A Level Physics Edexcel

10. Space

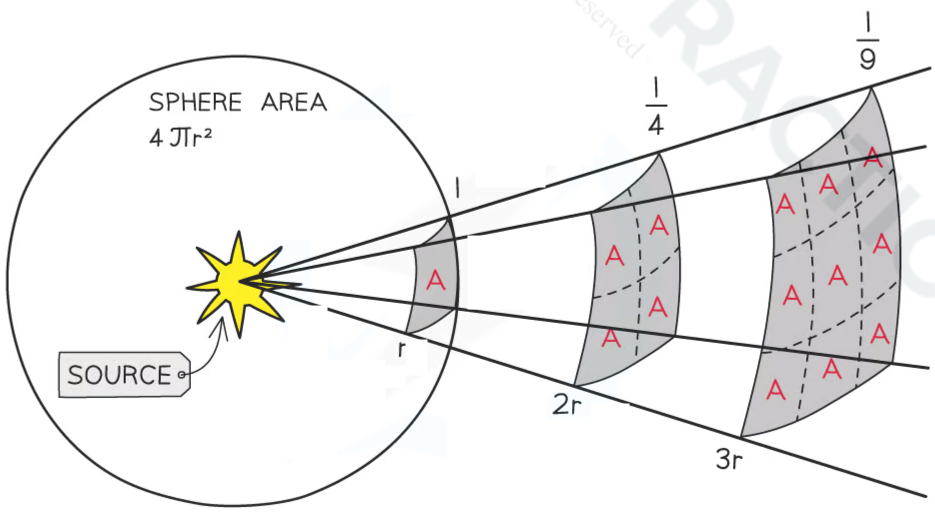
CONTENTS

Inverse Square Law of Flux

- The moment the light leaves the surface of the star, it begins to spread out uniformly through a spherical shell
  - Light sources which are further away appear fainter because the emitted light has been spread over a greater area
- The surface area of a sphere is equal to $\mathbf{4\pi r^2}$
  - The radius *r* of this sphere is equal to the distance *d* between the star and the Earth
  - Therefore the radiation received at Earth has been spread over an area of $4\pi d^2$
- The inverse square law of flux can therefore be calculated using:

$$F = \frac{L}{4\pi d^2}$$

- Where:
  - F = radiant flux intensity, or observed intensity on Earth ($W\,m^{-2}$)
  - L = luminosity of the source (W)
  - d = distance between the star and the Earth (m)
- This equation assumes:
  - The power from the star radiates uniformly through space
  - No radiation is absorbed between the star and the Earth
- This equation tells us:
  - For a given star, the luminosity is constant
  - The radiant flux follows an inverse square law
  - The greater the radiant flux (larger *F*) measured, the closer the star is to the Earth (smaller *d*)



Inverse square law; when the light is twice as far away, it has spread over four times the area, hence the intensity is four times smaller

Worked Example

A star has a luminosity that is known to be 4.8 × 10^{29} W. A scientist observing this star finds that the radiant flux intensity of light received on Earth from the star is 2.6 nW m^{-2}. Determine the distance of the star from Earth.

Step 1: Write down the known quantities

Luminosity, L = 4.8 × 10^{29} W

Radiant flux intensity, F = 2.6 nW m^{-2} = 2.6 × 10^{-9} W m^{-2}

Step 2: Write down the inverse square law of flux

$$F = \frac{L}{4\pi d^2}$$

Step 3: Rearrange for distance *d*, and calculate

$$d = \sqrt{\frac{L}{4\pi F}} = \sqrt{\frac{4.8 \times 10^{29}}{4\pi \times (2.6 \times 10^{-9})}} = 3.8 \times 10^{18}\ m$$

Determining Distance using Parallax

- The **principle of parallax** is based on how the position of an **object** appears to change as the position of the **observer** changes
  - For example, when **observing** the scale on a metre ruler, looking at eye level gets a different reading to viewing from above or below the scale

- **Stellar parallax** can be used to measure the distance to **nearby stars**

- Stellar Parallax is defined as:

  The apparent shifting in position of a nearby star against a background of distant stars when viewed from different positions of the Earth, during the Earth's orbit about the Sun

- It involves observing how the position of a **nearby** stars changes over a period of time against a fixed background of **distant** stars
  - From the **observer's** position the distant stars do not appear to move
  - However, the closer object does appear to move
  - This difference creates the effect of stellar parallax

Using Stellar Parallax

- A **nearby star** is viewed from the Earth in January and again in July
  - The observations are made six months apart to maximise the distance the Earth has moved from its starting position
- The Earth has completed half a full orbit and is at a **different position** in its orbit around the Sun
  - The nearby star will appear in different positions against a backdrop of distant stars which will appear to not have moved
  - This **apparent movement** of the nearby star is called the stellar parallax

Calculating Stellar Parallax

- Applying trigonometry to the parallax equation:
  - 1 AU = radius of Earths orbit around the sun
  - *p* = parallax angle from earth to the nearby star
  - *d* = distance to the nearby star
  - So, $\tan(p) = \frac{AU}{d}$

- For small angles, expressed in radians, $\tan(p) \approx p$, therefore: $p = \frac{AU}{d}$

- If the distance to the nearby star is to be measured in parsec, then it can be shown that the relationship between the distance to a star from Earth and the angle of stellar parallax is given by

$$p = \frac{1}{d}$$

- Where:
  - p = parallax (")
  - d = the distance to the nearby star (pc)
- This equation is accurate for distances of up to 100 pc
  - For distances larger than 100 pc the angles involved are so small they are hard to measure accurately

Worked Example

The nearest star to Earth, Proxima Centauri, has a parallax of 0.768 seconds of arc.

