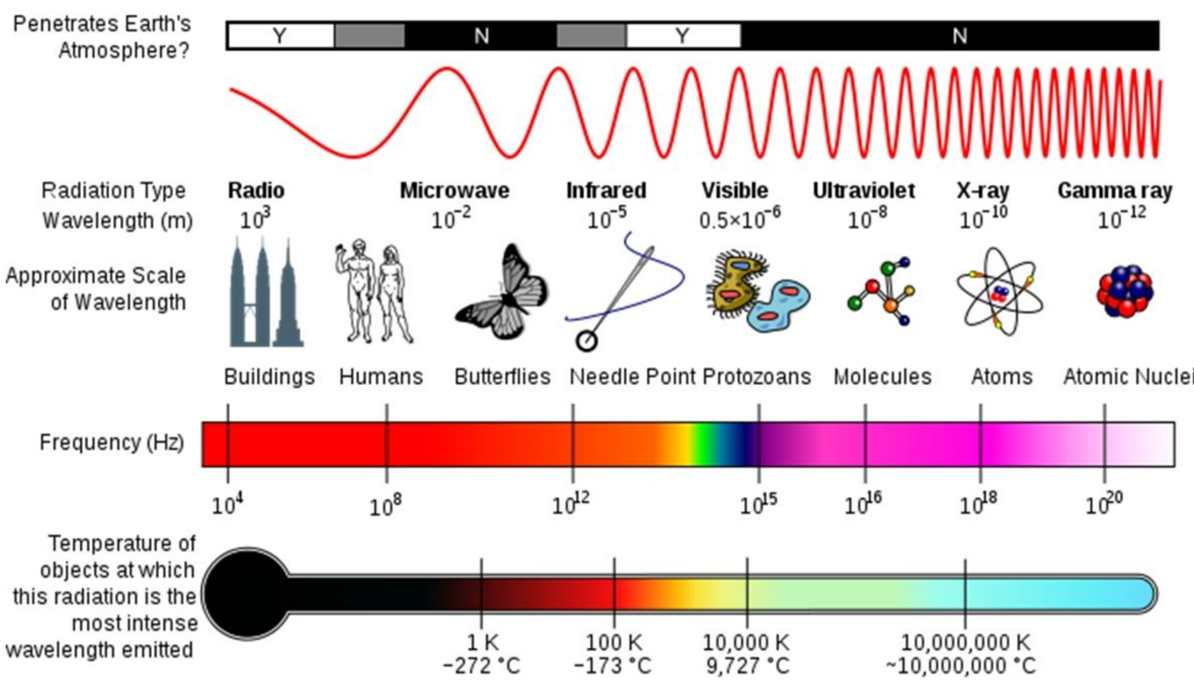
Chapter 02
Light and Matter
The Inner Workings of the Cosmos

