OCR A Level Physics

Your notes

Stellar Evolution

Contents

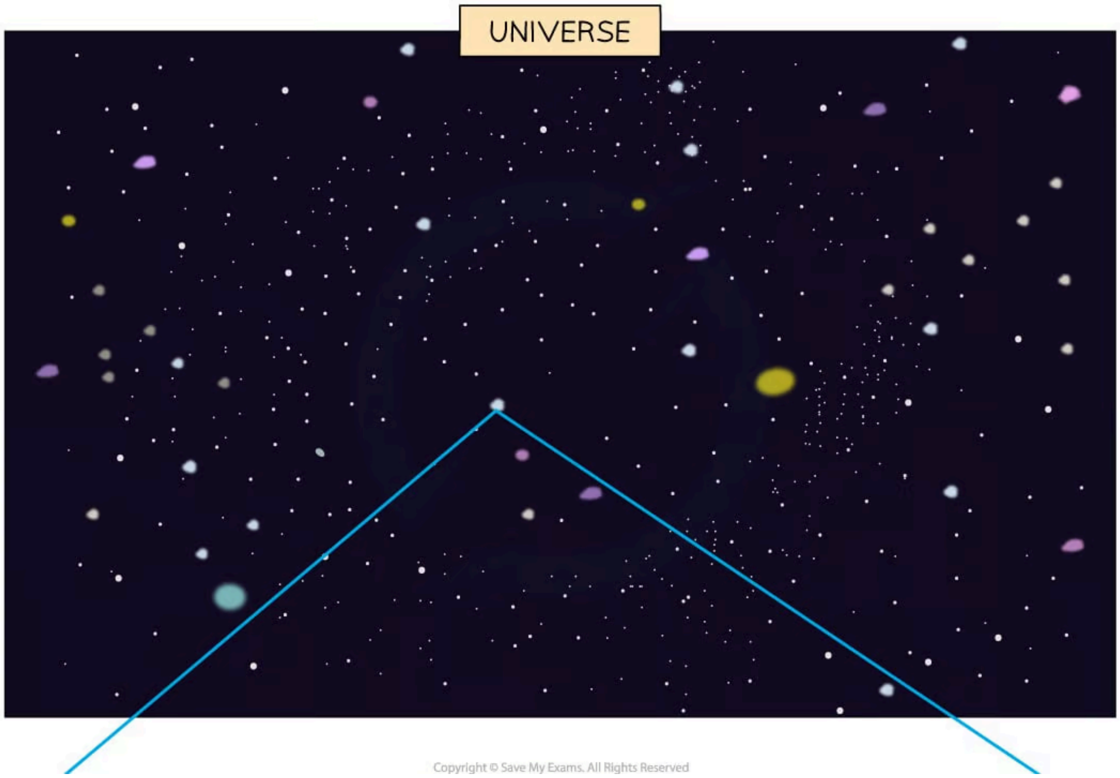
Definitions of Astronomical Objects

Your notes

Definitions of Astronomical Objects

- Everything that exists is contained within the **universe**, including:
  - Galaxies
  - Stars
  - Solar systems
  - Planets
  - Planetary satellites
  - Comets
  - Plus many more structures
- The **universe** is a large collection of billions of galaxies
  - It is the largest known structure
- The **observable universe** is the portion of the universe from which electromagnetic radiation has had time to reach Earth since the formation of the universe
  - The universe is expanding

Your notes




MILKY WAY GALAXY
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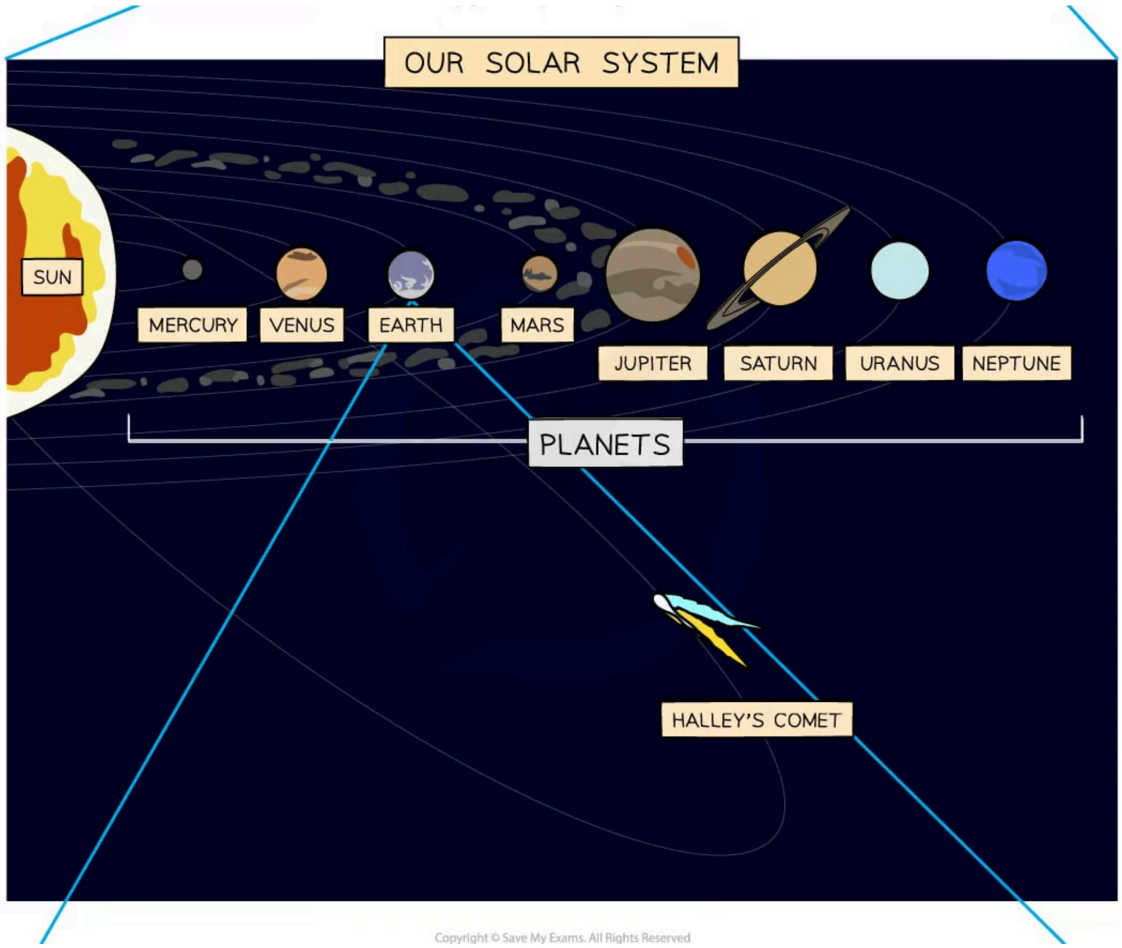
OUR SOLAR SYSTEM
SUN
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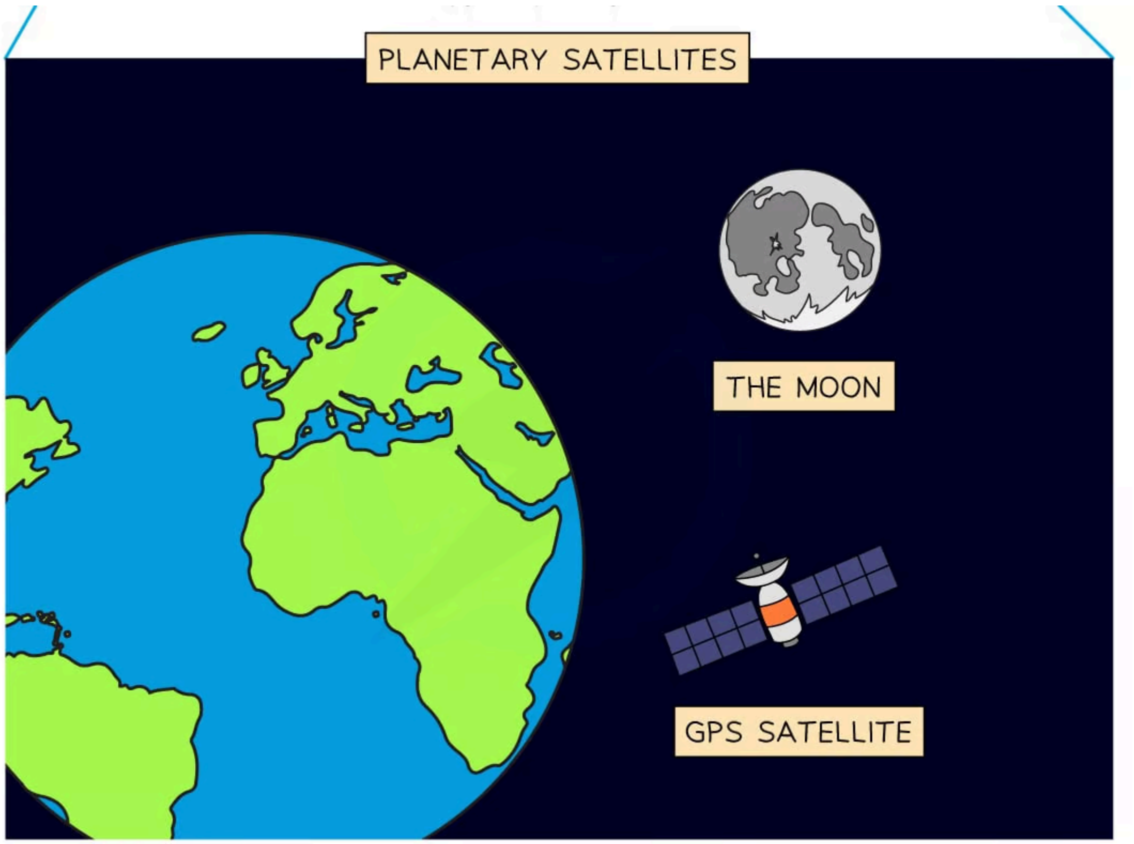


