Thursday Lab Announcement

- Jonah will start the Lab at 6:00 PM.
  - Two pieces of Glass and HST
  - Lunar Phases

Topics For Today’s Class

- Black Body Radiation Laws
  - Stephan’s Boltzmann Law
  - Wein’s Displacement Law
- Stellar Spectra
  - Formation of a spectrum
  - Kirchhoff’s Laws of Radiation
  - Hydrogen Atom and Balmer Thermometer
  - Spectrum Classification
  - Composition of Stars
- Doppler Effect
  - Red shift and Blue shift
  - Calculating Doppler velocity

Recap: Bohr Model of the Atom

- Electron and an atom can only occupy discrete (quantized) energy levels.
- Photons are emitted/absorbed when an electron makes a transition from one energy level to another
  - Wavelength depends upon the energy difference between the two levels ($\lambda = \frac{h}{\Delta E}$).
  - Each spectral line represents an electron transition between two energy levels
  - Each element has a unique set of spectral lines that can be used to identify its presence

Recap: What is a Black Body?

Black Body Radiator. A hypothetical object that emits Electromagnetic radiation and whose spectrum is continuous with a peak in the wavelength that corresponds to the temperature of the object.

Star can be approximated as Black Body Radiators
Two Laws of Blackbody Radiation

• The Stefan-Boltzmann law:
  - The hotter an object is, the more energy it emits
    \[ L = E = \sigma T^4 \]
  where
  \[ E = \text{Energy Flux} = \text{Energy given off in the form of radiation, per unit time and per unit surface area} \ [\text{J/s/m}^2] \]
  \[ \sigma = \text{Stefan-Boltzmann constant} \]

Two Laws of Blackbody Radiation (cont'd.)

• Wien's Law:
  - The peak of the black body spectrum shifts towards shorter wavelengths when the temperature increases
    \[ \lambda_{\text{max}} = \frac{3,000,000 \text{ nm}}{T} \]
  where \( T \) is the temperature in Kelvin

Color and Temperature

• Stars appear in different colors
  - The colors tell us about the star's temperature

Sun's Temperature

• The sun \( \lambda = 500 \text{ nm} \)
  - \( T = \frac{3 \times 10^6}{500} = 6000 \text{ K} \)
  - 10,000 °F
  - Wien's Law gives the surface temperature

Sun's Luminosity

• The sun: \( T = 6000 \text{ K}, \ R = 7 \times 10^8 \text{ meters} \). What is its Luminosity?
  - \( L = E = 4 \times 3.14 \times (7 \times 10^8)^2 \times 6 \times 10^{-8} (6000)^4 = 5 \times 10^{26} \text{ Watts} \)
  - Compare with 40 watts light bulb

Light and Matter

Spectra of stars are more complicated than pure blackbody spectra. They contain

→ characteristic lines, called absorption lines.

To understand those lines, we need to understand atomic structure and the interactions between light and atoms.

a) Spectrum of the Sun b) NGC 2392 Emission Nebula

Kirchhoff's Laws of Radiation allow us to do just that
1. A solid, liquid, or dense gas excited to emit light will radiate at all wavelengths and thus produce a continuous spectrum.

2. A low-density gas excited to emit light will do so at specific wavelengths and thus produce an emission spectrum.

3. If light comprising a continuous spectrum passes through a cool, low-density gas, the result will be an absorption spectrum.

The Spectra of Stars
- Inner, dense layers of a star produce a continuous (blackbody) spectrum.
- Cooler surface layers absorb light at specific frequencies.
- Spectra of stars are absorption spectra.

The Hydrogen Atom: The Balmer Lines
- Transitions from 2nd to higher levels of hydrogen
- The only hydrogen lines in the visible wavelength range
- 2nd to 3rd level = Hα (Balmer alpha line)
- 2nd to 4th level = Hβ (Balmer beta line)

Lines of Hydrogen
- Most prominent lines in many astrophysical objects: Balmer lines of hydrogen
Absorption Spectrum Dominated by Balmer Lines

Modern spectra are usually recorded digitally and represented as plots of intensity vs. wavelength.

Observations of the H-Alpha Line

- Excited clouds of gas in space emit light at all of the Balmer wavelengths, but you see only the red, blue, and violet photons blending to create the purple-pink color typical of ionized hydrogen.
- Emission nebula, dominated by the red Hα line.

The Balmer Thermometer

Balmer line strength is sensitive to temperature:

- Most hydrogen atoms are ionized => weak Balmer lines.
- Most hydrogen atoms in the ground state (electrons in the n = 1 orbit) => few transitions from n = 2 => weak Balmer lines.