2.1 Information from the Skies

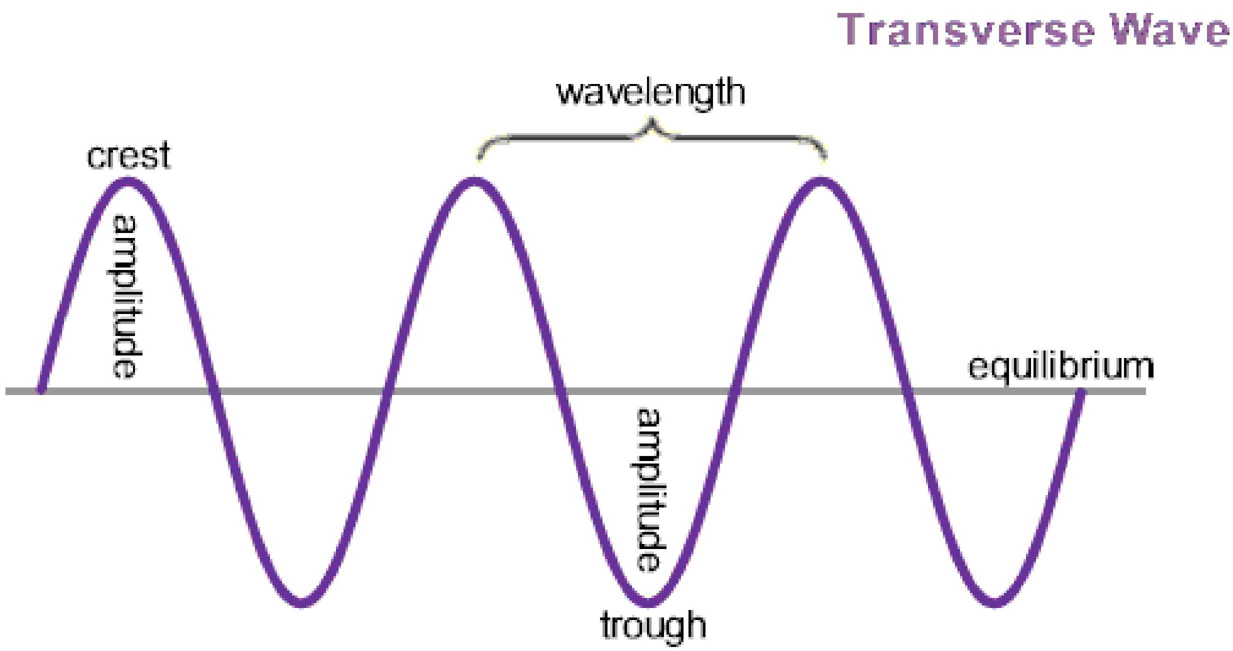
- Light and Radiation
  - The way we know everything about the universe is by following the laws of physics
  - Electromagnetic Radiation is the way that light travels through space and consists of several different groups of radiation that are used in many scientific ways.
    - Gamma Rays are the most dangerous form of radiation
      - Includes all wavelengths shorter than .01 nm
    - X-Rays are high energy waves
      - Wavelengths range from .001 nm to 100 nm
    - Ultraviolet Light is radiation less energetic than X-rays, but more than visible light
      - Wavelengths range from 1 nm to 400 nm
    - Visible Light is the specific range that the human eyes can detect.
      - Wavelengths range from 400 nm to 700 nm
    - Infrared Light is radiation less energetic than visible light, but more than microwaves
      - Wavelengths range from 700 nm to 1 mm
    - Microwaves are radiation less energetic than infrared, but more than radio waves
      - Wavelengths range from 1 mm to 1 m
    - Radio Waves are the weakest form of electromagnetic radiation
      - Includes all wavelengths longer than 1 m



- Wave Motion
  - All electromagnetic radiation travels through space as waves
    - A Wave is the way that energy is transferred from place to place without physical movement of the material.
      - It is NOT a physical object!!!
    - Waves have specific properties that are quantified and tell us about them
      - The Wave Period is the number of seconds needed for the wave to repeat itself at some point in space

- The Wavelength is the number of meters need for the wave to repeat itself at a given moment in time
    - Wavelength is measured in meters
- The Amplitude is the maximum departure of the wave from the undisturbed state known as the baseline
    - Crest is the amplitude above the baseline
    - Trough is the amplitude below the baseline
- The Frequency is the number of crests that pass any given point per unit time
    - It is measured in Hertz (Hz) which is waves per second

