AQA A2 Physics Answer Sheet – Astrophysics - Classification of stars

Model Answers and Mark Schemes | Total Marks: 48

Question 1 (1 mark)

> *Define the term 'main sequence star'.*

MODEL ANSWER

A main sequence star is a star that is in the stable, hydrogen-fusing phase of its life cycle, where it generates energy by fusing hydrogen into helium in its core.

MARK SCHEME

✓ Star fusing hydrogen into helium in its core [1 mark]

Question 2 (2 marks)

> *State two physical properties of a star that determine its position on the Hertzsprung-Russell (HR) diagram.*

MODEL ANSWER

The two physical properties are luminosity (or absolute magnitude) and surface temperature (or spectral class/colour).

MARK SCHEME

✓ Luminosity / absolute magnitude [1 mark]

✓ Surface temperature / spectral class / colour [1 mark]

Question 3 (3 marks)

> *Explain why the temperature of a red giant star is lower than that of a main sequence star of similar luminosity.*

MODEL ANSWER

A red giant star has a much larger surface area than a main sequence star of similar luminosity. Since luminosity (L) is proportional to R^2T^4, for a given luminosity, a larger radius (R) necessitates a lower surface temperature (T) to maintain that luminosity.

MARK SCHEME

- ✓ Red giant has a much larger radius/surface area [1 mark]
- ✓ $L = 4\pi R^2 \sigma T^4$ / $L \propto R^2T^4$ [1 mark]
- ✓ For similar luminosity, larger R implies smaller T [1 mark]

Question 4 (4 marks)

A star has a surface temperature of 5800 K and a luminosity of 3.8×10^{26} W. Calculate the radius of this star. Assume the Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}.

MODEL ANSWER

Using the Stefan-Boltzmann law: $L = 4\pi R^2 \sigma T^4$

Rearranging for R: $R = \sqrt{(L / (4\pi\sigma T^4))}$

$R = \sqrt{(3.8 \times 10^{26} / (4\pi \times 5.67 \times 10^{-8} \times (5800)^4))}$

$R = \sqrt{(3.8 \times 10^{26} / (4\pi \times 5.67 \times 10^{-8} \times 1.13 \times 10^{15}))}$

$R = \sqrt{(3.8 \times 10^{26} / (8.05 \times 10^{8}))}$

$R = \sqrt{(4.72 \times 10^{17})}$

$R = 6.87 \times 10^{8}$ m

STEP-BY-STEP WORKING

1. Write down the Stefan-Boltzmann law: $L = 4\pi R^2 \sigma T^4$.
2. Rearrange the formula to solve for R: $R = \sqrt{(L / (4\pi\sigma T^4))}$.
3. Substitute the given values: $L = 3.8 \times 10^{26}$ W, T = 5800 K, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}.
4. Calculate T^4: $(5800)^4 = 1.1316 \times 10^{15}$.
5. Calculate the denominator: $4\pi \times 5.67 \times 10^{-8} \times 1.1316 \times 10^{15} \approx 8.05 \times 10^{8}$.
6. Perform the division: $3.8 \times 10^{26} / 8.05 \times 10^{8} \approx 4.72 \times 10^{17}$.
7. Take the square root: $\sqrt{4.72 \times 10^{17}} \approx 6.87 \times 10^{8}$ m.

MARK SCHEME

- ✓ Correct formula $L = 4\pi R^2 \sigma T^4$ [1 mark]
- ✓ Correct rearrangement for R [1 mark]
- ✓ Correct substitution of values [1 mark]
- ✓ Correct final answer with unit (6.87×10^{8} m to 3 s.f.) [1 mark]

Question 5 (5 marks)

Describe the main characteristics of a white dwarf star, including its typical size, density, and energy source.

MODEL ANSWER

A white dwarf is a very dense, compact stellar remnant. It typically has a mass comparable to the Sun but a radius similar to that of the Earth (e.g., 0.01 $R_\odot$). This results in an extremely high density, often millions of times greater than water. White dwarfs no longer undergo nuclear fusion; their energy source is the residual thermal energy from their formation, which they slowly radiate away over billions of years, gradually cooling down.

MARK SCHEME

- ✓ Mass comparable to Sun [1 mark]
- ✓ Radius similar to Earth / very small (e.g., 0.01 $R_\odot$) [1 mark]
- ✓ Extremely high density (e.g., millions of times water) [1 mark]
- ✓ No longer undergoing nuclear fusion [1 mark]
- ✓ Radiates residual thermal energy / slowly cooling down [1 mark]

Question 6 (7 marks)

Star	*Surface Temperature (K)*	*Luminosity ($L_\odot$)*
P	*3500*	*10^4*
Q	*10000*	*10^2*
R	*5000*	*10^{-2}*
S	*25000*	*10^5*

a) Plot these stars on a sketch Hertzsprung-Russell (HR) diagram. Label the axes and indicate the positions of the main sequence, red giants, and white dwarfs.
b) Classify each star (P, Q, R, S) based on its position on your HR diagram.

