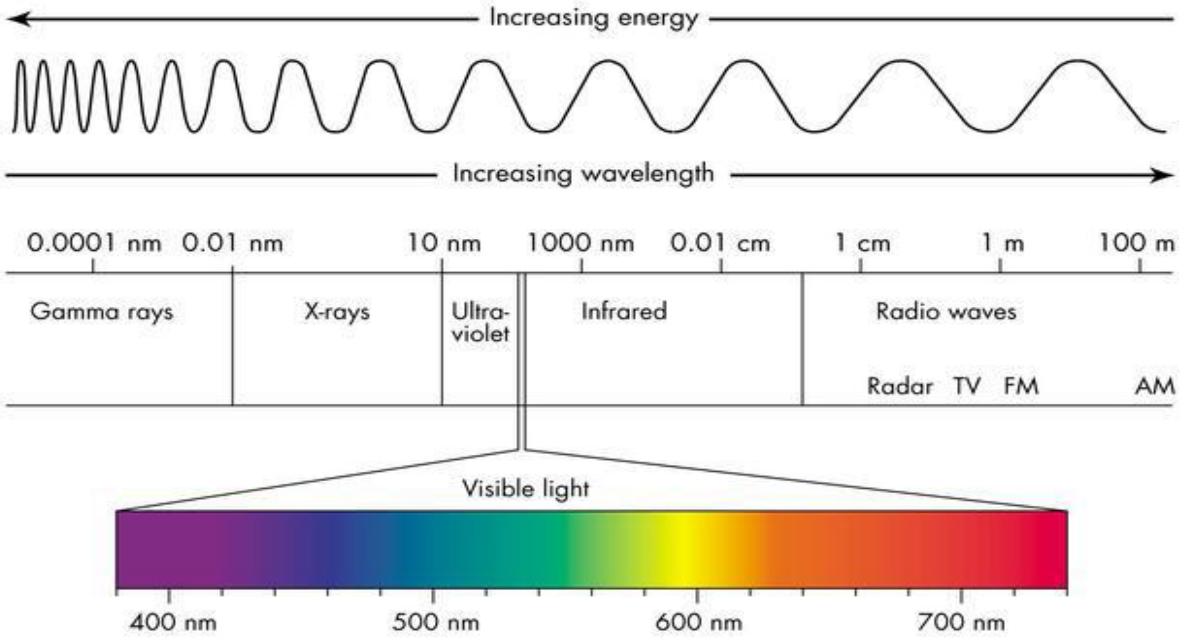
II. Astronomy Light:

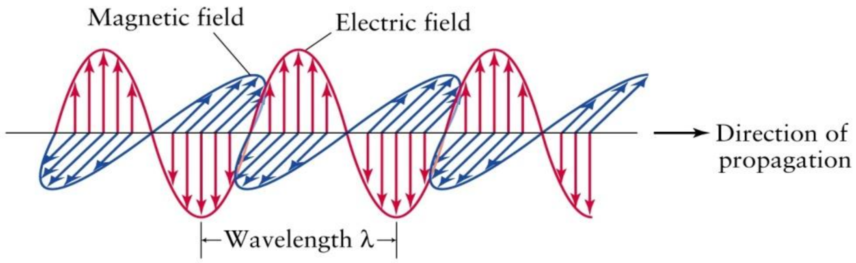


A. Analysis of light is by far the primary method with which astronomers obtain information about the Universe.
   1. Astronomy is an observational science; classical experiments generally can't be done. A physicist, for example, can weigh an object to measure it's mass, submerge it in water to find it's volume.
   2. Counterexamples:
      a. Meteorites.
      b. Probes sent to planets and moons.
      c. Energetic particles that reach Earth from great distances.
   3. An object in the sky can be photographed, revealing it's brightness, shape, and relative postion.
      a. The stars in a cluster, for example, have different brightness.
      b. Photographs obtained through different filters can be appropriately combined to give a nearly "true color" rendition.
   4. The *spectrum* of the object can also be analyzed.
      a. If one passes "white light" (ordinary sunlight) through a glass prism or water droplets, a rainbow (spectrum) is formed.
      b. Roy G. Biv character can be used as a mnemonic.

