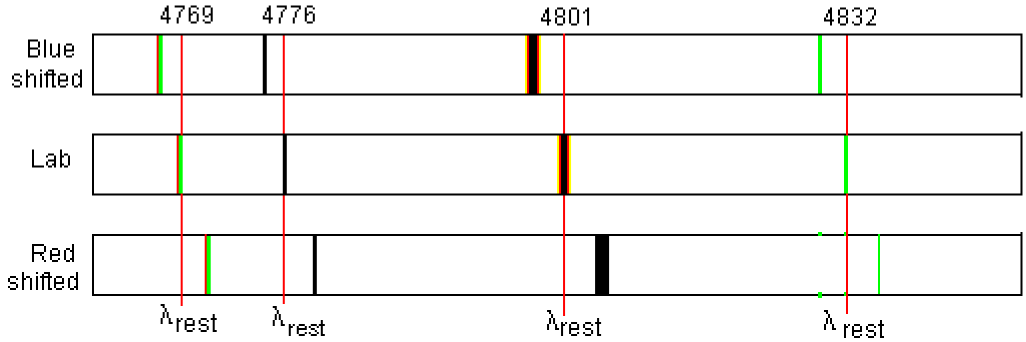


Figure 7H2. Schematic spectra illustrating Doppler Shifts for 3 different cases.

7-H.2. Calculating Radial Velocity

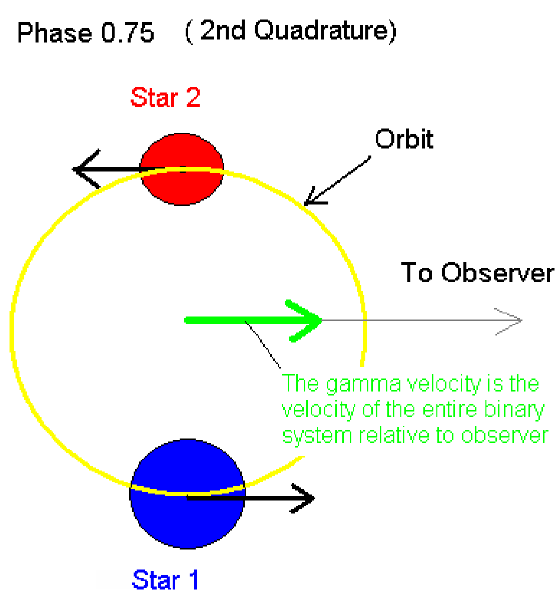
Now consider the 4801A line in the top spectrum of Fig. 2. The Doppler shift for this spectral line has been measured to be: $\Delta\lambda = -2.9$ Å. The minus sign indicates that the Doppler shift is a blueshift. The relative speed of this star along the line of sight, which is called the radial velocity, **v,** can be calculated using Doppler's equation:

