Atoms and Spectroscopy

Lecture 3
ONE SMALL STEP FOR MAN

ONE GIANT LEAP FOR MANKIND
FROM ATOMS TO STARS AND GALAXIES

HOW DO WE KNOW?

The Scientific Method

• Observations

• Hypothesis

• Verifications

• “LAW”
Spectroscopy

- Electromagnetic radiation travels with the speed of light.
- \( c = 3 \times 10^{10} \text{ cm/sec} \)
- Wavelength of radiation: \( \lambda \)
- Frequency of radiation: \( f \)
- \( c = \lambda f \)

What is “frequency”? 

- If a wave goes by while you are sitting in a boat you go up and down at a given rate.
- This is the frequency of the wave.
- The analogy carries over to light waves.
The E-M spectrum:
Our “Window” to the Universe

<table>
<thead>
<tr>
<th>Type of Rad.</th>
<th>Approx. Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma rays</td>
<td>$10^{-2}$ A or $10^{-6}$ μm</td>
</tr>
<tr>
<td>X-rays</td>
<td>1 A</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>1000 A</td>
</tr>
<tr>
<td>Visible</td>
<td>5000 A</td>
</tr>
<tr>
<td>Infrared</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Microwave</td>
<td>1 mm</td>
</tr>
<tr>
<td>Radio</td>
<td>&gt; 1 cm</td>
</tr>
</tbody>
</table>
Atmospheric Windows

- The atmosphere only allows certain wavelengths to pass through it.

- Visible: 3500 - 10000 Å
- Radio: 1 mm - 100 m

- This is one reason why astronomers want observatories in space.

Spectroscopy

- Isaac Newton determined that when light passes through a PRISM (next slide), it disperses into various “colors”.
- In essence, he used a PRISM to make a rainbow, and invented spectroscopy.
- Spectroscopy breaks the light into different (wavelengths) colors.

1 Å = 1 Angstrom = 10^{-10} m
Where does light come from?

• It had been known during the 19th century that
  – accelerated charges produce light
  – and hence emit energy

• If we picture an electron as in orbit around the nucleus, it should radiate light
  – changing direction is acceleration!

A major problem w/ “classical” physics

• But if the electron radiated, it would lose energy and soon spiral into the nucleus.

• The world would collapse instantly!
  – Fortunately it doesn’t.

• What is wrong with this picture?

• Enter Quantum Mechanics (QM)
The “New” Physics

- Quantum Mechanics was developed during the revolution which occurred in physics from 1900 - 1930.

- Both Special Relativity and General Relativity were developed during this time.

The Bohr Model of the Atom

- Niels Bohr 1913:
  - Formulated 3 rules regarding atoms.

  1. Electrons can only be in discrete orbits.
- Bohr Model (cont’d)

2. A photon can be emitted or absorbed by an atom only when an electron jumps from one orbit to another.

\[ \text{Photon} \]

\[ h_f \]

\[ \text{Absorption} \]

\[ h_f \]

Emission

\[ e^- \]

\[ h_f \]

Bohr model (cont’d)

3. The photon energy equals the energy difference between the orbits.

The photon energy, \( E = h_f = hc/\lambda \).

since \( c = \lambda f \), and \( f = c/\lambda \).
Quantum Numbers (Q.N.)

• An electron can reside in one of many orbits.
• $n =$ number of orbit = Principal Q.N.
• $n = 1$ is the lowest energy state.
• If $n > 1$, then the atom is “excited.”
Electronic Transitions

• An electron transition occurs when an electron moves between two orbits.
• When absorption of a photon occurs, an electron goes up, e.g. from $n = 1$ to $n = 2$.
• Emission of a photon occurs when an electron moves down, e.g. from $n = 2$ to $n = 1$.

A Quantum Mechanical Aside

• The discrete (quantum) nature of the energy “levels” of the electron gives QM its name.
• QM describes the microscopic world
  – Physics of the small
• And there are some very non-intuitive things associated with it.
Spectra from Atoms

• A spectrum is the intensity of light seen from an object at different wavelengths.
  – e.g. done by spectroscopy with a prism.

• Individual atoms, like H, show spectral lines, i.e. For H, these are the Balmer lines in the visible.

• For a “Conversational” lecture on spectral lines see http://www.colorado.edu/physics/2000/quantumzone/

The Spectrum of Hydrogen

• H has one electron => simplest spectrum.
• Discrete emission and absorption lines
  – Need a photon of the correct energy to move up a level.
• Spectral lines occur in ultraviolet, visible, infrared, and radio.
• Visible lines called Balmer lines.
Hydrogen Balmer spectrum

Note the discrete “lines” where there is emission.

Hydrogen Energy Level Diagram

The energies in atoms are usually expressed in electron volts (eV).

1 eV = 1.6 x 10^{-19} J

For instance, the energy difference between n = 2 and n = 1 in H is 10.2 eV.

Since $E = hc/\lambda$, $\lambda = 1216$ A

Lyman Lines - Ultraviolet
- Lyα: n=2 → 1, $\lambda = 1216$ A
- Lyβ: n=3 → 1, $\lambda = 1026$ A
- Lyγ: n=4 → 1, $\lambda = 973$ A
- ...

Balmer Lines - Visible
- Hα: n=3 → 2, $\lambda = 6563$ A
- Hβ: n=4 → 2, $\lambda = 4861$ A
- Hγ: n=5 → 2, $\lambda = 4341$ A
- ...

Ground State = Lowest Energy Level
Hydrogen Balmer Spectrum: Revisited

Notes on H Spectral Lines

- The energy levels get closer together as the quantum numbers get larger.
- The greater the difference between the quantum numbers, the larger the energy of the photon emitted or absorbed.
The "Continuum"

If \( h\nu > 13.6\) eV, electron can leave the atom.

- An electron in the continuum has escaped from the proton.
  - This can happen if the Hydrogen atom absorbs a photon with energy \((hf)\) greater than 13.6 eV.
  - And the hydrogen atom is “ionized.”

Ionization and ions

- If a photon has enough energy, it can ionize an atom, i.e. promote an electron into the continuum.
- An atom becomes an ion when one or more electrons have been removed.
Hydrogen ionization

• The ionization energy of hydrogen is 13.6 eV.
• To ionize an electron from the ground state (n=1) of hydrogen requires photons of energy 13.6 eV or greater.
  \[ \lambda < 912 \text{ Å} \]
• Ionized hydrogen is just a proton by itself!

Helium Ions

Neutral Hel

Once Ionized Hell

Twice Ionized Helll
Spectral Signatures: Astronomy’s Rosetta Stone

• The set of spectral lines associated with a given ion are unique.
• We call this the spectral signature of an ion.
• This is of fundamental importance to astronomy, allowing the identification of elements clear across the galaxy and universe.

Spectra of several elements

- White Light
- Hydrogen
- Helium
- Lithium
- Beryllium
- Boron
- Carbon
- Nitrogen
Spectral Signatures (cont’d)

• With spectral signatures we can identify oxygen, carbon, iron, etc.
• In addition these signature provides information on:
  – Chemical composition of the stars
  – Abundances of the elements
  – Physical conditions of the gases
    • Densities and Temperatures