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Unit-IV Stars

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UNIT 4

STARS

4.1 Introduction

A star is a celestial body of gases that radiates energy derived from fusion reactions in its interior. A star is a celestial body composed primarily of gases, predominantly hydrogen and helium that radiates energy derived from nuclear fusion reactions occurring in its core. These fusion reactions convert hydrogen into helium, releasing immense amounts of energy in the form of light and heat, which makes stars the fundamental building blocks of galaxies.

Stars vary widely in size, color, temperature, and luminosity, ranging from small, dim red dwarfs to massive, brilliant blue giants. Their life cycle, which includes phases such as birth in nebulae, stable main-sequence periods, and eventual death as white dwarfs, neutron stars, or black holes, reveals the complex interplay of physics that governs the universe.

Stars not only illuminate the night sky but also play a critical role in the cosmic ecosystem. They forge heavier elements in their cores, which are eventually dispersed into space during their death throes, enriching the interstellar medium and enabling the formation of planets, life, and future generations of stars.

4.2 Stellar Spectra

Stellar spectra refer to the detailed breakdown of light emitted by stars, separated into different wavelengths using a spectrometer. When starlight passes through a prism or diffraction grating, it splits into a rainbow-like spectrum. This spectrum is not smooth; it contains dark lines (absorption lines) or bright lines (emission lines). These lines are fingerprints of the elements and physical processes occurring in the star's atmosphere.

Understanding Stellar Spectra in Detail

A star’s spectrum provides a wealth of information about its **temperature, chemical composition, velocity, magnetic field, and evolutionary stage**. This is achieved through the analysis of:

1. Continuous Spectrum

- **Description**:
    - A continuous spectrum contains **all wavelengths of light** emitted by a hot, dense light source, such as a blackbody radiator.
    - It appears as a smooth gradient of colors (rainbow-like) without any gaps.
- **Source**:
    - Produced by dense objects like stars, incandescent bulbs, or any object at a high temperature.
    - The light emitted is characteristic of the thermal radiation from the source.
- **Graph**:
    - Shows brightness smoothly varying across all wavelengths.
    - Example: The Sun emits a nearly continuous spectrum due to its hot, dense core.

2. Emission Spectrum

- **Description**:
    - Consists of **bright colored lines** on a dark background, where each line corresponds to a specific wavelength of light emitted by atoms or molecules in an excited state.
- **Source**:
    - Produced by **hot, low-density gas**.
    - When electrons in atoms or molecules absorb energy, they jump to higher energy levels. As they return to lower energy levels, they emit photons of specific wavelengths.
- **Graph**:
    - Shows sharp peaks of brightness at specific wavelengths, with no brightness in between.
    - Example:
        - The bright-line spectra of elements such as hydrogen and helium, which are used to identify their presence in stars or interstellar gas.

3. Absorption Spectrum

- **Description**:

- Consists of a **continuous spectrum with dark lines or gaps**, which represent specific wavelengths of light absorbed by a cooler gas in front of a continuous light source.
- These dark lines are known as **absorption lines**.

- **Source**:
  - Produced when light from a hot, dense object passes through a cooler gas.
  - The atoms or molecules in the cooler gas absorb specific wavelengths of light, leaving dark lines in the spectrum.
- **Graph**:
  - Shows dips in brightness at specific wavelengths corresponding to the absorbed light.
  - Example:
    - The absorption lines in the Sun's spectrum (called **Fraunhofer lines**) are caused by cooler gases in the Sun's atmosphere absorbing specific wavelengths.

