

## Chapter 8 Illuminating Light

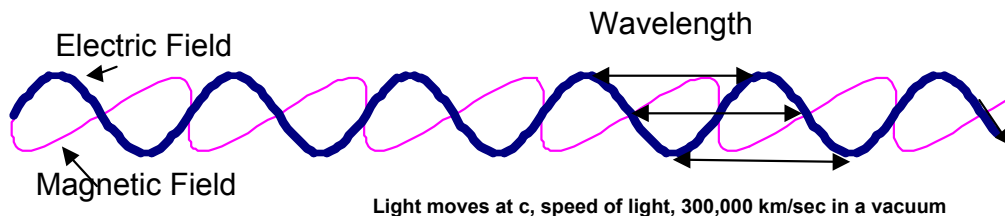
Humans are largely earthbound. To date we have stood only on the Earth and the Moon. We have landed spacecraft on the Moon, Triton, Venus and Mars and have parachuted a probe into the upper layers of Jupiter. We have flown by all the planets except Pluto and have orbited Mercury, Venus, Jupiter and Saturn. We get some samples from the Solar Wind and from meteorites. So how is it that we have the gall to say that we know anything about what planets and stars are made of? Are astronomers just making it up?

Many people think that if an idea is called a "theory" it is one among many equally good notions. In science, many ideas called theories are supported by a large interlocking web of evidence. If a different underlying idea is proposed, it must be consistent with all the known data. Alternate concepts need to address the evidence and be successful in explaining it.

It does happen that there is more than one explanation consistent with the observations, as we saw for the geocentric and heliocentric models of the universe. But eventually the data may distinguish between the models (as happened when the phases of Venus and the parallax of stars was finally observed).

Astronomers are not just spouting off randomly when they describe conditions at places we have not been. They are using the laws of physics and observations.

Light consists of a combination of an electric field and a magnetic field changing strength and direction and moving through space. The structure of light is particularly simple because it always has the layout shown below.



The electric and magnetic fields are at right angles. They are usually at their maxima at the same place. There is no particular direction for the electric field. Since one field creates the other, there is no such thing as just an oscillating electric field moving through space at  $c$  without the magnetic field.

The major feature of light is the wavelength. It tells how long between repeats of the wave. The figure shows the wavelength between peaks of the electric field. But there is nothing special about any part of the wave. The wavelength is the distance between the repeats, however they are arranged.

Light goes at a fixed speed through a vacuum. The speed is called  $c$ , and the numerical value is 300,000 km/sec (This is the same as 186,000 miles/second, but we will be using the metric system). It doesn't matter whether you are moving, light, from whatever source moves at  $c$  with respect to you.

