4.6 Classification of Stars

Stars are classified based on various physical properties such as their temperature, luminosity, size, mass, and spectral characteristics.

1. Overview of Star Classification

Stars are classified into groups based on the following parameters:

1. **Temperature:** Determines the color of the star.
2. **Spectral Type:** Indicates the star's absorption lines in its spectrum.
3. **Luminosity:** The total energy radiated by the star per second.
4. **Size (Radius):** Stars vary from small dwarf stars to massive supergiants.
5. **Mass:** Determines the star's lifetime and evolution.
6. **Chemical Composition:** The relative abundance of hydrogen, helium, and heavier elements.

Key Classification Systems:

1. **Harvard Classification System** (based on spectral type and temperature).
2. **Yerkes or Morgan-Keenan (MK) Classification** (based on luminosity class and spectral type).
3. **Hertzsprung-Russell (H-R) Diagram** (a graphical representation of stars based on luminosity and temperature).

Among these, the Harvard Classification System is the most widely used method for organizing stars based on their spectral type and temperature.

2. The Harvard Classification System

The Harvard Classification System categorizes stars according to their **spectral type** (the pattern of absorption lines in the star's spectrum) and **surface temperature**. It was developed at the Harvard College Observatory in the late 19th and early 20th centuries, primarily by **Annie Jump Cannon**.

Spectral Types:

Stars are grouped into seven primary spectral classes: **O, B, A, F, G, K, M**. These are arranged in order of decreasing temperature, with O-type stars being the hottest and M-type stars being the coolest. The system follows the **OBAFGKM** sequence:

1. **O-Type Stars**:

- Extremely hot and massive
- Emit most of their energy in the UV spectrum
- Short life span due to rapid nuclear fusion
- Rae but very luminous
- Color: Blue
- Temperature: >30,000K
- Appearance: With strong ionized helium lines and weak hydrogen lines.
- Example: Zeta Puppis.

2. **B-Type Stars**:
   - Often found in young star-forming regions
   - Slightly cooler than O-type stars
   - Color: Blue - White
   - Temperature: 10,000−30,000K
   - Appearance: Prominent helium lines & weaker hydrogen lines.
   - Example: Rigel.
3. **A-Type Stars**:
   - Easily visible with the naked eye
   - Color: White
   - Temperature: 7,500−10,000K
   - Appearance: With strong hydrogen Balmer lines.
   - Example: Sirius.
4. **F-Type Stars**:
   - Color: Yellow - White
   - Temperature: 6,000−7,500K
   - Appearance: Ionized metals such as calcium and iron are more prominent (e.g., Ca II).
   - Example: Procyon.
5. **G-Type Stars**:
   - Stable and long-lived, making them favourable for supporting planetary systems.
   - Color: Yellow
   - Temperature: 5,000−6,000K
   - Appearance: With strong calcium and weak hydrogen lines.
   - Example: Sun.
6. **K-Type Stars**:
   - Cooler than G-type stars
   - Ofter found in the later stages of stellar evolution
   - Color: Orange
   - Temperature: 3,500−5,000K
   - Appearance: With prominent metallic lines (eg., Fe I, Mg I)
   - Example: Arcturus.

7. **M-Type Stars**:
   - Cool red stars. Includes red dwarfs and red giants.
   - Temperature: <3,500K
   - Appearance: With molecular absorption bands (e.g., TiO).
   - Example: Betelgeuse.

Spectral Classes:

Spectral Class	Surface Temperature (K)	Color	Key Absorption Lines	Examples of Stars
O	>30,000	Blue	Strong ionized helium, weak hydrogen lines	Zeta Puppis
B	10,000–30,000	Blue-White	Neutral helium and moderate hydrogen lines	Rigel, Spica
A	7,500–10,000	White	Strong hydrogen lines (Balmer series)	Sirius, Vega
F	6,000–7,500	Yellow-White	Moderate hydrogen and ionized metal lines	Canopus, Procyon
G	5,200–6,000	Yellow	Weak hydrogen, strong ionized calcium lines	Sun, Alpha Centauri A
K	3,700–5,200	Orange	Neutral metals (iron, calcium)	Arcturus, Aldebaran
M	<3,700	Red	Molecular bands (e.g., titanium oxide)	Betelgeuse, Proxima Centauri

3. Subclasses in the Harvard System

Each spectral class is further divided into **subclasses** numbered from 0 to 9, where 0 is the hottest and 9 is the coolest within that spectral class. For example:

- A0 is hotter than A9.
- G2 (like the Sun) falls within the G-class but is cooler than G0.