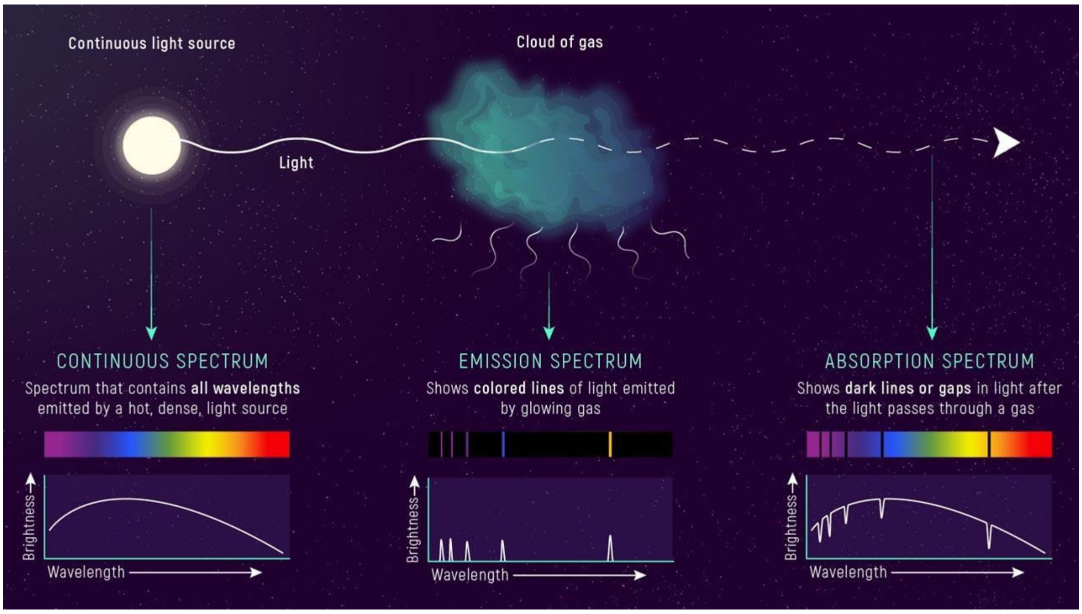

Fig: Spectrum

The image above illustrates the three main types of spectra—Continuous Spectrum, Emission Spectrum, and Absorption Spectrum—and how they are produced, based on the interaction of light with matter. These types of spectra are fundamental to the field of spectroscopy, which is used to analyze the composition and properties of celestial and terrestrial objects.

How These Spectra Are Useful in Astronomy

1. **Identifying Composition**:

  - Different elements produce unique spectral lines (both emission and absorption). This allows scientists to identify the chemical composition of stars, planets, and interstellar gas.
2. **Measuring Physical Properties**:
  - The intensity, position, and width of spectral lines can provide information about temperature, pressure, and motion (via the Doppler effect) of the emitting or absorbing material.
3. **Understanding Star Formation**:
  - Emission spectra reveal the presence of glowing gas in star-forming regions, while absorption spectra help study light passing through gas clouds.
4. **Detecting Exoplanets**:
  - The absorption spectrum of a star changes slightly when a planet transits in front of it, helping astronomers study the planet's atmosphere.

Origins of Stellar Spectra

1.1 Blackbody Radiation

- A star behaves approximately like a blackbody, an ideal emitter whose radiation depends solely on its temperature.
- The emitted spectrum is described by Planck's Law:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda k_B T} - 1}.$$

Where, $B_\lambda(T)$ is the spectral radiance, T is temperature, h is Planck's constant, c is the speed of light, k_B is Boltzmann's constant, and λ is the wavelength.

- The shape of the spectrum depends on the star's temperature:
  - Hotter stars emit more light at shorter (bluer) wavelengths.
  - Cooler stars emit more light at longer (redder) wavelengths.

Wien's Law: The wavelength of maximum emission (λ_{max}) shifts inversely with temperature:

$$\lambda_{\text{max}} = \frac{b}{T}$$

- where b≈2.897×10−3m\cdotpK

Stefan-Boltzmann Law: The total radiated energy per unit surface area is proportional to T^4:

$$F = \sigma T^4$$

Where, σ is the Stefan-Boltzmann constant.

1.2 Formation of Spectral Lines

When light passes through the star's atmosphere, atoms and molecules absorb specific wavelengths, forming dark lines (absorption lines) in the spectrum.

- **Transitions and Energy Levels**:
  - Atoms absorb photons when electrons move to higher energy levels.
  - The energy of these photons matches the difference between two quantized energy levels, $E2-E1=hv$, where v is the frequency.
- **Factors Influencing Line Formation**:
  - **Ionization**: Higher temperatures cause more atoms to lose electrons, changing line intensities.
  - **Pressure Broadening**: Collisions between particles in dense regions broaden spectral lines.
  - **Temperature**: Determines the distribution of atoms across energy levels (via the Boltzmann equation).

