



UNDERSTAND



APPLY



PRACTISE



IMPROVE

Astrophysics and Cosmology

OWNER DETAILS



NAME:

GROUP:

TEACHER:



Welcome to your workbook

Astrophysics and Cosmology

What is this book for?

This workbook follows the OCR A A-level Physics specification. It takes you from the forces governing planetary motion to the physics of stars and the evidence for an expanding Universe.

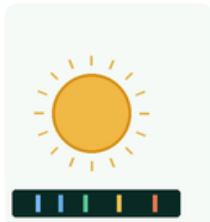
What you'll study



5.4

Gravitational fields and planetary motion

- Gravitational force, field strength and potential
- Kepler's laws, orbital motion and geostationary satellites
- Gravitational potential energy and escape speed



5.5.1–5.5.2

Stars and electromagnetic radiation

- Star formation and evolution; the Hertzsprung–Russell diagram
- Electron energy levels, spectra and diffraction gratings
- Black-body radiation, Wien's law and Stefan's law



5.5.3

Cosmology and the expanding Universe

- Astronomical distances, parallax and the Doppler effect
- Galactic redshift, Hubble's law and the age of the Universe
- The Big Bang, cosmic microwave background and dark components

How to use this workbook

1 Learn and annotate

Use the blank spaces to record your teacher's explanations, modelled calculations and diagrams.

2 Practise and apply

Attempt MCQs, calculations and exam-style problems. Show working in your book where directed.

3 Check and improve

Use the consolidation pages to review specification points, identify gaps and revisit difficult questions.

Think carefully. Use the physics. Explain your reasoning.

5-A-Day

The Sun emits energy at a rate of $3.8 \times 10^{26} \text{ W}$. The radius of the sun is $7 \times 10^8 \text{ m}$. For this exercise, assume that 10% of the Sun's total power output is emitted as photons with a wavelength of 500 nm.

1. Calculate the energy of a single photon with a wavelength of 500 nm.
2. Calculate the number of 500 nm photons emitted by the Sun each second.
3. Light takes approximately 8.3 minutes to travel from the Sun to the Earth. Calculate the distance between the Sun and the Earth.
4. State Kepler's third law, describing the relationship between orbital period and orbital size.
5. Pluto takes 248 Earth years to complete one orbit of the Sun. Using your answer to Question 3 and Kepler's third law, calculate the semi-major axis of Pluto's orbit.

5-A-Day

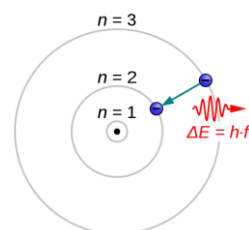
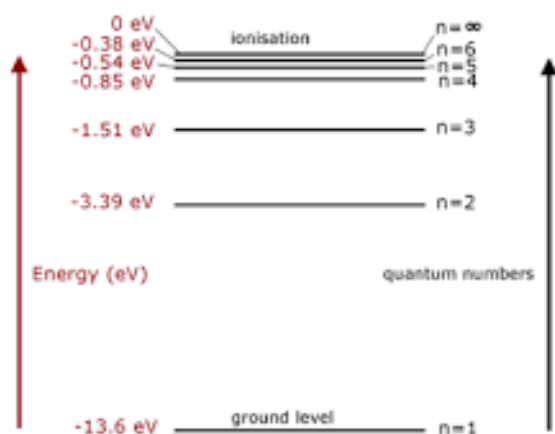
1. State the lifecycle of a low mass star.
2. Explain how the surface temperature of a high mass star changes as it evolves from a main sequence star to a red supergiant.
3. Name the process of creating elements in stars.
4. Describe the characteristics of a neutron star and black hole.
5. The 'event horizon' of a black hole is the point at which light cannot escape. Calculate the radius of the event horizon if we were to compress the Earth into a point dense enough to be a black hole.

