From binary stars, we know that luminosity, radius, and temperature all increase with mass. We use mass as the descriptive (dependent) variable, since that is most easily measured in binary systems.

What about stars in general? Can we create a classification scheme that can be applied to any/all observable stars?

Yes – spectral classification.

Historically based on optical spectra, now being extended to IR.
Spectroscopy

Two different representations of the same data.

Top: Intensity coded by brightness of pixel. Dark = absorption line.
Bottom: Cross-cut of above, shown as normal graph.
Absorption Lines

Balmer series: Hα, Hβ, Hγ, Hδ and onward.
Na I
Ca II (K and H)
TiO bands

Original classification scheme based on strength of Balmer lines. Spectra were ordered alphabetically from A to P, where A was Strongest, P weakest.

Harvard Spectral Classes.
Most modern sciences are based on early work that grouped (classified) similar entities together. Think of, e.g., biology – Darwin; chemistry – periodic table. By creating order out of apparent chaos, scientists were able to discover the underlying physical principles. This is usually called progress.

Stellar classification was primarily due to the Harvard College Observatories, under the direction of Edward Pickering.

Annie Jump Cannon and her colleagues examined thousands of stellar spectra. From 1911 – 1924, AJC classified 225,000 stars in the Henry Draper catalog.

AJC’s classification scheme built on the previous A to P letters, but reorganized in terms of stellar temperatures, not line strengths per se.

O B A F G K M
Underlying Physics

• Despite all this work, it wasn’t until 1925 that the underlying physics was discovered.

• Recall, Boltzman and Saha equations:

\[ \frac{N_B}{N_A} = \frac{g_B}{g_A} \exp\left( \frac{(E_A - E_B)}{kT} \right) \quad \text{Boltzman eq.} \]

\[ \frac{N_+}{N_o} = \left( \frac{A (kT)^{3/2}}{N_e} \right) \exp\left( -\frac{\chi_o}{kT} \right) \quad \text{Saha eq.} \]

N = number density

\( g \) = multiplicity of level

E = energy

T = temperature

\( A \) = atomic constants and probabilities

\( \chi_o \) = ionization potential
By looking at relative strengths of these features, we can determine the temperature of the stellar photosphere. Note: metallicity effects are also present, but dominant effect is from temperature.
More generally,
<table>
<thead>
<tr>
<th>Spectral class</th>
<th>Color</th>
<th>Temperature (K)</th>
<th>Spectral lines</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>Blue-violet</td>
<td>30,000–50,000</td>
<td>Ionized atoms, especially helium</td>
<td>Naos (ζ Puppis), Mintaka (δ Orionis)</td>
</tr>
<tr>
<td>B</td>
<td>Blue-white</td>
<td>11,000–30,000</td>
<td>Neutral helium, some hydrogen</td>
<td>Spica (α Virginis), Rigel (β Orionis)</td>
</tr>
<tr>
<td>A</td>
<td>White</td>
<td>7500–11,000</td>
<td>Strong hydrogen, some ionized metals</td>
<td>Sirius (α Canis Majoris), Vega (α Lyrae)</td>
</tr>
<tr>
<td>F</td>
<td>Yellow-white</td>
<td>5900–7500</td>
<td>Hydrogen and ionized metals such as calcium and iron</td>
<td>Canopus (α Carinae), Procyon (α Canis Minoris)</td>
</tr>
<tr>
<td>G</td>
<td>Yellow</td>
<td>5200–5900</td>
<td>Both neutral and ionized metals, especially ionized calcium</td>
<td>Sun, Capella (α Aurigae)</td>
</tr>
<tr>
<td>K</td>
<td>Orange</td>
<td>3900–5200</td>
<td>Neutral metals</td>
<td>Arcturus (α Boötis), Aldebaran (α Tauri)</td>
</tr>
<tr>
<td>M</td>
<td>Red-orange</td>
<td>2500–3900</td>
<td>Strong titanium oxide and some neutral calcium</td>
<td>Antares (α Scorpii), Betelgeuse (α Orionis)</td>
</tr>
<tr>
<td>L</td>
<td>Red</td>
<td>1300–2500</td>
<td>Neutral potassium, rubidium, and cesium, and metal hydrides</td>
<td>Brown dwarf Teide 1</td>
</tr>
<tr>
<td>T</td>
<td>Red</td>
<td>below 1300</td>
<td>Strong neutral potassium and some water (H₂O)</td>
<td>Brown dwarf Gliese 229B</td>
</tr>
</tbody>
</table>
H-R Diagrams: Magnitude vs Spectral Type

Hertzsprung and Russell each independently came up with this diagram.