Calculate the distance of Proxima Centauri from Earth

a. in parsec
b. in light-years

Part (a)

Step 1: List the known quantities

- Parallax, p = 0.768"

Step 2: State the parallax equation

$$p = \frac{1}{d}$$

Step 3: Rearrange and calculate the distance d

$$d = \frac{1}{p} = \frac{1}{0.768} = 1.30\ pc$$

Part (b)

Step 1: State the conversion between parsecs and metres

- From the data booklet:

$$1 \text{ parsec} \approx 3.1 \times 10^{16} \text{ m}$$

Step 2: Convert 1.30 pc to m

$$1.30 \text{ pc} = 1.30 \times (3.1 \times 10^{16}) = 4.03 \times 10^{16} \text{ m}$$

Step 3: State the conversion between light-years and metres

- From the data booklet

$$1 \text{ light-year} \approx 9.5 \times 10^{15} \text{ m}$$

Step 4: Convert 4.03×10^{16} m into light-years

$$\frac{4.03 \times 10^{16}}{9.5 \times 10^{15}} = 4.2 \text{ ly (to 2 s.f)}$$

Exam Tip

It is important to recognise the simplified units for arc seconds and arc minutes:

arcseconds = "

arcminutes = '

Determining distance using standard candles

Standard Candles

- A standard candle is defined as:

  An astronomical object which has a known luminosity due to a characteristic quality possessed by that class of object

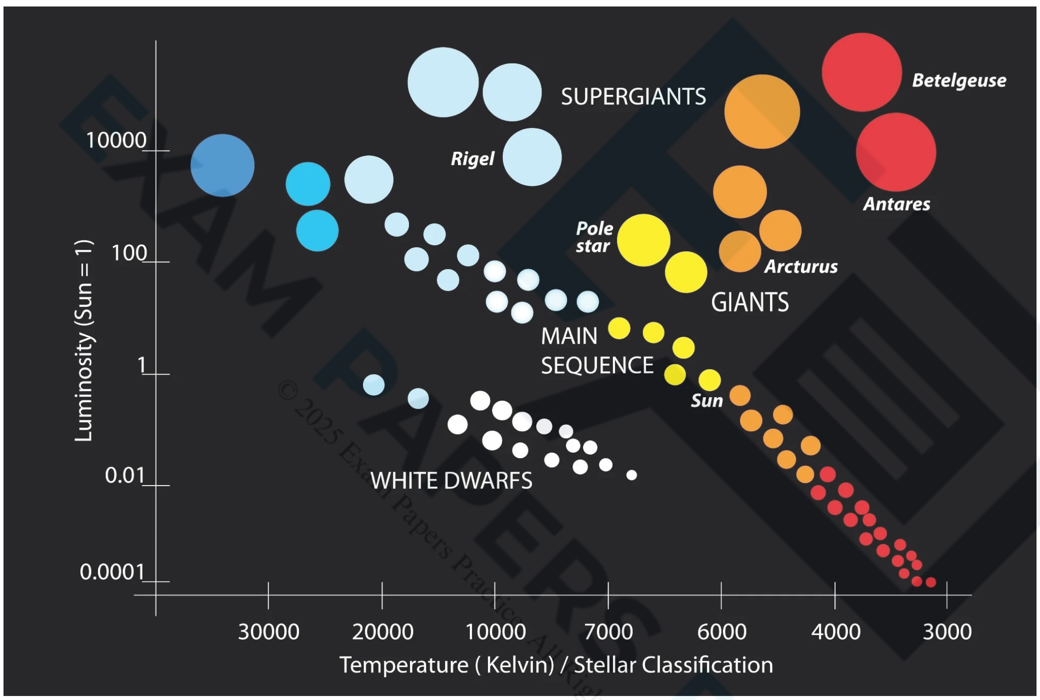
- Examples of standard candles are:
- Cepheid variable stars
  - A type of pulsating star which increases and decreases in brightness over a set time period
  - This variation has a well defined relationship to the luminosity
- Type 1a supernovae
  - A supernova explosion involving a white dwarf
  - The luminosity at the time of the explosion is always the same

Determining distances using standard candles

- Measuring astronomical distances accurately is an extremely difficult task
- A direct distance measurement is only possible if the object is close enough to the Earth
- For more distant objects, indirect methods must be used - this is where standard candles come in useful
- If the luminosity of a source is known, then the distance can be estimated based on how bright it appears from Earth
  - Astronomers measure the radiant flux intensity, of the electromagnetic radiation arriving at the Earth
  - Since the luminosity is known (as the object is a standard candle), the distance can be calculated using the inverse square law of flux
- Each standard candle method can measure distances within a certain range
- Collating the data and measurements from each method allows astronomers to build up a larger picture of the scale of the universe

The Hertzsprung – Russell Diagram

- Danish astronomer Ejnar Hertzsprung, and American astronomer Henry Noris Russell, independently plotted the **luminosity** of different stars against their **temperature**
  - Luminosity relative to the Sun, on the y-axis, goes from dim (at the bottom) to bright (at the top)
  - Temperature in degrees kelvin, on the x-axis, goes from **hot** (on the left) **to cool** (on the right)



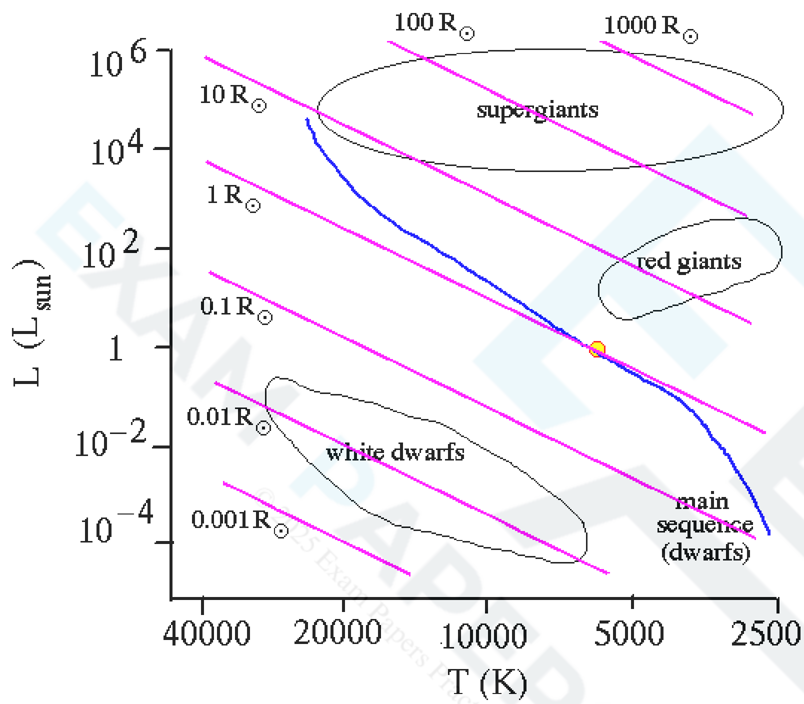
The Hertzsprung-Russell Diagram

- Hertzsprung and Russel found that the stars clustered in **distinct areas**
- Most stars are clustered in a band called the **main sequence**
  - For main sequence stars, luminosity increases with surface temperature
- A smaller number of stars clustered above the main sequence in two areas, **red giants,** and **red super giants**
  - These stars show an increase in luminosity at cooler temperatures
  - The only explanation for this is that these stars are much **larger** than main sequence stars
- Below and to the left of the main sequence are the **white dwarf stars**
  - These stars are hot, but not very luminous