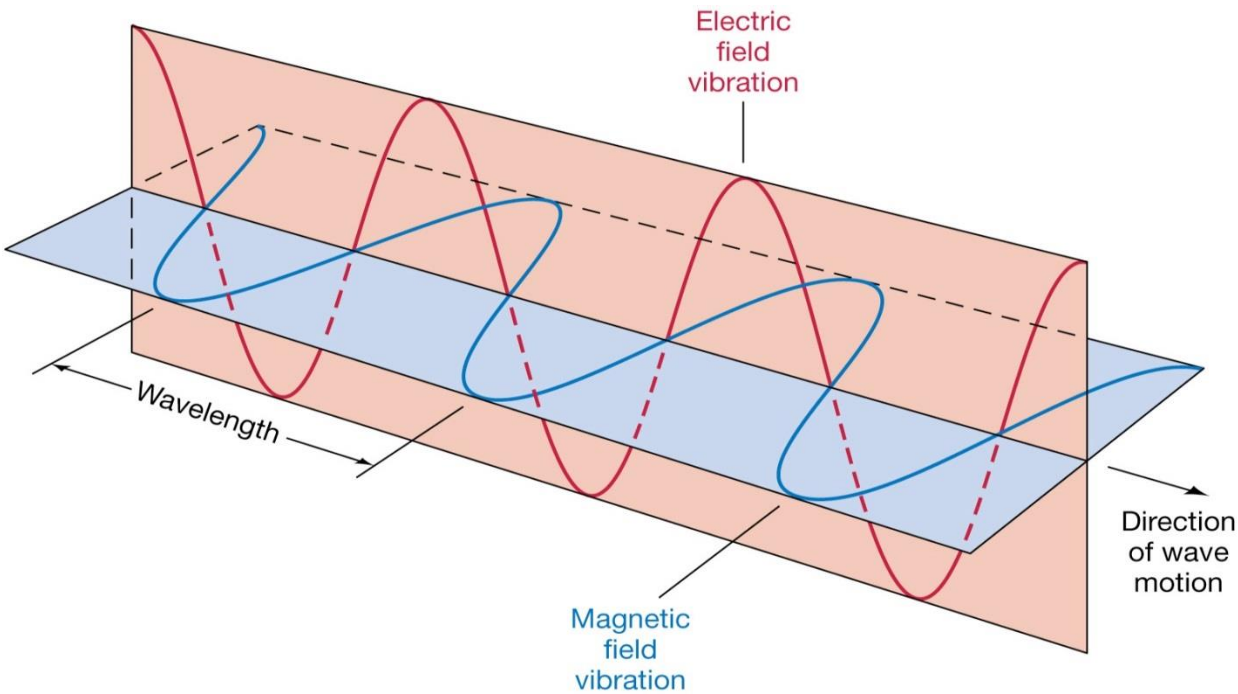
$$frequency = \frac{1}{period} \qquad wavelength \times frequency = velocity$$



2.2 Waves in What?

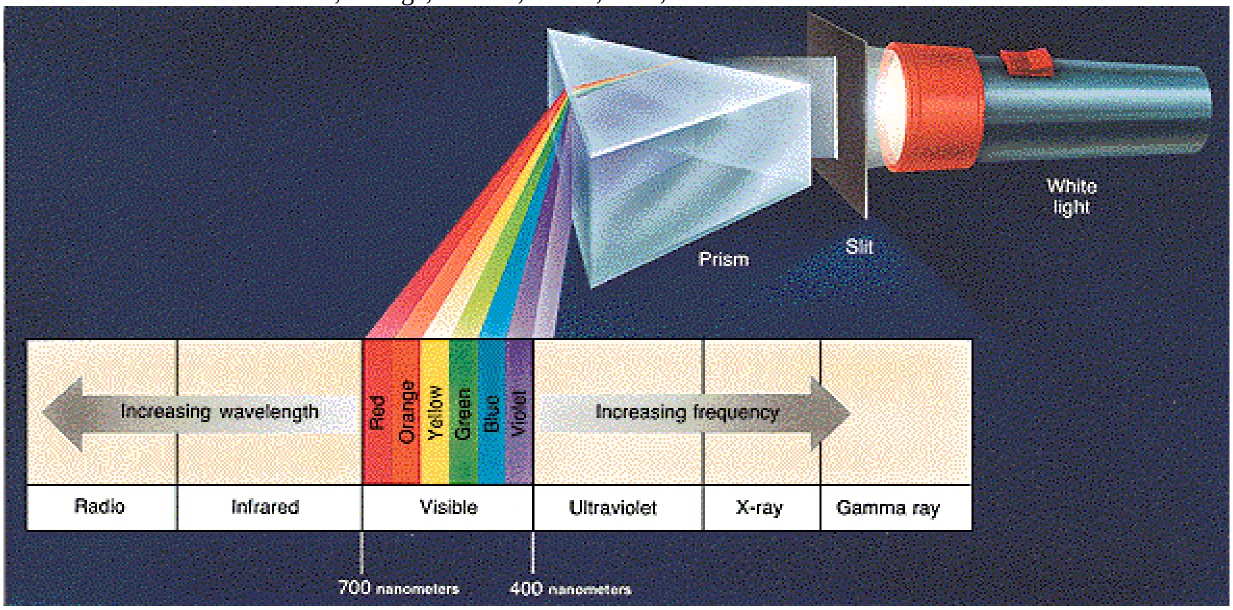
- Diffraction is the apparent bending of waves around corners
    - Similar to sound waves bouncing down the hallway or water waves bending around a breaker
- Interference is when waves from different sources reinforce or partially cancel each other out
    - Similar to waves of water being pushed between two people in a pool
- Interactions Between Charged Particles
    - Just as objects with mass exert a gravitational force on other objects around them, charged particles exert an electric force on other charged particles around them
        - Gravitational force is always attractive, but electric force can be attractive or repulsive
            - Protons are positively charged particles
            - Electrons are negatively charged particles
            - Opposite charges attract, similar charges repel
        - An Electric Field is an area surrounding a charged particle that determines the electric force applied by the object at that location
            - The closer to the charged particle, the stronger the force it applies
                - It follows the same inverse-square law as gravity does, with charge instead of mass and the electric instead of gravitational constant

