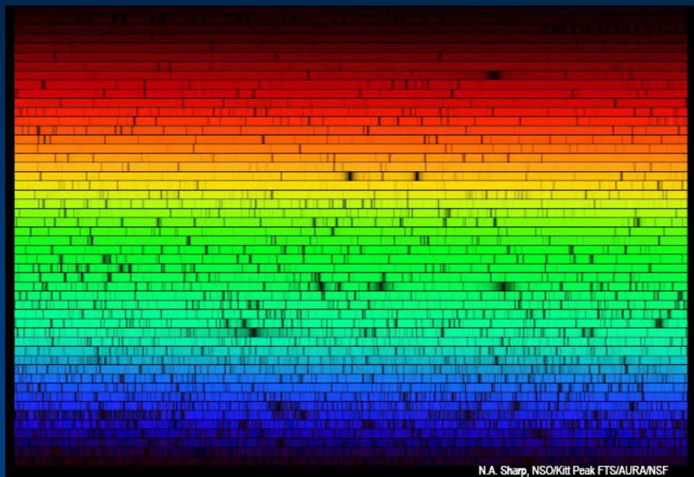
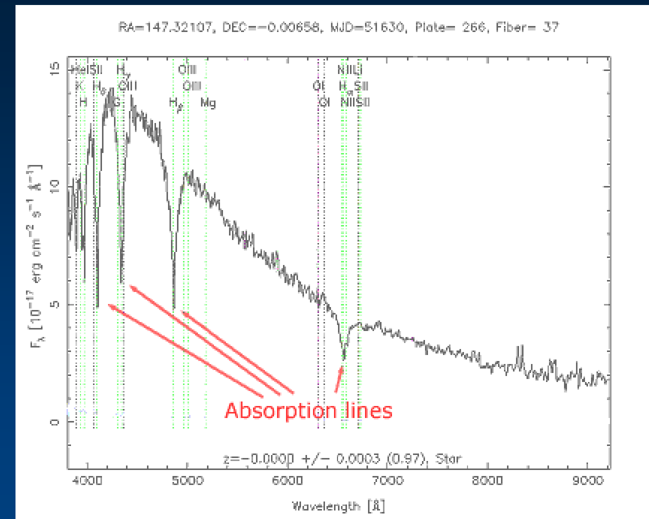
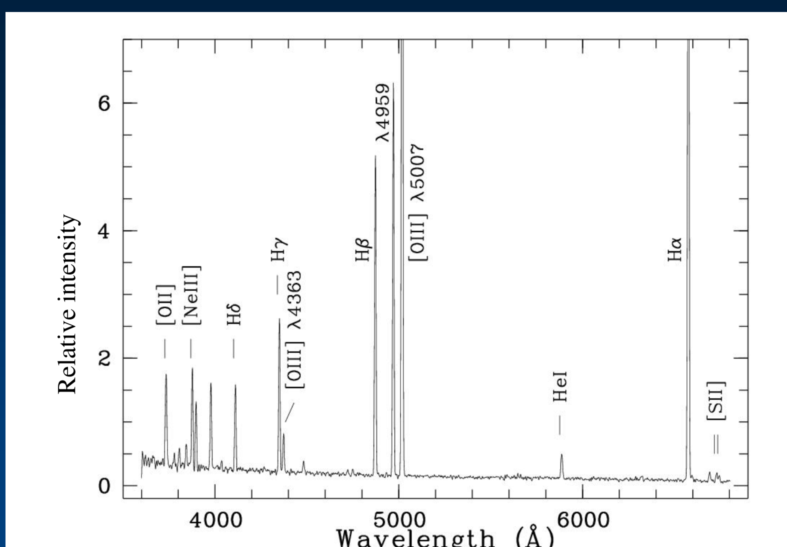
Optical spectrum of the Sun – absorption line spectrum. Broadly a blackbody, but with many absorption lines.