3. Doppler and Zeeman Effects

- **Doppler Shifts**: Motion of the star relative to the observer shifts line wavelengths.
  - **Blueshift**: Wavelengths are shorter (star approaching).
  - **Redshift**: Wavelengths are longer (star receding).
- **Zeeman Effect**: Magnetic fields split spectral lines into multiple components, providing a measure of field strength.

Information Extracted from Spectra

1. **Temperature**: Derived from continuum and line intensities.
2. **Composition**: Identified by absorption lines of specific elements (e.g., hydrogen, helium, calcium).
3. **Velocity**: Measured through Doppler shifts.
4. **Magnetic Fields**: Detected via Zeeman splitting.
5. **Stellar Activity**: Emission lines reveal chromospheric activity.

4.3 Stellar Structure

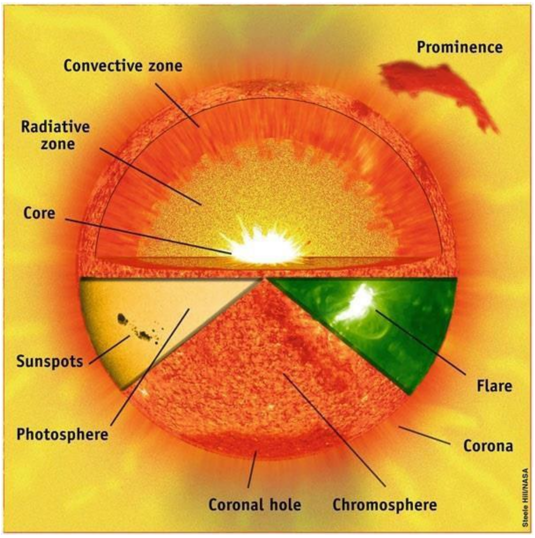

Fig: Stellar Structure

This image represents the internal structure of a typical main-sequence star (such as the Sun) and its various external and internal features. It illustrates the layered structure of a star and highlights phenomena that occur at different regions.

1. Core

- **Location**: The innermost region of the star.
- **Function**: The powerhouse of the star where **nuclear fusion** takes place.
  - Hydrogen nuclei (protons) are fused into helium nuclei via processes like the **proton-proton chain reaction** or the **CNO cycle** (depending on the star's mass).
  - This process releases immense amounts of energy in the form of photons and neutrinos.
- **Temperature**: Approximately **15 million Kelvin** in the Sun.
- **Pressure and Density**: Extremely high, enabling fusion to occur.

2. Radiative Zone

- **Location**: Surrounds the core.
- **Function**: Energy from the core is transported outward through **radiation**.
  - Photons are absorbed and re-emitted repeatedly by ions in this region, a process known as **radiative diffusion**.
  - It can take thousands to millions of years for a photon to pass through this zone due to continuous scattering.
- **Temperature Gradient**: Temperature decreases gradually outward.

3. Convective Zone

- **Location**: Surrounds the radiative zone.
- **Function**: Energy is transported by **convection** (bulk motion of plasma).
  - Hot plasma rises toward the surface, cools, and then sinks back.
  - This region is dominated by **convective currents** due to the opacity of the material, which prevents efficient radiative transport.
- **Result**: Convection creates **granulation patterns** on the photosphere.

4. Photosphere

- **Location**: The visible surface of the star.
- **Appearance**: Appears as a smooth, bright layer but shows **granulation** when closely examined.
  - **Granulation** is caused by convection currents in the convective zone.
- **Function**: The layer from which the majority of the star's light is emitted (blackbody radiation).
  - It's where absorption lines in the stellar spectrum are formed.
- **Temperature**: Approximately **5,500 Kelvin** in the Sun.
- **Features**:
  - **Sunspots**: Cooler, darker regions caused by strong magnetic fields inhibiting convection.