- Electromagnetism
    - A Magnetic Field is an area surrounding each changing electric field
        - It travels with the electric field but is perpendicular to the electric field
    - Electromagnetism is the combination of the magnetic fields and electric field
        - They are actually the two parts of the same phenomenon
        - This is the electromagnetic wave discussed in section 2.1
    - All electromagnetic waves travel through space at 3.0×10^8 m/s (3.0×10^5 km/s)
        - The Speed of Light is the velocity of electromagnetic waves through space

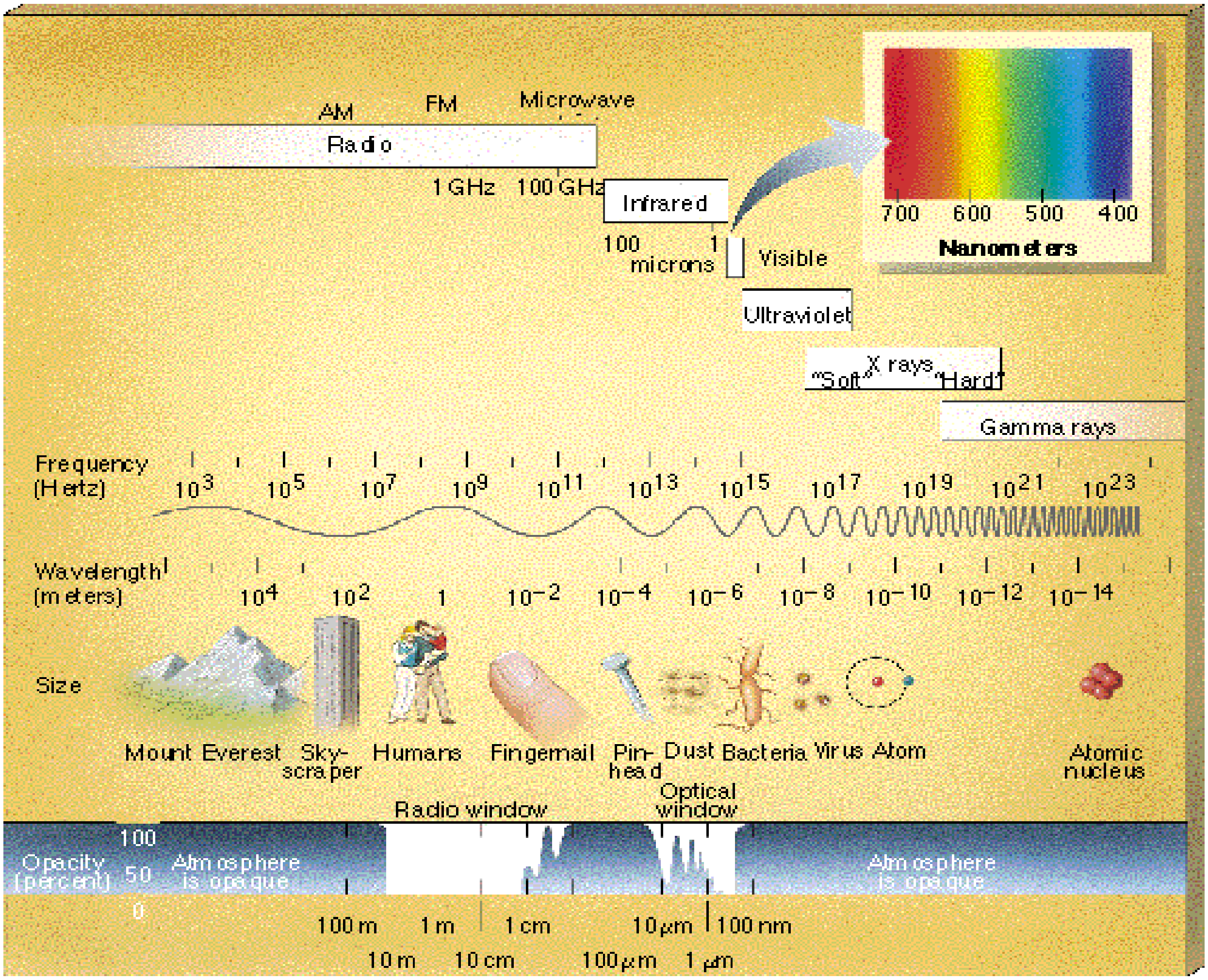


2.3 The Electromagnetic Spectrum

- Components of Visible Light
    - The spectrum of visible light contains six major hues
        - Red, Orange, Yellow, Green, Blue, Violet



- The Full Range of Radiation
  - The Electromagnetic Spectrum is the combination of all the possible frequencies of radiation
    - The Earth's atmosphere filters most of the spectrum out and there are only 2 windows where the radiation can be detected from Earth through the atmostphere
      - Radio Window
        - Between wavelengths of 5 cm and 10 m come completely through
      - Optical Window
        - Visible spectrum and very little of the infrared spectrum almost come all the way through



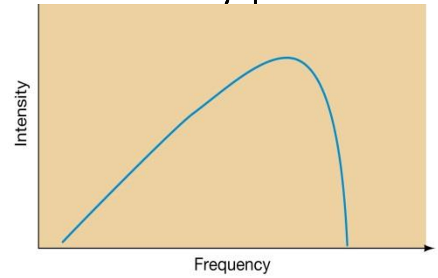
2.4 Thermal Radiation

- Temperature is the direct measure of the amount of microscopic motion within an object
  - The faster the particles are moving, the hotter the temperature
    - In Science temperature is measured in Kelvins
      - Absolute Zero is 0 K and the point where all motion of particles has stopped