- Therefore, they must be much **smaller** than main sequence stars
- The Hertzsprung-Russell Diagram only shows stars that are in **stable phases**
  - Transitory phases happen quickly in relation to the lifetime of a star
  - Black holes cannot be seen since they emit no light

Worked Example

Stars can be classified using the Hertzsprung-Russell Diagram.



a. State the types of stars found in areas A, B, C and D.

b. Star X has a surface temperature of 20 000 K and a luminosity 10 000 times greater than the Sun. Plot star X's place on the Hertzsprung-Russell diagram and label it Star X.

Step 1: Identify the main sequence on the Hertzsprung-Russell diagram

- The main sequence is the long band diagonally central to the diagram where the majority of stars are found
  - The main sequence is region **B**

Step 2: Identify the white dwarf region on the HR diagram

- White dwarf stars are hot, but not very luminous
- Identify the area with a **lower luminosity** than the main sequence
  - The white dwarf region is area **A**

Step 3: Identify the red giant and red supergiant regions on the HR diagram

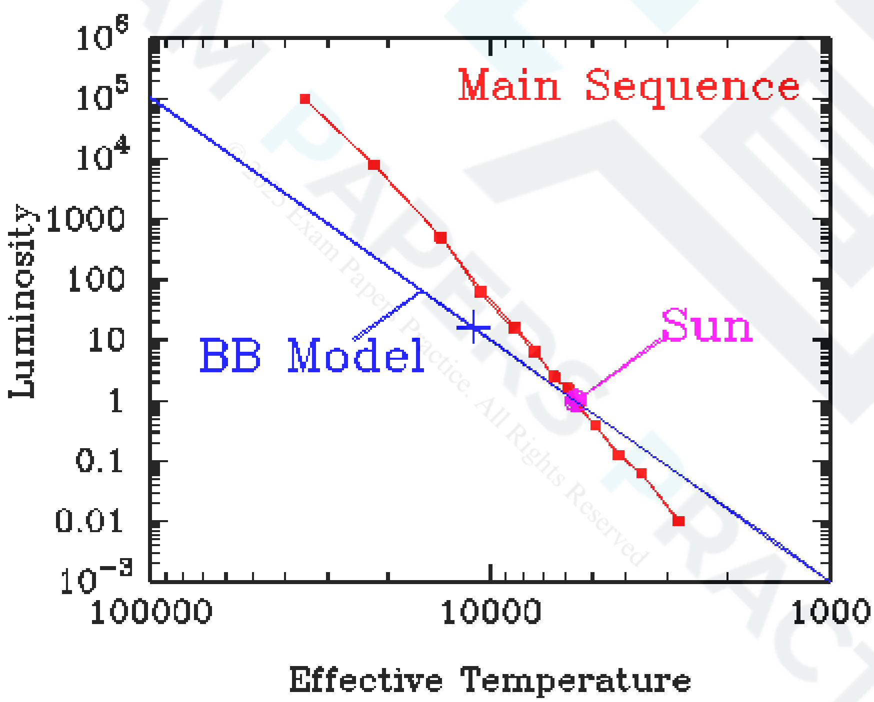
- Red giants and super red giants have a greater luminosity than main sequence stars at a lower temperature
- Super red giants are **more luminous** than the red giants and will appear **above** them on the graph
  - The super red giant region is area **C**
  - The red giant region is area **D**

Step 4: List the known quantities given in part b

- Surface temperature of Star X = 20 000 K
- Luminosity of Star X = 10 000 times that of the Sun

Step 5: Use the graph to find the value for the luminosity of the Sun

- Use a ruler and pencil to draw a line from the position of the Sun to the luminosity axis (y-axis)
- The Sun's luminosity on this scale is 1 because the luminosities given are relative to the luminosity of the Sun



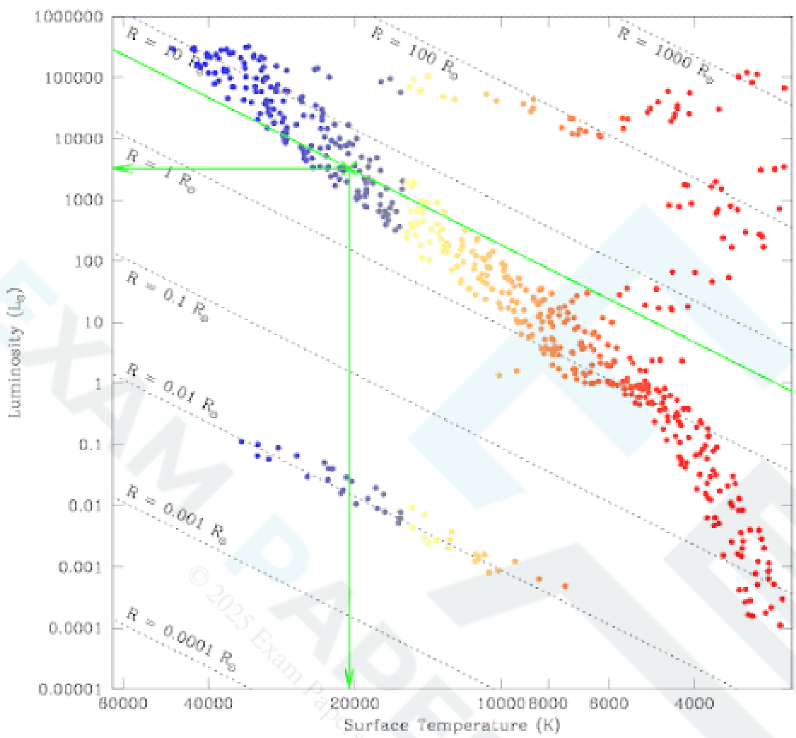
Step 6: Calculate the luminosity of Star X