Measuring the Temperatures of Stars

Comparing line strengths, we can measure a star’s surface temperature!

Spectral Classification of Stars (1)

Different types of stars show different characteristic sets of absorption lines.

Spectral Classification of Stars (2)

\[ T = \frac{3 \times 10^6}{\lambda (nm)} \]
Spectral Classification of Stars (3)

<table>
<thead>
<tr>
<th>Spectral Class</th>
<th>Approximate Temperature (K)</th>
<th>Hydrogen Balmer Lines</th>
<th>Other Spectral Features</th>
<th>Noted Car Eccentric</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>40,000</td>
<td>Weak</td>
<td>Allowed lithium</td>
<td>Methodist (E)</td>
</tr>
<tr>
<td>B</td>
<td>20,000</td>
<td>Medium</td>
<td>Allowed helium</td>
<td>Abbeville (A)</td>
</tr>
<tr>
<td>A</td>
<td>10,000</td>
<td>Strong</td>
<td>Allowed helium</td>
<td>Abbeville (A)</td>
</tr>
<tr>
<td>F</td>
<td>6,000</td>
<td>Very weak</td>
<td>Allowed helium</td>
<td>Abbeville (A)</td>
</tr>
<tr>
<td>G</td>
<td>5,900</td>
<td>Weak</td>
<td>Allowed lithium</td>
<td>Abbeville (A)</td>
</tr>
<tr>
<td>K</td>
<td>4,800</td>
<td>Very weak</td>
<td>Allowed lithium</td>
<td>Abbeville (A)</td>
</tr>
<tr>
<td>M</td>
<td>3,800</td>
<td>Very weak</td>
<td>TID strong</td>
<td>Abbeville (A)</td>
</tr>
</tbody>
</table>

Mnemonics to remember the spectral sequence:

- Only Oh Only
- Brilliant Boy, Bad
- Artistic An Assistants
- Females FF or get
- Generate Grade Generally
- Killer Kills Known
- Mnemonics Me Mnemonics

Analyzing Absorption Spectra

- Each element produces a specific set of absorption (and emission) lines.
- Comparing the relative strengths of these sets of lines, we can study the composition of gases.

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage by Number of Atoms</th>
<th>Percentage by Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>70%</td>
<td>70.9%</td>
</tr>
<tr>
<td>Helium</td>
<td>26%</td>
<td>26.7%</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.008</td>
<td>0.1%</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.8%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Neon</td>
<td>0.01%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.003</td>
<td>0.06%</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.003</td>
<td>0.07%</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.002</td>
<td>0.04%</td>
</tr>
<tr>
<td>Iron</td>
<td>0.003</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

By far the most abundant elements in the Universe:

- Hydrogen
- Helium

Spectra can also tell us about velocity

- The Doppler effect allows us to measure the component of the source’s velocity along our line of sight

The Doppler Effect

The light of a moving source is blue/red shifted by

\[ \frac{\Delta \lambda}{\lambda_0} = \frac{v_r}{c} \]

where \(\lambda_0\) is the actual wavelength emitted by the source, \(\Delta \lambda\) is the wavelength change due to Doppler effect, and \(v_r\) is the radial velocity

Example:

Take \(\lambda_0\) of the H\(\alpha\) (Balmer alpha) line:

\[ \lambda_0 = 656 \text{ nm} \]

Assume, we observe a star’s spectrum with the H\(\alpha\) line at \(\lambda = 658 \text{ nm}\). Then,

\[ \Delta \lambda = 2 \text{ nm} \]

We find \(\Delta \lambda / \lambda_0 = 0.003 = 3 \times 10^{-3}\)

Thus,

\[ \frac{v_r}{c} = 0.003 \]

or

\[ v_r = 0.003 \times 300,000 \text{ km/s} = 900 \text{ km/s}. \]

The line is red shifted, so the star is receding from us with a radial velocity of 900 km/s.
Doppler Broadening

In principle, line absorption should only affect a very unique wavelength. In reality, also slightly different wavelengths are absorbed. Lines have a finite width; we say they are broadened.

One reason for broadening: The Doppler effect!

Summary of Spectroscopy

- Spectral of stars can tell the temperature of stars.
- Spectra of stars can tell us the chemical composition of stars.
- Spectra of stars can tell us about the proper motion of stars.
- Spectra of stars can also tell us about the atomic and molecular motion in the atmosphere of stars.

Acknowledgment

- The slides in this lecture is for Tarleton: PHYS1411/PHYS1403 class use only
- Images and text material have been borrowed from various sources with appropriate citations in the slides, including PowerPoint slides from Seeds/Backman text that has been adopted for class.