1.

**Solar Spectrum**

2.

**Birth of Spectroscopy**

3.

**Kirchhoff's Laws**

- Gustav Kirchhoff derived three laws to explain how matter and light interact.
- He noted that three types of spectra arise under different conditions:
  - Continuous spectra
  - Emission line spectra
  - Absorption line spectra

4.

**Types of Spectra**

5.

**Kirchhoff's 1st Law**

- A hot and opaque solid, liquid or highly compressed gas emits a continuous spectrum.
- This is the blackbody spectrum.
Kirchhoff’s 2nd Law
- A hot, transparent gas produces a spectrum of bright emission lines. The number and colors of the lines depend on which elements are present.
- The emission lines are due to electrons moving to lower energy states.

Kirchhoff’s 3rd Law
- If a continuous spectrum passes through a transparent gas at a lower temperature, the cooler gas will cause the appearance of dark absorption lines, whose colors and number will depend on the elements present in the gas.

Kirchhoff’s Laws
- Late in the 19th century photography became good enough to record the spectra of a star.
- Annie Jump Cannon (1863-1941)
  - Harvard college observatory
  - Found that the spectra of stars fell into natural categories
  - She took spectra of nearly 400,000 stars
  - Began American dominance of observational astronomy

Classifying the Spectra of Stars
- Based on the strength of certain key features
  - Hydrogen
    - Cannon thought this was most important
  - Helium
  - Calcium
  - Magnesium
- No one understood what the sequence actually meant.

Stellar Spectra
- Stellar spectra: continuous + absorption lines

The Spectral Classes of Stars
- Based on the strength of certain key features
  - Hydrogen
    - Cannon thought this was most important
  - Helium
  - Calcium
  - Magnesium
- The hydrogen line is prominent for cool stars, while the helium line is prominent for more massive stars. The hydrogen line is in the infrared in this late 19th century.
- No one understood what the sequence actually meant.
Rutherford Scattering Experiment

Ionization of Atoms

- What is ionization?
  - Process by which an atom loses one electron
  - For a given element a minimum energy is needed to break an electron loose
  - Energy can come from photons or collisions between atoms

- Meghnad Saha (1920) - temperature controls the ionization of elements
  - Atoms move faster when hotter

Ionization

- Spectra of ions look different from spectra of neutral version of same element
- Different elements need different amounts of ionization energy
  - different temperatures
  - more complex atoms are ionized at lower temperatures

Heisenberg’s Uncertainty Principle

$$\Delta p \Delta x \geq \frac{1}{2} \hbar$$

$$\Delta E \Delta t \geq \frac{1}{2} \hbar$$
Stellar Abundances

- Cecilia Payne-Gaposhkin in her PhD thesis in 1925 determined that stars were made up mostly of hydrogen & helium contrary to notions of the time that stars were made up of the same elements found on earth
  - 90% H
  - 10% He
  - 1-2% everything else

1900 - 1979

Spectral Classes & Temperature

- If stars have similar chemical composition, why do they have different spectra?
- Cecilia Payne Geposhkin in her PhD thesis in 1925 recognized that differences in temperature not abundances were responsible for the differences observed in stellar spectra
- Devised basic temperature classification sequence – OBAFGKM

OBAFGKM

- Classification based on appearance & strength of lines in spectra
- Arranged in order of decreasing temperature
  - O stars hottest, M stars coolest
  - Each major class divided into 10 subclasses from 0 to 9
  - within each major class the spectra are similar, arranged so the classes merge smoothly into each other
  - B9 is more similar to A0 than B0

Laws of Thermodynamics

- I - Heat always diffused from hot to cold with temperature becoming uniform when thermodynamic equilibrium is reached
- II - Heat is a form of energy - Energy is always conserved
- III - Natural processes that starts from one equilibrium state and ends in another will go in the direction that causes the entropy of the system to increase
- III - There is an absolute zero to temperature (0 K) where all forms of matter become perfectly ordered (usually perfect crystals)

