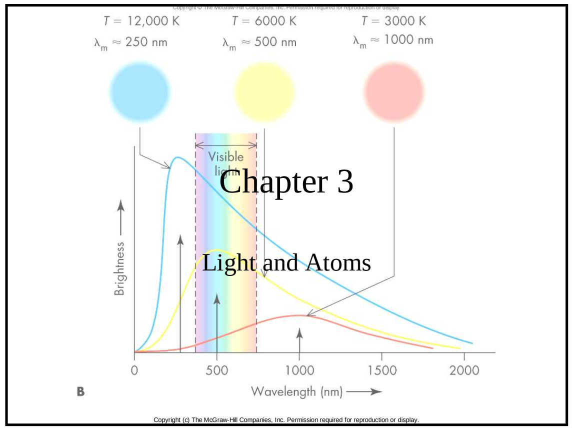
9/16/08 Tuesday

- Announce:
  - Observations?
- Milky Way Center movie
- Moon's Surface Gravity movie
- Questions on Gravity from Ch. 2
- Ch. 3
- Newton Movie



Chapter 3

Light and Atoms

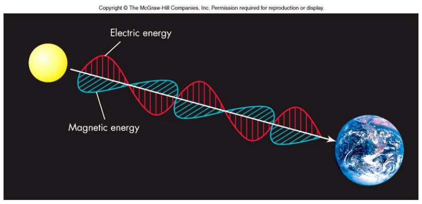
Light – the Astronomer's Tool

- Due to the vast distances, with few exceptions, direct measurements of astronomical bodies are not possible
- We study remote bodies indirectly by analyzing their light
- Understanding the properties of light is therefore essential
- Care must be given to distinguish light signatures that belong to the distant body from signatures that do not (e.g., our atmosphere may distort distant light signals)

Properties of Light

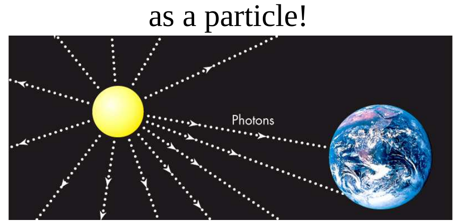
- *Light* is radiant energy: it does not require a medium for travel (unlike sound!)
- Light travels at 299,792.458 km/s in a vacuum (fast enough to circle the Earth 7.5 times in one second)
- Speed of light *in a vacuum* is constant and is denoted by the letter "c"
- However, the speed of light is reduced as it passes through transparent materials
  - The speed of light in transparent materials is dependent on color
  - Fundamental reason telescopes work the way they do!

Sometimes light can be described as a wave…



- The wave travels as a result of a fundamental relationship between electricity and magnetism
- A <u>changing</u> magnetic field creates an electric field and a <u>changing</u> electric field creates a magnetic field

…and sometimes it can be described as a particle!



- Light thought of as a stream of particles called ***photons***
- Each photon particle carries energy, depending on its ***frequency*** or ***wavelength***

So which model do we use?

– Well, it depends!
- In a vacuum, photons travel in straight lines, but behave like waves
- Sub-atomic particles also act as waves
- *Wave-particle duality:* All particles of nature behave as both a wave and a particle
- Which property of light manifests itself depends on the situation
- We concentrate on the wave picture henceforth

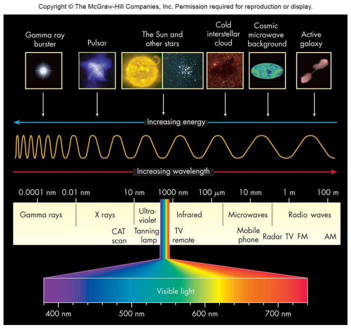
Light and Color

- Colors to which the human eye is sensitive is referred to as the ***visible spectrum***
- In the wave theory, color is determined by the light's ***wavelength*** (symbolized as λ)

– The ***nanometer*** (10^{-9} m) is the convenient unit

– Red = 700 nm (longest visible wavelength), violet = 400 nm (shortest visible wavelength)

