1 Surveying the Stars

1.1 Star Magnitudes

- One **light year** is the distance light travels through space in 1 year.
- The sun and nearby stars are in a **spiral arm** of the Milky Way galaxy.
- **Galaxies** are assemblies of stars prevented from moving away from each other by their **gravitational attraction**.
- The most distant galaxies near the edge of the **observable universe** were formed shortly after the Big Bang.
- **Parallax**: nearby stars shift in position against the background of more distance stars as the Earth moves in its orbit,
- The **astronomical unit** is the mean distance from the centre of the Sun to the Earth.
- The **parallax angle** θ is the angle subtended to the star by the line between the Sun and the Earth.

$$\theta \approx \tan\theta = \frac{R}{d}$$

- One **arc second** is $\dfrac{1^\circ}{3600}$
- One **parsec** is defined as the distance to a star which subtends an angle of 1 arc second to the line from the centre of the Earth to the centre of the Sun.

$$d \text{ (parsec)} = \frac{R \text{ (au)}}{\theta \text{ (arc seconds)}}$$

Star Magnitudes

The brightness of a star depends on the **intensity** of the star's light on earth - intensity is the light **energy per second per unit surface area** received from the star at **normal incidence** on a surface.

The **Hipparcos scale** define a difference of 5 magnitudes as a hundredfold change in the intensity of light received from the star.

- The **apparent magnitude** m of a star in the night sky is a measure of its brightness - its intensity.

$$m_y - m_x = 2.5 \log \frac{I_X}{I_Y}$$

- The **absolute magnitude** M of a star is defined as the star's apparent magnitude m, if it was at a distance of 10 parsecs away from the earth.

$$m - M = 5 \log \frac{d}{10}$$

1.2 Classifying Stars

Stars differ in **colour and brightness**. Stars that appear white appear in their true colours when viewed through a telescope, because a telescope **collect more light** than the unaided eye, and activating the colour-sensitive cells in the retina.

- The thermal radiation from a hot object at constant temperature consists of a **continuous range of wavelengths**.
- The **distribution of intensity** with wavelength changes as the temperature of the hot object is increased.
- A **black body** is defined as a body that is a perfect absorber of radiation, and therefore emits a continuous spectrum of wavelengths.
- A **black body radiation curve** shows the intensities of the wavelengths emitted by a black body.

Law's of Thermal Radiation

Wien's Displacement Law

The wavelength at peak intensity is inversely proportional to the absolute temperature of the object.

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

where $b = 0.0025 \mathrm{m\,K}$

It is used to calculate the **absolute temperature of the photosphere** (the light-emitting outer layer) of a star.

Stefan's Law

The total energy per second emitted by a black body is proportional to its **surface area** and to T^4.

$$P = \sigma A T^4$$

where the **Stefan constant** $\sigma = 5.67 \times 10^{-8} \mathrm{Wm^{-2}K^{-4}}$.

The power output of a start is sometimes called the **luminosity** of the star.

Stellar Spectral Classes

The spectrum of light from a star is used to classify it.

Spectral class	Intrinsic colour	Temperature	Absorption lines
O	Blue	25K - 50K	He^+, He, H
B	Blue	11K - 25K	He, H
A	Blue-white	7.5K - 11K	H, ionised metals
F	White	6K - 7.5K	Ionised metals
G	Yellow-white	5K - 6K	Ionised & neutral metals
K	Orange	3.5K - 5K	Neutral metals
M	Red	2.5K - 3.5K	Neutral atoms & TiO

The spectrum of light from a star contains **absorption lines** due to an atmosphere of hot gases surrounding the star above its photosphere.

- Atoms of the gas **absorb light of certain wavelengths**.
- The light that passes through these hot gases is therefore **deficient of this wavelengths**, its spectrum therefore contains **absorption lines**.

The wavelengths of absorption lines are **characteristics of the elements in the corona of hot gases** surrounding a star. The wavelengths of these absorption lines can be used to identify the **elements present in the star**.

Balmer lines are **hydrogen absorption lines** correspond to excitation of hydrogen atoms from the $n = 2$ state to higher energy levels. They are only visible in O, B, A class stars.

- Hydrogen atoms in $n = 2$ state exist in hot stars.
- Such atoms absorb visible photons at certain wavelengths, producing absorption lines.

Note hydrogen atoms in $n = 1$ state does not absorb visible photons, as they do not have sufficient energy to cause excitation from $n = 1$.

1.3 The Herzsprung-Russell Diagram

The power output (luminosity) of the sun is given by

$$P = 4\pi r^2 I$$

Star diameters are determined by comparing the absolute magnitude of the star with that of the sun.

- A **dwarf star** is a star that is much smaller in diameter than the sun.
- A **giant star** is a star that is much larger in diameter than the sun.

Note Stefan's law gives the power output across the entire spectrum, absolute magnitudes relate to the visible spectrum.