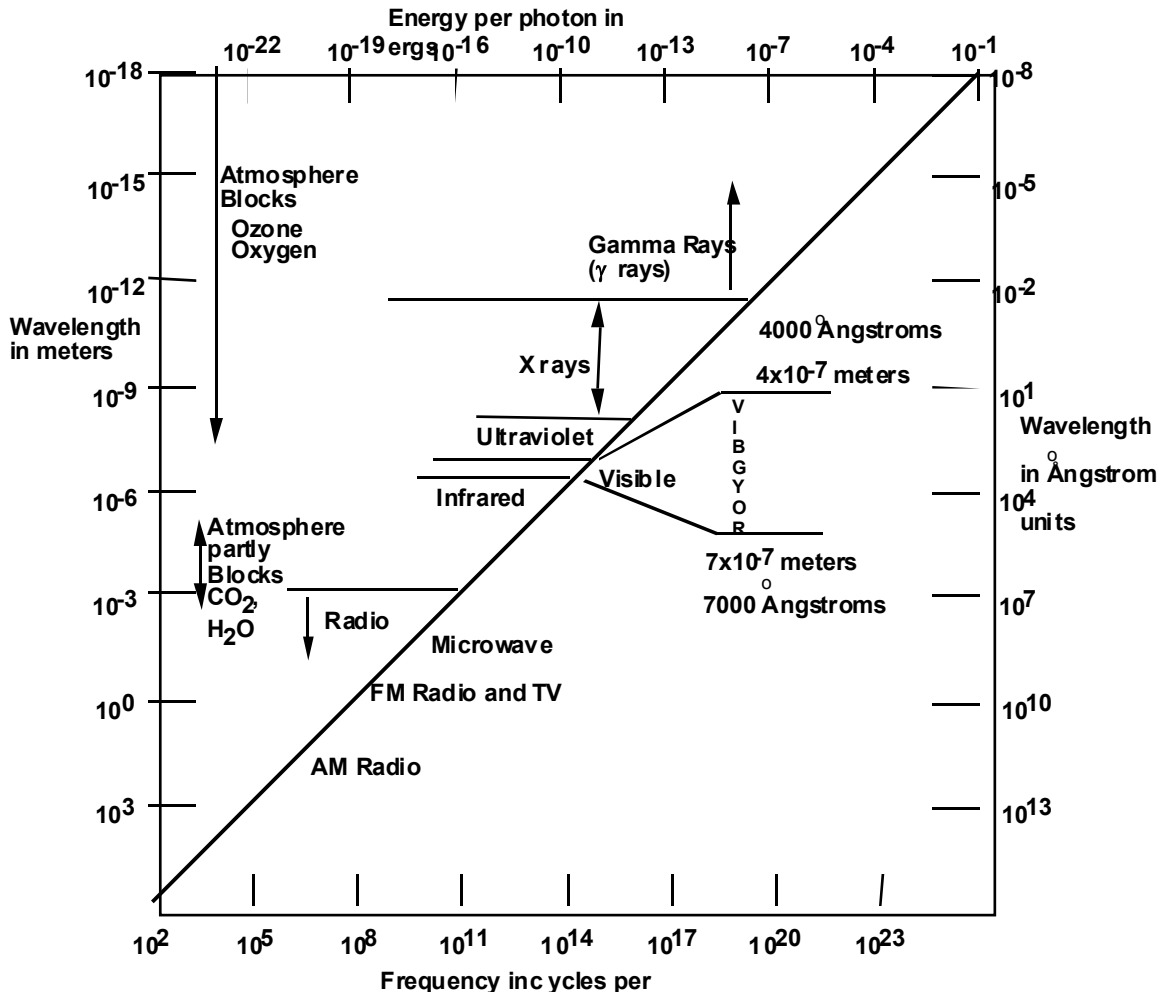
Because light has a fixed speed, one can characterize it by either the wavelength, or by the frequency, the number of waves passing a point every second. If you know one, you know the other because

$$(\text{length of each wave}) \times (\text{number of waves passing each second}) = \text{speed of wave packet}$$

Hopefully this word equation is no surprise. The speed is always the same,  $c$ , 300,000 km/sec. So if you know the wavelength, the frequency can be found and conversely.

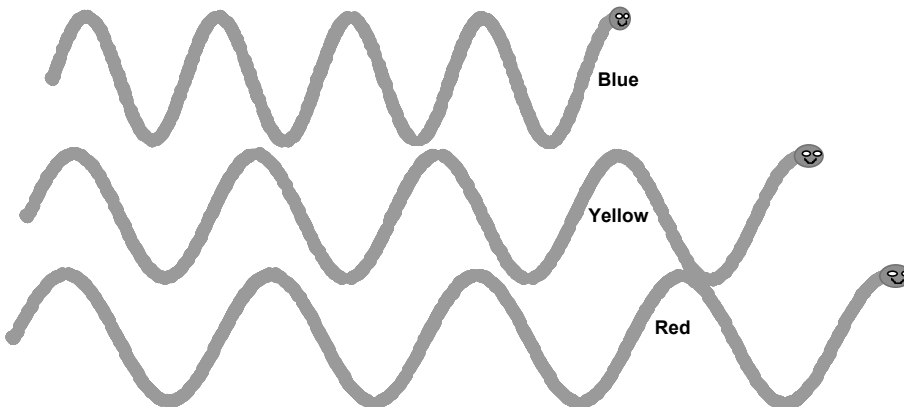
Different wavelengths cause different physiological responses in us. When light has a wavelength between  $4 \times 10^{-7}$  and  $7 \times 10^{-7}$  meters or 4000 and 7000 Ångstrom units, we can see light and the different wavelengths appear as different colors (a nanometer is  $10^{-9}$  meters). Other wavelengths

usually cannot be sensed, but do have effects. The figure below shows some of the names for wavelengths of light.



All of these names refer to the very same set up, crossed electric and magnetic fields moving through space at the speed  $c$ . The names arose because different wavelengths are detected differently. While all these names are given to different wavelengths of light, there are a couple of similarly named things that are NOT light. Sound is a vibration of material, not a form of light. Cosmic rays are particles from outer space. Radiation is a general term that includes light, but also includes particles given off from radioactive elements,

Light comes in individual packets called photons. When light is brighter, there are MORE



photons, not photons with higher waves. The shorter the wavelength, the more energy carried by each photon.