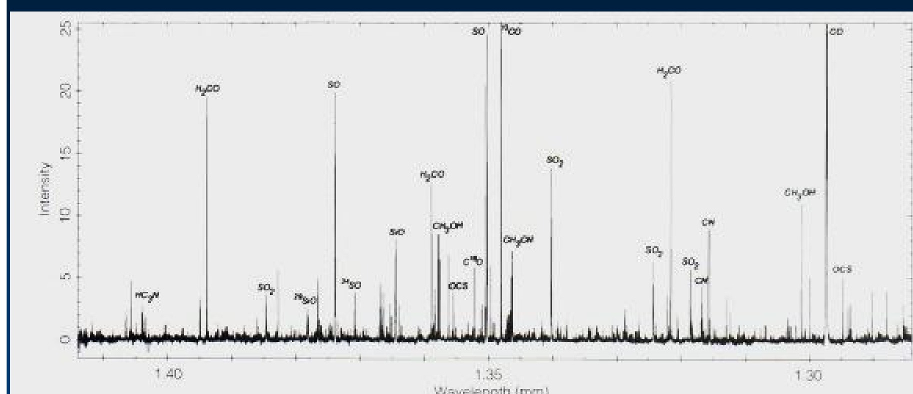
Absorption line spectrum – stars



Emission line spectrum – an "HII region"



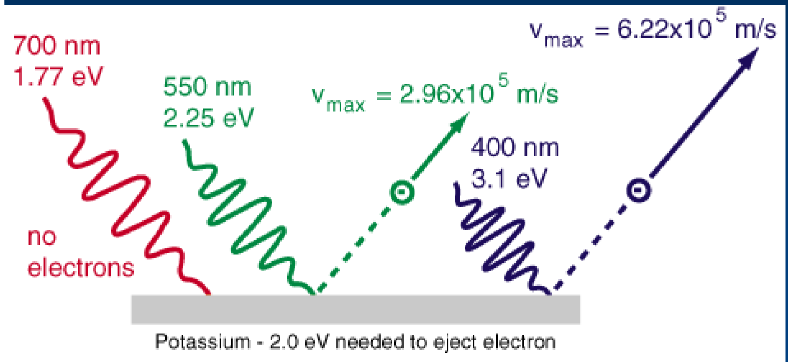
Emission line spectrum – a molecular cloud



How can we understand absorption and emission lines?

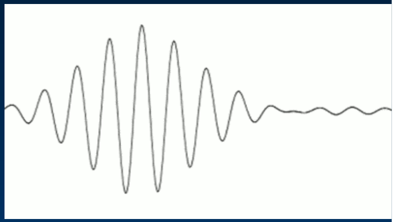
Photoelectric effect

- Light hitting a metal will knock out single electrons, but only if the frequency is high enough, not the intensity.
- Energy of ejected electrons also depends only on incoming light frequency, not on intensity.



The dual nature of radiation

Explanation (Einstein 1905, Nobel Prize): on scale of atoms, can consider light as a stream of massless particles (photons), with energy dependent on frequency. Only photons with sufficient energy can liberate electrons from atoms. Excess energy goes into KE of electrons. Photons still have well defined λ, ν.



Photon energies

$E = h\nu$ or equivalently $E = hc/\lambda$

$h = 6.6 \times 10^{-34}$ J s (Planck's constant again)

$h = 4.1 \times 10^{-15}$ eV s

(1 eV = 1.6×10^{-19} J – energy an electron gains by accelerating through an electric potential of 1 V)

Question: which has more energy, a photon of blue light, or of red light? UV or Radio?