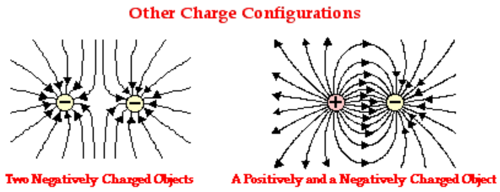
        c. The brightness (intensity) of light coming from a given object can be plotted as a function of color after passing the light through a prism, for quantitatively analysis of the object's spectrum.

B. Visible light is one type of electromagnetic radiation or electromagnetic wave.

    1. The wave consist of self-propagating, oscillating electric and magnetic fields that are perpendicular to each other and perpendicular to the direction of motion.



        a. A static electric field exists around a stationary charge such as an electron.



        b. A static magnetic field exists around a stationary magnet.
        c. There is a deep connection between electric and magnetic fields. For example, a current (which consists of electrons in motion through a wire) produces a magnetic field, as in an electromagnet. Conversely, passing a loop of wire through a magnetic field produces a current in the wire.
        d. Sustained rotation of the magnet or back-and-forth motion of the charge produces a continuous disturbance in the associated field : the strength and direction of the field oscillate (change sinusoidally) with time.
        e. An oscillating electric field produces an oscillating magnetic field, and vice versa. These propagate outward as electromagnetic waves.
        f. The *wavelength*, denoted by the Greek letter λ (lambda), is the distance from one wave crest to the next. This has the units of length, such as meter (m).
        g. The *frequency,* denoted by the letter f, is the number of times per second that a crest passes a fixed point; the units hare 1/seconds, or Hertz (Hz). Hence, the *period* of the wave, P (in seconds) is simply 1/f.
        h. In general, the length per wave (λ) multiplied by the number of waves per second (f) gives the length per second traversed by the wave. This is it's *speed* v: $v = f\lambda$. In astronomy $v = c$.

    2. Different colors of visible light correspond to electromagnetic waves having different wavelengths.

        a. The typical unit of wavelength measurement of visible light is the Angstrom (Å), which is 10^{-10} meters or 0.1 nanometer (0.1 nm).

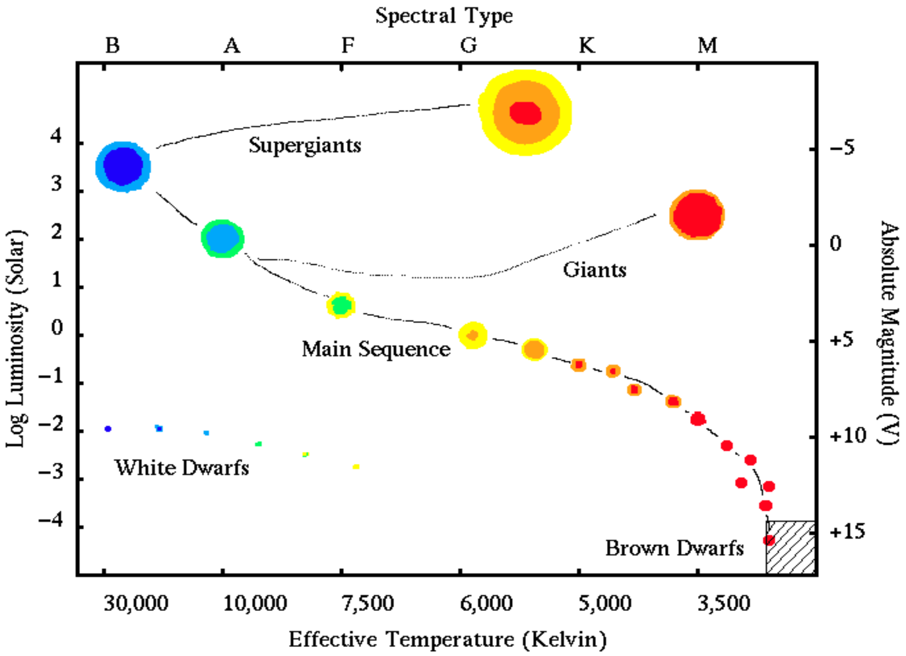
        b. Violet, blue, green, yellow, orange, and red light correspond to wavelengths of about 4000 Å, 4500 Å, 5000 Å, 5500 Å, 6000 Å, and 6500 Å, respectively.