$$\mathbf{v} = (\Delta\lambda / \lambda_{rest})\, c$$

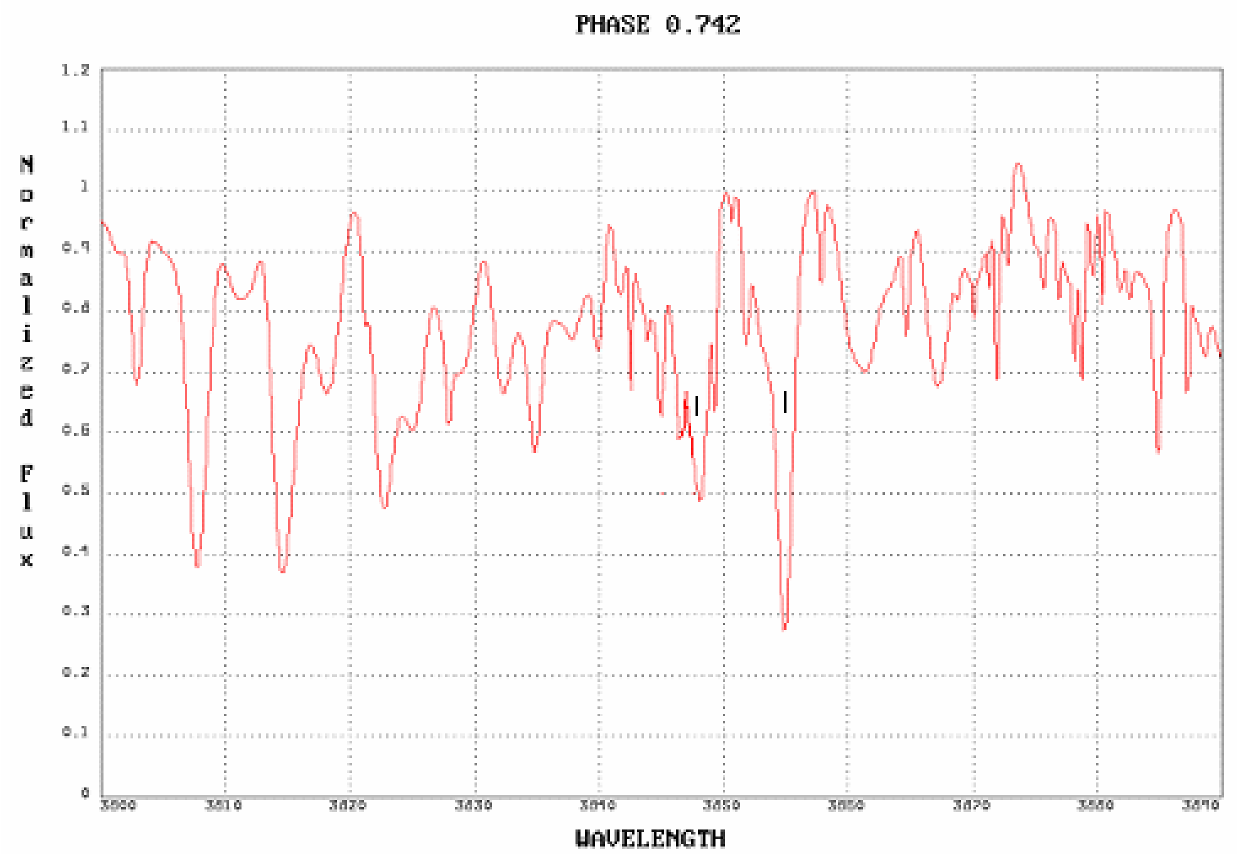
In this equation $c = 3 \times 10^5$ km/sec, the speed of light. Doing the calculation we obtain that **v** for this star is -181 km/sec. You should verify this calculation. The value of 181 km/sec is rather large for stellar speeds relative to the sun in this part of the galaxy, but it is only meant to illustrate the method of determining radial velocity from a Doppler shift.

7-H.3 Application to Binary Stars

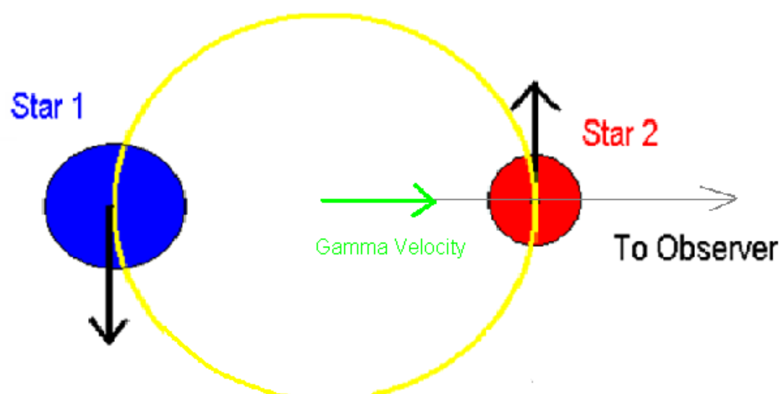
The adjacent diagram is a schematic representation of a binary star system showing the orbital velocities of the component stars at Keperian orbital phase 0.75, which is known as 2nd quadrature. The entire system has a velocity relative to the Sun called the gamma velocity. The orbital velocities of the two stars are superposed on the gamma velocity. The latter may be determined only by a complete analysis of what is called the radial velocity curve for the system.



The figure below shows the spectrum of such a binary star system but at phase 0.742. Notice how the spectral feature near 3852 Å consists of a separate absorption feature for each star separated by about 7Å. A determination of the velocities of the two stars by measuring the Doppler shift of the spectral lines yields a pair of points in the radial velocity diagram.



The next diagram shows the stars near conjunction at orbital phase 0.0. The motions of the stars are now perpendicular to the line of sight and therefore, the Doppler shift in the spectral lines is at a minimum. Hence, there is now what is called minimum Doppler resolution of the spectral lines. However, the gamma velocity of the system results in the combined spectral line to be shifted relative to the rest wavelength of the line. The spectrum then resembles the one shown in the figure below.