Hierarchy of the Universe

- A **galaxy** is a cluster of billions of stars held together by gravity
  - Earth and the Solar System are located in a spiral galaxy called the Milky Way
  - The Sun takes ~230 million years to complete one revolution of the galaxy
  - Galaxies are moving away from one another; the further apart they are, the faster apart they move
- **Stars** fuse hydrogen into helium by nuclear fusion, releasing vast amounts of energy as electromagnetic radiation
  - Stars are formed from gas and dust pulled together under the force of gravity
  - The Sun is the star closest to Earth
  - The Sun is an average-sized **small-mass star** with a total mass of 2×10^{30} kg
- **Solar systems** consist of a star and the gravitationally bound objects that orbit it

Your notes

- Earth is the third of eight planets orbiting the Sun
- The Earth takes 365.25 days to orbit the Sun
- Planetary satellites, comets and asteroids, as well as planets, orbit the Sun

- **Planetary satellites** are bodies that orbit a planet
  - The Moon is a planetary satellite of Earth
  - The Moon takes 27.3 days to orbit the Earth which is the exact time it takes to revolve once on its own axis
  - Artificial satellites, such as GPS and communication satellites, orbiting Earth are planetary satellites

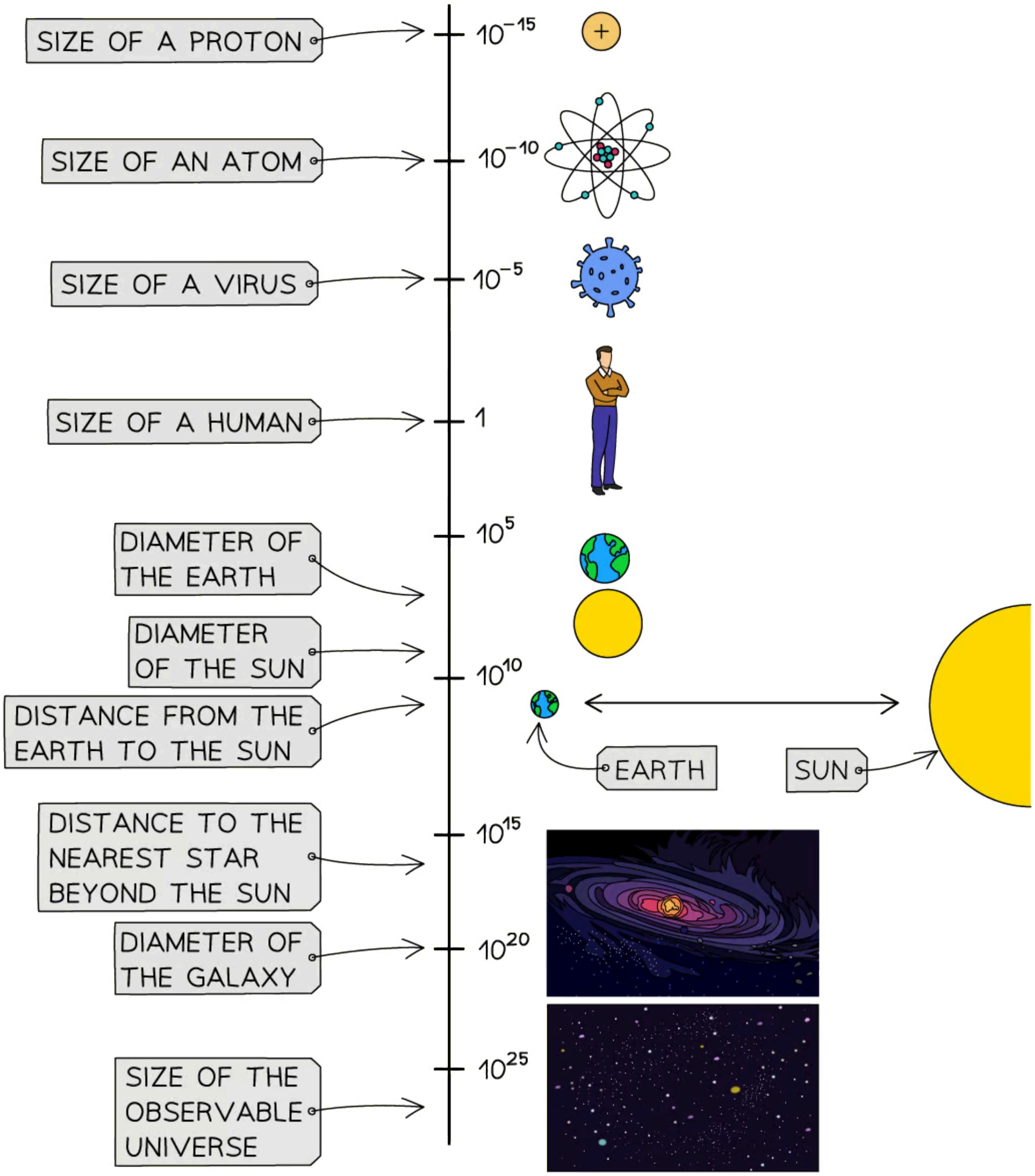
Object	Distance/km	Distance/m	Distance/ light years
Diameter of Earth	6450	6.45×10^6	0.00000000068
Distance from Earth to the Moon	250 000	2.5×10^8	0.000000026
Distance from Earth to the Sun	150 000 000	1.5×10^{11}	0.000016
Distance from the Sun to the nearest star, Alpha Centauri	40 000 000 000 000	4×10^{16}	4.24
Diameter of the Milky Way galaxy	950 000 000 000 000 000	9.5×10^{20}	100 000
Thickness of the Milky Way galaxy	9 500 000 000 000 000	9.5×10^{18}	1000
Distance from the Sun to the nearest galaxy, Canis Major Dwarf Galaxy	2 400 000 000 000 000 000	2.4×10^{21}	250 000
Diameter of the observable universe	880 000 000 000 000 000 000 000	8.8×10^{26}	93 000 000 000

- **Comets** are made from ice and rock, and travel in elliptical orbits around the Sun
  - Comets originate from the Oort Cloud
  - Halley's Comet completes one revolution every 76 years

Scale of the Universe

- Evidence suggests that the universe was created **13.8 billion years ago** and that the observable universe spans a diameter of 93 billion light years
  - One light-year is the distance light travels in one Earth year
  - 1 light year = 9.5×10^{15} m

- Speed of light in a vacuum, $c = 3.00 \times 10^{8}$ m s^{-1}



Your notes

Examiner Tips and Tricks

Your notes

You will be given the values of a light year, and the speed of light in your data booklet, so you do not have to learn them. Although it is handy if you do!

Your notes

Star Formation

Star Formation

- The life cycle of stars goes 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 **between** 0.5 and 10 times the mass of the Sun (0.5 M_{Sun} – 10 M_{Sun})
  - **High mass**: stars with a mass **more** than about 10 times the mass of the Sun (> 10 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

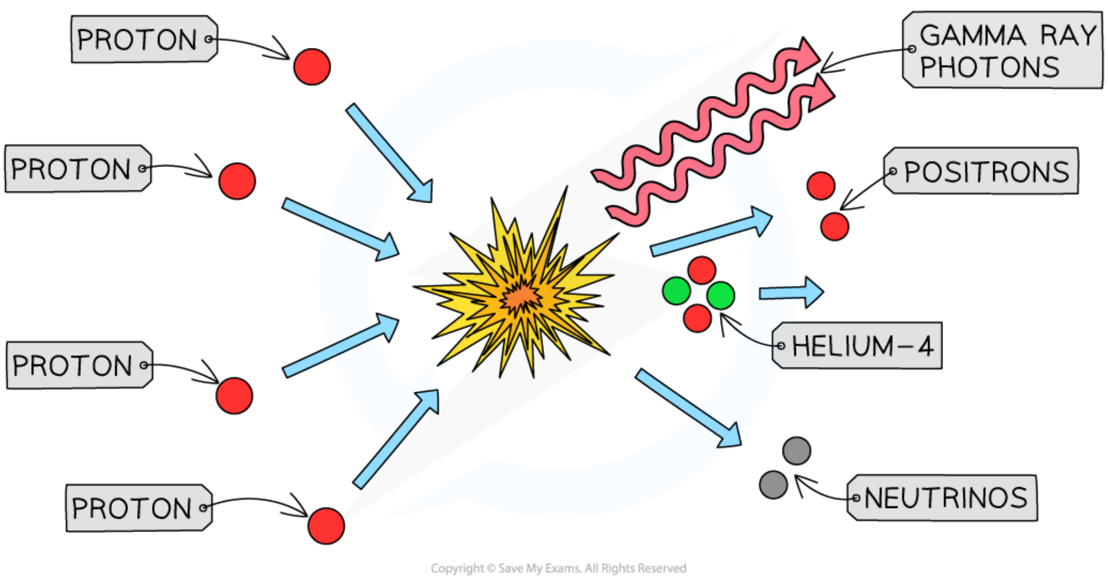
- The gravitational collapse causes the gas to heat up and glow, forming a **protostar**
  - Work done on the particles of gas and dust by collisions between the particles causes an increase in their kinetic energy, resulting in an increase in **temperature**
  - Protostars can be detected by telescopes 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
- Four hydrogen nuclei (protons) are fused into one helium nucleus, producing two gamma-ray photons, two neutrinos and two positrons