C. The complete electromagnetic spectrum spans a vast range of wavelengths.
    1. The main types are as follows, but the numerical dividing lines are only approximate.
        a. Gamma rays have wavelengths shorter than about 0.1 Å.
        b. X-rays have wavelengths roughly in the range 0.1 – 100 Å.
        c. Ultraviolet (UV) light spans wavelengths of 100 – 4000 Å.
        d. Infrared (IR) radiation goes from 7000 Å – 1 mm
        e. Radio waves are longer than 1 mm.
    2. Instruments used to detect them are often very different.
    3. The human eye is sensitive to visible light.
    4. All electromagnetic waves in a vacuum travel with the same speed, c, regardless of λ. The measured speed of light is independent of the relative speeds of the observer and the light source. This is admittedly counterintuitive, but it has been completely verified; indeed, it is one of the foundations of Einstein's theory of relativity.
    5. Electromagnetic waves slow down in media such as glass and water, and the speed is generally a function of wavelength. This, in fact, is what leads to the dispersion (spreading out) of the colors when light passes through a prism. (Blue is slowed down more than red)

D. Light can also behave as discrete particles known as *photons* (wave or energy "packets"). This is a fundamental aspect of quantum theory.
    1. With the right equipment, photons can be detected as discrete lumps of energy.
        a. A photon has no rest mass, but it's energy E is given by the product of Planck's constant h (names after the quantum physicist Max Planck) and it's frequency f: $E = hf$. Planck's constant is very small 6.627 X 10^{-27} erg seconds, where an erg is a unit of Energy.
        b. Photons of higher energy therefore have higher frequency and shorter wavelength: $E = hf = h(c/\lambda)$ since $f = c/\lambda$
        c. The photon nature of light is most easily recognized at high energies: objects generally emit gamma rays and x-rays so rarely that the photons are detected one at a time.
    2. Collectively, many photons having the same energy produce an electromagnetic wave with the corresponding wavelength λ. Sunlight and the light from most bulbs consist of photons having a broad range of energies or wavelengths.
    3. Each *individual* photon has wave-like properties, too.
        a. Constructive and destructive interference effects, such as those seen in waves flowing through gaps in a breakwater, are produced even when photons are sent *one at a time* through holes in a screen.
        b. A photon must therefore interfere with itself, and it can only do this by passing through all of the holes; it behaves like a wave.
        c. If the experiment is modified in such as was as to actually determine which hole the photon went through, the interference (wave-like) effects disappear. The photon acts like a particle in this case; the measurement "disturbs" the photon, destroying the wave.
        d. Thus, either the wave-like or particle-like properties of light can be measured in a given experiment; both cannot be measured simultaneously.

4. It turns out that the wave-particle duality of light is also a quantum aspect of normal matter.
    a. An electron, for example, can behave as a wave of wavelength $\lambda=h/mv$, where m is the mass and v is it's speed relative to the observer. Electrons passing through holes in a screen produce interference effects, just as light does.
    b. The large masses of most particles imply that their wavelengths are exceedingly small, making it more difficult to discern their wavelike nature than is the case for light.