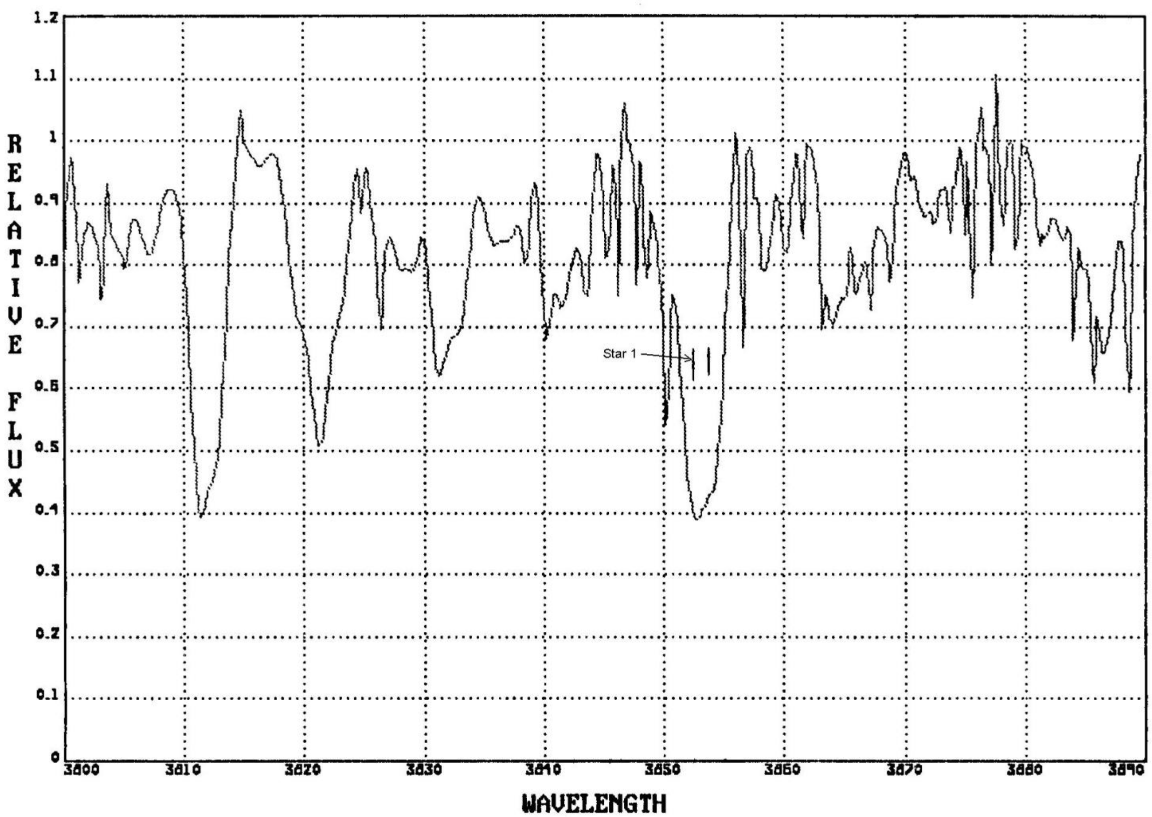
Measuring the radial velocities of the stars in spectra taken at different phases then permits one to construct the radial velocity diagram for the system. An example of such a diagram is shown below. One then draws the best fit to the two separate radial velocity curves, one for each star, taking into account random errors in the data points. The best fit must adhere to the following criteria:

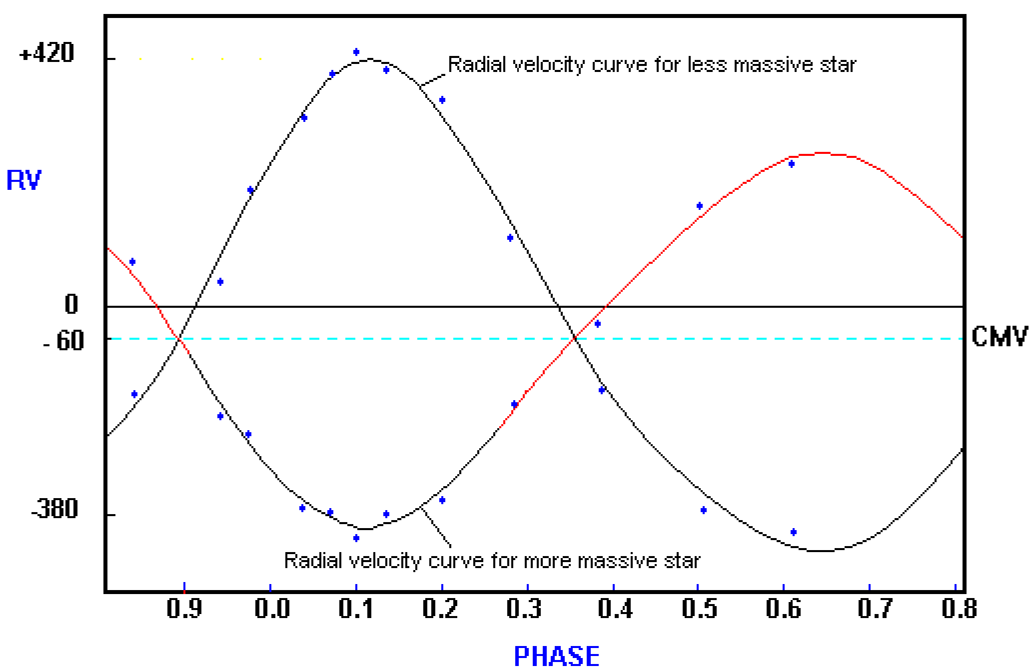
1. The peaks of the two curves must be at the same orbital phase.
2. The two curves must intersect at the same velocity.