5. Chromosphere

- **Location**: Above the photosphere.
- **Function**: Emits light in specific wavelengths, especially in the red hydrogen-alpha line.
  - It is visible as a thin reddish layer during a solar eclipse.
- **Temperature**: Increases outward, from around **4,500 K to 25,000 K**.
- **Phenomena**:
  - **Spicules**: Jet-like features extending outward.
  - **Prominences**: Large loops of plasma held in place by magnetic fields.

6. Corona

- **Location**: The outermost layer of the star's atmosphere.
- **Function**: Extremely hot, tenuous plasma that emits X-rays.
  - The corona is heated by mechanisms such as **magnetic reconnection** or **wave heating**.
- **Temperature**: Exceeds **1 million Kelvin**, much hotter than the photosphere (this paradox is an area of ongoing research).

- **Appearance**: Visible during total solar eclipses as a glowing halo around the star.
- **Phenomena**:
    - **Solar Wind**: A stream of charged particles emanating from the corona.
    - **Coronal Holes**: Regions of lower density, where solar wind escapes more easily.

7. Sunspots

- **Location**: On the photosphere.
- **Function**: Regions of intense magnetic activity, appearing darker because they are cooler (about **4,000 K**) than the surrounding photosphere.
- **Phenomena**:
    - **Solar Cycles**: Sunspot activity follows an 11-year cycle, linked to the star's magnetic field reversals.

8. Prominences

- **Location**: Extend from the chromosphere into the corona.
- **Function**: Large loops of plasma supported by magnetic fields.
- **Behavior**: Can last for weeks to months, but some may erupt as **coronal mass ejections (CMEs)**.

9. Coronal Hole

- **Location**: In the corona.
- **Function**: These are areas where the Sun's magnetic field lines open out into space, allowing solar wind to escape.
- **Result**: High-speed streams of solar wind, which can interact with Earth's magnetic field, causing geomagnetic storms and auroras.

10. Flares

- **Location**: Often near sunspots, in the chromosphere or corona.
- **Function**: Sudden, intense bursts of energy caused by the reconnection of magnetic field lines.
- **Impact**: Flares emit X-rays, UV radiation, and charged particles, which can affect space weather and satellite communications on Earth.

Dynamic Interplay between Layers

Each layer of the star interacts dynamically:

1. Energy generated in the **core** drives processes outward.
2. The **convective zone** influences surface features like **granules** and **sunspots**.
3. The **chromosphere** and **corona** are shaped by magnetic field lines extending outward from the star.

Significance of Understanding Stellar Structure

- **Astrophysical Insight**: Explains energy generation and transport in stars.
- **Space Weather Predictions**: Helps predict solar flares, CMEs, and their impacts on Earth.
- **Stellar Evolution**: Provides clues about how stars age and eventually evolve into red giants, white dwarfs, or other end states.

By studying these features in detail, scientists can decipher the lifecycle of stars and their influence on planetary systems.