E. When astronomers speak of the apparent magnitude of a star or other celestial object, they are referring to what we actually see in the sky.
    1. Astronomers still use the archaic *magnitude* scale proposed by the Greek astronomer Hipparcos around 140 BC.
        a. He called typical very bright stars 1st magnitude, and the faintest naked-eye stars 6th magnitude.
        b. Thus, the magnitude scale goes *backwards* (faint objects have large magnitudes).
        c. Apparent magnitude represents a change in apparent brightness of about 2.5 times.
        d. Brighter objects have lower numbers. For example, our Sun, the brightest object in the sky, has a magnitude of -26.7; the full Moon's magnitude is -12; Sirius, the brightest star in the sky, is -1.5 and the dimmest stars that most of us can see are about magnitude +6.
        e. The faintest objects photographed with ground-bases telescopes are around 28 mag.
        f. The faintest galaxies photographed with the Hubble Space Telescope are about 30 mag.
        g. A difference of 5 magnitudes between two stars means that the lower-magnitude star is one hundred times brighter than the other star.
        h. Unless otherwise noted, "magnitude" refers to "apparent magnitude," which is a measure of apparent brightness. "Absolute magnitude" is the apparent magnitude at a standardized distance of 10 pc; it is related to the intrinsic power (luminosity) of an object.
        i. Astronomers also refer to an object's absolute magnitude, which is the apparent magnitude of a star of other cosmic object if it were at a distance of 32.6 ly (10 parsec).
    2. Hertz-sprung and Russell (1900s) plotted the relationship between brightness and spectral types of nearby stars on a graph. A star's position in this graph tells a great deal about it's age, size (volume and mass), brightness, color, and temperature.
        a. When astronomy students say, "Oh! Be a fine girl, kiss me," they are learning the spectral classes of the main sequence stars: O-B-A-F-G-K-M.
        b. The major differences of these stars are differences in temperature and mass, which are related----from the big, hot O stars to the small, cool M stars.



   c. The majority of these stars, approximately 90% of them, are known as main sequence star---a grouping in which they spend the greater part of their lifetimes.

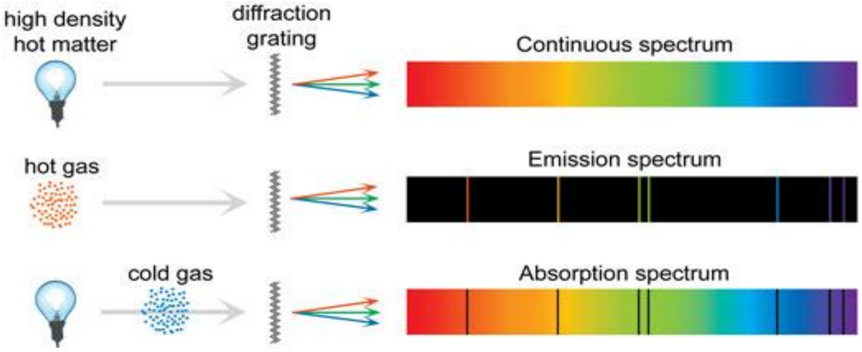
F. Astronomers study matter elsewhere in the Universe through analysis of the light that it emits and with which it interacts. We first consider the structure of atoms, the basic constituents of matter.

   1. An **atom** consists of a nucleus surrounded by a cloud of electrons. A **molecule** consists of at least two atoms bound together.
      a. The atomic nucleus contains positively charged protons and a roughly equal number of uncharged neutrons, all closely packed together. Protons and neutrons have diameters of only about 10^{-13} cm.
      b. In a **neutral** atom, the number of negatively charged electrons is **exactly** equal to the number of protons. The electrons form a cloud about 10^{-8} cm in diameter. An atom is mostly empty space. Each electron has a mass of 9.1 X10^{-28} g, only 1/1840 times that of a proton or a neutron.
      c. The number of protons determines the type of **element**: hydrogen has on proton, helium has two protons, lithium has three protons and so on. A convenient arrangement of all these is the periodic table of the elements.
   2. Different **isotopes** of a given element have the same number of protons, but different numbers of neutrons.
      a. By far the most common isotope of hydrogen has zero neutrons, but deuterium (rare) has one neutron, and tritium (very rare) has two neutrons.
      b. The most common isotope of helium has two neutrons, but there is a rare lighter isotope that has only one neutron.
      c. Different isotopes of the same element have the same chemical behavior, which is determined by the **number of electrons**.