Your notes

- Massive amounts of energy are released
- The momentum of the gamma-ray photons results in an outward acting pressure called radiation pressure

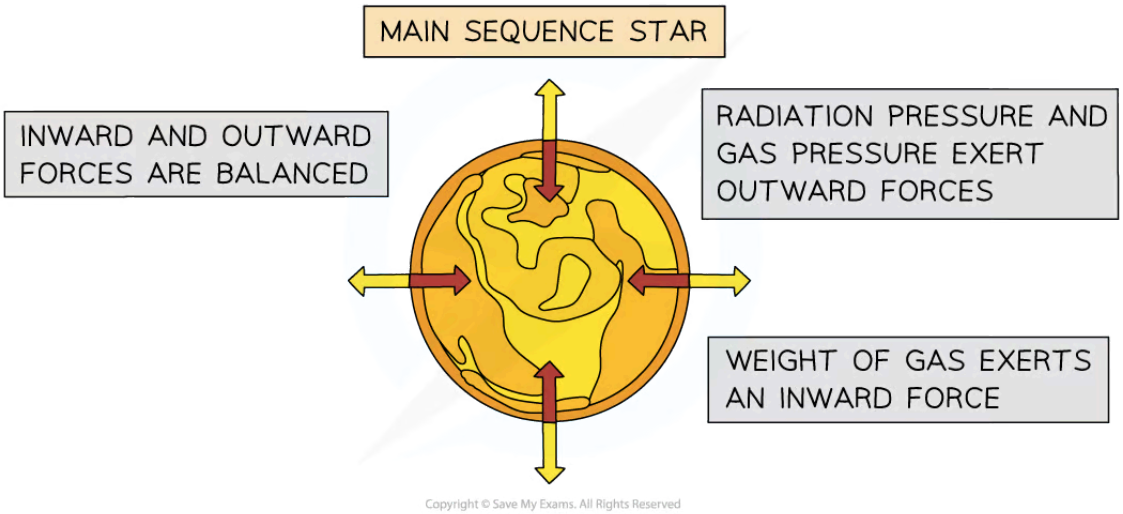


Nuclear fusion of hydrogen nuclei to form helium nuclei

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
    - The gas pressure and the radiation pressure act **outwards** to balance the gravitational force (weight, $F = mg$) acting **inwards**

Your notes



Forces acting within a star. The centre red circle represents the star's core and the orange circle represents the stars outer layers

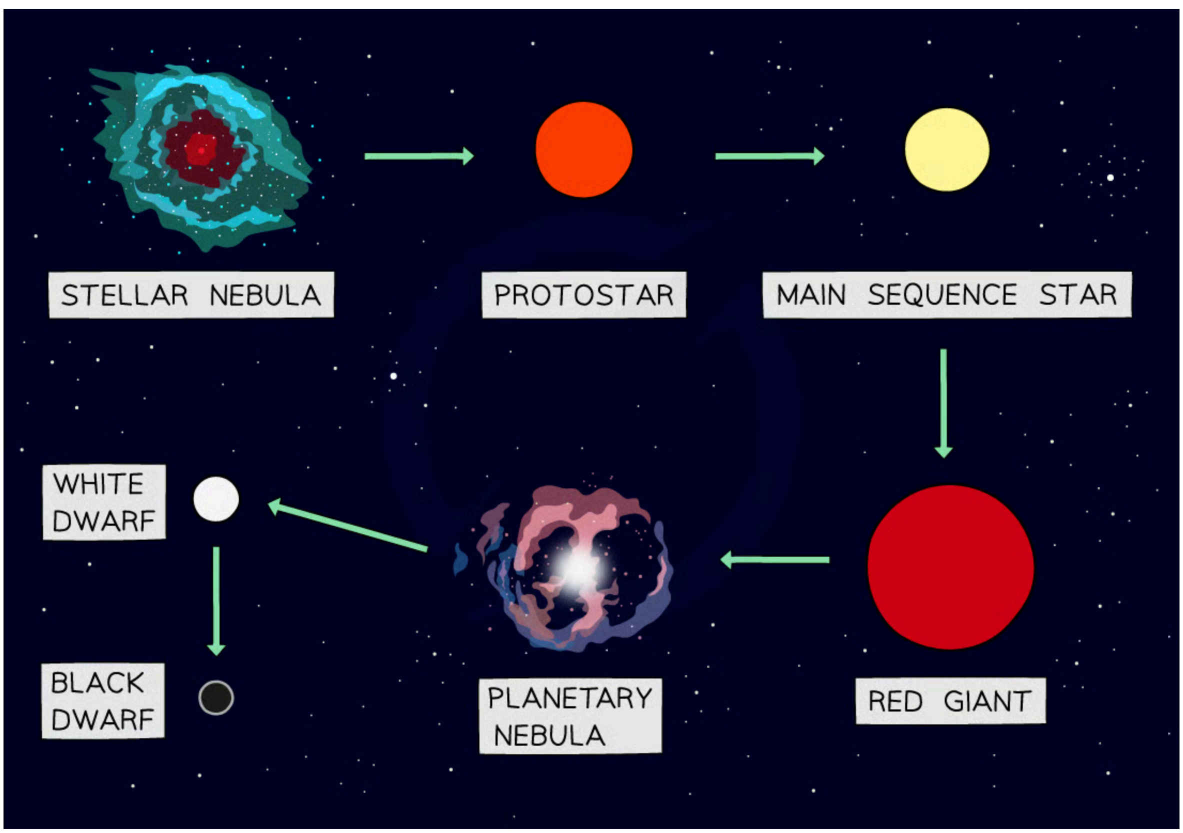
- If the **temperature** of a star **increases**, the **outward pressure** will also **increase**
  - This will cause the star to **expand**
- If the **temperature drops** the **outward pressure** will also **decrease**
  - This will cause the star to **contract**
- As long as these two forces balance, the star will remain **stable**
- A star will spend most of its life on the **main sequence**
  - 90% of stars are currently 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

Your notes

Evolution of a Low-Mass Star

Evolution of a Low Mass Star

- Once the internal forces within a star become **unbalanced**, then they will no longer be in equilibrium causing the star to **expand** or **contract**
  - This happens when **fusion** in the core of stars stops, and hence thermal expansion **ceases** at the end of the star's life
- The fate of a star beyond the main sequence depends on its **mass**
  - A star is classed as a **low-mass star** if it has a mass between 0.5 and 10 times the mass of the Sun ($0.5\ M_{Sun} – 10\ M_{Sun}$)
  - A low-mass star will become a **red giant** before turning into a **white dwarf**



The lifecycle of a low-mass star

1. Red Giant

Your notes

- The hydrogen fuelling the star begins to run out, nuclear fusion stops, the star shrinks and then swells and cools to form a **red giant**
  - Most of the hydrogen nuclei in the core of the star have been fused into helium and so **nuclear fusion slows** and the energy released by fusion decreases
  - The radiation pressure caused by the fusion reaction also **decreases**, so the inward gravitational force becomes greater than the outward force from the gas pressure and radiation pressure
  - The **core collapses**, leading to an increase in temperature as it compresses under the weight of the star
  - **Fusion** in the core **stops**
  - The outer layers of the star **expand** and then **cool** forming a **red giant**
- Fusion continues in the **shell** around the core
  - There are still hydrogen nuclei in the areas **outside** of the core
  - The heat generated by the collapsing core provides temperatures high enough for this hydrogen to fuse in a process called **shell hydrogen burning**
  - Contraction of the core continues, providing temperatures high enough to fuse helium into **carbon** and **oxygen** in a process called **core helium burning**

2. Planetary Nebula

- The **outer layers** of the star are **released**
  - Helium burning in the core releases massive amounts of energy in the fusion reactions
  - The outward **radiation pressure** increases balancing the inward and outward forces
  - When the helium in the core runs out, the core contracts again producing temperatures high enough to fuse the helium in the areas **outside** the core in a process called **helium shell burning**
  - The carbon-oxygen core is not hot enough to fuse the heavy elements, the star becomes **unstable** and begins to **collapse** again
  - The outer layers of gas are **ejected** back into space forming a **planetary nebula**

3. White Dwarf

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

- No further fusion reactions take place
- White dwarfs continue to radiate energy in the form of **photons** that were produced in **previous fusion** reactions
- Eventually, the white dwarf will cool to a few degrees Kelvin and will no longer emit any significant heat or light (black dwarf)

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.

Answer:

Step 1: Underline the command words 'describe' and 'explain'

- **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: Understand what the question is asking for

- The stars in the question are less massive than the Sun, therefore it is referring to **low-mass stars**
- The question asks for the **next** stage of evolution after **becoming** a red giant, so assume that it requires an explanation of the processes **during** the red giant phase

Step 3: 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 keywords 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 a remnant core

Step 4: Begin writing the answer using words from the question stem

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

Step 5: Use the plan to keep the answer concise and logically sequenced

- Low mass stars will leave the main sequence and become red giants when the hydrogen in the core runs out
- There is a reduction in the energy released by fusion, so the radiation pressure decreases
- The 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

Examiner Tips and Tricks

If an exam question asks you to **describe** the evolution of a low-mass star, refer to the main steps in the process.