There is a variety of ways to cause light. A changing electric field can generate light. This is the way that radio stations form their over-the-air signal. Their antennas are visible near SF Bay on the mud flats. They are just straight, vertical antennas about 1/4 wavelength. Electrons, negatively charged particles, are sent up and down the antenna. Each charge carries an electric field. The electron's motion causes a varying electric field. The electric field causes the magnetic field. And the combination is a form of light. The resultant radiation is what you pick up on a radio receiver. The sound you hear is the result of the signal being used to vibrate a mechanical piece, often made of paper.

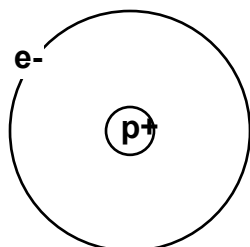
In astronomy we are very concerned with light made by atoms and molecules because it allows us to find out about the source. To understand the way it works requires that we learn about atoms and molecules.

Atoms all have a nucleus with positively charged particles called **protons** and neutral (no charge) particles called **neutrons**. Almost all of the mass of the atom is in the nucleus, although the nucleus takes up about 1/100,000 of the radius of the atom. The number of protons determines the type of atom, that is what **element** it is. Each element can have a various numbers of neutrons. The number of neutrons determines the **isotope** (of the element).

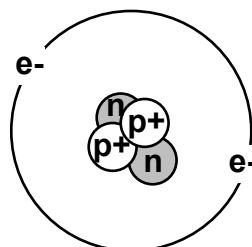
As you may have heard electric charge comes in both positive and negative and opposites attract, like in love. The closer together, the stronger the attraction or repulsion. The attraction keeps negatively charged particles in orbits as close to the nucleus as physics allows. The reason that protons in the nucleus stay together (in spite of their electric repulsion) is that there is another, stronger force, called the strong force acting on the protons and neutrons. The strong force is much stronger than the electrical repulsion at small distances. The strong force gets much smaller than the electrical force at large distances.

Negatively charged particles, called **electrons** move around the nucleus in paths or areas orbitals. These orbitals have a variety of sizes and shapes. Each orbital can be occupied by up to a specific number of electrons. "Normally" the number of electrons is the same as the number of protons, so all the charges cancel. If the number of electrons is NOT the same, the situation is called an **ion**.

**Hydrogen Atom**  
1p, 1e



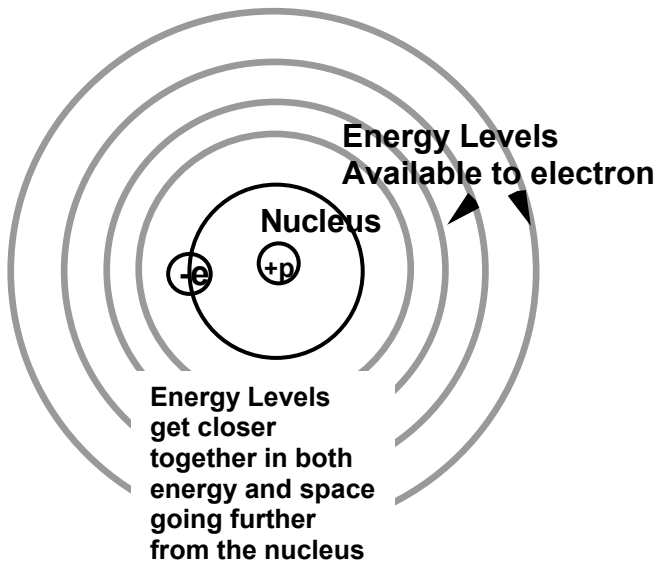
**Helium Atom**  
2p, 2n, 2e



All of chemistry, all of the processes that usually occur on earth are changes in how the electrons from one or more atoms are shared. The nucleus of the atom is not normally affected.

Electric force pulls the electrons toward the nucleus. Electrons have kinetic energy that keeps them from falling into the nucleus. This is rather like the case with planets orbiting the Sun. Gravity pulls the planets, their kinetic energies keep them from falling in. If we want to move electrons to orbits further away from the nucleus, energy needs to be added.

Unlike the orbits of the planets, the electrons cannot go to just any path around the nucleus. Each type of atom, molecule and ion has a unique set of orbitals corresponding to the possible energy levels. These orbitals have no physical presence when no electron is in them, but they define the only paths the electrons can take.



Electrons have a lowest energy level, typically the orbital allowing the electron to be closest to the nucleus (compatible with the positions of other electrons). When an electron is in any but the lowest energy level, it will eventually return to the lowest level. As it does this, the excess energy is released. Typically a photon with just the right energy is given off to get rid of the energy.