3. Atoms are ionized if they have lost one or more electrons.
    a. If one electron was lost, the atom is "ionized as -1".
    b. If two electrons were lost, the atom is "ionized as -2". (and so on)
    c. Atoms can become ionized by collisions with other particles, or by absorption of energetic photons.
4. Although we often think of electrons "orbiting" the nucleus like planets orbiting the Sun, this leads to an inconsistency in classical physics: motion along an orbit should cause the electron to emit radiation (since it accelerates), and it would rapidly spiral into the nucleus as it loses energy. Thus, atoms shouldn't exist!
    a. According to quantum physics, electrons instead form a cloud or "probability distribution". Nevertheless, it is sometimes useful to think of electrons in **distinct** "orbits", as in the model developed by Niels Bohr.
    b. An electron can only occupy well-defined, **discrete energy levels** in a given atom, rather than a continuum of levels. Each of these levels can be associated with a particular "orbit" for convenience.
    c. Electrons in outer "orbits" (levels) have greater energy than those in lower levels.
    d. A given atom is in it's **ground state** if all of the electrons are in their lowest possible energy levels.
    e. If one or more electrons are not in their lowest possible energy levels, the atom is in an **excited state**.

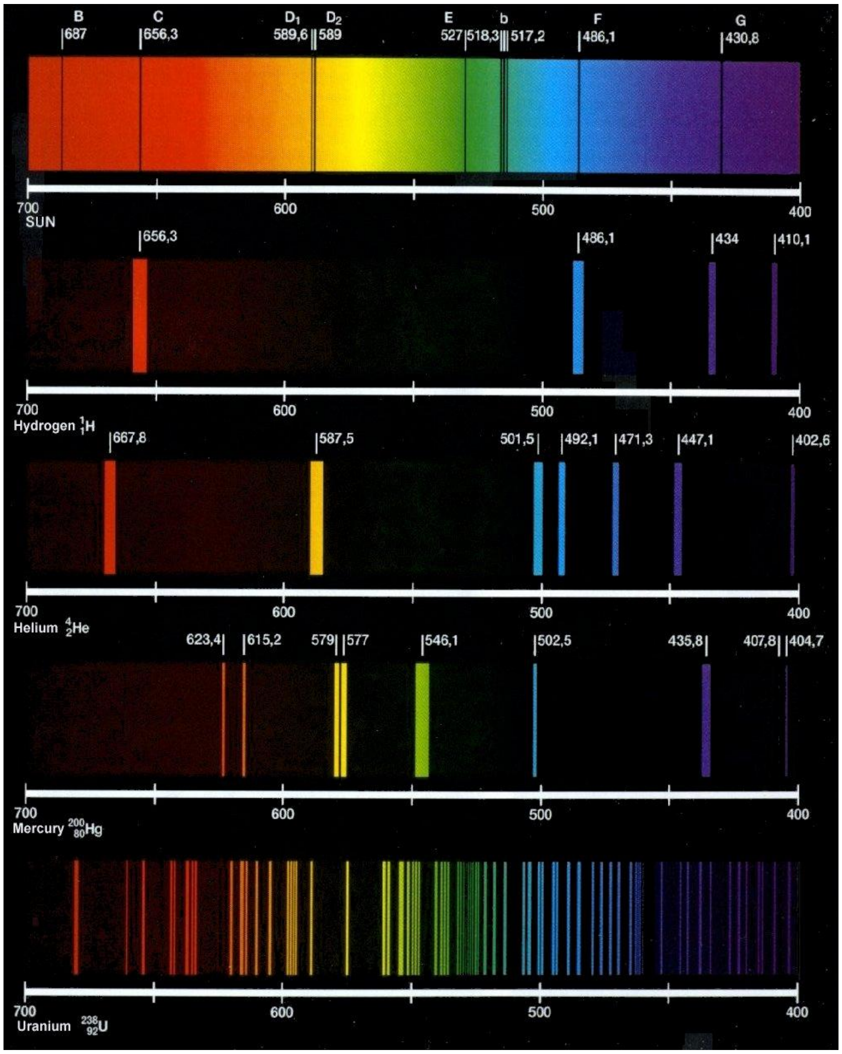
G. Light interacts with matter by producing transitions between different electronic energy levels.
1. An electron can "jump" from a low energy level to a higher energy level by absorbing a photon. This destroys the photon.
    a. The energy of the absorbed photon must be exactly equal to the difference between the two energy levels occupied by the electron.
    b. If the absorbed energy equals ΔE then it's frequency and wavelength can be calculated from $E = hf = h(c/\lambda)$
    c. An electron cannot take only part of the energy of a photon and jump to a higher level, leaving a lower-energy photon; either all or none of the energy is absorbed. (Reflected)
    d. A sufficiently energetic photon can completely dislodge an electron from an atom. This process is known as ionization, and it can occur with any photon more energetic that the minimum required energy.
2. A cloud of gas containing numerous atoms with an electron in the same initial energy level can absorb many or most of the photons whose energy is exactly the amount needed to kick the electron to an allowed higher level.
    a. For example: Many green photons would be absorbed when a beam of white light is shined through hydrogen gas.
    b. A spectrum of the light beam that passed through the gas would therefore show a deficit at this green wavelength. This is called an **absorption line**.
    c. There may be absorptions lines in the spectrum, due to other transitions from lower to higher electronic energy levels.