Atomic structure

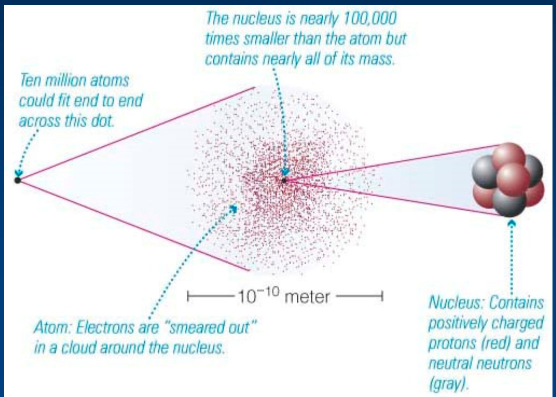
Nucleus contains subatomic particles with most of atom's mass:

Protons (positively charged)

Neutrons (uncharged)

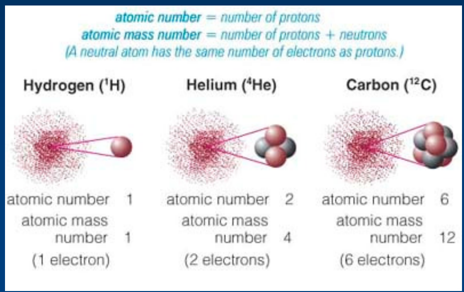
Electrons in a cloud orbiting the nucleus (negatively charged)

Atoms have charge balance



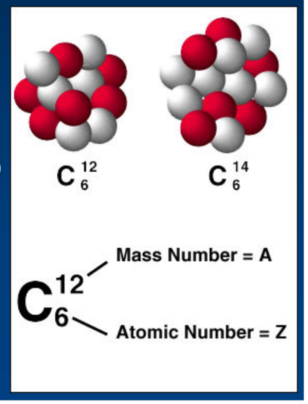
Chemical elements

- Atoms are distinguished into *elements* by the total number of protons in the nucleus.
- This is called the atomic number:
  - 1 proton: Hydrogen
  - 2 protons: Helium
  - 3 protons: Lithium



Each element can have isotopes

- Same number of protons, but different number of neutrons.
- ^{12}C has 6 protons and 6 neutrons
- ^{13}C has 6 protons and 7 neutrons
- ^{14}C has 6 protons and 8 neutrons
- Typically one isotope dominates (e.g. ^{12}C)



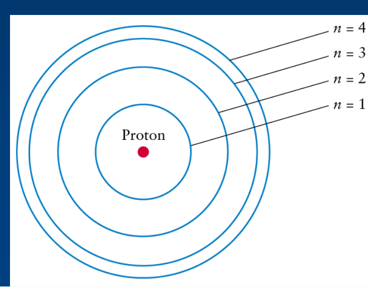
How is energy stored in atoms?

- Atoms can contain energy in three ways:
- Mass energy $E=mc^2$ (because of their mass, more when we discuss Sun)
- Kinetic energy (because of their motion)
- Electric potential energy (because of arrangement of electrons), important here because it is altered by EM radiation
- To understand how the atom reacts to EM radiation (and to interpret the results!) we need to know how atoms gain and release electric potential energy.

Inside the atom

Our understanding comes from the field of Quantum Mechanics:

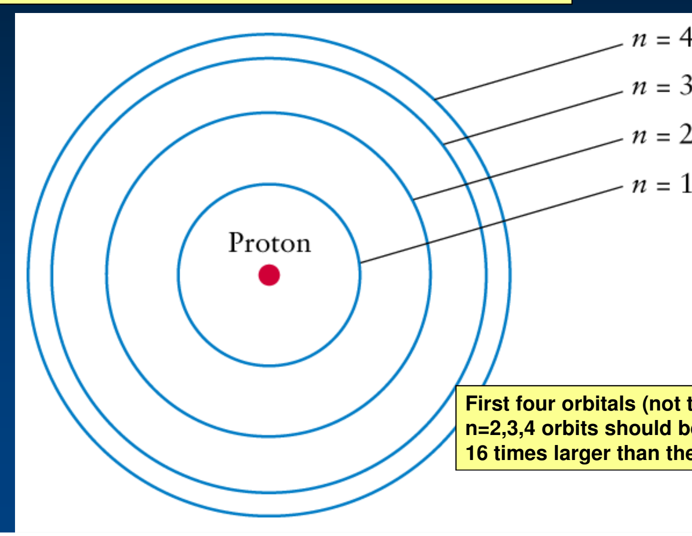
- For practical purposes we can ignore fuzziness of electrons and consider them as discrete particles. Consider the "Bohr model" (1913) for H.
- Proton and orbiting electron attracted. Takes energy to increase separation.
- But, only certain discrete orbitals, or energies, allowed
- Electron in "excited" state quickly decays to lower levels.