4. Luminosity Classes (Combined with the MK System)

Spectra also reveal a star's luminosity class, distinguishing between supergiants, giants, and dwarfs (e.g., Ia, Ib, III, V).

The Harvard system focuses on spectral types, but luminosity classes were later added in the **Yerkes (MK) system** to distinguish stars based on their size and brightness. Luminosity classes are denoted by Roman numerals:

Luminosity Class	Description	Example
I	Supergiants	Betelgeuse (M2 I)
II	Bright Giants	Canopus (F0 II)
III	Giants	Aldebaran (K5 III)
IV	Subgiants	Procyon (F5 IV-V)
V	Main Sequence (Dwarfs)	Sun (G2 V), Sirius (A1 V)
VI	Subdwarfs	
VII	White Dwarfs	Procyon B

5. The Physics behind Spectral Lines

Spectral Line Formation:

- The absorption lines in a star's spectrum arise when atoms and ions in the star's atmosphere absorb specific wavelengths of light.
- The lines correspond to electron transitions between energy levels in atoms.
- The strength and type of absorption lines depend on the star's temperature, density, and composition.

Temperature Dependence:

- At higher temperatures (e.g., O and B stars), atoms are ionized, and lines from ionized species (e.g., He II) dominate.
- At lower temperatures (e.g., M stars), molecules form, and molecular bands (e.g., titanium oxide) dominate.

6. The Role of the Harvard System in Modern Astronomy

1. **Determining Stellar Properties:**
    - Spectral type provides information about the star's temperature, size, and luminosity.

   - Combined with luminosity classes, it allows precise classification.
2. **Understanding Stellar Evolution:**
   - The Harvard system helps track a star's evolution from its main sequence phase (e.g., G-type Sun-like stars) to red giants or white dwarfs.
3. **Population Studies:**
   - Helps astronomers classify stars in clusters and galaxies to study stellar populations.
4. **Exoplanet Studies:**
   - Identifying stars similar to the Sun (e.g., G2 V) is crucial for finding potentially habitable exoplanets.

4.7 Hertzsprung-Russell Diagram

The **Hertzsprung-Russell (H-R) diagram** is one of the most important tools in astrophysics. It is a graphical representation of stars, plotting their **luminosity** (or absolute magnitude) against their **surface temperature** (or spectral class). By organizing stars in this way, the H-R diagram reveals key insights into the physical properties, life cycle, and evolutionary stages of stars.

1. Overview of the Hertzsprung-Russell Diagram

The H-R diagram was independently developed in the early 20th century by **Ejnar Hertzsprung** (1911) and **Henry Norris Russell** (1913). It is not a map of star locations in space but rather a tool for understanding the relationships between a star's luminosity, temperature, size, and evolutionary status.

Axes of the H-R Diagram:

1. **X-axis (Horizontal):**
   - Represents the star's **surface temperature**.
   - Temperature decreases from **left to right**, with the hottest stars (O-type) on the left and the coolest stars (M-type) on the right.
   - Alternatively, it can show **spectral class** (O, B, A, F, G, K, M).
2. **Y-axis (Vertical):**
   - Represents the star's **luminosity** (in solar units, $L/L_{\odot}$).
   - Luminosity increases **upward**, with the brightest stars at the top and the dimmest stars at the bottom.
   - Alternatively, it can show **absolute magnitude**, which decreases upward (brighter stars have lower magnitudes).

2. Structure of the H-R Diagram

The H-R diagram is broadly divided into several regions, each representing a distinct type of star or evolutionary stage:

(A) Main Sequence

- The **main sequence** is a diagonal band stretching from the top-left (hot, luminous stars) to the bottom-right (cool, dim stars).
- Stars on the main sequence are in their **hydrogen-burning phase**, fusing hydrogen into helium in their cores.
- About **90% of stars**, including the Sun, fall on the main sequence.
- **Characteristics:**
    - Hotter main-sequence stars (e.g., O and B types) are more massive, more luminous, and have shorter lifespans.
    - Cooler main-sequence stars (e.g., K and M types) are less massive, less luminous, and live longer.