      - Water freezes at 273 K
      - Water boils at 373 K
    - The other two temperature units are related to Kelvin temperature by these equations

$$Kelvin = ℃ + 273 \qquad ℉ = 1.8℃ + 32$$

- The Blackbody Spectrum
  - Intensity is the term used to specify the amount or strength of radiation at any point in space
    - Like frequency and wavelength, intensity is a basic property of electromagnetic radiation
      - No natural object emits all of its radiation at just one frequency, but instead it is spread out over a range of frequencies
  - A Blackbody is an ideal object that absorbs all radiation falling upon it and reemits all the radiation it absorbs

Blackbody Spectrum



- The Radiation Laws
  - The blackbody curve emitted by an object will shift further up the electromagnetic spectrum (to higher frequency) as the temperature of the object increases.
    - Wilhelm Wien noticed that the wavelength of peak emission of the object is inversely proportional to the temperature of the object (0.29 cm is the proportionality constant

$$\lambda \propto \frac{1}{T} \qquad \lambda = \frac{0.29}{T}$$

    - Josef Stefan noticed that the energy emitted per second (Flux) by a body rises by a power of 4 as the temperature increases (5.67×10^{-8} W/m^2 K^4 is the proportionality constant)

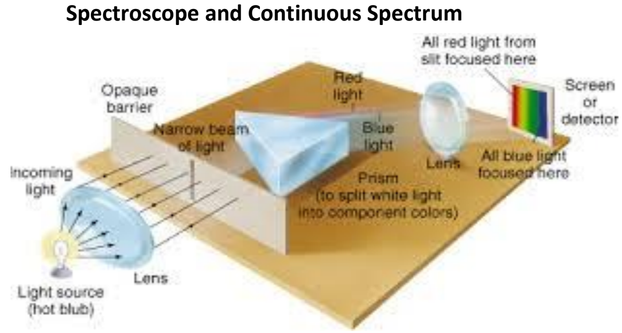
$$F = 5.67 \times 10^{-8} \cdot T^4$$

- Astronomical Applications
  - These two formulas are used to help determine the temperature and of objects in space by just observing the peak wavelength of light that reaches us here on Earth