5-A-Day

1. Sketch a Hertzsprung–Russell (H–R) diagram, correctly labelling both axes and showing the region occupied by main-sequence stars.
2. On your H–R diagram, mark the approximate positions of the Sun during its main-sequence, red giant and white dwarf stages. Use arrows to indicate its approximate evolutionary path.
3. Explain how the surface temperature and luminosity of the Sun change as it evolves from a main-sequence star into a red giant and eventually a white dwarf.
4. Draw a flow diagram showing the evolution of a high-mass star whose core becomes too massive to be supported by electron degeneracy pressure. Include the Chandrasekhar limit, the main stages of evolution and the two possible stellar remnants.
5. The Sun has a mass of 2.0×10^{30} kg and a radius of 7.0×10^8 m. Calculate the gravitational field strength at the surface of the Sun.

5-A-Day

1. An electron in a hydrogen atom makes a transition from $n = 3$ to $n = 1$. Calculate the energy released during this transition in joules.
2. Calculate the frequency and wavelength of the photon emitted in Question 1.
3. A hydrogen atom in its ground state is exposed to a photon of wavelength 180 nm. Determine whether the photon can be absorbed, explaining your answer using the energy levels.
4. Calculate the minimum energy required to ionise a hydrogen atom from its ground state. Give your answer in eV and joules.
5. A hydrogen atom in its ground state absorbs a photon of frequency 3.6×10^{15} Hz, causing ionisation. Calculate the speed of the emitted electron, assuming the excess photon energy is transferred entirely to its kinetic energy.



5-A-Day

1. Explain how an absorption line spectrum is produced when continuous light from a hot source passes through a cooler gas.
2. Explain how an emission line spectrum is produced by a hot, low-density gas.
3. A diffraction grating contains 500 lines per millimetre. Calculate the grating spacing, d , in metres.
4. Monochromatic light of wavelength 700 nm is incident normally on the diffraction grating.
5. Calculate the highest possible diffraction order and hence the total number of principal maxima that could be observed, including the central maximum.
6. Calculate the angular separation between the first-order and second-order maxima on the same side of the central maximum.

5-A-Day

1. State **Wien's displacement law** and the **Stefan–Boltzmann law**, including their equations.
2. A star with a peak emission wavelength of 450 nm has a surface temperature of approximately 6440 K. Calculate the peak wavelength of a second star with a surface temperature of 4500°C.
3. Two stars have the same radius. Star A has a surface temperature of 5000 K and Star B has a surface temperature of 7500 K. Calculate the ratio of their luminosities, A.
4. A star has a surface temperature of 5000 K and a radius of 4.2×10^8 m. Assuming the star radiates as a black body, calculate its total luminosity.
5. A square solar panel with sides of length 30 cm receives 120 W of solar radiation when positioned perpendicular to the Sun's rays just outside Earth's atmosphere. Assuming the Sun emits radiation uniformly in all directions, estimate its total luminosity.

5-A-Day

1. Arrange the following distances in ascending order, from smallest to largest.
 1.2×10^9 m, 1 AU, 380×10^3 km, 2.7 Mm
2. Define the term parsec (pc), referring to the parallax angle and the Earth–Sun distance.
3. A star has a measured annual parallax angle of 0.040 arcseconds. Calculate its distance from Earth in parsecs.
4. Convert the distance calculated in Question 3 into light-years (ly).
5. Calculate the time taken, in seconds, for light from this star to reach Earth.

5-A-Day

1. State the Doppler shift equation for light and define each variable.
2. An ambulance travels directly away from a stationary observer. The speed of sound is 340 m s^{-1} . The observed frequency of the siren is 4.0% lower than its emitted frequency. Calculate the speed of the ambulance.
3. A spectral line has a wavelength of 500 nm when measured in a laboratory. The same spectral line is observed at 506 nm in light from a distant star. Explain whether this is a redshift or blueshift and what it tells us about the motion of the star.
4. Calculate the radial velocity of the star in Question 3.
5. Calculate the change in frequency of the light between emission and observation. State whether the frequency has increased or decreased.

5-A-Day

1. State Hubble's law and sketch a graph of recessional velocity against distance for distant galaxies. Explain what the gradient represents.
2. Hubble's constant has a measured value of $80 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Convert this value into SI units of s^{-1} .
3. Use this value of Hubble's constant to estimate the age of the Universe in billions of years. Assume that galaxies have moved apart at constant speeds since the expansion began.
4. A spectral line from a distant galaxy is observed at a wavelength 0.14% greater than its laboratory wavelength. Assuming the redshift is entirely due to the expansion of the Universe, calculate the distance to the galaxy in metres.
5. A second galaxy is observed at half the distance of the galaxy in Question 4. Explain how its percentage change in spectral wavelength would compare and calculate the expected percentage change.