When a sample of a material has its electrons excited, different electrons go into different levels. As the electrons come back to lower energy levels, the pattern of

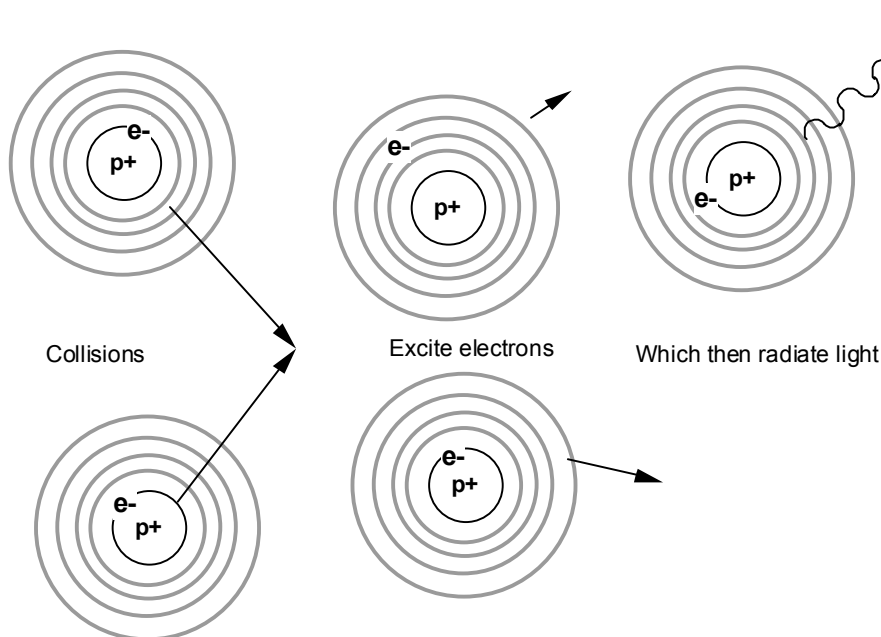
wavelengths (colors of light) allows us to distinguish the type of atom or molecule. It is rather like the fingerprint of the material.

The pattern of bright light from a diffuse gas is called an emission spectrum. It consists of bright light at the wavelengths (energies) corresponding to the transitions to lower energy levels.

Hydrogen light gives a pattern of Red, Teal, and many purple photons when its electrons jump to lower energy levels. Mercury vapor gives Purple, Green and brownish-yellow. Atoms also give light in many wavelengths we cannot see with our eyes. For us to be able to see these colors, the material must not be too dense and the light from the material must not be overwhelmed by radiation from the background,

Electrons can be given energy by collisions, by subjecting them to an electric field to counteract the attraction of the nucleus or by letting them absorb light.

The random motions of atoms result in collisions. The hotter a material, the faster its particles move and the more energy transferred in a collision.