- Star X is 10 000 times that of the Sun
- The luminosity of the Sun is 1

$$10\,000 \times 1 = 10\,000 \text{ or } 10^4$$

Step 7: Plot the position of Star X on the HR diagram

- Locate the surface temperature of Star X at 20 000 K
- Locate the luminosity of Star X at 10^4



- Plot the point and label it Star X

The Life Cycle of Stars

- The life cycle of stars go in predictable stages
- The exact route a star's development takes depends on its initial mass

Initial Stages for All Masses

- The first four stages in the life cycle of stars are the same for stars of all masses
- After these stages, the life-cycle branches depending on the whether the star is:
  - **Low mass**: stars with a mass **less** than about 1.4 times the mass of the Sun ($< 1.4\ M_{Sun}$)
  - **High mass**: stars with a mass **more** than about 1.4 times the mass of the Sun ($> 1.4\ M_{Sun}$)

1. Nebula

- All stars form from a giant cloud of **hydrogen gas** and **dust** called a **nebula**
  - **Gravitational attraction** between individual atoms forms denser clumps of matter
  - This inward movement of matter is called **gravitational collapse**

2. Protostar

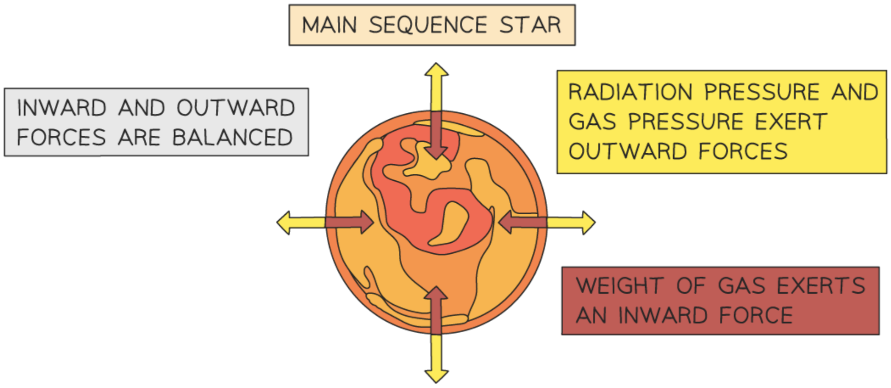
- The gravitational collapse causes the gas to heat up and glow, forming a **protostar**
  - Work done on the particles of gas and dust by collisions between the particles causes an increase in their kinetic energy, resulting in an increase in temperature
  - Protostars can be detected by telescopes that can observe **infrared radiation**

3. Nuclear Fusion

- Eventually the temperature will reach millions of **degrees Kelvin** and the fusion of hydrogen nuclei to helium nuclei begins
  - The protostar's gravitational field continues to attract more gas and dust, increasing the temperature and pressure of the core
  - With more frequent collisions, the kinetic energy of the particles increases, increasing the probability that fusion will occur

4. Main Sequence Star

- The star reaches a **stable state** where the inward and outward **forces** are in **equilibrium**
  - As the temperature of the star increases and its volume decreases due to gravitational collapse, the **gas pressure** increases
- A star will spend most of its life on the **main sequence**
  - 90% of stars are on the main sequence
  - Main sequence stars can vary in mass from ~10% of the mass of the Sun to 200 times the mass of the Sun
  - The Sun has been on the main sequence for 4.6 billion years and will remain there for an estimated 6.5 billion years



Next Stages for Low Mass Stars

- The fate of a star beyond the main sequence depends on its **mass**
  - The cut-off point is **1.4 times the mass of the Sun**
  - A star is classed as a low-mass star if it has a mass less than 1.4 times the mass of the Sun
  - A low-mass star will become a **red giant** before turning into a **white dwarf**

5. Red Giant

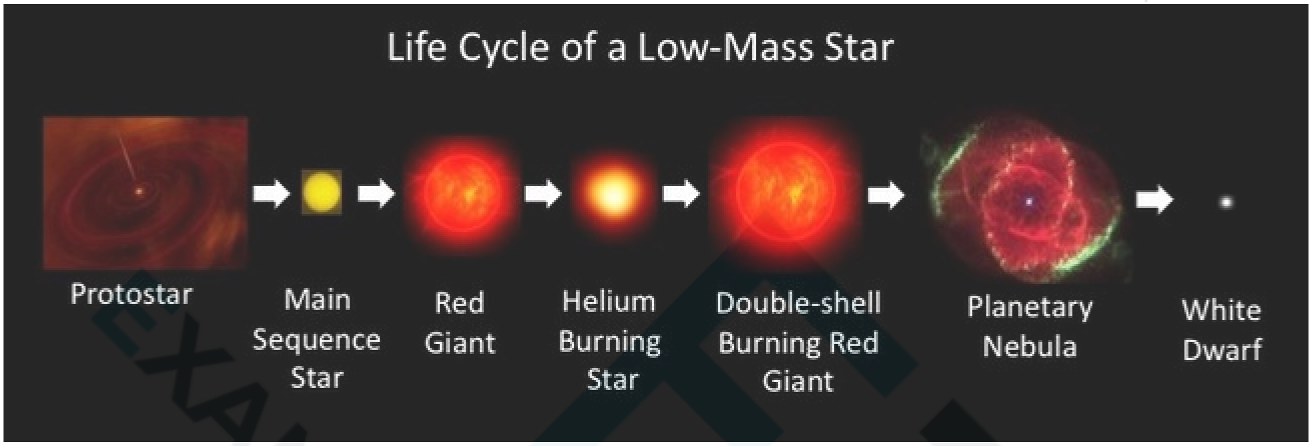
- Hydrogen fuelling the star begins to run out
  - Most of the hydrogen nuclei in the core of the star have been fused into helium
  - Nuclear fusion **slows**
  - Energy released by fusion decreases
- The star initially shrinks and then swells and cools to form a **red giant**
- Fusion continues in the **shell** around the core

6. Planetary Nebula

- The **outer layers** of the star are **released**
  - Core helium burning releases massive amounts of energy in the fusion reactions