$L$ is equivalent to $M_V$
Spectral type is equivalent to temperature.

“greatest synthesis in all of astronomy”
Color-Magnitude Diagram

Very similar to above, but easier to obtain.
→ Requires photometry and distance measurement.
If we plot Galactic stars on a CMD, we find two Populations (Pop I and Pop II).

Pop I = metal-rich (young)
Pop II = metal-poor (old)
Pop III = metal-zero (oldest; hypothetical)
We will need to think about what physical processes could lead to these luminosity classes. Why doesn’t a single main sequence work? (This is a homework problem).
Giants and Supergiants

Luminosity effect
Surface gravity effect
Pressure effect

\[ L = 4 \pi R^2 F \]

\[ F = \sigma T^4 \]

\[ \Rightarrow L = 4 \pi R^2 \sigma T^4 \]

L increases as R increases and as T increases.
Example

G2 supergiant is 12.5 mag brighter than our sun.
→ Luminosity ratio of $10^5$ and → radius of 300 $R_\odot$.

Surface gravity significantly less than for the dwarf. And density is less than the dwarf.
→ Lower density will effect ionization equilibrium.

Recall atmospheres:
Assume thermodynamic equilibrium (LTE)
Assume perfect gas: $P = n \, k \, T$
Mean molecular weight: $1/\mu = m_H \, n / \rho$ for ionized gas (photosphere).

$$1/\mu = 2 \, X + \frac{3}{4} \, Y + \frac{1}{2} \, Z \sim 1.6$$

Mass fraction = percent by mass of 1 species relative to total.
For steady-state atmosphere:
$$dP/dr = -(GM/R^2) \, \rho = -g \, \rho$$
Define $H = kT/gm \sim$ constant

$$P(h) = P(h_0) \, \exp \left(-\frac{h}{H}\right)$$
What happens to line shapes?

Broadening mechanisms
(1) Natural broadening
(2) Thermal doppler broadening
(3) Collisional broadening
(4) The Zeeman effect
(5) Kinematic motions: expansion and rotation

Natural broadening:
Quantum: $\Delta E = (1/2\pi)(h/\Delta t)$
$\Delta \nu = \Delta E/h \sim 1/\Delta t$

lifetimes $\sim 10^{-8}$ s for electronic
$\rightarrow \Delta \lambda \sim 0.05$ mÅ for visible light.
Thermal Doppler Broadening:

\[ v_p = (2kT/m)^{1/2} \] for Maxwellian distribution.

for Hydrogen at 6000 K, \( v = 10 \text{ km/s} \)

\[ \Delta \lambda / \lambda \sim v/c \sim 3 \times 10^{-5} \Rightarrow \Delta \lambda \sim 0.02 \text{ nm} \]

Collisional Broadening (Pressure broadening):

Energy levels are shifted by neighboring particles (particularly charged particles). \( \Rightarrow \) Stark effect \( \Rightarrow \) Broader line. Perturbations are larger if perturber is near \( \Rightarrow \) dependence on particle density (or pressure, for ideal gas).
The Zeeman effect:
Magnetic fields split energy levels because of electron’s dipole moment. If Zeeman components are not resolved, we see only one broad line.

Kinematic motions:

(1) Expansion

(2) Rotation
Summary

- Intensity of line related to temperature (Boltzmann and Saha eq.), density, gravity, and composition.

- Width of line related to density, gravity, temperature, and kinematics.

- Wavelength – quantum and kinematics
Confusing Nomenclature: Equivalent Width

When is a “width” not a width? When it is representative of an intensity!

Traditional to measure intensity in terms of “equivalent width” (EW)

\[ I \lambda \Delta \lambda = EW \]

or, \[ EW \times I_0 = \text{Area} \]

By convention, an absorption line has a positive EW and an emission line has a negative EW (although extragalactic astronomers tend to drop the negative sign when reporting H\(\alpha\) EW results…)