For example:

- Hydrogen runs out and nuclear fusion stops
- The star shrinks and swells into a red giant
- Fusion continues in the shell around the core
- The outer layers are released and the core collapses into a white dwarf

But if the question asks to you explain, you must also include details of **why** those events take place

Always read the question carefully and take a moment to plan your answer!

Your notes

Your notes

White Dwarfs & the Chandrasekhar Limit

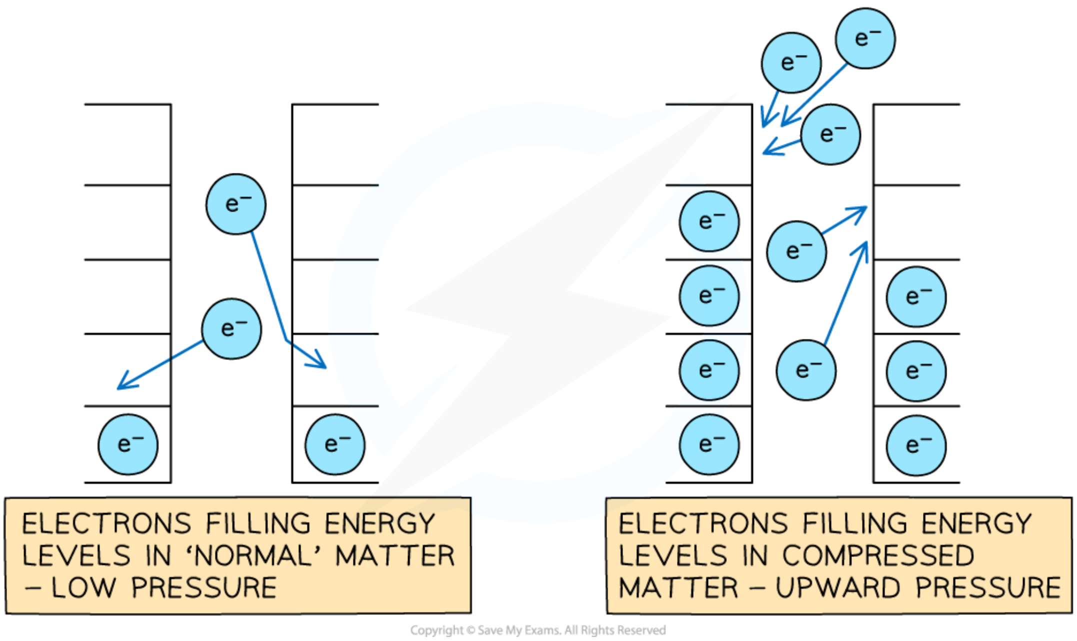
White Dwarf's & the Chandrasekhar Limit

- A white dwarf is the remnant of a low mass star
- At the end of the star's life, the outer layers of the star have been ejected, leaving a core which is:
  - Very hot
  - Dense
  - Solid
- Nuclear fusion no longer takes place and the heavier elements (usually carbon and oxygen) remain
  - Instead, it radiates energy in the form of photons from previous fusion reactions

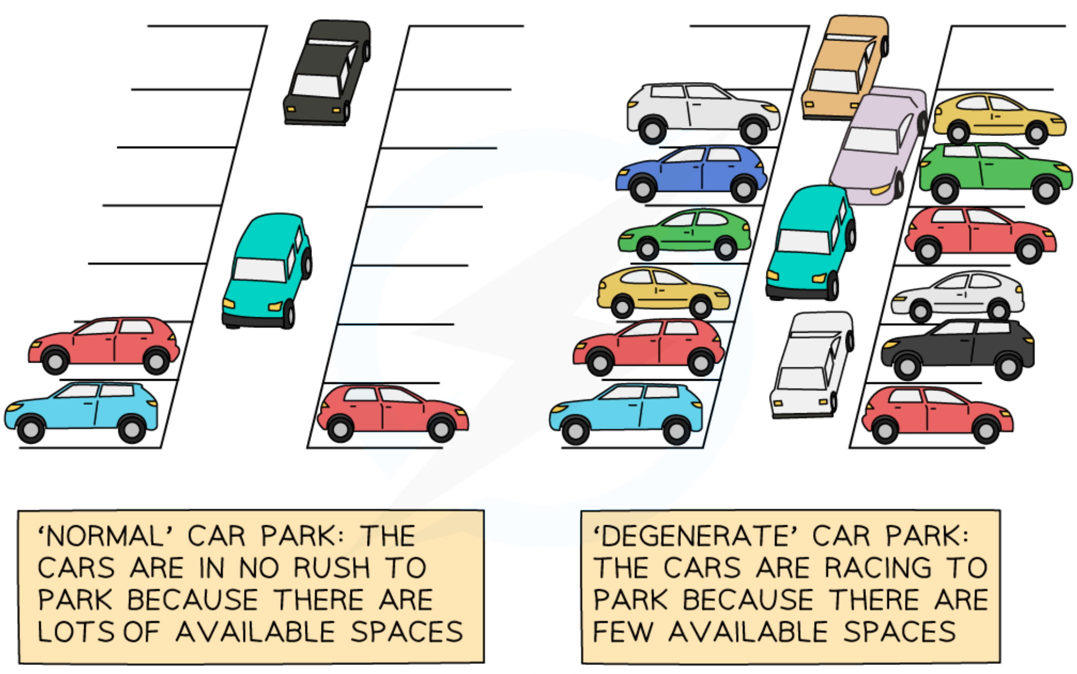
Electron Degeneracy Pressure

- Matter is **compressed** into a very **small volume** when the core of a star collapses
- The electrons in the atoms are no longer free to move between energy levels
- Electrons are forced to fill the available energy levels
  - Electrons fill the lowest available energy levels first
  - Usually, only excited electrons will fill the higher energy levels
  - Compression of the matter in a collapsing core forces electrons into higher energy levels, not because they are in a higher energy state, but because there is nowhere else to go
  - This rush of electrons to find an available space creates a pressure called **electron degeneracy pressure**, resulting in an outward acting force

Your notes



- For a **low-mass star**, the outward electron degeneracy pressure **balances** the inward gravitational force, preventing further collapse and resulting in a **stable** white dwarf star



Car Park Analogy for Electron Degeneracy Pressure

Your notes

The Chandrasekhar Limit

- The **Chandrasekhar limit** is the maximum mass of a stable white dwarf star
- This is when the mass of a core is up to 1.4 times the mass of the Sun

The Chandrasekhar limit of a white dwarf is 1.4 M_{Sun}

- If a white dwarf **exceeds** the Chandrasekhar limit:
  - Electron degeneracy pressure no longer can prevent the collapse of the core
  - Protons and electrons combine to become neutrons - this is how a **neutron star** forms
- A **low-mass** star will:
  - Become a **red giant** and then a **white dwarf**
  - If the core's mass is **less than 1.4 M_{Sun}**
- A **high-mass** star will:
  - Become a **red supergiant** and then a **neutron star** or a **black hole**
  - If the core's mass is **greater than 1.4 M_{Sun}**

Worked Example

Once fusion has been exhausted in some red giant stars, it will begin to expel its outer layers until a white dwarf remains.

Which of the following could be the mass of a white dwarf?

You may take the mass of the Sun to be 2.0 × 10^{30} kg.

A. 2.5 × 10^{30} kg

B. 3.0 × 10^{30} kg

C. 2.0 × 10^{31} kg

D. 2.8 × 10^{31} kg

Answer: A

Step 1: List the known quantities

- Solar mass = 2.0×10^{30} kg

Step 2: Calculate the mass of a white dwarf at the Chandrasekhar limit

- The Chandrasekar Limit is 1.4 solar masses
- Multiply the solar mass by the Chandrasekhar limit

$$1.4 \times (2.0 \times 10^{30} \text{ kg}) = 2.8 \times 10^{30} \text{ kg}$$

Step 3: Identify the mass given in the question that is below 2.8×10^{30} kg

- Masses below 2.8×10^{30} kg will form stable white dwarf stars
- Masses above 2.8×10^{30} kg will not form stable white dwarf stars
- Therefore, the only mass that fits this criterion is 2.5×10^{30} kg