MODEL ANSWER

a)
HR Diagram Sketch:
- X-axis: Surface Temperature (K), decreasing from left to right (e.g., 30000 K to 3000 K) [1 mark]
- Y-axis: Luminosity ($L_\odot$), increasing upwards (logarithmic scale, e.g., 10^{-4} to 10^6) [1 mark]
- Main Sequence: Diagonal band from top-left to bottom-right [1 mark]
- Red Giants: Top-right region [1 mark]
- White Dwarfs: Bottom-left region [1 mark]
- Points P, Q, R, S plotted correctly relative to the regions and each other [1 mark]

b)
P: Red Giant
Q: Main Sequence
R: White Dwarf
S: Main Sequence (or Supergiant, depending on exact placement, but main sequence is acceptable for this temperature/luminosity)

MARK SCHEME

✓ {'label': 'a', 'marks': 6, 'question': 'Plot these stars on a sketch Hertzsprung-Russell (HR) diagram. Label the axes and indicate the positions of the main sequence, red giants, and white dwarfs.', 'model_answer': '**HR Diagram Sketch:**

- ✓ X-axis: Surface Temperature (K), decreasing from left to right (e.g., 30000 K to 3000 K) [1 mark]
- ✓ Y-axis: Luminosity ($L_\odot$), increasing upwards (logarithmic scale, e.g., 10^{-4} to 10^6) [1 mark]
- ✓ Main Sequence: Diagonal band from top-left to bottom-right [1 mark]
- ✓ Red Giants: Top-right region [1 mark]
- ✓ White Dwarfs: Bottom-left region [1 mark]
- ✓ Points P, Q, R, S plotted correctly relative to the regions and each other [1 mark]

', 'step_by_step': "1. Draw axes for a sketch HR diagram. Label the x-axis 'Surface Temperature (K)' with values decreasing from left to right. Label the y-axis 'Luminosity ($L_\odot$)' with values increasing upwards, using a logarithmic scale.
2. Sketch the main regions: the diagonal main sequence, the red giant region in the top-right, and the white dwarf region in the bottom-left.
3. Plot each star based on its given temperature and luminosity. For example, Star P (3500 K, 10^4 $L_\odot$) will be in the top-right, placing it in the red giant region."}

✓ {'label': 'b', 'marks': 1, 'question': 'Classify each star (P, Q, R, S) based on its position on your HR diagram.', 'model_answer': 'P: Red Giant
Q: Main Sequence
R: White Dwarf
S: Main Sequence (or Supergiant, depending on exact placement, but main sequence is acceptable for this temperature/luminosity)', 'mark_scheme': ['P: Red Giant [0.25 mark]', 'Q: Main Sequence [0.25 mark]', 'R: White Dwarf [0.25 mark]', 'S: Main Sequence / Supergiant [0.25 mark]'], 'step_by_step': '1. Locate each plotted star on the HR diagram from part (a).
2. Identify the region each star falls into (Main Sequence, Red Giant, White Dwarf, Supergiant).'}

Question 7 (4 marks)

> *Explain the significance of the spectral classification system (OBAFGKM) for stars.*

MODEL ANSWER

The OBAFGKM spectral classification system categorises stars based on their surface temperature, which is inferred from the absorption lines present in their spectra. 'O' stars are the hottest and bluest, while 'M' stars are the coolest and reddest. This system is significant because a star's surface temperature is directly related to its colour, luminosity, and evolutionary stage. It allows astronomers to quickly infer fundamental properties of a star and its position on the main sequence or other evolutionary branches of the HR diagram.