7. White Dwarf

- The solid **core collapses** under its own mass, leaving a very hot, dense core called a **white dwarf**



The lifecycle of a low mass star

Next Stages for Massive Stars

5. Red Super Giant

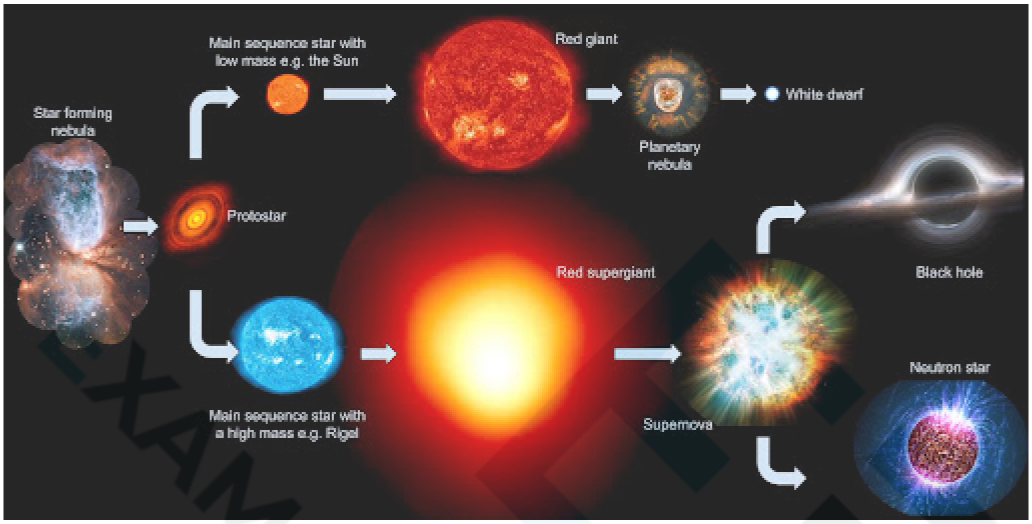
- The star follows the same process as the formation of a red giant
  - The **shell burning** and **core burning** cycle in massive stars goes beyond that of low-mass stars, fusing elements up to **iron**

6. Supernova

- The iron core collapses
- The outer shell is blown out in an explosive **supernova**

7. Neutron Star (or Black Hole)

- After the supernova explosion, the collapsed **neutron core** can remain intact having formed a **neutron star**
  - If the neutron core mass is greater than 3 times the solar mass, the pressure on the core becomes so great that the core collapses and produces a **black hole**



Lifecycle of massive stars

Worked Example

Stars less massive than our Sun will leave the main sequence and become red giants.

Describe and explain the next stages of evolution for such stars.

Step 1: Underline the command words

- **Describe** questions require details of the processes occurring
- **Explain** questions require details of how and why those processes occur
  - This question requires **both**

Step 2: Identify the mass of the star

- The stars in the question are less massive than the Sun, therefore it is referring to **low-mass stars**

Step 3: Identify the stage of life cycle being asked about

- The question asks for the **next** stage of evolution after **becoming** a red giant
- It requires an explanation of the processes **during** the red giant phase

Step 4: Plan the answer

- Make a list of the remaining stages in the evolution of a low-mass star

- Red giant
    - Planetary nebula
    - White dwarf
- Add to the list any important points or key words that need to be included in the answer
    - Red giant
        - Fuel runs out
        - Forces no longer balanced
        - Expands and cools
        - Fusion continues in shell
    - Planetary nebula
        - Carbon-oxygen core not hot enough for further fusion
        - Outer layers released
    - White dwarf
        - core collapses leaving remnant core

Step 5: Begin writing the answer using words from the question stem

- Low-mass stars will leave the main sequence and become red giants…

Step 6: Use the plan to keep the answer concise and logically sequenced

- Low mass stars leave the main sequence and become red giants when the hydrogen in the core runs out.
- Reduced energy released by fusion leads to radiation pressure decreasing
    - Radiation pressure and gas pressure no longer balance the gravitational pressure and the core collapses
    - Fusion no longer takes place inside the core.
- The outer layers expand and cool to form a red giant
- Temperatures generated by the collapsing core are high enough for fusion to occur in the shell around the core
    - Contraction of the core produces temperatures great enough for the fusion of helium into carbon and oxygen inside the core
    - The carbon-oxygen core is not hot enough for further fusion, so the core collapses
- The outer layers are ejected forming a planetary nebula
- The remnant core remains intact leaving a hot, dense, solid core called a white dwarf

Worked Example

Describe the evolution of a star much more massive than our Sun from its formation to its eventual death.

Step 1: Underline the command word

- Underline the command word 'describe'
- A **describe** question does **not** need you to **explain why** the processes happen, but you do need to go into detail about what happens in each stage

Step 2: Identify the mass of the star

- The star in the question is more massive than the Sun, therefore it is referring to **high-mass stars**

Step 3: Identify the stage of life cycle being asked about

- This question is about the whole life cycle from formation to death
- The common first five steps are needed, and then the steps which only apply to massive stars

Step 4: Plan the answer

- Use the white space around the question to plan your answer
- List the stages that a massive star goes through, this will help you form your answer in a logical sequence of events
  - Nebula
  - Protostar
  - Nuclear fusion
  - Main sequence
  - Red super giant
  - Supernova
  - Neutron star/black hole

Step 5: Add to the list any important points or key words that need to be included for each stage

- Nebula – gravitational collapse
- Protostar – heats up and glows
- Nuclear fusion – H to He generates energy
- Main sequence – stable, forces balanced
- Red supergiant – expands and cools
- Supernova – core collapses
- Neutron star/black hole – remnants

