Lecture 12
Line Spectra
The Doppler Effect
Emission and Absorption Lines
Hydrogen Balmer Lines
Lines from more complex atoms
Doppler Effect: line-of-sight motion

Light: Photons

1) Light: energy-wise, it behaves not as a wave, but as a particle, a "photon". A photon associated with a particular wavelength carries a specific amount of energy "E".

\[ E(\text{photon}) = h \times \text{frequency} = h \times \frac{c}{\text{wavelength}} \]

"h" is a very tiny constant called "Planck's Constant"

• So here is the electromagnetic spectrum again:

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Gamma-ray</th>
<th>X-Ray</th>
<th>Ultraviolet</th>
<th>Blue</th>
<th>Yellow</th>
<th>Red</th>
<th>Infrared</th>
<th>Microwave</th>
<th>Radio</th>
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<tbody>
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<td>Frequency</td>
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<td>Photon energy</td>
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Atoms: Energy States

2) Atoms (and Molecules): have only certain, well-defined amounts of energy that they can carry

• depends on number of protons, neutrons, and (especially) electrons (and molecular arrangement).

• Called "energy states" or "energy levels".

• This energy is stored in a variety of ways. For now, we will be talking about "chemical" energy, the energy of motion of the electrons around the nucleus. (later we will talk about nuclear energy, energy of neutrons and protons in the nucleus)

Energy Level Facts

• There is a lowest energy state called the "ground state".

• There is a highest possible energy beyond which the electron is ejected (the atom is ionized) called the ionization energy.

• There is a finite number of energy levels between ground and ionization

• Every different atom, ion, or molecule has a different set of energy levels

• An atom changes its energy state by gaining or losing energy from light (photons) or collisions (temperature). A real gas has a mixture of atoms in different states, constantly changing as they collide and emit or absorb light
Forming Spectral Lines

- **Emission line**: atom emits photon with a well-defined amount of energy to get to a lower state.
  - Since each photon energy corresponds with only one wavelength, *only one wavelength works for each lower state*.
  - For visible-wavelength photons, this energy goes into electron energy (chemical energy).
- **Absorption line**: atom absorbs a photon with just the right energy allowing it to reach some higher energy state.

Example: Hydrogen

- Hydrogen: simplest atom, simplest spectrum, most abundant gas in the universe!
  - $^1$H nucleus: one proton (no neutrons)
  - Neutral hydrogen: one electron
- Niels Bohr (1885 - 1962) was able to work out the very simple rules for the energy states of Hydrogen. It turns out that hydrogen in its second energy state (energy $E_2$) is able to absorb a famous set of lines called the **Balmer Lines**, a set of lines between near UV and red which is unique to hydrogen.
Balmer Lines

- \( E_3 - E_2 = 1.89 \text{ “electron -volts” (eV)} \)
  - Wavelength(3,2) = 656 nm (red) this is called H-alpha. Emission. This makes the Orion Nebula red. Absorption
- \( E_4 - E_2 = 2.55 \text{ eV} \)
  - Wavelength(4,2) = 486 nm (blue-green) called H-beta. Absorption
- \( E_n - E_2 = 2.86 - 3.4 \text{ eV} \)
  - Wavelength (n,2) = 434, 410, 397, 389 ...(n = 5,6,7,8, ...) (blue, getting closer together) H-gamma, delta, etc
- To ionize Hydrogen from the second state > 3.4 eV
  - Wavelength/ionize) = < 365 nm (near UV). No lines here: any wavelength ionizes out of the second state.

Line spectra of real gases

- Emission lines from multiple electron atoms
  - Only outermost electron is involved
  - electron states of different elements (and different ions of these elements) are different -> different lines
- Real gases
  - a mixture of different molecules and elements, in different ionization stages, and energy states
  - strength of different lines depends on composition, temperature, pressure. Wavelengths remain the same.
- The upshot of this is that from the pattern of lines in a spectrum one can work out how much of each atom and molecule is present and even something about its physical state (which energy state it is in).
Doppler Effect

Yet another thing you can get from spectra!

**Doppler Effect**: The wavelength of light received from an object is different from that which was emitted if there is motion between emitter and observer. Quantitatively:

- Wavelength received =
  
  \[ \text{Wavelength emitted} \times \left(1 + \frac{\text{radial speed}}{c}\right) \]

("radial speed" is the motion along a line connecting emitter and observer; it is positive if they are receding, and negative if approaching).

If you know the emitted wavelength and measure the observed, you can deduce the relative radial speed of the emitter.

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Doppler Effect Example

- Suppose Voyager II spacecraft is broadcasting at emitted wavelength = 10.0000 cm,
- On Earth we now measure received wavelength = 10.0001 cm,

then

- \(1 + \frac{v_r}{c} = 1.00001\),
- \(\frac{v_r}{c} = +10^{-5}\),
- \(v_r = +3 \text{ km/sec}\) (+ => away from us).
- (\(v_r\) is radial speed; we can't deduce its sideways speed, so don't get full velocity)
Balmer Emission Lines

Electron drops from level 4 to 2.

\[ \lambda = 486 \text{ nm} \]

Blue light emitted

Orion Nebula
Balmer Absorption

Electron raised from level 2 to 3
656 nm Red light absorbed

Electron raised from level 2 to 4
486 nm Blue light absorbed

Visible Lines of Neutral H and He

The other neutral elements

Hydrogen

Orbit 6 → 2
Orbit 5 → 2
Orbit 4 → 2
Orbit 3 → 2

Helium
Some Astronomical Spectra

Doppler Effect