2.5 Spectroscopy

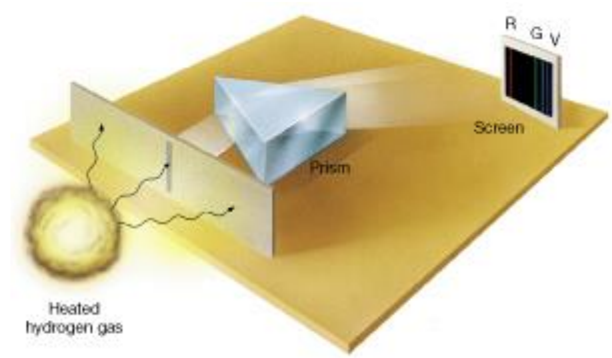
- The Spectroscope is the name of the instrument used to analyze radiation
  - Consists of a single slit, a prism, and a detector
    - The single slit allows only a narrow beam of light through a barrier
    - The prism splits the light into its component colors
    - The detector determines which colors are present

Spectroscope and Continuous Spectrum



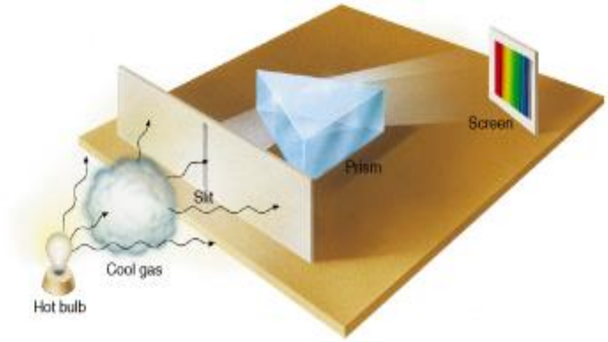
- Emission Lines
  - Continuous Spectra are emissions that emit radiation in all wavelengths without any interruption
    - The emission shown in the diagram above is continuous
  - Emission Spectra are emissions of only very specific wavelengths of radiation
    - Emission Lines are narrow slices of the continuous spectrum that when all are put together create a continuous spectrum
    - These lines are unique to each element in the periodic table

Emission Spectrum



- Absorption Lines
  - Absorption Spectra are emissions of a continuous spectrum with only very specific wavelengths of radiation missing
    - Absorption Lines are narrow slices of the continuous spectrum that have been removed (absorbed) by the substance the continuous source has traveled through
      - These lines occur at the exact same wavelengths as the same gas emits in its emission spectrum

Emission Spectrum

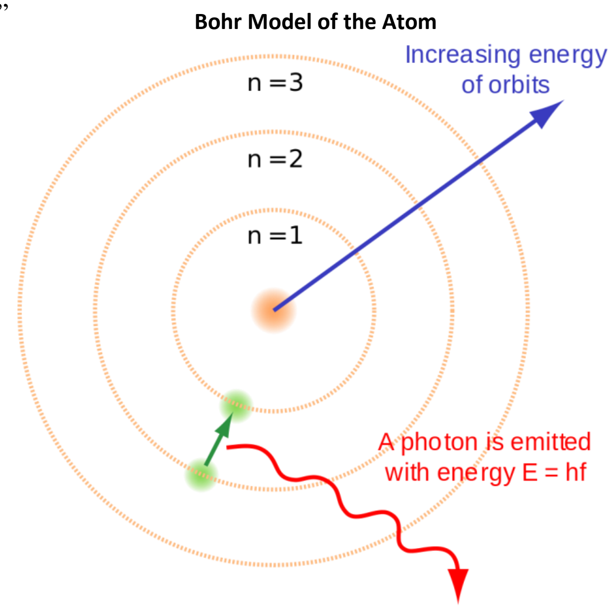


- Spectroscopy
  - Since the absorption and emission lines are the exact same, either method will allow you to determine the composition of the gas being measured
    - Spectroscopy is the study in which matter emits and absorbs radiation
  - Kirchoff's Laws summarize spectroscopy
    - Kirchoff's First Law
      - A luminous solid or liquid, or a sufficiently dense gas, emits light of all wavelengths and produces a continuous spectrum of radiation
    - Kirchoff's Second Law
      - A low-density hot gas emits light whose spectrum consists of a series of bright emission lines. These lines are characteristic of the chemical composition of the gas
    - Kirchoff's Third Law
      - A low-density cool gas absorbs certain wavelengths from a continuous spectrum, leaving dark absorption lines in their place, superimposed on the continuous spectrum. These lines are characteristic of the composition of the intervening gas. They occur at precisely the same wavelengths as the emission lined produced by the gas at higher temperatures
- Astronomical Applications
  - Using the spectrum of light from the Sun, scientists were able to discover the previously unknown element Helium (named after the Greek word for Sun *helios*)