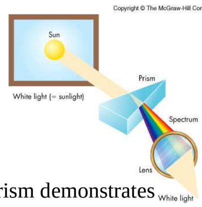
The Visible Spectrum

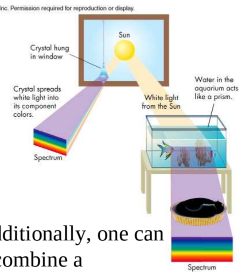


Frequency

- Sometimes it is more convenient to talk about light's frequency
  – ***Frequency*** (or ν) is the number of wave crests that pass a given point in 1 second (measured in Hertz, Hz)
  – Important relation: $\nu\lambda = c$
  – Long wavelenth = low frequency
  – Short wavelength = high frequency

White light – a mixture of all colors



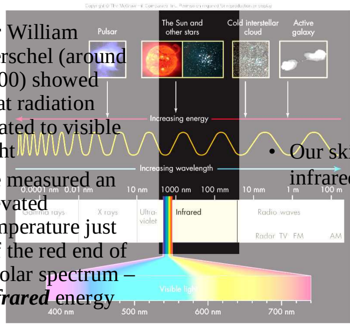


- A prism demonstrates that white light is a mixture of wavelengths by its creation of a spectrum
- Additionally, one can recombine a spectrum of colors and obtain white light

The Electromagnetic Spectrum

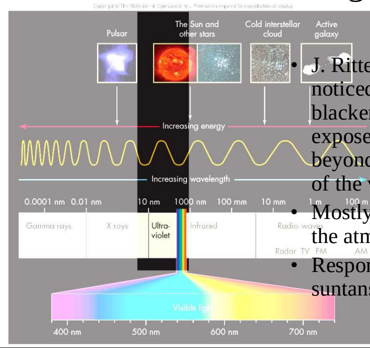
- The ***electromagnetic spectrum*** is composed of radio waves, microwaves, infrared, visible light, ultraviolet, x rays, and gamma rays
- Longest wavelengths are more than 10^3 km
- Shortest wavelengths are less than 10^{-18} m
- Various instruments used to explore the various regions of the spectrum

Infrared Radiation



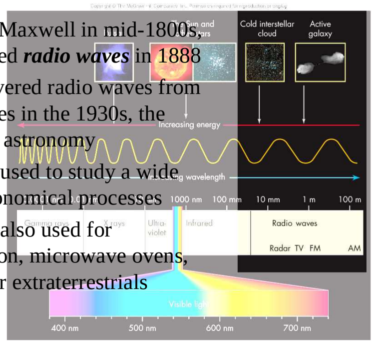
- Sir William Herschel (around 1800) showed heat radiation related to visible light
- He measured an elevated temperature just off the red end of a solar spectrum – ***infrared*** energy
- Our skin feels infrared as heat

Ultraviolet Light



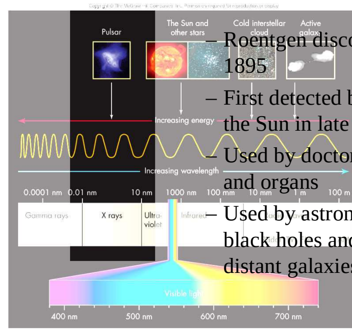
- J. Ritter in 1801 noticed silver chloride blackened when exposed to "light" just beyond the violet end of the visible spectrum
- Mostly absorbed by the atmosphere
- Responsible for suntans (and burns!)

Radio Waves



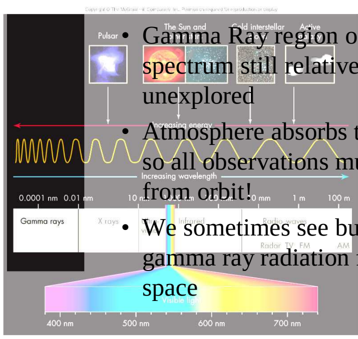
- Predicted by Maxwell in mid-1800s, Hertz produced ***radio waves*** in 1888
- Jansky discovered radio waves from cosmic sources in the 1930s, the birth of radio astronomy
- Radio waves used to study a wide range of astronomical processes
- Radio waves also used for communication, microwave ovens, and search for extraterrestrials

X-Rays



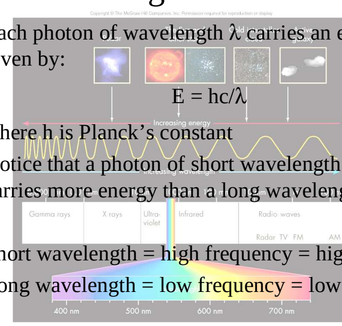
- Roentgen discovered X rays in 1895
  - First detected beyond the Earth in the Sun in late 1940s
  - Used by doctors to scan bones and organs
  - Used by astronomers to detect black holes and tenuous gas in distant galaxies