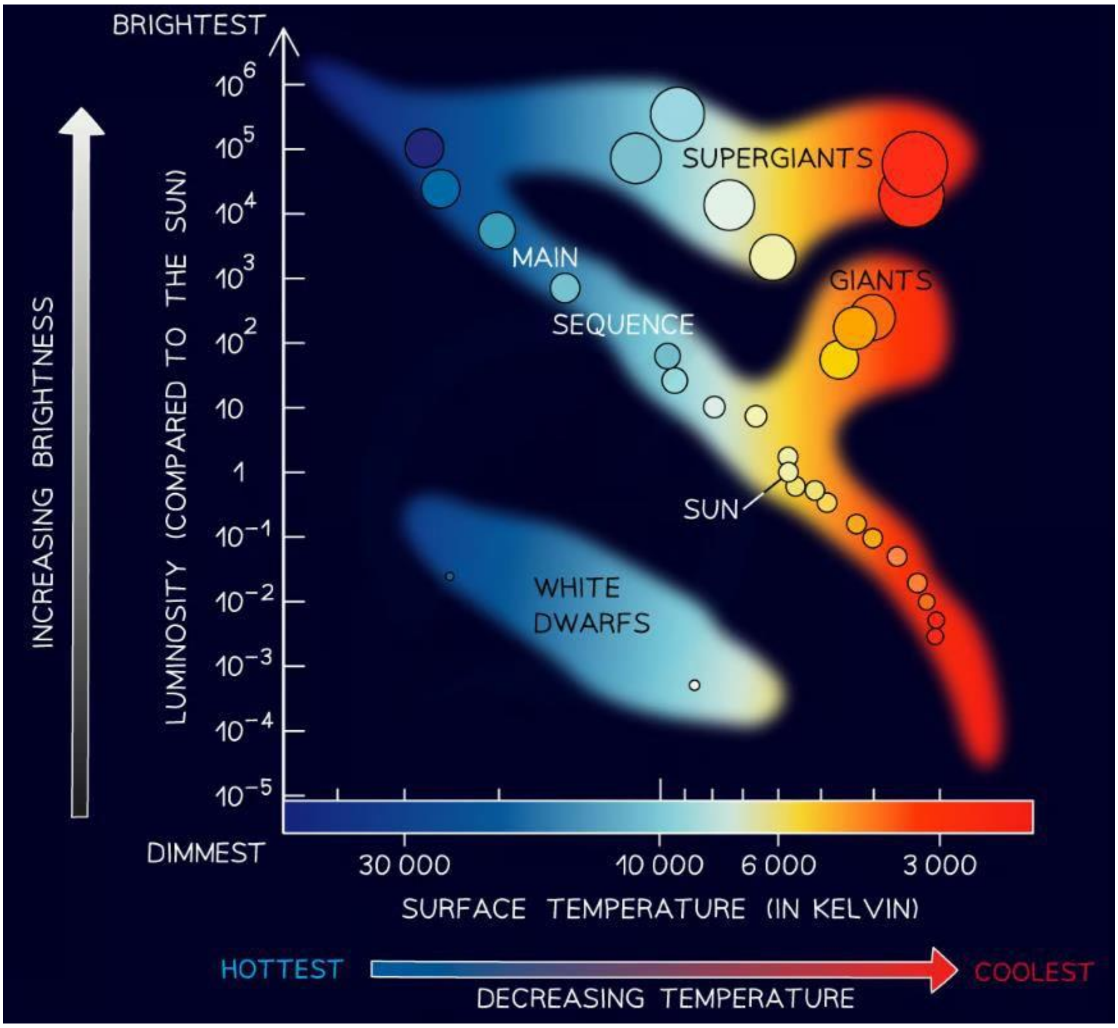

Fig: Hertzsprung-Russell Diagram

- The properties of stars can be classified using the Hertzsprung-Russell (HR) diagram
- Usually, it is given in solar units, where the luminosity of the Sun = 1, so
  - For stars which are **brighter** than the Sun, luminosity > 1
  - For stars which are **dimmer** than the Sun, luminosity < 1
- Surface temperature is measured in kelvin (K) and is plotted backwards from hottest to coolest
- It can also be displayed as a colour where
  - The **hottest** stars are blue
  - The **coolest** stars are red
- The key areas of the H-R diagram are:
  - The **brightest** stars (high luminosity) are found near the top
  - The **dimmest** stars (low luminosity) are found near the bottom
  - The **hottest** stars (high temperature) are found towards the left
  - The **coolest** stars (low temperature) are found towards the right
- The life cycle of a star can be shown on a Hertzsprung-Russell diagram
- The main features of the Hertzsprung-Russell diagram are:
  - Most stars are found to lie on the **main sequence**. This is the band of stars going from top left to bottom right
  - Below the main sequence (and slightly to the left) are the **white dwarfs**
  - Above the main sequence on the right-hand side are the **red giants**
  - Directly above the red giants are the **red supergiants**
- This means that
  - The **hottest, brightest** stars are the largest main sequence stars, also called supergiant stars
  - The **coolest, brightest** stars are red supergiants
  - The **hottest, dimmest** stars are white dwarfs
  - the **coolest, dimmest** stars are the smallest main sequence stars, also called red dwarfs

(B) Giant and Supergiant Stars

- Found above the main sequence in the **upper-right** region of the diagram.
- These stars have exhausted hydrogen in their cores and are burning heavier elements (helium, carbon, etc.).
- **Giants:** Large, luminous, but cooler stars (e.g., Aldebaran).
- **Supergiants:** Extremely large and luminous stars (e.g., Betelgeuse, Rigel).