The simple Bohr model for the hydrogen atom.

Allowed electron orbits (energies) shown.

First orbital = ground state (n=1). Lowest energy orbital the electron can reside in. Higher orbitals: excited states (n=2,3,4…)

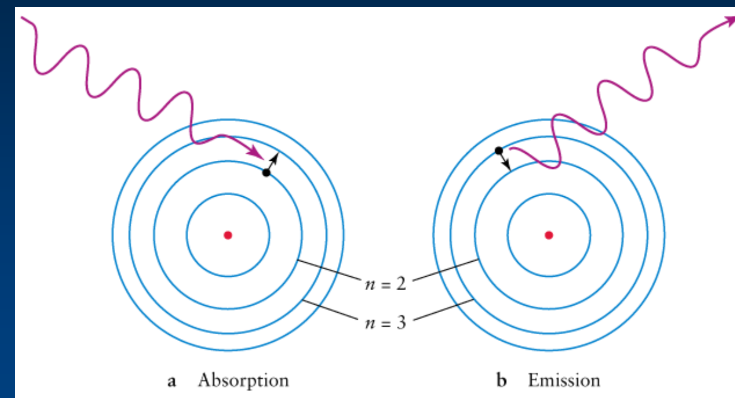


First four orbitals (not to scale, the n=2,3,4 orbits should be 4, 9 and 16 times larger than the n=1 orbit).

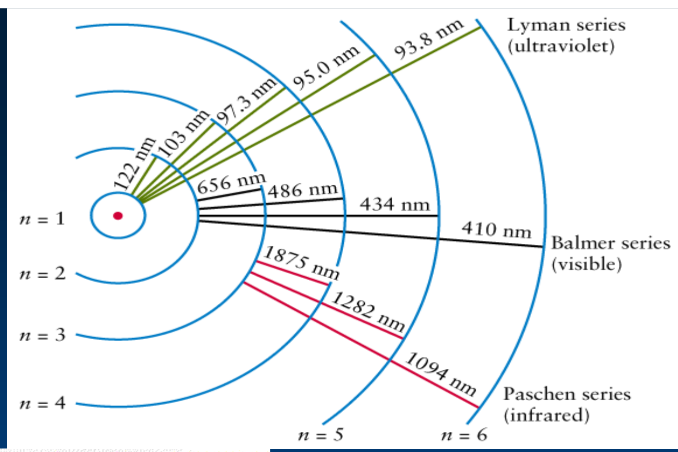
Emission and Absorption

- Electrons can get into excited states by either
  - Colliding (with other atoms or free electrons)
  - Absorbing photons
- Absorption: only photons with exact energy (or frequency) to cause an excitation are absorbed, ALL others pass through unaffected (exception: ionization, see later).
- Electrons get out of excited states by emitting photons in random directions.

- An atom can absorb a photon, causing electron to jump up to a higher energy level, if photon has energy equal to difference of energy levels.
- An atom can emit a photon, as an electron falls down to a lower energy level. Photon's energy equals difference of energy levels. Emitted photon has no memory of direction of absorbed photon.



- May jump more than one level, and fall back down by various paths, emitting multiple photons.