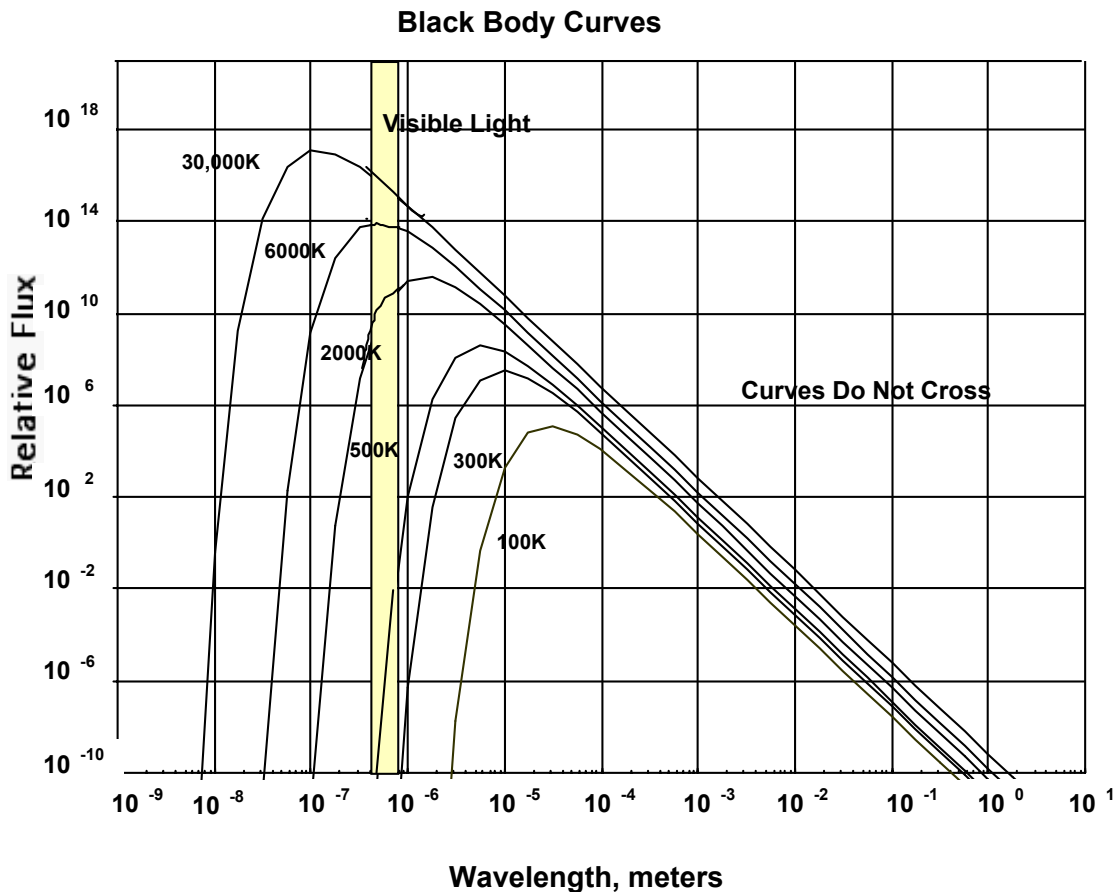
(Absolute zero is the temperature where particles have as little motion as possible.) If the collision causes an electron to move to a higher level, the electron emits light as it returns to a lower level.

If the material is dense enough (like most solids and liquids and some dense gasses), the electrons drop from the higher levels to lower levels, but they do not succeed in giving off exactly the characteristic energy. Collisions from other materials change the

energy slightly. Many molecules have a great number of energy levels, so a small change in these levels smears them together. This makes a **continuous spectrum**.

A **continuous spectrum** includes all colors including wavelengths not visible to our eyes. The density obscures the information about the type of material, but it does allow us to tell the temperature of the material. The distribution of particle velocities, determined by temperature, determines the amount and the distribution of energy given by a body. **Black body spectrum** is the name given to the distribution of energy given by a sample of dense material where collisions cause the excitation.

The curves below show the amount of radiation a black body gives at each wavelength. The curves are for bodies of the same size and at the same distance from the observer. A formula gives the shape of the curve. Astronomers observe the light from a distant body, and compare the distribution of energy or the peak of the energy distribution to the theoretical curves. Matching the curve and the observations tells the temperature of the body, In many cases, a comparison of the amount of light at only two wavelengths is enough to find the temperature. There is also a formula relating the total amount of energy per second to the temperature for a body of known size. This formula can be used to find the total amount of energy given by a body.



Ideally a black body absorbs any incoming light equally well and emits any wavelength with no impediment. Realistically, the overall black body distribution can be used to tell the temperature of most bodies without too much difficulty.

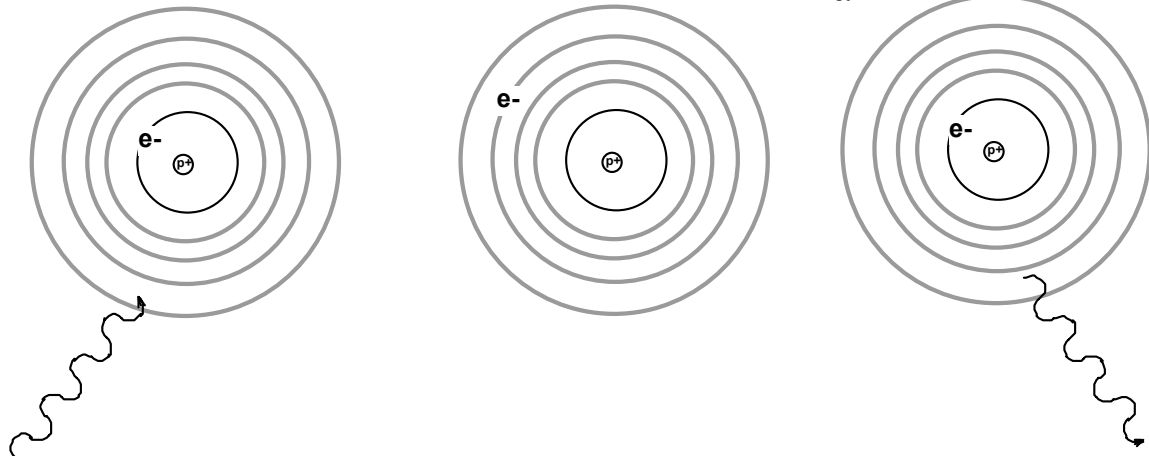
When an atom encounters light, it can absorb the light if the light is at just the right energy to raise the electron to a higher energy level. It is not all right for the light to have more energy than is needed to change the energy level. The electron cannot absorb just part of the energy. It can only accept light with exactly correct energy. After an atom absorbs energy and goes to a higher