Step 6: Begin writing the answer using words from the question stem to begin

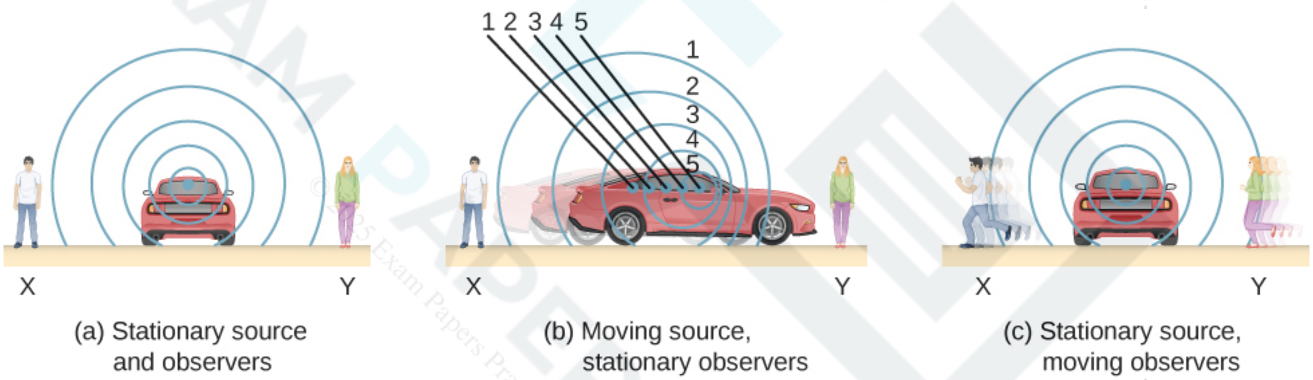
- A star more massive than our Sun will form from...

Step 7: Use the plan to keep the answer concise and logically sequenced

- A star more massive than our Sun will form from clouds of gas and dust called a nebula
- The gravitational collapse of matter increases the temperature of the cloud causing it to glow - this is a protostar
- Nuclear fusion of hydrogen nuclei to helium nuclei generates massive amounts of energy
- The outward radiation pressure and gas pressure balances the inward gravitational pressure and the star become stable entering the main sequence stage
- When the hydrogen runs out, the outer layers of the star expand and cool forming a red super giant
- Eventually, the core collapses and the star explodes in a supernova
- The remnant core either remains intact forming a neutron star, or the core collapses further resulting in a black hole

Doppler Shift

- If a wave source is stationary, the wavefronts spread out **symmetrically**
- If the wave source is moving, the waves can become **squashed** together or **stretched** out
  - If the wave source is moving **towards** an observer the wavefronts will appear **squashed**
  - If the wavefront is moving **away** from an observer the wavefronts will appear **stretched** out
- Therefore, when a wave source moves relative to an observer there will be a change in the observed **frequency** and **wavelength**

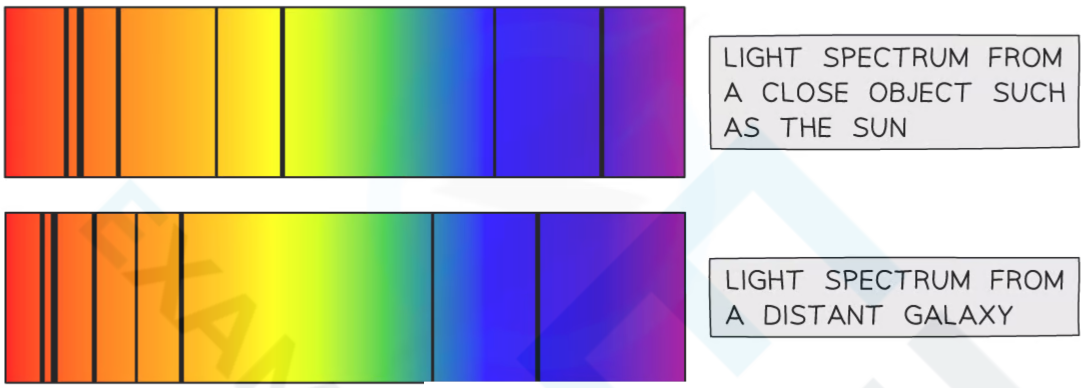


Wavefronts are even in a stationary object but are squashed in the direction of the moving wave source

- A moving object will cause the **wavelength**, λ, (and frequency) of the waves to change:
  - The **wavelength** of the waves **in front** of the source **decreases** (λ – Δλ) and the **frequency increases**
  - The wavelength **behind** the source **increases** (λ + Δλ) and the **frequency decreases**
- Note: Δλ means '**change in wavelength**'
  - The actual wavelength emitted by the source remains the same
  - It is only the wavelength that is received by the observer that appears to have changed
- This effect is known as the **Doppler effect** or **Doppler shift**
- The Doppler effect is defined as:

the apparent shift in wavelength occurring when the source of the waves is moving

- The Doppler effect, or Doppler shift, can be observed using any form of **electromagnetic radiation**
- It can be observed by comparing the light spectrum produced from a close object, such as our Sun, with that of a distant galaxy
  - The light from the distant galaxy is shifted towards the red end of the spectrum (There are more spectral lines in the red end)
  - This provides evidence that the universe is expanding



Comparing the light spectrum produced from the Sun and a distant galaxy

Redshift Equation

- Recall the Doppler effect is defined as:

    The apparent change in wavelength or frequency of the radiation from a source due to its relative motion away from or toward the observer

    - On Earth, the Doppler effect is most easily observed when something which is both fast moving and emitting a loud sound (such as an ambulance or fast car) moves past an observer, producing a characteristic change in the pitch of the sound that is heard
- In space, the Doppler effect of light can be observed when spectra of distant stars and galaxies are observed, this is known as:
    - **Redshift** if the object is moving away from the Earth, or
    - **Blueshift** if the object is moving towards the Earth
- Redshift is defined as:

    The fractional increase in wavelength (or decrease in frequency) due to the source and observer receding from each other

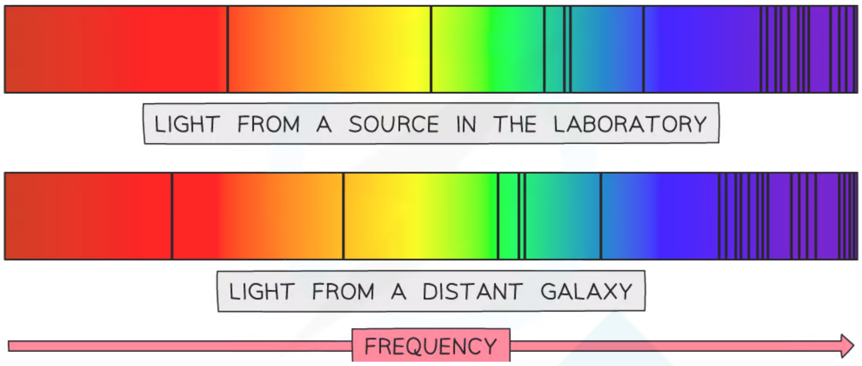
- For non-relativistic galaxies, Doppler redshift can be calculated using:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta f}{f} = \frac{v}{c}$$

- Where:
    - $\Delta\lambda$ = shift in wavelength (m)
    - λ = wavelength emitted from the source (m)
    - Δf = shift in frequency (Hz)
    - f = frequency emitted from the source (Hz)
    - v = speed of recession (m s^{-1})
    - c = speed of light in a vacuum (m s^{-1})

Worked Example

The spectra below show dark absorption lines against a continuous visible spectrum.