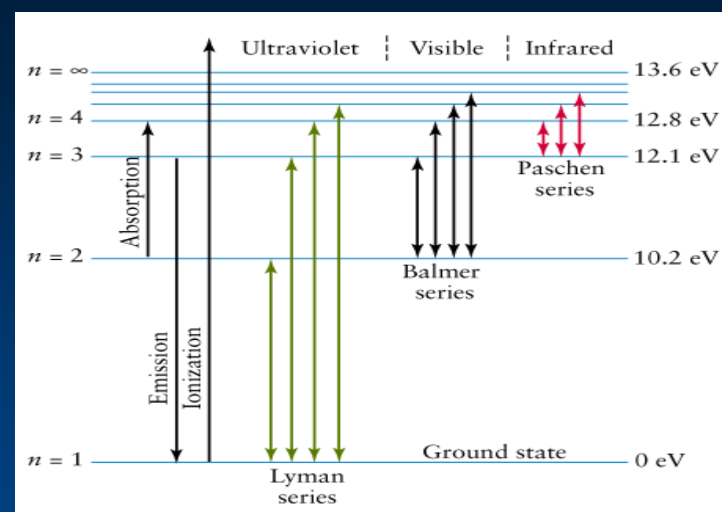
Bohr formula for hydrogen wavelengths

$$\frac{1}{\lambda} = R\left(\frac{1}{N^2} - \frac{1}{n^2}\right)$$

N = number of inner orbit
n = number of outer orbit
R = Rydberg constant = 1.097×10^7 m^{-1}
λ = wavelength (in meters) of emitted or absorbed photon

Remember: $E = h\nu = hc/\lambda$, so equation gives E's too.

Energy level diagram for hydrogen:



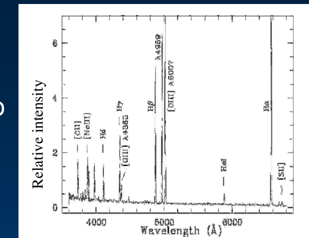
Each element has its own energy levels! This is because attraction of electrons to nucleus changes when the number of particles changes. Energies of typical lines range from fractions of an eV to 1000's of eV.

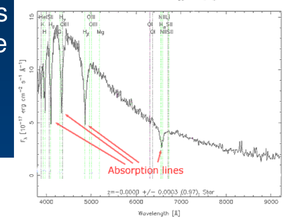
Ionization

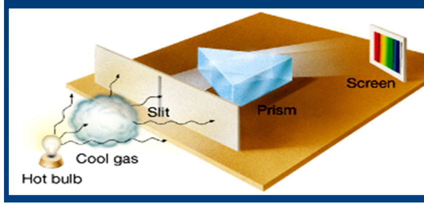
- If an atom or a molecule absorbs enough energy from a photon or a collision, an electron can escape the nuclear attraction => positive ion. For H in ground state, takes at least a 13.6 eV photon. Any extra photon energy goes into KE of electron.
- By adding electrons, you can get a negative ion
- Each ion has its own energy levels
- N II: N with one electron removed, O III: O with two electrons removed, etc. Takes higher energy photons to remove more electrons (e.g. O II: 13.6 eV, O III: 35 eV).

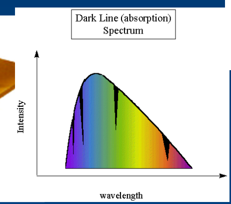
Emission and absorption line spectra

- Hot, low density gas, where collisions between atoms have sufficient energy to cause electrons to move to higher levels, gives emission lines.
- Light from continuous spectrum through cooler gas gives absorption lines, as absorbed photons cause electrons to move to higher levels. Re-emitted photons are in random direction, so incident light in original direction much reduced.



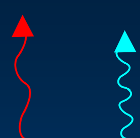


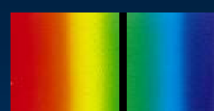




So why do stars have absorption line spectra?