MARK SCHEME

- ✓ Classifies stars based on surface temperature [1 mark]
- ✓ Inferred from absorption lines in spectra [1 mark]
- ✓ O are hottest/bluest, M are coolest/reddest [1 mark]
- ✓ Allows inference of other properties (e.g., colour, luminosity, evolutionary stage) [1 mark]

Question 8 (3 marks)

> *A star has a peak emission wavelength of 290 nm. Calculate its surface temperature. Wien's displacement constant b = 2.90 × 10^{-3} m K.*

MODEL ANSWER

Using Wien's Displacement Law: $\lambda_{max}T = b$

Rearranging for T: $T = b / \lambda_{max}$

Convert λ_{max} to metres: 290 nm = 290 × 10^{-9} m = 2.90 × 10^{-7} m

T = (2.90 × 10^{-3}) / (2.90 × 10^{-7})

T = 1.00 × 10^{4} K (or 10000 K)

STEP-BY-STEP WORKING

1. Write down Wien's Displacement Law: $\lambda_{max}T = b$.
2. Rearrange to solve for T: $T = b / \lambda_{max}$.
3. Convert the given peak wavelength from nanometres to metres: 290 nm = 290 × 10^{-9} m = 2.90 × 10^{-7} m.
4. Substitute the values for b and λ_{max}: T = (2.90 × 10^{-3} m K) / (2.90 × 10^{-7} m).
5. Calculate the temperature: T = 1.00 × 10^{4} K.

MARK SCHEME

- ✓ Correct formula $\lambda_{max}T = b$ [1 mark]
- ✓ Correct conversion of wavelength to metres [1 mark]
- ✓ Correct final answer with unit (1.00 × 10^{4} K) [1 mark]

Question 9 (5 marks)

> *Compare and contrast the evolutionary paths of a low-mass star (like the Sun) and a high-mass star (e.g., 10 $M_{\odot}$) after they leave the main sequence.*

MODEL ANSWER

After leaving the main sequence, both low-mass and high-mass stars expand and cool, becoming red giants/supergiants. However, their subsequent evolution diverges significantly.

A low-mass star (like the Sun) will become a red giant, then shed its outer layers to form a planetary nebula, leaving behind a white dwarf. The white dwarf will slowly cool over billions of years.

A high-mass star (e.g., > 8 $M_{\odot}$) evolves into a red supergiant, undergoing fusion of heavier elements in its core (up to iron). Once the iron core forms, fusion stops, and the core collapses catastrophically, leading to a Type II supernova explosion. The remnant of the supernova will either be a neutron star (if the core mass is between ~1.4 $M_{\odot}$ and ~3 $M_{\odot}$) or a black hole (if the core mass exceeds ~3 $M_{\odot}$).

MARK SCHEME

- ✓ Both expand and cool (red giant/supergiant phase) [1 mark]
- ✓ Low-mass: Planetary nebula formation [1 mark]
- ✓ Low-mass: White dwarf remnant [1 mark]
- ✓ High-mass: Fusion of heavier elements up to iron [1 mark]
- ✓ High-mass: Supernova explosion [1 mark]
- ✓ High-mass: Neutron star OR Black hole remnant (depending on core mass) [1 mark]

Question 10 (6 marks)

A star has a surface temperature of 4000 K and a radius 100 times that of the Sun ($R_\odot = 6.96 \times 10^8$ m). The Sun's surface temperature is 5800 K.

a) Calculate the luminosity of this star in terms of the Sun's luminosity ($L_\odot$).

b) Based on your answer to part (a) and the given temperature, classify this star.

MODEL ANSWER

a) Using the Stefan-Boltzmann law, $L = 4\pi R^2 \sigma T^4$.

For the star: $L_{star} = 4\pi(100R_\odot)^2\sigma(4000\ K)^4$

For the Sun: $L_\odot = 4\pi R_\odot^2\sigma(5800\ K)^4$

Ratio of luminosities: $L_{star} / L_\odot = [(100R_\odot)^2(4000)^4] / [R_\odot^2(5800)^4]$

$L_{star} / L_\odot = (100^2) \times (4000/5800)^4$

$L_{star} / L_\odot = 10000 \times (0.6896)^4$

$L_{star} / L_\odot = 10000 \times 0.226$

$L_{star} / L_\odot = 2260$

So, $L_{star} = 2260\ L_\odot$

b) With a temperature of 4000 K (cooler than the Sun) and a luminosity of approximately 2260 $L_\odot$ (much higher than the Sun), this star is a red giant.

M A R K   S C H E M E

✓ {'label': 'a', 'marks': 4, 'question': "Calculate the luminosity of this star in terms of the Sun's luminosity ($L_{\odot}$).", 'model_answer': 'Using the Stefan-Boltzmann law, $L = 4\pi R^2 \sigma T^4$.