Example

- A cool interstellar grain absorb visible starlight and re-emits the radiation thermally, giving off a large number of low energy photons.
- In equilibrium:
  - energy of emitted photons = energy of the absorbed starlight
  - entropy of emitted radiation larger
    - final state - large number of low energy photons moving in unpredictable arbitrary directions → higher entropy
    - initial state - single photon carrying a large amount of energy is more orderly → lower entropy

Thermodynamics & Statistical Mechanics

- Thermodynamic principles apply to large numbers of particles and photons - statistical in nature
  - no such thing as the temperature of a single atom
- In thermodynamic equilibrium, particles in a gas will have a distribution of energies
  - unlikely that one particle will hog all of gas' energy for itself
  - the number of particles at high energies will decrease exponentially with increasing energy – Boltzmann's Law
**Maxwell Boltzmann Distribution**

- **Ionization of Atoms**
  - What is ionization?
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- **Meghnad Saha (1920) - temperature controls the ionization of elements**
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**Ionization**

- Spectra of ions look different from spectra of neutral version of same element
- Different elements need different amounts of ionization energy
  - different temperatures
  - more complex atoms are ionized at lower temperatures

**High Temperature Stars**

- O & B stars; $T > 20,000$ K
  - No spectral lines from metals
    - high temperatures cause ionization of metals
    - transitions of ions are in the ultraviolet
    - Remaining electrons are more tightly bound
    - Need more energy to excite transitions

- Weak hydrogen lines
  - larger fraction of H ionized in hot stars
- Absorption lines from He I & He II
  - temperatures high enough to excite He to higher energy states
  - hottest stars have ionized He (He II)
    - remaining electron can undergo transitions & produce spectral lines

**Medium Temperature Stars**

- A, F, G stars; $T = 5,000 - 12,000$ K
  - A few more spectral lines in visual spectrum than in O & B stars
    - metals are readily excited & ionized at these temperatures
    - lines from metals in the ultraviolet
  - Hydrogen lines strong
    - temperature is high enough to excite electrons in H atoms but not to ionize them
Question

• In very cool stars would you expect the hydrogen lines to be stronger or weaker than in a warm G star?

• Why?

Low Temperature Stars

• K & M Stars; T < 5,000 K
• Complex spectra
• Temperatures sufficient to excite electrons in most elements other than H & He
• Metals easily excited since outer electron is weakly held to nucleus
• Large number of absorption lines

What kind of star is this and why?

The Hertzsprung-Russell Diagram

• The American, Henry Norris Russell (ca. 1913) and the Danish engineer, Ejnar Hertzsprung (ca. 1911) independently found a relation between luminosity and temperature using data from Cannon

The HR Diagram

• Hertzsprung and Russell found
  - Stars did not occur with all possible combination of temperature and luminosity
  - Stars tended to group together
  - A large number of stars (including the sun) were found in a band they called the Main Sequence
• This suggested that the observed properties of stars are interrelated
Luminosity Classes

- Stars with same temperatures but different luminosities fall into “luminosity classes”
  - I – Supergiants
  - II – bright Giant
  - III – Giant
  - IV – Subgiant
  - V – Dwarf (MS)
  - VI – Subdwarf

The Sizes of Stars

- If you know the absolute luminosity of a star and its temperature you can find its surface area and thus size
- Need distance and apparent luminosity to find absolute luminosity
- The temperature plus the Stefan-Boltzman law give you the amount of energy emitted for a square meter on the star
- The luminosity divided by the energy emitted per square meter gives the surface area of the star
- The surface area of the star is related to the radius (area=$4\pi r^2$)

Sizes of Stars

- Rise of MS is due to temperature and size
  - Hot MS stars about 10x the size of Sun
  - Cold MS stars about 1/10x the size of Sun
- Supergiants are about 1000x the Sun
- White dwarfs are about 1/100x the Sun

Elemental Abundance Effects

- Wolf-Rayet Stars
- Hot emission line stars
- Peculiar A stars
- Carbon stars
- Heavy metal Oxide Stars