A particle line in the spectrum of light from a source in the laboratory has a frequency of 4.570×10^{14} Hz.

The same line in the spectrum of light from a distant galaxy has a frequency of 4.547×10^{14} Hz.

a) What speed is the distance galaxy moving in relation to the Earth?

b) Is it moving towards or away from the Earth?

Part (a)

Step 1: Write down the known quantities

- Emitted frequency, $f = 4.570 \times 10^{14}$ Hz
- Shift in frequency, $\Delta f = (4.547 - 4.570) \times 10^{14} = -2.3 \times 10^{12}$ Hz
- Speed of light, $c = 3.0 \times 10^{8}$ m s^{-1}

Step 2: Write down the Doppler redshift equation

$$\frac{\Delta f}{f} = \frac{v}{c}$$

Step 3: Rearrange for speed v, and calculate

$$v = \frac{c\Delta f}{f} = \frac{(3.0 \times 10^{8}) \times (2.3 \times 10^{12})}{4.570 \times 10^{14}} = \mathbf{1.5 \times 10^{6}\ m\ s^{-1}}$$

Part (b)

Step 1: Compare the frequencies and answer the question

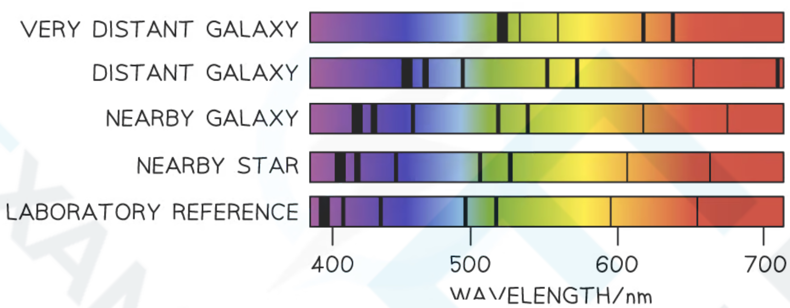
- The observed frequency is **less** than the emitted frequency (the light from a laboratory source),
- The source is **receding** (moving away from) from the Earth

Exam Tip

In your exam, be sure to emphasise that redshift means the wavelength of spectral lines increases towards the red end of the spectrum, **do not** say that the spectral lines become red, as this is incorrect.

The Hubble Equation

- In 1929, the astronomer Edwin Hubble showed that the universe was **expanding**
  - He did this by observing that the absorption line spectra produced from the light of distant galaxies was shifted towards the **red** end of the spectrum
  - This **doppler shift** in the wavelength of the light is evidence that distant galaxies are moving away from the Earth
- Hubble also observed that light from more distant galaxies was **shifted further** towards the red end of the spectrum compared to closer galaxies
  - From this observation he concluded that galaxies or stars which are **further away** from the Earth are **moving faster** than galaxies which are closer



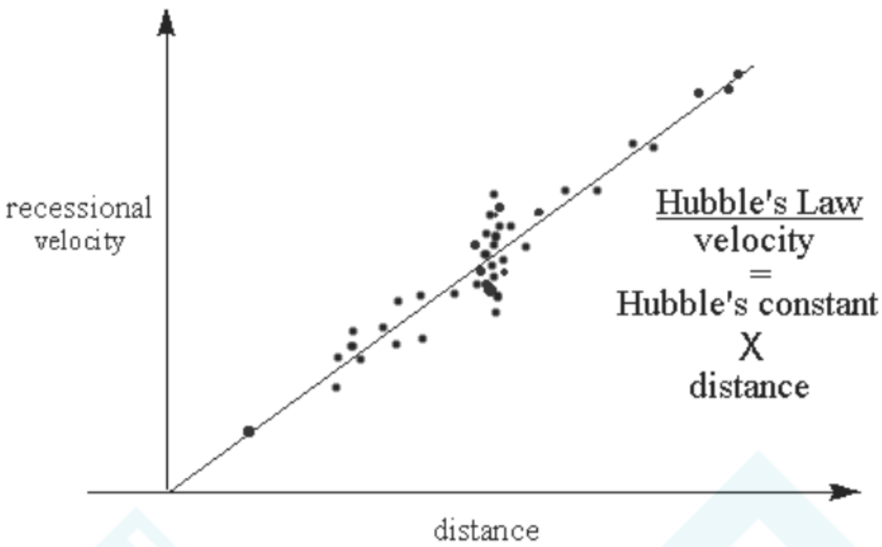
- Hubble's law states:

The recessional velocity, v, of a galaxy is proportional to its distance from Earth

- Hubble's law can be expressed as an equation:

$$v \approx H_0 d$$

- Where:
  - v = recessional velocity of an object, the velocity of an object moving **away** from an observer (km s^{-1})
  - H_0 = Hubble constant, this will be provided in your examination along with the correct units (km s^{-1} Mpc^{-1})
  - d = distance between the object and the Earth (Mpc)
- Alternatively, if the velocity of the receding object was measured in km s^{-1} and the distance from the earth to the object was measured in km, then then unit for the Hubble constant would be s^{-1}
- Hubble's law shows:
  - The further away a star is from the Earth, the faster it is moving away from us



A key aspect of Hubble's law is that the furthest galaxies appear to move away the fastest

Worked Example

A distant galaxy is 20 light-years away from Earth.

Use Hubble's Law to determine the velocity of the galaxy as it moves away from Earth.

The Hubble constant is currently agreed to be 2.2×10^{-18} s^{-1}.