Gamma Rays



- Gamma Ray region of the spectrum still relatively unexplored
- Atmosphere absorbs this region, so all observations must be done from orbit!
- We sometimes see bursts of gamma ray radiation from deep space

Energy Carried by Electromagnetic Radiation



- Each photon of wavelength λ carries an energy E given by:

$$E = hc/\lambda$$

where h is Planck's constant

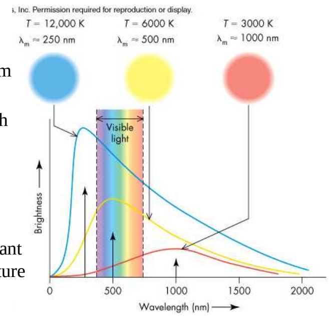
- Notice that a photon of short wavelength radiation carries more energy than a long wavelength photon
- Short wavelength = high frequency = high energy
- Long wavelength = low frequency = low energy

Radiation and Temperature

- Heated bodies generally radiate across the entire electromagnetic spectrum
- There is one particular wavelength, λ_m, at which the radiation is most intense and is given by ***Wien's Law:***

$$\lambda_m = k/T$$

Where k is some constant and T is the temperature of the body



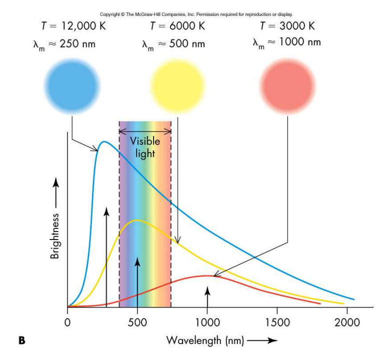
Radiation and Temperature

- Note hotter bodies radiate more strongly at shorter wavelengths
- As an object heats, it appears to change color from red to white to blue
- Measuring λ_m gives a body's temperature
- Careful: Reflected light does not give the temperature

Blackbodies and Wien's Law

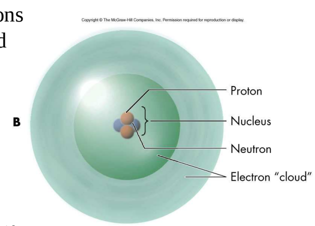
- A ***blackbody*** is an object that absorbs all the radiation falling on it
- Since such an object does not reflect any light, it appears black when cold, hence its name
- As a blackbody is heated, it radiates more efficiently than any other kind of object
- Blackbodies are excellent absorbers and emitters of radiation and follow Wien's law
- Very few real objects are perfect blackbodies, but many objects (e.g., the Sun and Earth) are close approximations
- Gases, unless highly compressed, are not blackbodies and can only radiate in narrow wavelength ranges

Blackbodies and Wien's Law



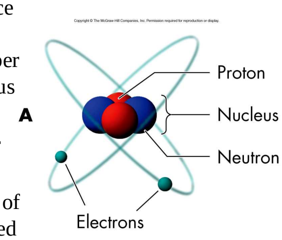
The Structure of Atoms

- Nucleus – Composed of densely packed neutrons and positively charged protons
- Cloud of negative electrons held in orbit around nucleus by positive charge of protons
- Typical atom size: 10^{-10} m (= 1 Å = 0.1 nm)

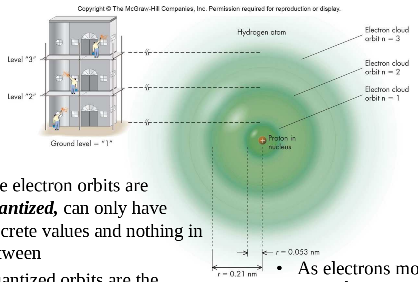


The Chemical Elements

- An ***element*** is a substance composed only of atoms that have the same number of protons in their nucleus
- A neutral element will contain an equal number of protons and electrons
- The chemical properties of an element are determined by the number of electrons