For the star: $L_{star} = 4\pi(100R_{\odot})^2\sigma(4000\text{ K})^4$

For the Sun: $L_{\odot} = 4\pi R_{\odot}^2\sigma(5800\text{ K})^4$

Ratio of luminosities: $L_{star} / L_{\odot} = [(100R_{\odot})^2(4000)^4] / [R_{\odot}^2(5800)^4]$

$L_{star} / L_{\odot} = (100^2) \times (4000/5800)^4$

$L_{star} / L_{\odot} = 10000 \times (0.6896)^4$

$L_{star} / L_{\odot} = 10000 \times 0.226$

$L_{star} / L_{\odot} = 2260$

So, $L_{star} = 2260\ L_{\odot}$', 'step_by_step': "1. Write down the Stefan-Boltzmann law for both the star and the Sun: $L = 4\pi R^2\sigma T^4$.

2. Form a ratio of the star's luminosity to the Sun's luminosity: $L_{star} / L_{\odot} = [4\pi(100R_{\odot})^2\sigma(4000\text{ K})^4] / [4\pi R_{\odot}^2\sigma(5800\text{ K})^4]$.

3. Cancel out common terms (4π, σ, $R_{\odot}^2$): $L_{star} / L_{\odot} = (100^2) \times (4000/5800)^4$.

4. Calculate $100^2 = 10000$.

5. Calculate the ratio of temperatures and raise to the power of 4: $(4000/5800)^4 \approx (0.689655)^4 \approx 0.226$.

6. Multiply the results: $L_{star} / L_{\odot} = 10000 \times 0.226 = 2260$.

7. State the luminosity of the star: $L_{star} = 2260\ L_{\odot}$."}

✓ {'label': 'b', 'marks': 2, 'question': 'Based on your answer to part (a) and the given temperature, classify this star.', 'model_answer': 'With a temperature of 4000 K (cooler than the Sun) and a luminosity of approximately 2260 $L_{\odot}$ (much higher than the Sun), this star is a red giant.', 'mark_scheme': ['Correct classification: Red Giant [1 mark]', 'Justification based on high luminosity and low temperature (relative to Sun/main sequence) [1 mark]'], 'step_by_step': "1. Consider the star's temperature (4000 K) which is cooler than the Sun (5800 K).

2. Consider the star's luminosity (2260 $L_{\odot}$) which is significantly higher than the Sun's.

3. On an HR diagram, stars that are cooler but much more luminous than main sequence stars are classified as red giants."}

Question 11 (8 marks)

> *Discuss the physical processes that lead to the formation of a neutron star and a black hole. Explain the conditions under which each of these stellar remnants forms, and describe their key properties.*

MODEL ANSWER

Both neutron stars and black holes are formed from the gravitational collapse of the core of a massive star after it has exhausted its nuclear fuel and undergone a Type II supernova explosion.

Neutron Star Formation:
For stars with initial masses typically between 8 and 20-25 solar masses, the core collapses under gravity. If the core's mass after collapse is between approximately 1.4 $M_\odot$ (the Chandrasekhar limit) and about 3 $M_\odot$ (the Tolman-Oppenheimer-Volkoff limit), the gravitational forces are strong enough to overcome electron degeneracy pressure. Protons and electrons are forced together to form neutrons, releasing neutrinos. This process halts the collapse, and the outer layers rebound, causing a supernova. The remnant is a neutron star.
Key Properties: Extremely dense (a teaspoon would weigh billions of tonnes), small radius (typically 10-20 km), composed almost entirely of neutrons, rapidly rotating, and possesses extremely strong magnetic fields.

Black Hole Formation:
If the core of a very massive star (initial mass > 25 $M_\odot$) collapses and its remnant mass exceeds the Tolman-Oppenheimer-Volkoff limit (approximately 3 $M_\odot$), even neutron degeneracy pressure is insufficient to resist the immense gravitational forces. The collapse continues indefinitely, forming a singularity – a point of infinite density. This creates a black hole.
Key Properties: An event horizon (a boundary beyond which nothing, not even light, can escape), a singularity at its centre, immense gravitational pull, and no physical size in the traditional sense (defined by its event horizon radius, the Schwarzschild radius).

MARK SCHEME

- ✓ Both form from core collapse of massive stars after supernova [1 mark]
- ✓ **Neutron Star:**
- ✓ Core mass between Chandrasekhar limit (~1.4 $M_\odot$) and TOV limit (~3 $M_\odot$) [1 mark]
- ✓ Electron degeneracy pressure overcome / protons and electrons combine to form neutrons [1 mark]
- ✓ Neutron degeneracy pressure supports the star [1 mark]
- ✓ **Black Hole:**
- ✓ Core mass exceeds TOV limit (~3 $M_\odot$) [1 mark]
- ✓ Neutron degeneracy pressure overcome / collapse continues indefinitely [1 mark]
- ✓ Forms a singularity / event horizon [1 mark]
- ✓ No light/matter can escape from within event horizon [1 mark]