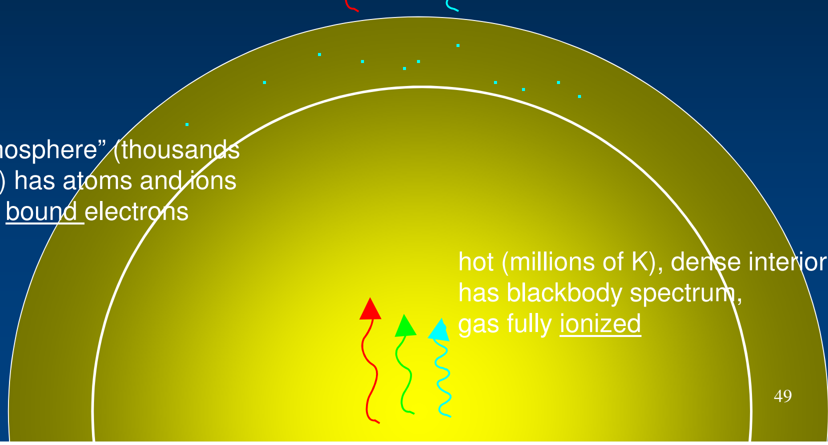
Simple case: let's say these atoms can only absorb green photons. Get dark absorption line at green part of spectrum.





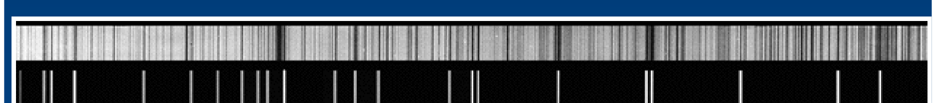
"atmosphere" (thousands of K) has atoms and ions with bound electrons

hot (millions of K), dense interior has blackbody spectrum, gas fully ionized

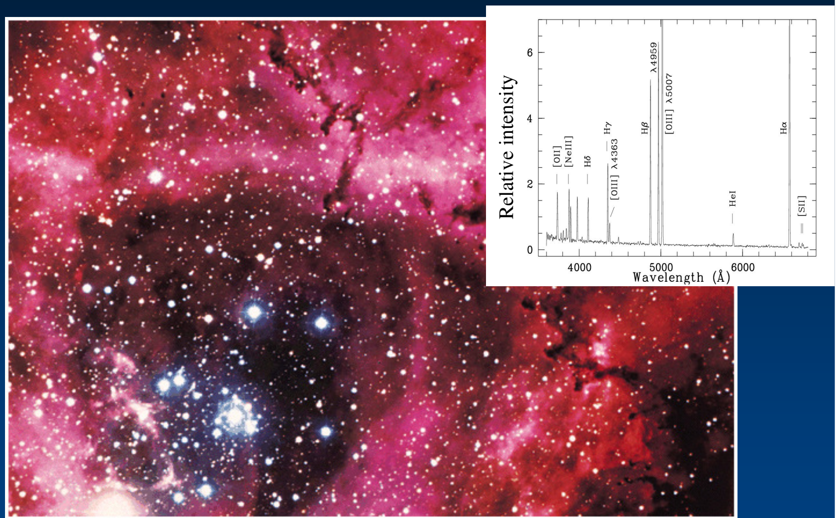


Key points

- Different elements have different sets of energy levels => electron transitions produce or absorb photons of different and unique energies.
- Different energies = different wavelengths. The wavelengths of light tell you what elements you're dealing with. Spectral lines are a fingerprint of the element.
- Example: This is part of the Sun's spectrum, along with emission lines of vaporized iron.



Excited, low-density hydrogen gas. Red due to "H-alpha" emission line, n = 3 to n = 2.