4.4 Stellar Evolution

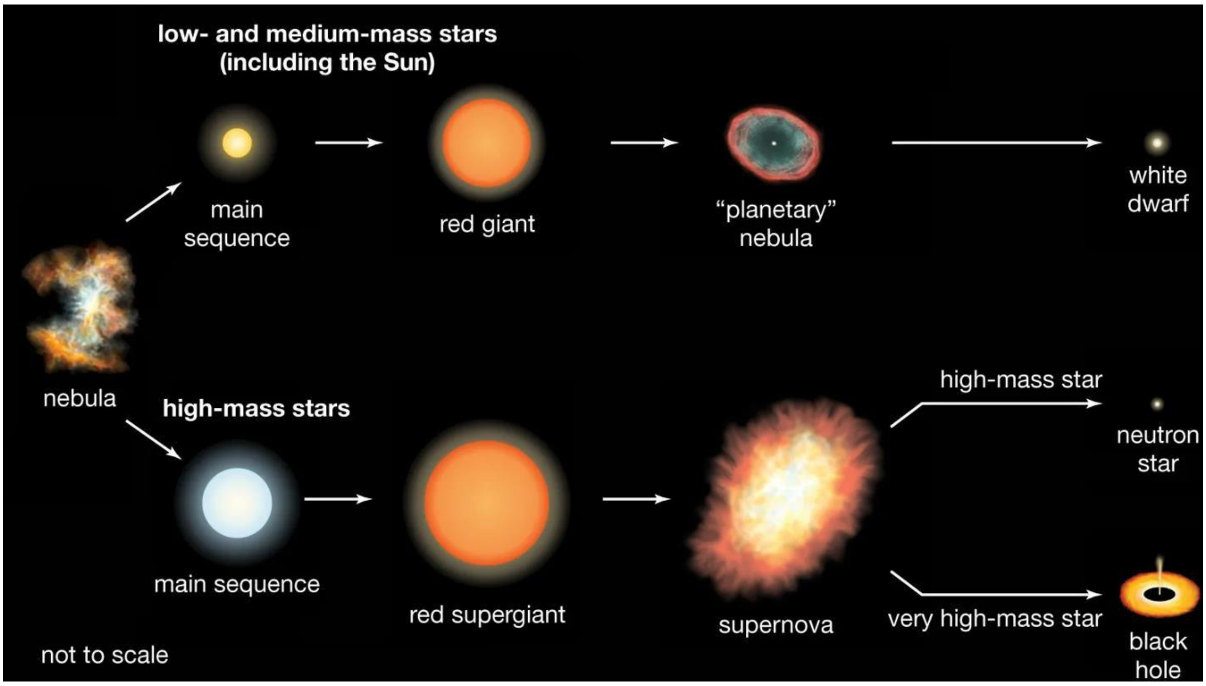

Fig: Stellar Evolution

This diagram outlines the life cycle of stars based on their mass, detailing the evolutionary paths of low- and medium-mass stars (such as the Sun) and high-mass stars. This diagram outlines the life cycle of stars based on their mass, detailing the evolutionary paths of low- and medium-mass stars (such as the Sun) and high-mass stars.

Stage 1: Nebula (Star Formation)

1. **The Birthplace of Stars:**
   - A **nebula** is a vast cloud of gas (primarily hydrogen, with smaller amounts of helium and trace elements) and dust particles spread across space. These nebulae are often the remnants of previous generations of stars that ended their lives in supernova explosions, enriching the interstellar medium with heavy elements.
2. **Gravitational Collapse:**
   - Over time, regions of higher density within the nebula experience gravitational instability (Jeans instability), causing them to collapse under their own gravity.
   - The collapse leads to the formation of dense regions called **protostars**, where gravitational potential energy converts into thermal energy.
3. **Formation of a Protostar:**
   - As the collapsing core becomes denser and hotter, a spinning disk of gas and dust forms around it. This is the **accretion disk**, feeding material into the protostar.
   - Magnetic fields and stellar winds begin to shape the environment, leading to the bipolar outflows that help clear away excess material.
4. **Initiation of Nuclear Fusion:**
   - When the core temperature reaches **10 million Kelvin**, hydrogen nuclei (protons) begin fusing into helium via the **proton-proton chain reaction** (for stars less than 1.5 solar masses) or the **CNO cycle** (in higher-mass stars).

Stage 2: Main Sequence (The Longest Phase)

1. **Hydrostatic Equilibrium:**
   - The inward pull of gravity is exactly balanced by the outward thermal pressure generated by nuclear fusion in the core.
   - The star becomes stable and luminous, emitting light and heat continuously.
2. **Energy Production:**

- **Low- to Medium-Mass Stars (e.g., the Sun):**
  - Dominated by the **proton-proton chain**, where four hydrogen nuclei fuse into one helium nucleus, releasing energy in the form of photons and neutrinos.
  - Energy is transported outward from the core via **radiative diffusion** and **convection**.
- **High-Mass Stars:**
  - The core temperature is higher, enabling the **CNO cycle**, where carbon acts as a catalyst in fusing hydrogen into helium. This process is faster, consuming hydrogen more rapidly.

3. **Lifespan of Main Sequence Stars:**
   - A star's lifespan on the main sequence depends on its initial mass:
     - Low-mass stars (e.g., red dwarfs): Trillions of years.
     - Medium-mass stars (e.g., the Sun): Approximately 10 billion years.
     - High-mass stars: A few million years due to their rapid consumption of hydrogen.