energy level, it eventually returns to the lower energy level, emitting light. The sequence of events is shown below.

Light with the correct energy comes to the atom

The atom absorbs the light and the electron jumps to a higher energy level

Later the electron jumps to a lower energy level and emits the light needed to make up the energy difference



Notice that the electron in the figure above has jumped up TWO levels, rather than one. This is perfectly all right, if the light has enough energy (and some other relationships between the levels are met). The electron need not come down to the original lowest level all at once. It could come to the second level, emitted a photon, and then come down to the lowest level, emitting another photon.

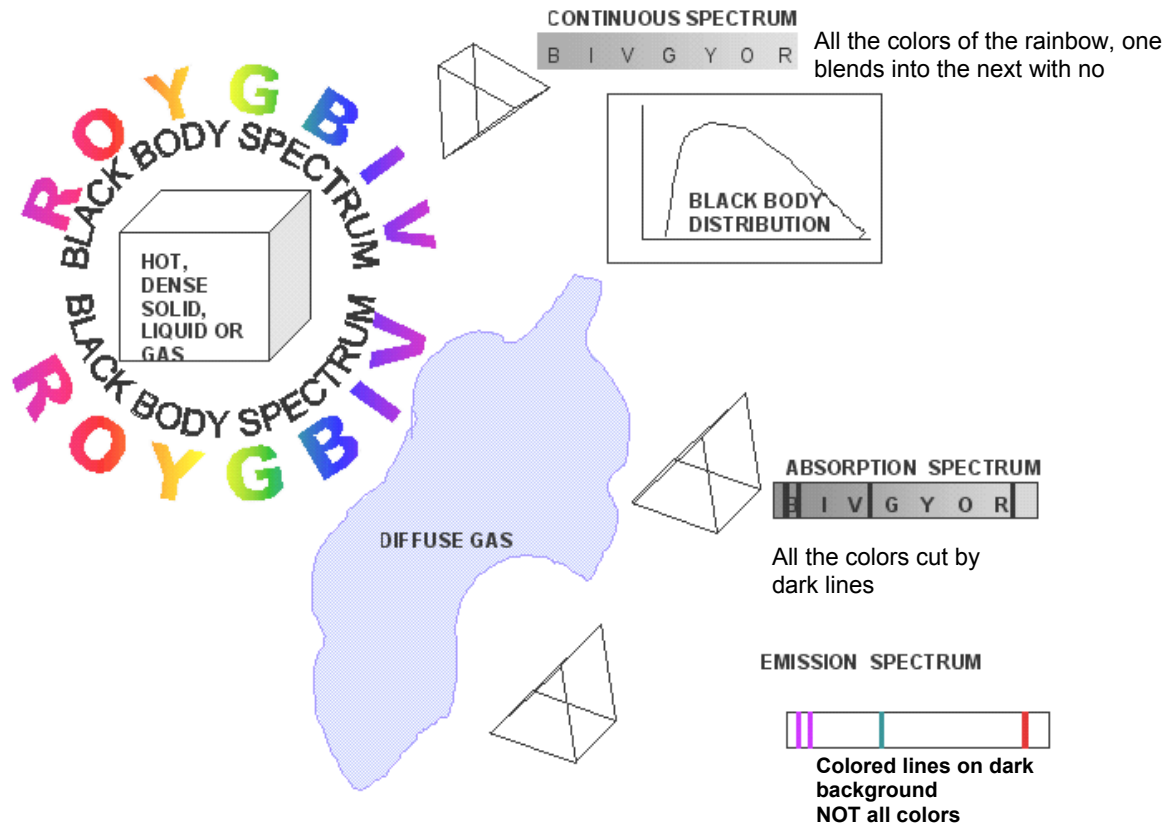
The direction of the outgoing light is usually independent of the direction of the incoming light. If there is a bright continuous background (a rainbow), with diffuse (not dense) gas in front of it, there is a decrease in the amount of light received at those wavelengths absorbed by the gas. The appearance of the spectrum becomes a rainbow with dark lines where the gas would normally produce bright colors. This is called an absorption spectrum. The dark lines tell the same information that the bright lines would. The continuous background can be used to find the temperature of the background material.