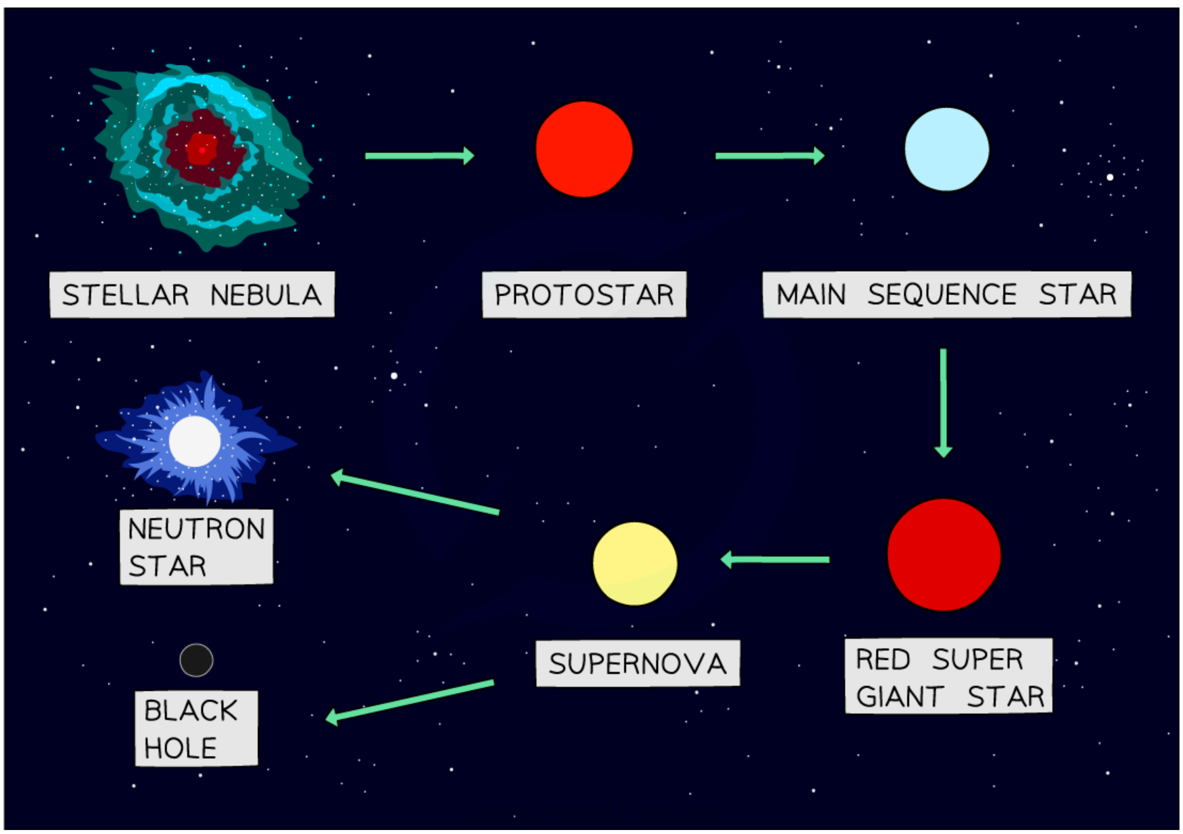
Your notes

Your notes

Evolution of a Massive Star

Evolution of a Massive Star

- The fate of a star beyond the main sequence depends on its **mass**
  - A star is classed as a **high-mass star** if it has a mass more than 10 times the mass of the Sun (> 10 M_{Sun})
  - **Massive stars** become **red supergiants** and then either a **neutron star** or a **black hole**
- Massive stars have more fuel, but they use it up faster, so they spend **less time** on the main sequence



Lifecycle of massive stars

1. Red Supergiant

- The star follows the same process as the formation of a red giant
  - Hydrogen in the core runs out

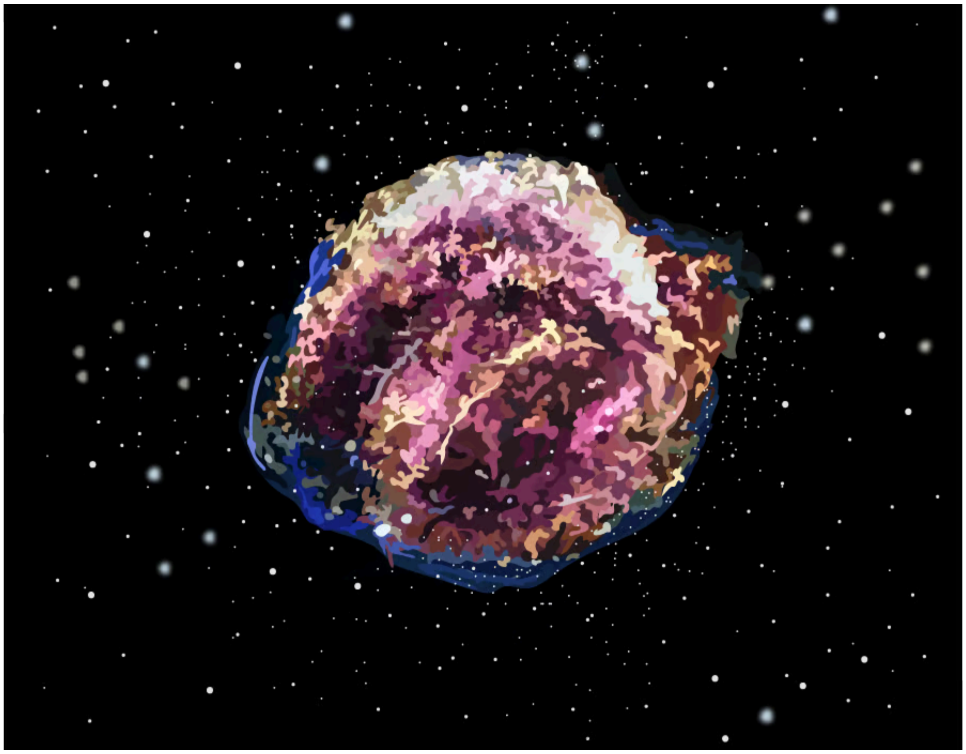
Your notes

- Nuclear fusion slows
- Radiation pressure decreases so the inward and outward acting forces are no longer in equilibrium
- The core collapses
- Fusion in the core stops and the outer layers expand and cool

- The **shell burning** and **core burning** cycle in massive stars goes beyond that of low-mass stars, fusing elements up to **iron**
  - There is still fuel in areas outside the core
  - Temperatures generated by the collapsing core are high enough to fuse nuclei in the shell (shell burning)
  - Contraction of the core generates temperatures high enough to fuse heavier elements in the core (core burning)
  - This cycle continues, fusing heavier and heavier elements at successively higher temperatures and pressures
  - In each stable fusion phase, electron degeneracy pressure and **radiation pressure** balance the gravitational force and prevent the core from collapsing
  - Eventually, an **iron core** is formed
- The Chandrasekhar limit determines if the core is stable enough to remain as a white dwarf
  - If the mass of the core is **less than** 1.4 times the mass of the sun, then it will remain as a white dwarf
  - If the mass of the core is **greater than** 1.4 times the mass of the sun, then the **electron degeneracy pressure** is not enough to prevent the core from collapsing

2. Supernova

- Once the iron core forms, it becomes unstable and begins to collapse as no more fusion reactions can occur
  - The gravitational potential energy transferred in the collapse produces intense heating
  - Gravitational pressure forces **protons** and **electrons** in the iron atoms to combine to form **neutrons**, releasing huge amounts of **energy**
- The outer shell is blown out in an explosive **supernova**
  - The outer layers fall inwards and rebound off the core causing shockwaves
  - The shockwaves cause the star to explode in a supernova
  - The supernova generates temperatures great enough to fuse **heavy nuclei** with **neutrons** to form all the known elements beyond iron



A Type II supernova: a bright and powerful explosion which happens at the end of a high-mass star's life. A shockwave ejects the materials in the outer shells of the star into space, and the core collapses

3. Neutron Stars & Black Holes

- After the supernova explosion, the collapsed **neutron core** can remain intact
  - This is known as a **neutron star**
- If the neutron core mass is greater than 3 times the solar mass (3 M_{Sun}), the pressure on the core becomes so great that the core collapses even further
- In this case, the gravitational forces are so strong that the **escape velocity** of the core is greater than the **speed of light**, hence, photons are unable to escape
  - This is known as a **black hole**

Worked Example

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

Answer:

Step 1: Underline the command words 'describe' and 'explain'

- 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: 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 3: 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 super giant – expands and cools
- Supernova – core collapses
- Neutron star/black hole – remnant

Step 4: Begin writing the answer using words from the question stem to begin

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

Step 5: 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 balance the inward gravitational pressure and the star becomes stable entering the main sequence stage
- When the hydrogen runs out, the outer layers of the star expand and cool forming a red supergiant
- Eventually, the core collapses and the star explodes in a supernova

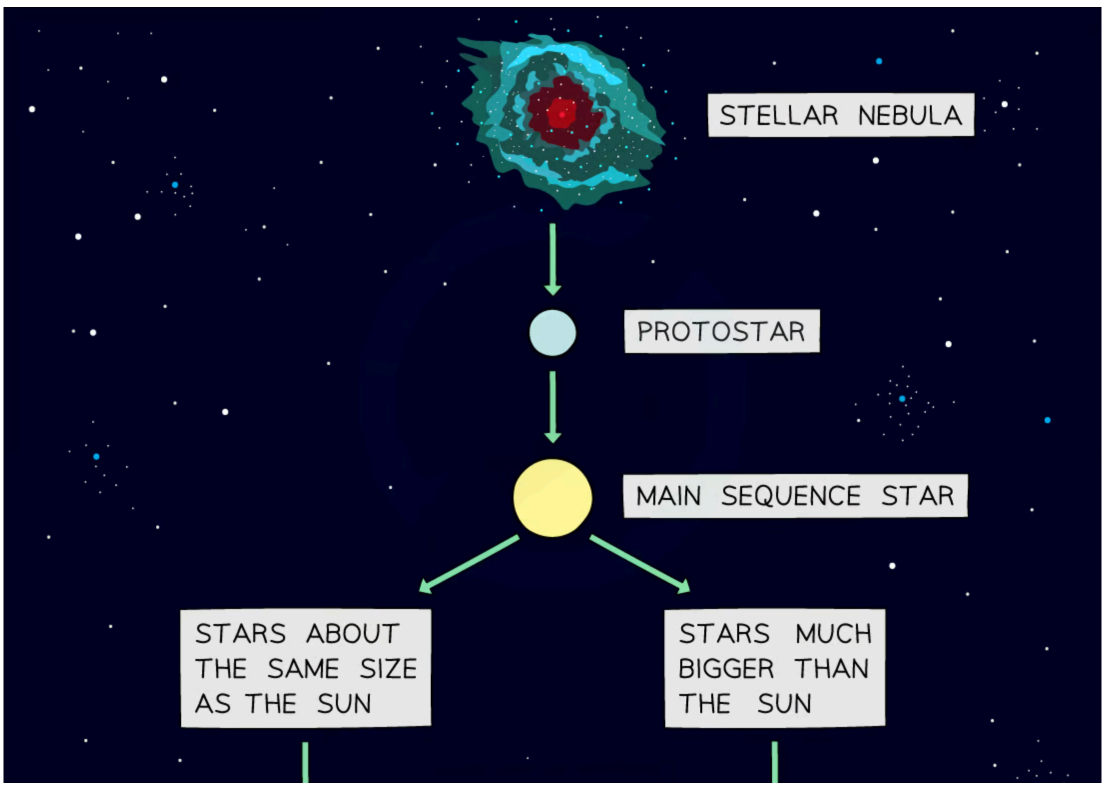
Your notes

- The remnant core either remains intact forming a neutron star, or the core collapses further resulting in a black hole