3. Electrons prefer to be in low energy levels. Very shortly after being boosted to a higher level by photon absorption, an electron can jump back down to the lower level.
    a. This process results in the **emission** of a photon.
    b. The photon is released in a random direction.
    c. Hence, in the example discussed above, the green absorption line becomes only slightly "filled in" by emission; most of the emitted photons escaped from the cloud of gas in other directions.
    d. A spectrum of the gas cloud taken from a direction that differs from that of the original beam of light will therefore show an **emission line** at the same (green) wavelength.



4. Note that the downward jump need not be directly to the final energy level, if there are allowed levels between the initial and final levels.
    a. Several jumps may occur on the way down, each of which results in the emission of a photon at a different wavelength.
    b. The sum of the energies of the emitted photons must equal the energy of the photon that would have been emitted had the electron jumped directly to it's final level.
    c. For example: Consider a hypothetical atom in which the electron absorbs a blue photon, jumping from the first to the third energy levels. The electron might subsequently jump from the third to the second energy levels, releasing a red photon, and then from the second to the first energy levels, releasing a green photon. The sum of the energies of the emitted green and red photons must equal the energy of the absorbed blue photon.
    d. Thus, the spectrum of a gas cloud viewed from a direction that differs from that of the original beam of light can consist of many emission lines having different wavelengths.

H. Each neutral element and ionized element produces unique patterns of absorption lines or emission lines having different wavelengths.