Compare a star X with the sun

$$\begin{aligned} P_X &= \sigma A_X {T_X}^4 \\ P_S &= \sigma A_S {T_S}^4 \\ \frac{A_X}{A_S} &= \frac{P_X}{P_S} \div \left(\frac{T_X}{T_S}\right)^4 \\ &= \frac{\text{power output ratio}}{(\text{temperature ratio})^4} \end{aligned}$$

- Same surface temperature + unequal absolute magnitudes
  $\Longrightarrow$ the one greater power output has the larger surface area.
- Same absolute magnitude + unequal surface temperatures
  $\Longrightarrow$ the hotter star has a smaller surface area.

Features of the The HR Diagram

- **Absolute magnitude** is plotted on the y-scale.
- **Temperature** is plotted in the x-scale.

The main features are as follows

- The **main sequence** is a heavily populated diagonal belt of stars, ranging from cool low-powered stars ($M = +15$) to very hot high powered stars ($M = 5$).
- **Giant stars** have absolute magnitudes $-2 < M < 2$, emit more power than the sun, and are 10 to 100 times larger. **Red giants** are cooler than the sun.
- **Supergiant stars** have absolute magnitude $-10 < M < -5$, they are relatively rare, and are much brighter and larger than giant stars, with diameters up to 1000 times of the sun.
- **White dwarf** stars have absolute magnitude $+10 < M < +15$ and are hotter than the sun, they are much smaller and emit much less power than the sun.

Stellar Evolution

1. **Formation** - a star is formed as gas clouds in space construct under their own gravitational attraction.
   - Gravitational energy is transformed into **thermal energy**.
   - If the **protostar** contains sufficient matter, the temperature at the core becomes hot enough for **nuclear fusion** to occur.
   - Fusion occurs as long as there are sufficient light nuclei.

2. **Main sequence** - In a state of **internal equilibrium** where gravitational attraction acting inwards is balanced by radiation pressure.
    - Absolute magnitude depends its mass.
    - The star remains at this position for most of its lifetime.
3. **Red giants** - most of the hydrogen in the core of the star has been converted to helium.
    - The outer layers of the star **expand and cool** as a result.
    - The temperature of the core increases as it collapses.
    - Luminosity increases and peak wavelength also increases.
4. **White dwarfs** - nuclear fusion ceases, the core contracts causing the outer layer of the star to be thrown off.
    - The outer layers forms a **planetary nebulae** around the star.
    - If the mass is 4-8 solar masses, the core continues to fuse heavier elements.

If mass is less than 1.4 solar masses, the core stops contracting because electrons in the core can no longer be forced any closer. Otherwise supernova.

1.4 Supernovae, Neutron Stars, and Black Holes

- Below 1.4 solar masses - the outer layers of the star, and the core stabilises into a white dwarf. The repulsive force between electrons in the core pushing outwards counterbalances the gravitational force pulling the core inwards.
- Above 1.4 solar masses, the electrons in the iron core can **no longer prevent further collapse** because they are forced to react with protons to **form neutrons**.

  The core becomes more and more dense until the neutrons can **no longer be forced any closer**. The core suddenly becomes rigid, collapsing matter hits the core and rebounds as a shock wave.

A **supernova** explosion throws matter surrounding the core into space at high speeds. Elements heavier than iron are formed by nuclear fusion in a supernova explosion, occurring as the shock wave travels through the layers of matter surrounding the neutron-filled core.

Type Ia Supernovae

Supernovae are classified according to their **line absorption spectra**.

- **Type I** supernovae have **no strong hydrogen lines**.

- **Type Ia** supernovae show a strong absorption line due to **silicon**.
  - Reaches peak luminosity then **decrease smoothly**.
  - White dwarf in a **binary system** attracts matter from a companion giant star, causing **fusion reactions to restart**: carbon to form silicon nuclei.
  - The fusion process becomes unstoppable and the white dwarf explodes.

  Because type Ia supernovae are characterised by **strong silicon absorption lines** and has a **known peak luminosity**, they are used as **standard candles**.

Neutron Stars and Black Holes

A neutron star is the core of a supernova after all surrounding matter has been through into space.

- **Pulsars** emit radio frequencies of up to 30Hz.
- Pulsars are rotating neutron stars.

A black hole is an object so dense not even light can escape from it.

- The escape velocity is above the speed of light.
- If a core is greater than 3 solar masses, the neutrons are unable to withstand the forces pushing them together, so it collapse on itself.
- The object is black because it doesn't emit any photons, and absorb any photons that are incident on it.

The **event horizon** of a black hole is a sphere surrounding the black whole from which nothing emerges.

The Schwarzschild radius R_s is the radius of the event horizon.

By the general relativity

$$R_s = \frac{2GM}{c^2}$$

1. Black hole **attracts surrounding matter**.
2. Matter falling towards the black hole **radiates energy** until it falls within the event horizon.
3. Matter is drawn towards a **singularity** at its centre.

A black hole is characterised by its mass, charge, and rotational motion. Any other property carried by in-falling matter is lost.

- **Supermassive black holes** exist at the centre of many galaxies.

- **Gamma-ray bursts** can be observed from random directions in space, each burst lasting from a fraction of a second to several minutes.

Gamma-ray bursts release huge amount of energy in form of gamma radiation shooting out from the poles of black holes.