Your notes

Examiner Tips and Tricks

When revising the life cycles of stars, it's useful to draw a flow diagram showing the life cycles of low-mass and high-mass stars together to ensure you are comfortable with the stages which both go through and which stages differ



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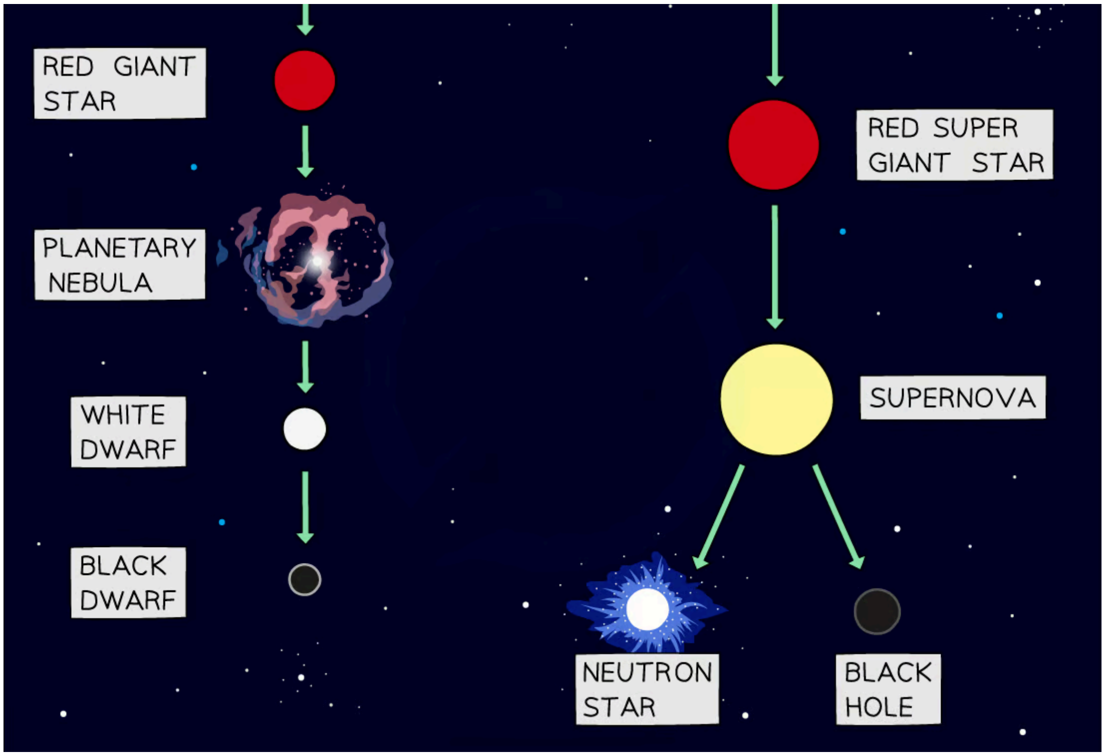

RED GIANT STAR
PLANETARY NEBULA
WHITE DWARF
BLACK DWARF
RED SUPER GIANT STAR
SUPERNOVA
NEUTRON STAR
BLACK HOLE

Neutron Stars & Black Holes

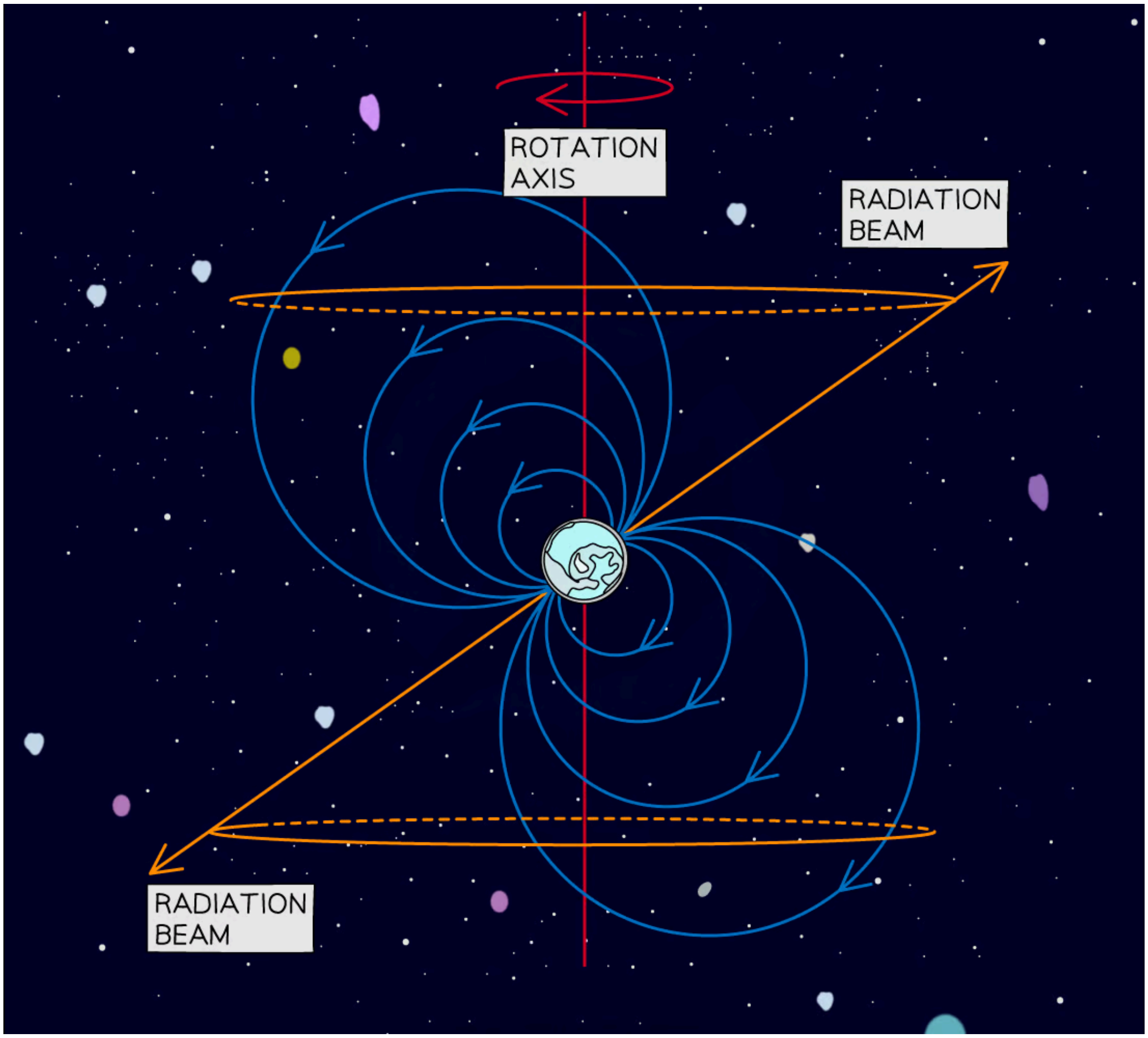
Your notes

Neutron Stars & Black Holes

- In the final evolutionary stages of a massive star's life cycle, the remnant left after a supernova explosion will either be:
  - A neutron star
  - A black hole

Characteristics of a Neutron Star

- Neutron stars are objects formed in stars with cores which have masses greater than the Chandrasekhar limit
- Neutron stars are:
  - Extremely **dense**
  - Very **small**
- To put into perspective how dense and small a neutron star is:
  - The density of a **neutron star** is 4×10^{17} kg m^{-3}
  - The density of the **Earth** is 5×10^{3} kg m^{-3}
  - The density of a **white dwarf** is 1×10^{9} kg m^{-3}
  - A neutron star with the mass of the Sun would be only 30 km in diameter
- Some neutron stars **rotate rapidly** (up to 600 times per second) emitting bursts of highly directional electromagnetic radiation
  - These stars are called **pulsars**