(C) White Dwarfs

- Found in the **lower-left** region of the diagram.
- White dwarfs are the remnants of low- to medium-mass stars that have shed their outer layers, leaving behind a hot, dense core.
- They are very hot but have low luminosity due to their small size.
- Example: Sirius B.

(D) Horizontal Branch

- Found in the **middle-right region**, where stars undergoing helium fusion settle temporarily.
- These are mostly post-main-sequence stars.

(E) Instability Strip

- Located in a vertical band crossing the main sequence.
- Stars in this region are **variable stars**, like Cepheids and RR Lyrae stars, which pulsate due to instabilities in their outer layers.

3. Properties and Physics of Stars on the H-R Diagram

Luminosity and Temperature:

- A star's position on the H-R diagram directly relates to its luminosity (L) and surface temperature (T), as described by the Stefan-Boltzmann Law:

$$L = 4\pi R^2 \sigma T^4$$

Where:

- R: Radius of the star
- σ: Stefan-Boltzmann constant
- T: Surface temperature

Thus, stars that are larger and hotter emit more energy, appearing higher on the diagram.

Mass-Luminosity Relationship:

For main-sequence stars, there is a strong correlation between mass (M) and luminosity (L):

$$L \propto M^{3.5}$$

This means that more massive stars are disproportionately more luminous.

Color and Spectral Class:

- The color of a star (blue, white, yellow, red) is directly related to its temperature.
- Hot stars emit more blue and ultraviolet light, while cooler stars emit more red and infrared light.
- Spectral classification (O, B, A, F, G, K, M) aligns with this trend.

4. Evolution of Stars on the H-R Diagram

The H-R diagram is essential for understanding the **stellar life cycle**. Stars move across the diagram as they age:

1. **Protostar Phase:**
   - Stars begin in the lower-right region as cool, dim protostars.
   - As they collapse under gravity and heat up, they move toward the main sequence.
2. **Main Sequence:**
   - Stars stabilize here, burning hydrogen in their cores.
   - Their position depends on their mass and temperature.
3. **Post-Main Sequence:**
   - Low- and intermediate-mass stars evolve into **red giants** or **supergiants** after exhausting core hydrogen.
   - High-mass stars may move to the supergiant region.
4. **End Stages:**
   - Low- and intermediate-mass stars shed their outer layers, leaving behind **white dwarfs**.
   - High-mass stars explode as **supernovae**, potentially forming neutron stars or black holes.

5. Applications of the H-R Diagram

1. **Stellar Evolution:**
   - Tracks how stars change their properties over time.
   - Reveals the life cycle of stars from formation to death.
2. **Determining Star Clusters' Age:**
   - In star clusters, the main-sequence turn-off point (where stars leave the main sequence) indicates the cluster's age.
3. **Distance Measurement:**

    - Cepheid variable stars, located in the instability strip, are used as standard candles to measure astronomical distances.
4. **Exoplanet Studies:**
    - Identifying Sun-like stars (G2 V) helps in the search for potentially habitable exoplanets.

4.8 Luminosity of a Star

The **luminosity of a star** is one of its most fundamental properties, representing the total amount of energy it radiates per unit time. It is a critical parameter for understanding the physical nature of stars, their evolution, and their classification within the Hertzsprung-Russell diagram.

Definition of Luminosity

The **luminosity (L)** of a star is the total power output, measured in watts (W), of all electromagnetic radiation emitted by the star. It accounts for energy radiated in all directions and across all wavelengths, from gamma rays to radio waves.

Mathematically, luminosity is expressed as:

$$L = 4\pi R^2 \sigma T^4$$

Where:

- L: Luminosity (W)
- R: Radius of the star (m)
- σ: Stefan-Boltzmann constant ($5.67\times10^{-8} Wm^{-2}K^{-4}$)
- T: Surface temperature of the star (K)

Factors Affecting Luminosity

Luminosity depends primarily on two factors:

1. **Radius (R)**: Larger stars radiate more energy because of their larger surface area.
2. **Surface Temperature (T)**: Hotter stars emit significantly more energy due to the T^4 dependence in the Stefan-Boltzmann law.

This means that a small, very hot star can have a luminosity comparable to or greater than a large, cool star.