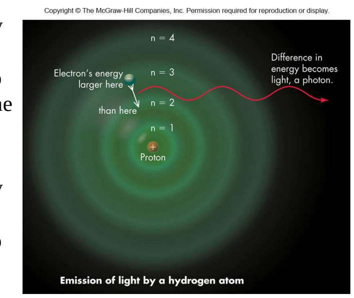
Electron "Orbits"



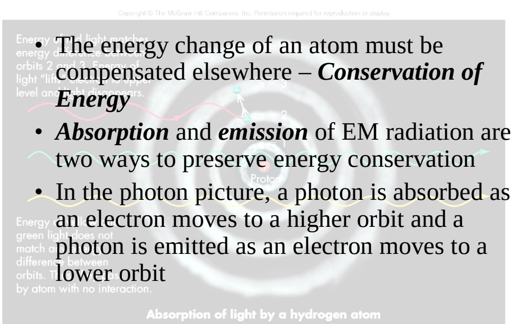
- The electron orbits are ***quantized,*** can only have discrete values and nothing in between
- Quantized orbits are the result of the wave-particle duality of matter
- As electrons move from one orbit to another, they change their energy in discrete amounts

Energy Change in an Atom

- An atom's energy is increased if an electron moves to an outer orbit – the atom is said to be ***excited***
- An atom's energy is decreased if an electron moves to an inner orbit

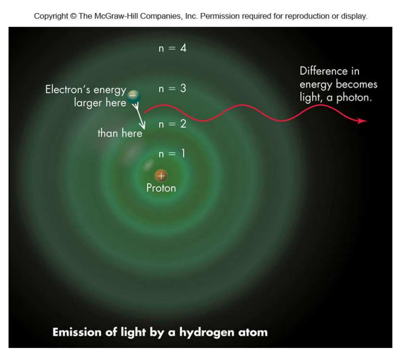


Conservation of Energy

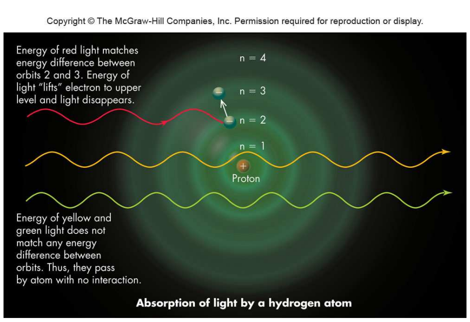


- The energy change of an atom must be compensated elsewhere – ***Conservation of Energy***
- ***Absorption*** and ***emission*** of EM radiation are two ways to preserve energy conservation
- In the photon picture, a photon is absorbed as an electron moves to a higher orbit and a photon is emitted as an electron moves to a lower orbit

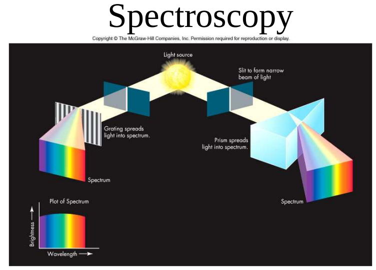
Emission



Absorption

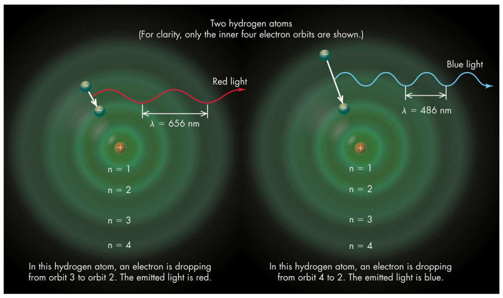


Spectroscopy



- Allows the determination of the composition and conditions of an astronomical body
- In ***spectroscopy,*** we capture and analyze a spectrum
- Spectroscopy assumes that every atom or molecule will have a unique spectral signature