#### Summarizing the types of spectra:

**A continuous spectrum is produced by dense bodies. The distribution of amount of energy at different wavelengths tells the temperature. The appearance of the spectrum is like a rainbow, all colors with varying amounts of different colors.**

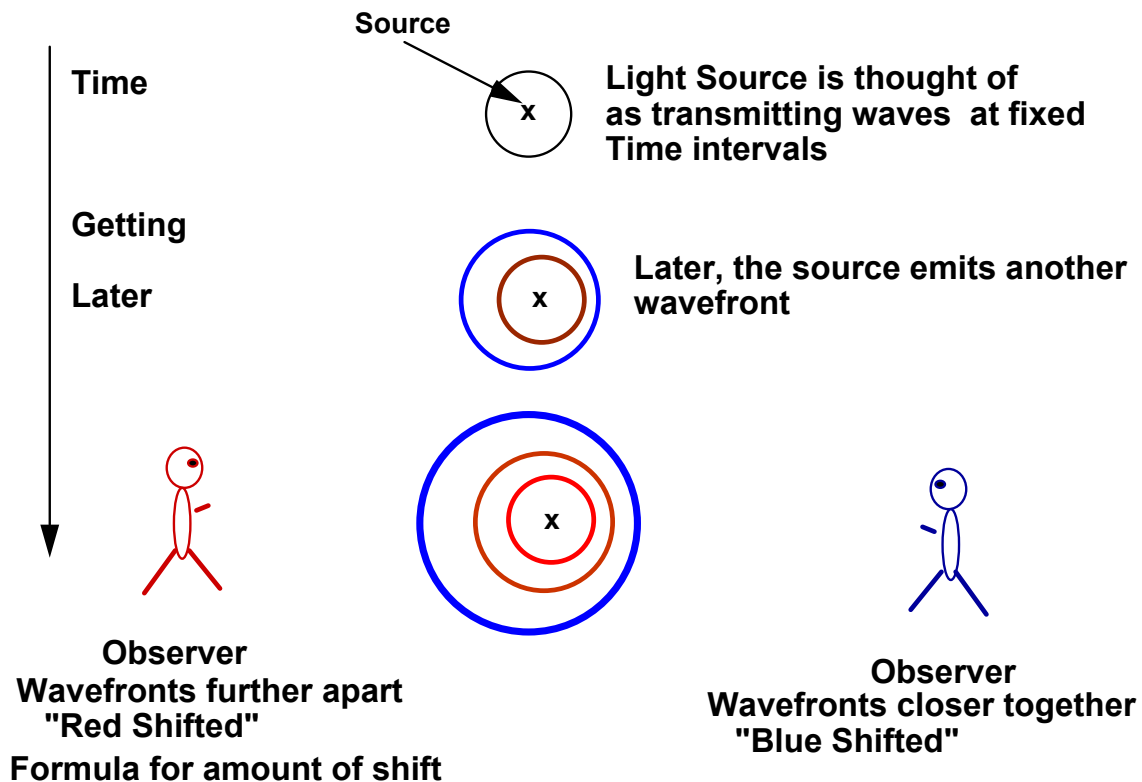
**Diffuse material with nothing bright behind it produces an emission spectrum, that is light at only those wavelengths specific to the material. The type of material can be found from the pattern of lines produced. The temperature of the material can usually be told from the distribution of lines and their intensity, but this requires a simulation of the gas.**

**An absorption spectrum results when diffuse material is viewed with a bright, continuous source of light behind it appears as though it was in silhouette. The continuous spectrum appears and dark lines appear at the wavelengths where the diffuse material is absorbing and reemitting light. The appearance is a rainbow with dark lines on top of it. It is called an absorption spectrum. The continuous background can be used to find the temperature of the material in the background. The absorption lines tell the same information as the emission spectrum would.**



Among the things we can tell from light, is how fast we and the source are moving toward or away from one another. This motion causes Doppler Effect is a change of the wavelength of light. Doppler effect also occurs for sound, and you have probably heard the change in pitch as a siren or a race car goes by you.