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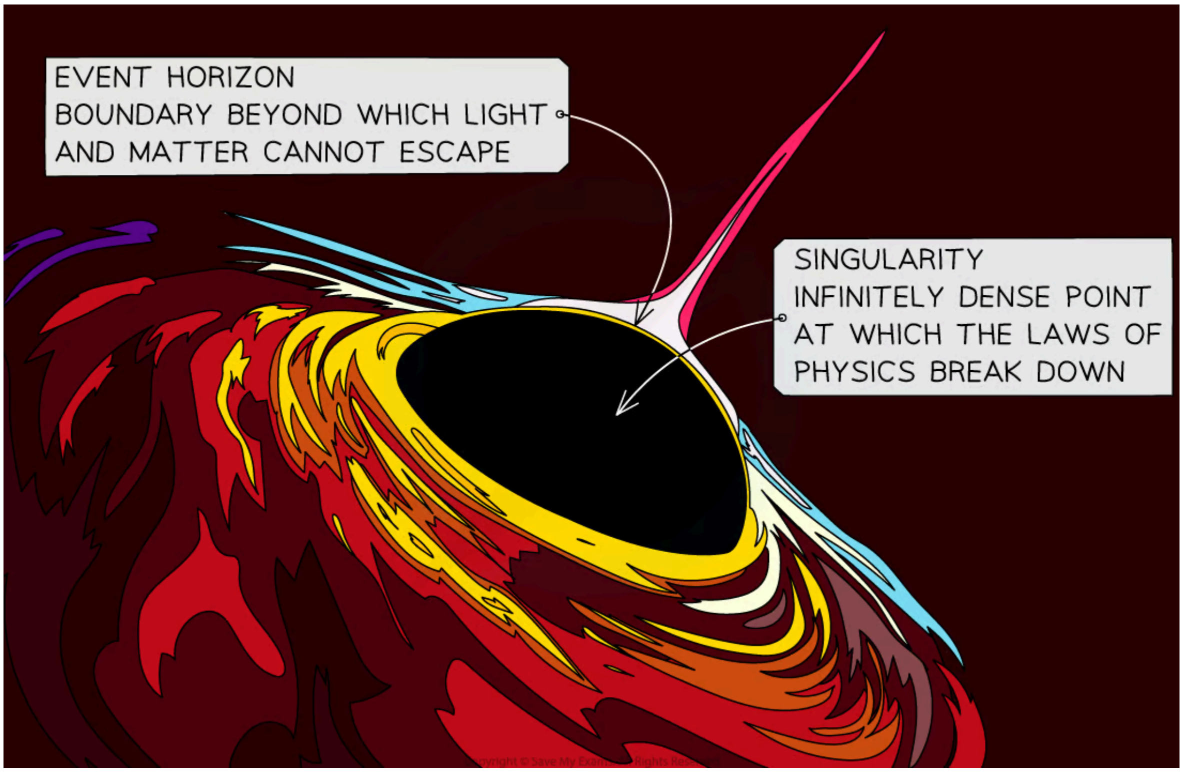
Characteristics of Black Holes

- The core collapses into an infinitely dense point called a **singularity**
- A singularity is defined as:

  A theoretical point at which matter is compressed to an infinitely small point and the laws of physics, as they are currently understood, break down

- The **gravitational field** is so strong that nothing, not even light, can escape it
  - This region is known as a **black hole**

- The boundary at which light and matter cannot escape the gravitation pull of the black hole is called the **event horizon**
- The escape velocity beyond the event horizon is greater than the speed of light, hence photons cannot escape from a black hole



Characteristics of a Black Hole

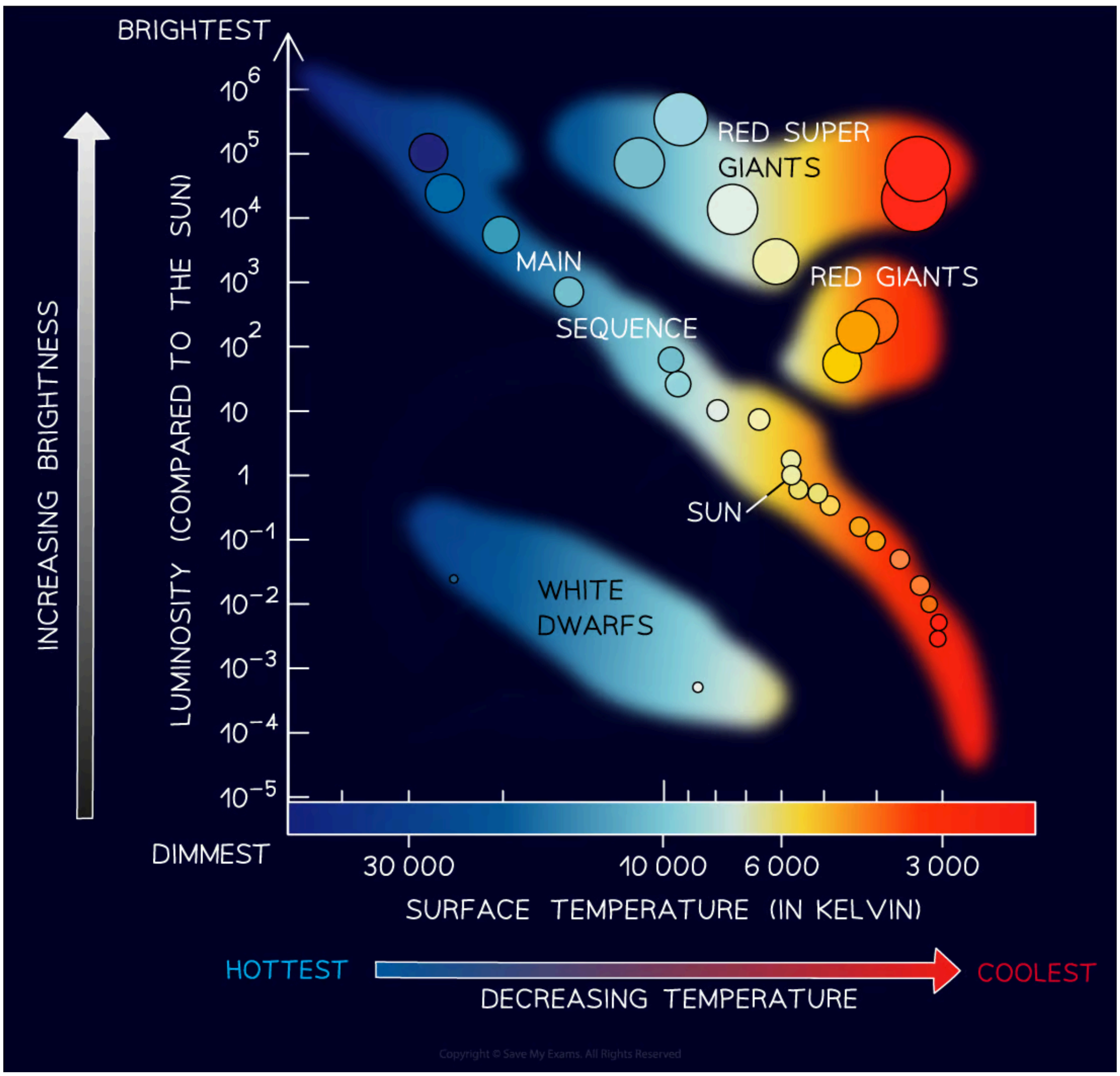
Your notes

Your notes

The Hertzsprung – Russell (HR) Diagram

The Hertzsprung – Russell (HR) 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 depicts the luminosity of stars against their temperature

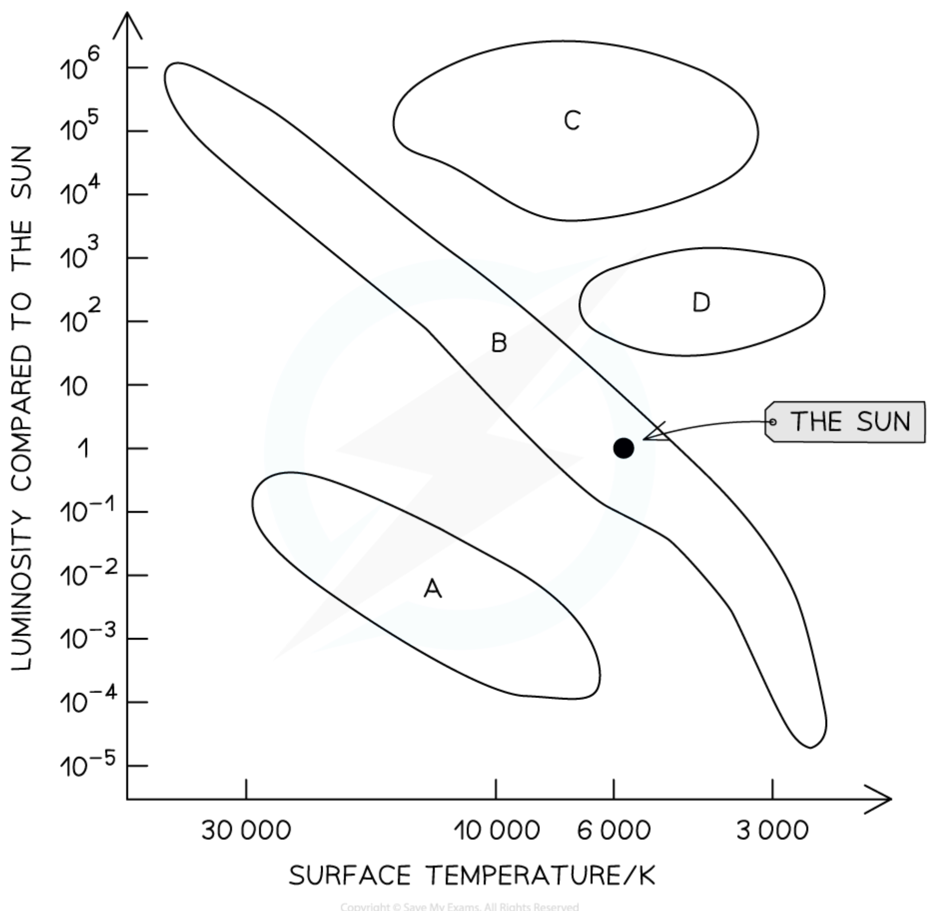
- Hertzsprung and Russel found that the stars clustered in **distinct areas**
- Most stars are clustered in a band called the **main sequence**
  - For main sequence stars, luminosity **increases** with surface temperature
- A smaller number of stars clustered above the main sequence in two areas, **red giants,** and **red supergiants**
  - 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 (H-R) Diagram.