Stage 3: Post-Main Sequence

As stars exhaust their hydrogen fuel, their evolution diverges depending on their mass.

Low- and Medium-Mass Stars:

1. **Red Giant Phase:**
   - **Hydrogen Shell Burning**:
     - Once hydrogen in the core is depleted, nuclear fusion halts, and the core begins to contract due to gravity.
     - The outer layers expand and cool as hydrogen fusion continues in a shell surrounding the core.
   - **Helium Fusion (Triple-Alpha Process):**
     - When the core temperature rises to about **100 million Kelvin**, helium nuclei (alpha particles) fuse into carbon and oxygen in a process called the **triple-alpha process**.
2. **Planetary Nebula:**
   - After helium is exhausted, the outer layers of the star are ejected due to pulsations and stellar winds, forming a glowing shell of gas called a **planetary nebula**.
   - This stage marks the end of fusion in the star, leaving behind its core.
3. **White Dwarf:**

   - The exposed core becomes a **white dwarf**, composed mostly of carbon and oxygen.
   - Supported by **electron degeneracy pressure**, the white dwarf is extremely dense (about 1.4 times the Sun's mass compressed into the size of Earth).
   - It gradually cools and fades over billions of years, becoming a **black dwarf** (theoretical, as the universe isn't old enough for black dwarfs to exist yet).

High-Mass Stars:

1. **Red Supergiant Phase:**
   - High-mass stars evolve into **red supergiants**, where successive fusion cycles occur:
     - Hydrogen → Helium (via the CNO cycle).
     - Helium → Carbon and Oxygen (triple-alpha process).
     - Carbon → Neon, Magnesium.
     - Neon → Oxygen.
     - Oxygen → Silicon.
     - Silicon → Iron.
   - **Iron Core Formation**:
     - Fusion stops at iron because it requires more energy to fuse than it releases.
2. **Core Collapse and Supernova:**
   - As the iron core exceeds the **Chandrasekhar limit** (about 1.4 solar masses), gravity overwhelms electron degeneracy pressure, causing the core to collapse.
   - The collapse triggers a massive explosion called a **supernova**, releasing enormous energy and dispersing heavy elements into space.
3. **Final State (Determined by Core Mass):**
   - **Neutron Star**:
     - For cores between **1.4–3 solar masses**, the collapse is halted by **neutron degeneracy pressure**.
     - A neutron star is an incredibly dense object (a sugar-cube-sized amount of its material weighs billions of tons).
   - **Black Hole**:
     - If the core exceeds **3 solar masses**, even neutron degeneracy pressure fails to stop the collapse, forming a black hole.
     - The black hole's gravity is so intense that nothing, not even light, can escape.

Astrophysical Significance of Stellar Evolution

1. **Chemical Enrichment:**
   - Elements heavier than hydrogen and helium (e.g., carbon, oxygen, nitrogen, and iron) are forged in stars and dispersed through supernovae and planetary nebulae.
   - This process, called **stellar nucleosynthesis**, is responsible for the chemical diversity of the universe.
2. **Formation of New Stars and Planets:**
   - The material ejected from dying stars contributes to the formation of new stars, planets, and even life.
3. **Astrophysical Phenomena:**
   - White dwarfs, neutron stars, and black holes provide insights into exotic states of matter, quantum mechanics, and the nature of space-time.
4. **Cosmic Recycling:**
   - The cycle of star formation and death ensures the continuous evolution of galaxies and their stellar populations.

Comparison of Stellar Evolution Paths

Parameter	Low-/Medium-Mass Stars	High-Mass Stars
End Product	White Dwarf	Neutron Star or Black Hole
Fusion Processes	Hydrogen (proton-proton chain)	Hydrogen (CNO cycle) + Heavy Element Fusion
Final Explosion	None	Supernova
Lifespan	Long (billions of years)	Short (millions of years)

4.5 Nucleo-synthesis and Formation of Elements

A star's energy comes from the combining of light elements into heavier elements in a process known as **fusion**, or "nuclear burning". It is generally believed that most of the elements in the universe heavier than helium are created, or synthesized, in stars when lighter nuclei fuse to make heavier nuclei. The process is called **nucleosynthesis**.