Step 1: List the known quantities:

- d = 20 light years
- $H_o = 2.2 \times 10^{-18}$ s^{-1}

Step 2: Convert 20 light-years to m:

- From the data booklet: 1 ly ≈ 9.5×10^{15} m
- So, 20 ly = 20 x (9.5×10^{15}) = 1.9×10^{17} m

Step 3: Substitute values into Hubble's Law:

- From the data booklet: $\mathbf{v \approx H_0 d}$
- So, v ≈ (2.2×10^{-18}) x (1.9×10^{17}) = 0.418 m s^{-1}

Step 4: Confirm your answer:

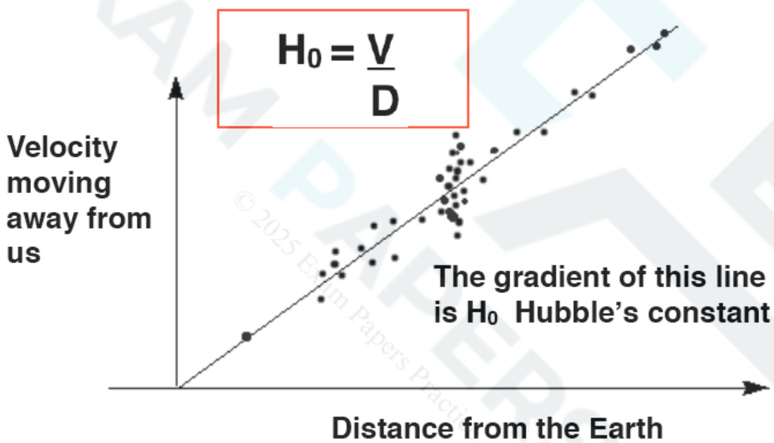
- The velocity of the galaxy as it moves away from Earth 0.42 m s^{-1}

The Hubble Constant

- By rearranging the equation for Hubble's law, we can determine that the Hubble constant, H_0, is:

$$H_0 \approx \frac{v}{d}$$

- Where:
- v = recessional velocity of an object (km s^{-1})
- d = distance between the object and the Earth (Mpc)
- H_0 = Hubble constant (km s^{-1} Mpc^{-1})



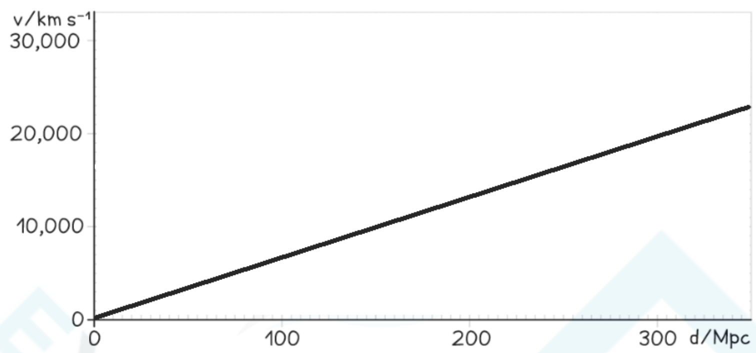
- The value for the Hubble constant has been estimated using data for thousands of galaxies
    - The latest estimate of the Hubble constant based on CMB observations by the Planck satellite is:

H_0 **= 67.4 ± 0.5 km** s^{-1} **Mpc**$^{-1}$ (Planck Collaboration VI 2020)

- It is difficult to be certain about just how accurate the values for the Hubble constant are
    - This is due to the random and systematic errors involved when calculating the distance to a galaxy or star

Worked Example

The graph shows how the recessional velocity, *v*, of galaxies varies with their distance, *d*, measured from the Earth.



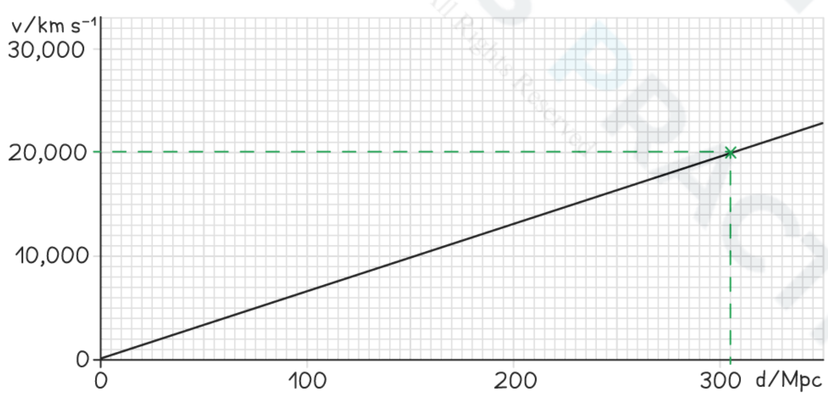
Use the graph to determine a value for the Hubble constant and state the unit for this constant.

Step 1: From the data booklet:

Hubble's Law: $v \approx H_0 d$

Step 2: Determine the Hubble constant, H_0, from the graph:

- y-axis = v = 20, 000
- x-axis = d = 305
- gradient = H_0



Step 3: Calculate the gradient of the graph:

- $H_0 = \frac{y_2 - y_1}{x_2 - x_1} = \frac{20\,000 - 0}{305 - 0} = 66 \text{ km s}^{-1}\text{ Mpc}^{-1}$

Step 4: Confirm your answer:

- The Hubble Constant = 66 km s^{-1} Mpc^{-1}

Dark Matter

- We would expect the **velocity** of an object within a galaxy to **decrease** as it moves away from the galaxy's centre because of weakening gravitational field strength
  - This is observed in smaller mass systems, like the solar system where planets orbiting **furthest** from the Sun have the **slowest orbital velocity**
  - This is not the case in bigger mass systems like entire galaxies
- Mass is not actually concentrated in the centre of galaxies; it is **spread out**
  - All the observable mass of a galaxy is, however, concentrated in its centre, so there must be another type of matter we can't see, called **Dark Matter**
- Dark matter is defined as:

Matter which cannot be seen and that does not emit or absorb electromagnetic radiation

- Dark matter cannot be detected directly through telescopes
  - It should make up 27% of the mass in the universe
  - It is detected based on its gravitational effects relating to either the rotation of galaxies or by the gravitational lensing of starlight