Formation of a Spectrum

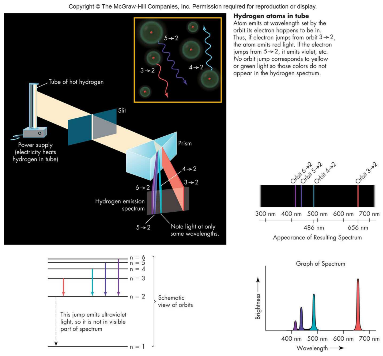


- A transition in energy level produces a photon

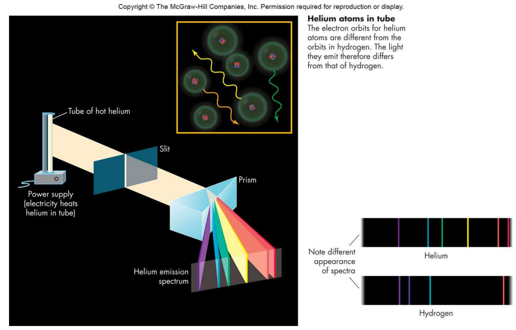
Types of Spectra

- *Continuous spectrum*
  - Spectra of a blackbody
  - Typical objects are solids and dense gases
- *Emission-line spectrum*
  - Produced by hot, tenuous gases
  - Fluorescent tubes, aurora, and many interstellar clouds are typical examples
- *Dark-line* or *absorption-line spectrum*
  - Light from blackbody passes through cooler gas leaving dark absorption lines
  - Fraunhofer lines of Sun are an example

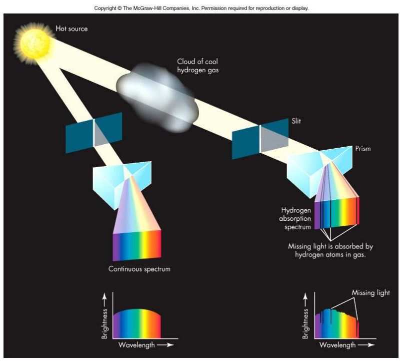
Emission Spectrum



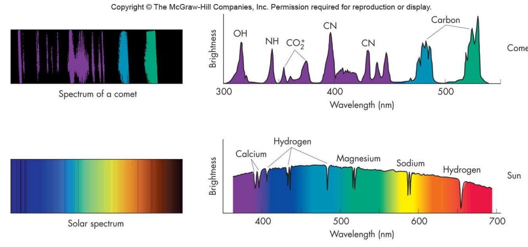
Emission Spectrum



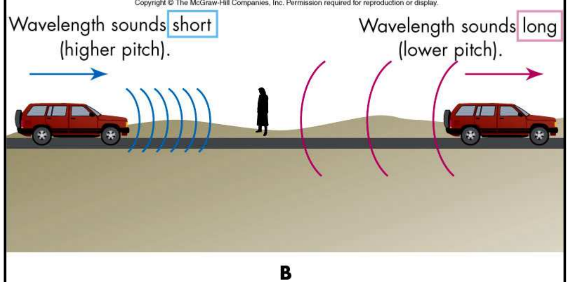
Continuous and Absorption Spectra



Astronomical Spectra

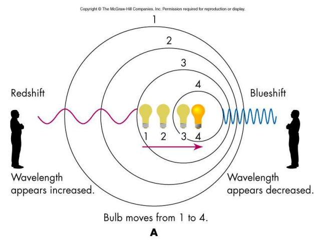


Doppler Shift in Sound



- If the source of sound is moving, the pitch changes!

Doppler Shift in Light



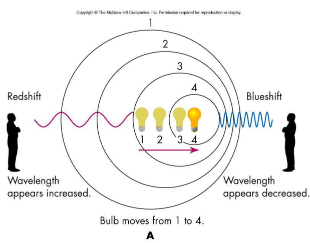
- If a source of light is set in motion relative to an observer, its spectral lines shift to new wavelengths in a similar way
- The shift in wavelength is given as

$$\Delta\lambda = \lambda - \lambda_o = \lambda_o v/c$$

where λ is the observed (shifted) wavelength, λ_o is the emitted wavelength, v is the source non-relativistic radial velocity, and c is the speed of light

Redshift and Blueshift

- An observed increase in wavelength is called a redshift, and a decrease in observed wavelength is called a blueshift (regardless of whether or not the waves are visible)
- Doppler shift is used to determine an object's velocity



Absorption in the Atmosphere

- Gases in the Earth's atmosphere absorb electromagnetic radiation to the extent that most wavelengths from space do not reach the ground
- Visible light, most radio waves, and some infrared penetrate the atmosphere through ***atmospheric windows,*** wavelength regions of high transparency
- Lack of atmospheric windows at other wavelengths is the reason for astronomers placing telescopes in space