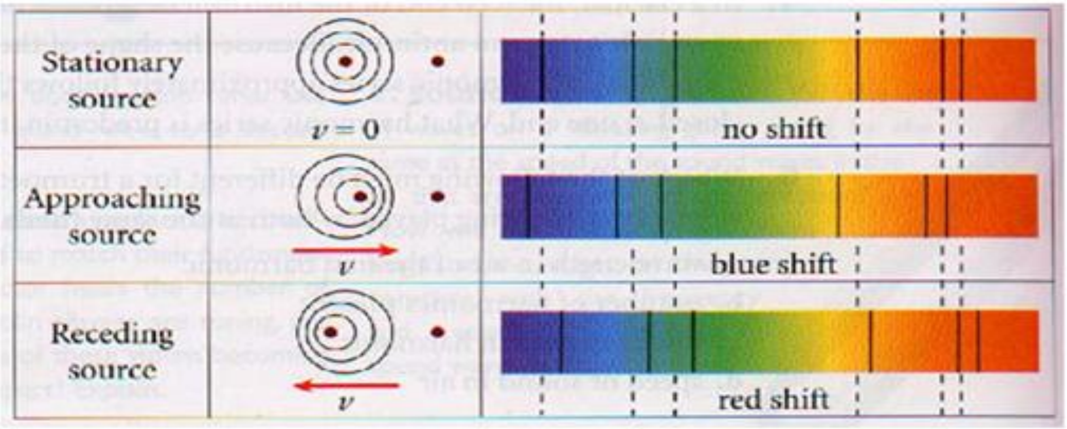


1. Atoms produce their own distinctive patterns of lines in a spectrum; one can even distinguish between neutral and ionized atoms. Each has a unique “fingerprint” that can be recognized.
   a. Thus, spectra can be used to deduce the chemical compositions of very distant stars and glowing clouds of gas.
   b. This is how we know that these objects consist of the same elements that are found on Earth and in the Sun (though not necessarily in the same proportions).

I. The **Doppler effect** is an enormously important tool that allows us to determine the radial velocity of an object (i.e., it’s speed toward or away from us) by measuring the wavelengths of absorption or emission lines in it’s spectrum.
   1. Consider a stationary source that is emitting light waves. The wavelength measured by the laboratory observer is denoted λ_0 (lambda-nought), and it is independent of the observer’s position relative to the source.
   2. Now suppose the source is moving relative to the observer.

   a. Along the direction of motion, the source partially keeps up with it's most recently emitted wave crest before it emits another wave crest. Thus, the crests bet bunched closer together.
   b. An observer standing along the direction of motion would therefore measure a shorter wavelength λ (i.e.,$\lambda<\lambda_0$). This is called a **blueshift**, in the sense that blue light has a shorter wavelength than red light.
   c. Opposite the direction of motion, the source partially pulls away from it's most recently emitted wave crest before it emits another wave crest. Thus, the crests get stretched farther apart.
   d. A observer standing opposite the direction of motion would therefore measure a longer wavelength λ (i.e.,$\lambda>\lambda_0$). This is called a redshift, in the sense that red light has a longer wavelength than blue light.
   e. Doppler effect does not measure a "transverse velocity" (perpendicular motion), but only a radial velocity.
3. For light waves, the quantitative relationship between λ, $\lambda_{0,}$ and v is as follows: $(\lambda-\lambda_0)/\lambda_0 = v/c$, where is the relative speed between the source and the observer.
   a. The above equation is valid only if v is much less than c. As v increases, the approximation becomes worse; by v = 0.2, the error is about 12%. An expression from the special theory of relativity must be used at high speeds.
   b. Note that when λ is larger than λ_0 the light is redshifted, so the source and the observer are receding away from each other. Similarly, when λ is smaller than λ_0 the light is blueshifted, so the source and the observer are approaching each other.
   c. The procedure to use with a star, for example, is to obtain it's spectrum, recognize a familiar pattern of absorption lines, measure the observed wavelengths of an absorption line, and compare it with the known laboratory (rest) wavelength to get $\Delta\lambda$.

Doppler Effect



Measuring the relative velocities of stars by the Doppler shift.

J. Questions:

1. Explain what is meant by the spectrum of an object.

2. Describe the wave nature of light and the properties of the wave.

3. Define the wavelength, frequency, period, and speed of a wave. State the relationships between these variables.

4. Discuss the different types of electromagnetic radiation, and their order from longest to shortest wavelength, including visible light.

5. State the relationship between the energy and frequency (or wavelength) of a photon.

6. How can it be possible for something to have both wave-like and particle-like properties.

7. What are some examples in which you know that magnetic or electric fields play a prominent role?

   Is there evidence that one type of field induces or interacts with the other?

8. List the main constituents of atoms.

9. Describe the electronic structure of an atom.

10. Discuss the criteria that must be fulfilled if a photon is to be absorbed by an atom.

11. Explain how spectral absorption and emission lines are formed when light passes through a cloud of gas.

12. Summarize how astronomers can determine the chemical composition of a distant object.

13. Describe the Doppler effect and it's origin.

14. If the Hά absorption line is found at λ = 6565 Å, and it's rest wavelength is known to be λ_0 = 6563 Å. Find v? (note: c = 3×10^5 Km/s)