2.6 The Formation of Spectral Lines

- Atomic Structure
  - An Atom is the smallest particle of matter upon which all matter is constructed
  - The Nucleus is the center of the atom
    - It takes up almost no space, yet contains all of the mass of an atom
    - Protons are the positively charged subatomic particles located in the nucleus
    - Neutrons are neutrally charged subatomic particles located in the nucleus
  - The Electron Cloud makes up the rest of the atom outside of the nucleus
    - Electrons are the negatively charged subatomic particles that move though the electron cloud
      - Early models of the atom had electrons free to move about this cloud, which would produce continuous spectrum when looking at elements
      - Elements do not give off continuous spectrum, but instead very specific and discrete wavelengths of radiation
  - An Ion is anything with a positive or negative charge
    - Things with extra electrons are negative (anions)
    - Things missing electrons are positive (cations)

- In 1913, a new model of the atom was developed to explain the emission spectrum of Hydrogen
  - The Bohr Model (developed by Niels Bohr) is a model which has the electron cloud consisting of different levels of energy where electrons can exist
    - The Ground State is the “normal” location of the electron in an atom, which will always be as close to the nucleus as possible
    - The Excited State is the location of an electron if it has moved further from the nucleus to another energy level
    - The difference in energy between the two states an electron moves two is equal to the energy absorbed (up to excited state) or emitted (down to ground state) by the electron
      - This makes the wavelength inversely proportional to the energy of the wave (or directly proportional to the frequency)



$E_{wave} \propto \frac{1}{\lambda}$ or $E_{wave} \propto f_{wave}$

- The Particle Nature of Radiation
  - The fact that the energy must be absorbed and emitted in little specific amounts, means that light must also have properties of particles
    - A Photon is the particle form of radiation
      - A photon’s energy is also directly proportional to the frequency of the radiation

$$E_{photon} \propto f_{photon}$$

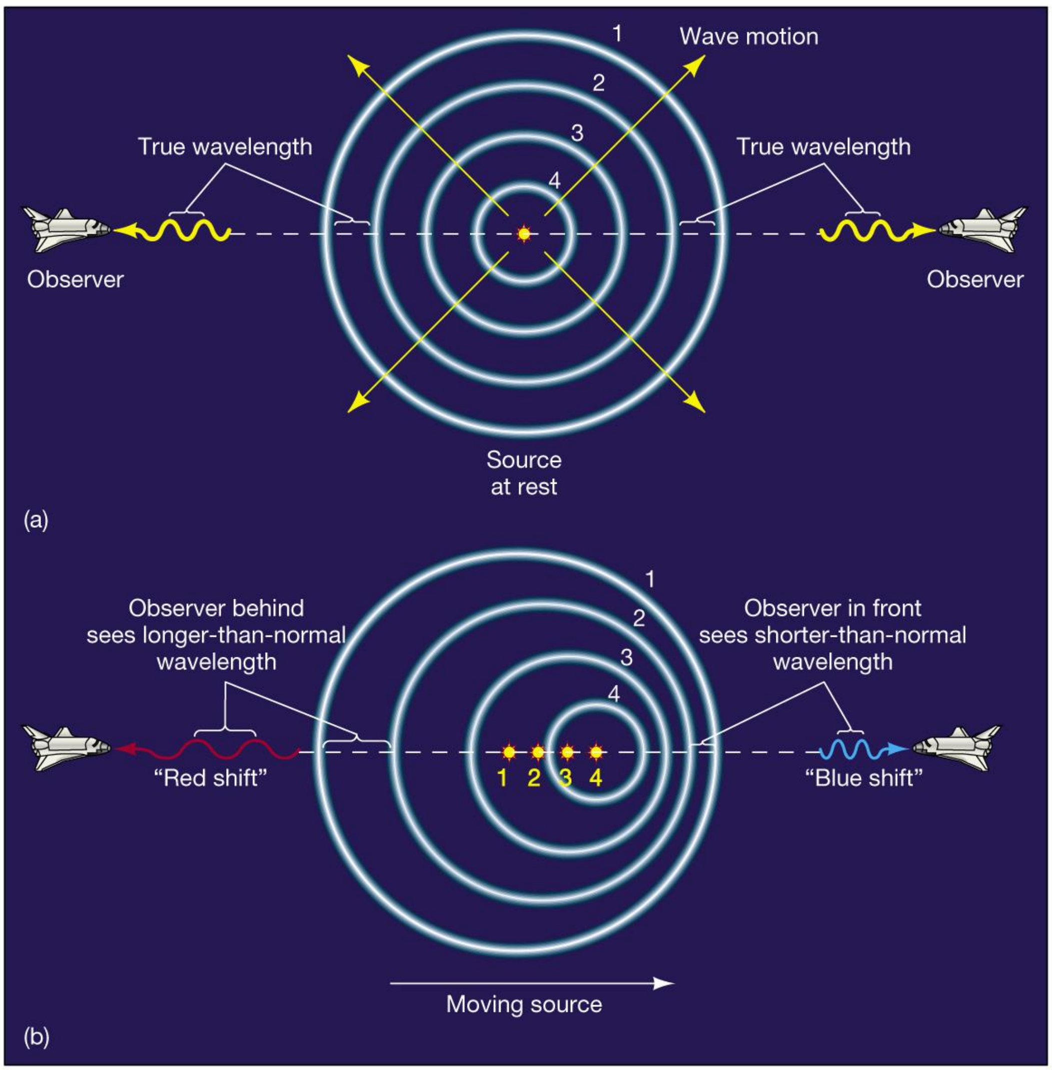
- The Spectrum of Hydrogen
  - Hydrogen is by far the simplest element, and it has only one electron, so using hydrogen allows us to determine the different ways electrons can move and we can see them one at a time
    - When looking at the emission spectrum of hydrogen, we notice more than one line
      - The electrons can jump directly from higher states all the way down to the ground state in one jump, releasing a larger amount of energy
      - The electrons can also jump from higher states and slowly jump back down one or two levels at a time until it gets back down to ground state, which appear as multiple lines of less energy than the large jumps do.