The reason that Doppler shift occurs is that the distance between the observer and the light



changes during the time that the light wave is being emitted. When the source approaches, the wavelength you get is smaller than the wavelength originally emitted. This is called **blue shift**. When the source recedes, the wavelength we get is longer and the effect is called **red shift**, regardless of the actual color involved. The formula relating the velocity to the Doppler effect is as follows.

$$\frac{V}{c} = \frac{\Delta\lambda}{\lambda}$$

$V$  is the velocity of the body relative to the observer (+receding, - approaching)  
 $c$  is the speed of light, 300,000 km/sec  
 $\lambda$  is the symbol for the ORIGINAL wavelength of the light, the wavelength sent  
 $\Delta\lambda$  is the change in the wavelength from when it left the source to when it was received. It is found by subtracting the original wavelength from the wavelength you receive. The combination  $\Delta\lambda$  does not mean to multiply, it is like a compound word.

If we have no idea what the original wavelength of the light was, it is not generally possible to find the velocity of the source. We assume, however, that the spectra of elements and compounds are the same everywhere. When there is a Doppler shift, all the light from the source is affected. The pattern of lines will be shifted in a predictable way. So the pattern will still be recognizable. So if we see the pattern from hydrogen, for example, the red, teal and purple lines would all have their wavelengths changed by Doppler effect, but the pattern still tells that it is from hydrogen.

Example: You receive the teal line from Hydrogen. It is normally emitted at 4861Å, but you receive it at 4859 Å. What is the velocity of the source with respect to you?

Write the original equation, then substitute for each variable. The original wavelength is 4861Å and the change is -2 Å , since what you receive is 2 Å less than what was sent. The speed of light is always the same, 300,000km/sec. So the Doppler Shift equation is

$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda}$$

Substituting

$$\frac{v}{300,000\text{km/sec}} = \frac{-2 \text{ Angstroms}}{4861 \text{ Angstroms}}$$

The Angstrom units cancel. Multiply both sides by 300,000km/sec to get  
 $v = 300,000\text{km/sec} \times -2 / 4861$

$$v = -123.4\text{km/sec}$$

The negative sign indicates that source and recipient are approaching one another. It is not possible to tell whether one or both are moving.

An effect like the Doppler shift is the way that we found out the universe is expanding. We talk about the red shift of distant galaxies. Sometimes you will hear the value of the red shift on the news. The way that it would be said is "Distant galaxy with redshift 6 has been found. The value 6

refers to **redshift,  $z = \frac{\Delta\lambda}{\lambda}$**

Actually galaxies with redshift nearly 7 have already been found. How can that be? The variable  $z$  is the same as the right hand side of the equation for  $V/c$ . Does it mean that the speed of the source is greater than  $c$ , the speed of light? Actually no. There is a more correct equation for the correspondence between shift and velocity. This other equation is

$$\frac{V}{c} = \frac{(z+1)^2 - 1}{(z+1)^2 + 1}$$

This is the formula to use for  $z$  greater than 0.1 or so. You will not need to compute with this equation in this class.

### Practice Questions

- 1) Helium normally emits light at  $5016\text{\AA}$ , but you receive this light at  $5011\text{\AA}$ , how fast are you moving compared to the source?
- 2) You plan to go to the Moon. Your speed might be as large as  $1\text{ km/sec}$  both coming and going. If you transmit a signal to NASA at  $2\text{ m}$  wavelength, what is the range of wavelengths that will be received?
- 3) You observe a Nitrogen line at  $4155.6\text{\AA}$ . It is normally seen at  $4152.0\text{\AA}$ . What can you tell?
- 4) You are planning to send a probe to Mars. If the probe goes at speeds up to  $25\text{ km/sec}$  in either direction, and if it sends  $0.5\text{ m}$  radio waves, what is the range of wavelengths you receive?

Ans 1)  $-299.043\text{ km/sec}$ , be sure to use  $5016\text{\AA}$  in the denominator. Negative velocity means that you and the source are getting closer together. You cannot tell what or who is moving. 2) Your speed would cause a Doppler shift ( $\Delta\lambda$ ) of  $\pm 6.6667 \times 10^{-6}\text{ m}$ . This is NOT the wavelength that is received, this is just the change in the wavelength. It can take either positive or negative sign because the path to and from the Moon is both approaching and receding from the Earth. To get the wavelength actually received, this change is added to the original wavelength. So the range of wavelengths actually received is from  $2.0000067$  to  $1.99999333\text{ m}$ . In this case, it is necessary to keep enough digits to demonstrate the effect of the Doppler effect 3) You and the source are getting further apart at  $260.12\text{ km/sec}$  4) From  $0.50004167\text{ m}$  to  $0.499958333\text{ m}$ .