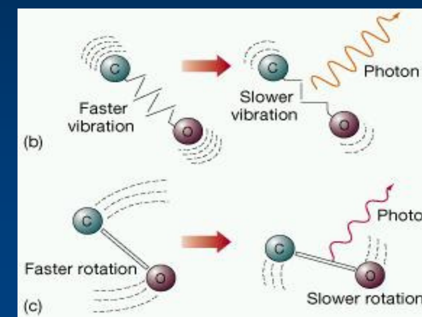


H is mostly ionized. Hence "HII region". Then why does neutral-H line give it its color? Later lecture.

Molecules

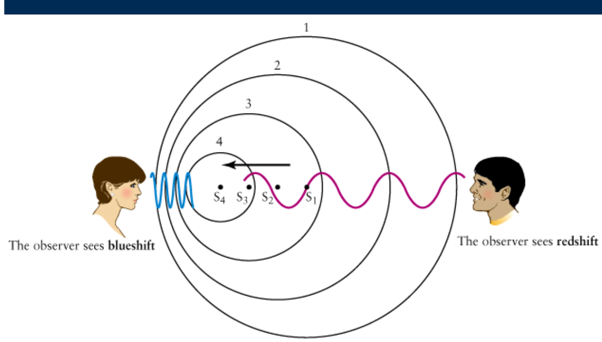
- Compounds of two or more atoms of same or different elements
- Share some electrons in common orbitals
- Have vibrational and rotational energy levels as well (IR, microwave, radio)

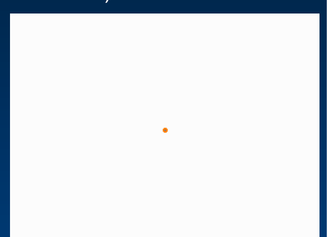
=> Very complex spectra!

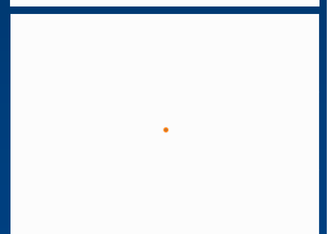


The Doppler shift

Frequency or wavelength of a wave depends on relative motion of emitter and receiver (along the direction of wave motion).





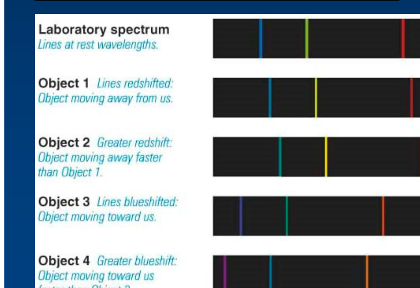


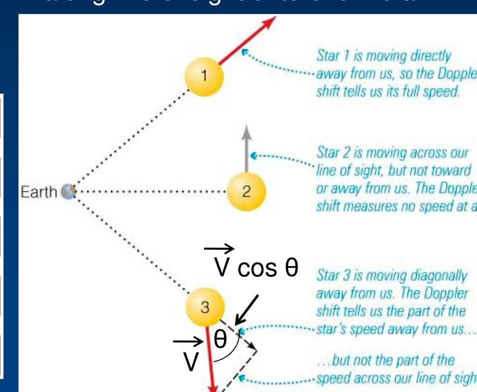
$$V = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}} c = \frac{\Delta\lambda}{\lambda_{emitted}} c$$

where V is the relative velocity along the line of sight, c is the speed of light (both speeds in same units). Note that motion away gives positive shift and velocity, motion towards gives negative.

If V is at some angle, only component along line of sight enters formula

Spectral lines are used to measure Doppler shift => gives us information about the motion of an object.





Example

- The spectrum of an object shows the Hα spectral line (rest wavelength 656.28 nm) shifted to 657.43 nm due to relative motion of the source. What is the velocity of the relative motion? Is it approaching or receding?

Spectroscopy is an important tool!

The spectrum of an objects tells us:

- Which atoms and molecules are present, and in which proportions
- Which atoms are ionized, and in which proportions
- How excited the atoms are, which tells us about the physical state (cold, hot, dense)
- How the object is moving

Particles emit and absorb radiation in other ways too. We'll examine them as they arise.