- More Complex Spectra
  - All other atoms above hydrogen get more complex very quickly as multiple electrons exist and are moving up and down in many different combinations. Each element has its own specific pattern, yet it is much more complex than hydrogen
  - Most things in the universe are not pure elements, but exist in compounds, which are MUCH more complicated as now there are multiple elements and multiple electrons bound in different ways that all affect the emission and absorption spectra
  - Despite the complexity, once a substance has its spectra mapped, it can be used to compare to experimental evidence from space to make inferences as to the composition of objects very far away from Earth as the light reaches us.

2.7 The Doppler Effect

- The Doppler Effect is the motion-induced change of the observed frequency of a wave
  - It is named after Christian Doppler, a 19th century Austrian physicist who first explained it
- There are 3 parts to the Doppler Effect:
  - A stationary object that is emitting waves will constantly radiate the waves at exactly the same rate
    - This is considered the "true wavelength"
  - If the object is moving toward the observer, the distance between flashes will decrease because the object itself closes some of the distance between the previous flash and the observer before it emits the next flash from a now closer location.
    - This makes the 2nd flash appear to be much closer to the 1st flash
  - If the object is moving away from the observer, the distance between flashes will decrease becaue the object itself opens some distance between the previous flash and the observer before it emits the next flash from a now further location
    - This makes the 2nd flash appear to be much further than the 1st flash

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$



2.8 Spectral Line Analysis

- With a spectrograph and a telescope, a list of properties that can be determined by analysis of radiation we observe from an object in space
  - The composition of an object is determined by matching its spectral lines with the laboratory spectra of known atoms and molecules
  - The temperature of an object emitting a continuous spectrum can be measured by matching the overall distribution of radiation with a blackbody curve. Temperature may also be determined from detailed studies of spectral lines.
  - The (line-of-sight) velocity of an object is measured by determining the Doppler shift of its spectral lines
  - An object's rotation rate can be determined by measuring the broadening (smearing out over a range of wavelengths) produced by the Doppler effect in emitted or reflected spectral lines
  - The pressure of the gas in the emitting region of and object can be measured by its tendency to broaden spectral lines. The greater the pressure, the broader the line
  - The magnetic field of an object can be inferred from a characteristic splitting it produces in many spectral lines, when a single line divides in two. Known as the Zeeman effect
- With sensitive enough equipment, there is almost no limit of how much data can be derived from starlight
  - The challenge is deciphering how much each of the different factors contributes to the spectral line profiles of each individual object and what it means about the source of the lines themselves