When this is done, the velocity at which the two curves intersect is the gamma velocity. In the example below, this is -60 km/s. Also, the mass ratio, q, for the two stars may be found from the semi-amplitudes of the two curves about the gamma velocity.

$$q = \text{mass of less massive star/mass of more massive star} < 1$$

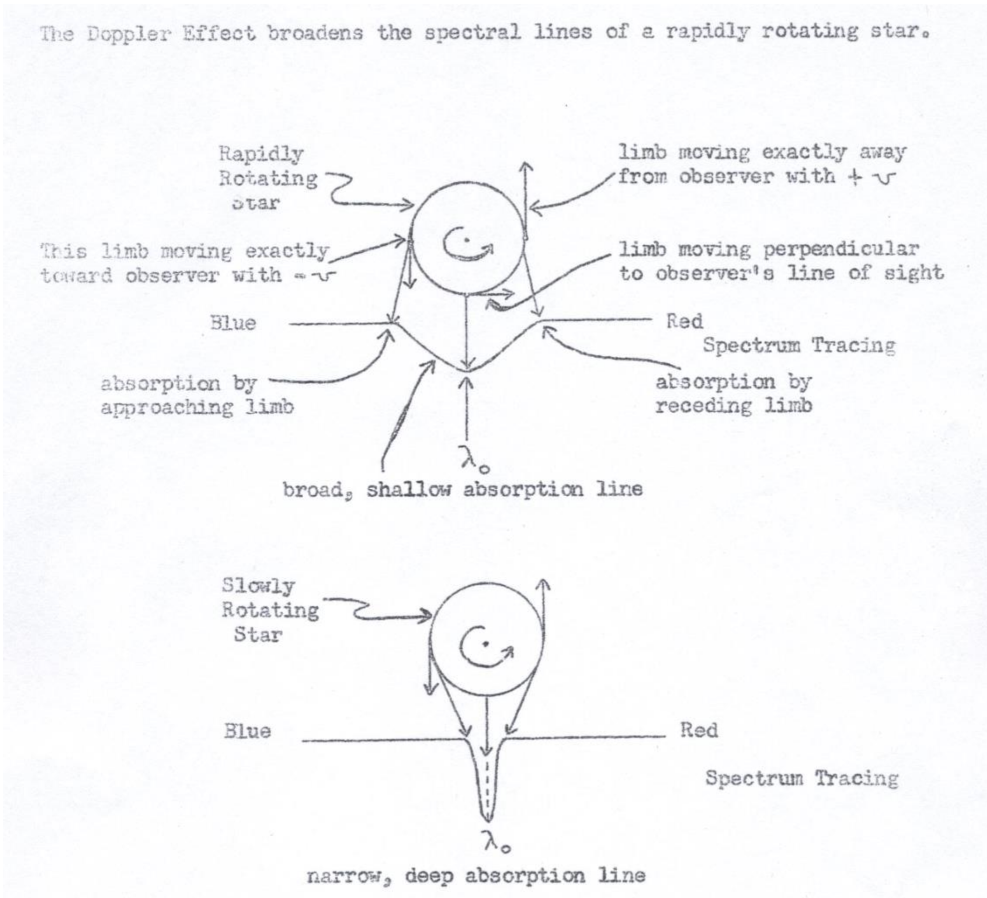
This ratio is the inverse of the semi-amplitudes of the two curves, since the less massive star has the greater velocity.





7-I Rotational Broadening

The Doppler Effect results in the broadening of an object's spectral lines, whether the object be planet, star or galaxy. The more rapidly the rotation is, the broader the lines are. This is illustrated in the diagram below.



Since we cannot see the disk of any star except the Sun, we cannot isolate the light from the two limbs of the star. Hence, we can only observe the spectrum formed by all place on the star's surface at once. The result is a spectrum of broadened spectral lines. The widths of the lines are indicative of the speed of rotation.