Your notes

Your notes



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

b) On the H-R diagram, plot the star with a surface temperature of 20 000 K and a luminosity 10 000 times greater than the Sun and label it Star X.

Answer:

Part (a)

Step 1: Identify the main sequence on the HR diagram

- The main sequence is the easiest to recognise as it 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
- That means that they are bigger than main sequence stars
- The bigger they are, the more luminous they are
- So, the 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**

Part (b)

Step 1: List the known quantities

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

Step 2: 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

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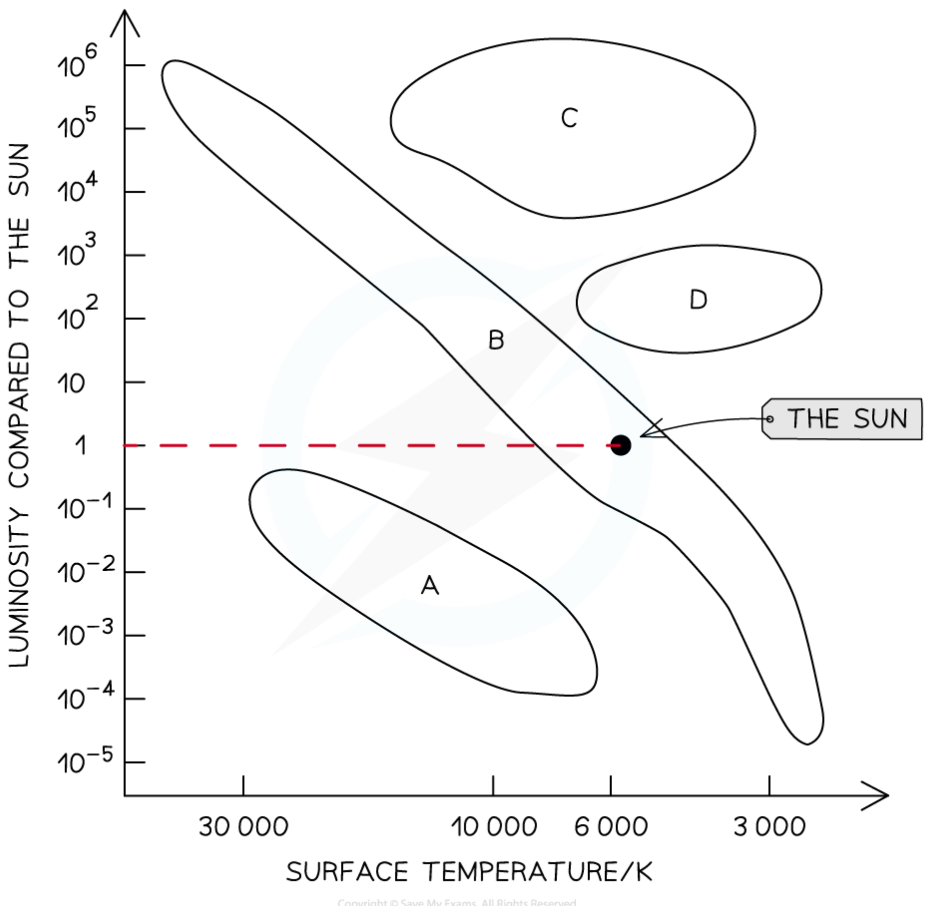

Step 3: Calculate the luminosity of Star X

- 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 4: 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

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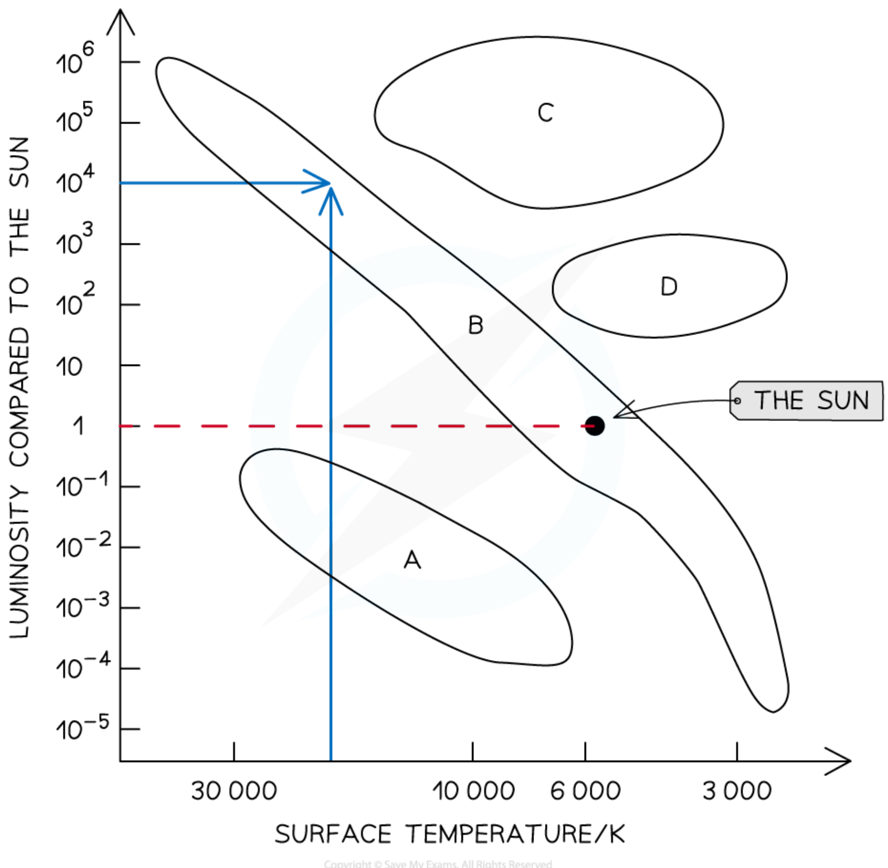
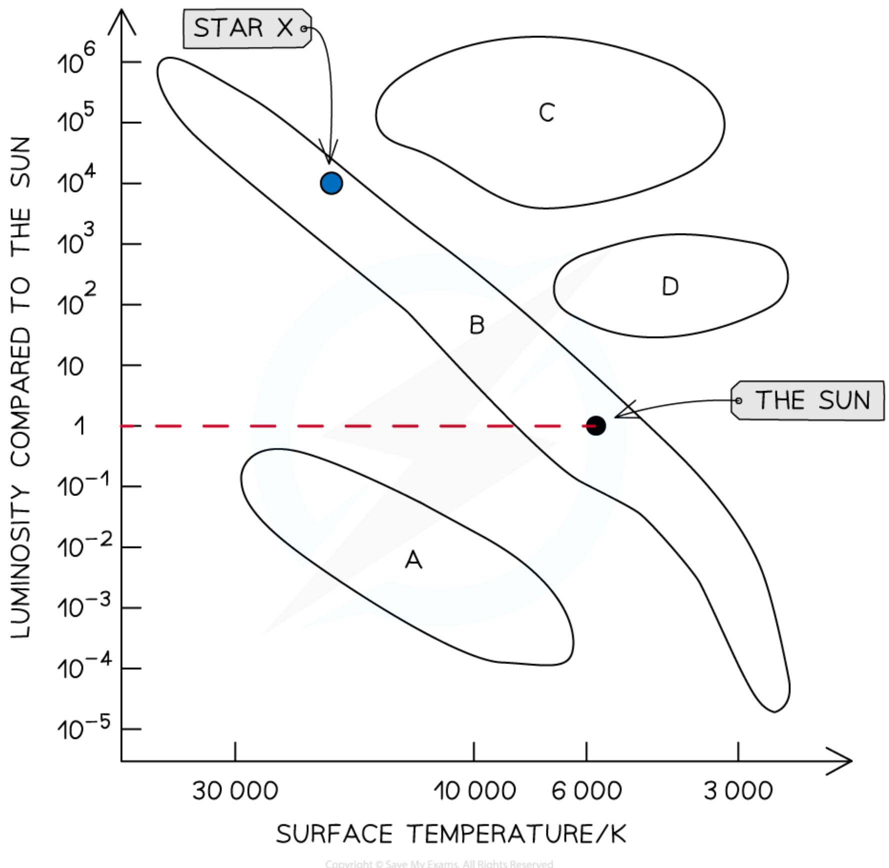


- Plot the point and label it Star X



Your notes

Examiner Tips and Tricks

You need to be able to identify the distinct areas of the Hertzsprung-Russell diagram out of context like in this exam question