5-A-Day

1. What is meant by the term cosmic microwave background radiation (CMBR)? Explain where this radiation originated.
2. Explain how observations of the CMBR provide evidence for the Big Bang model of the Universe.
3. State the approximate temperature of the CMBR today, in kelvin.
4. Most of the Universe's total mass–energy content is not ordinary matter. Name the two poorly understood components believed to make up most of it.
5. State the cosmological principle, referring to the distribution of matter and the appearance of the Universe on sufficiently large scales.

5.5.1 Stars

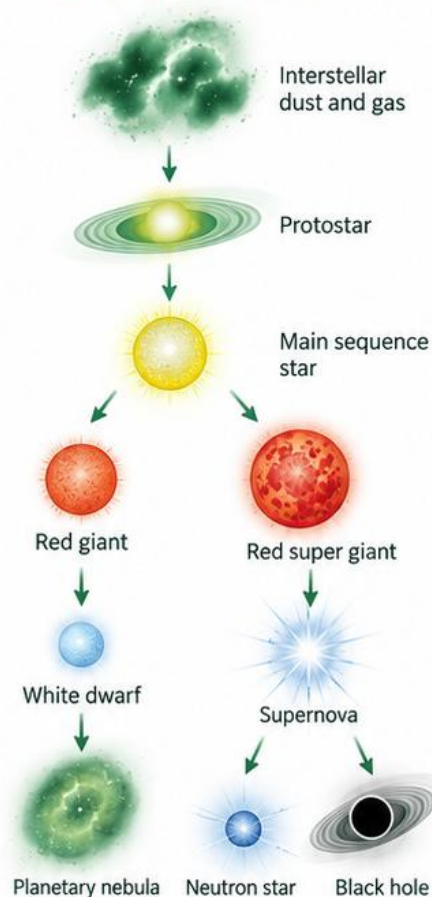
From clouds
of gas to
extraordinary
objects

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

- (a) the terms planets, planetary satellites, comets, solar systems, galaxies and the universe
- (b) formation of a star from interstellar dust and gas in terms of gravitational collapse, fusion of hydrogen into helium, radiation and gas pressure
- (c) evolution of a low-mass star like our Sun into a red giant and white dwarf; planetary nebula
- (d) characteristics of a white dwarf; electron degeneracy pressure; Chandrasekhar limit
- (e) evolution of a massive star into a red super giant and then either a neutron star or black hole; supernova
- (f) characteristics of a neutron star and a black hole
- (g) Hertzsprung–Russell (HR) diagram as luminosity-temperature plot; main sequence; red giants; super red giants; white dwarfs.

The life cycle of a star



Key idea 1



Stellar evolution:
stars form, change and
end in different ways
depending on their mass.

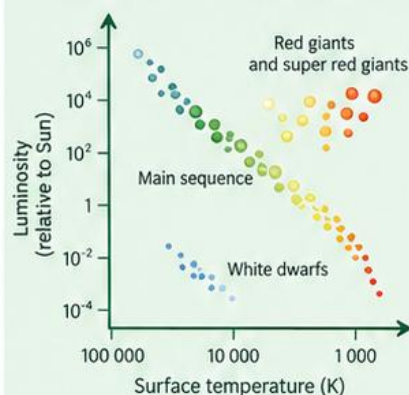
Key idea 2



The HR diagram helps
us compare stars by
luminosity and surface
temperature.

*"The same physics
shapes the cosmos."*

Hertzsprung–Russell diagram



Astrophysics – Crash course



Watch the video

<https://bit.ly/3dMoloz>

Start this part of the course by watching the video. It introduces some of the key ideas in this section.



Describe the following objects in our universe.



Planets

.....

.....



Planetary satellites

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Comets

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Solar systems

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Galaxies

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Universe

.....

.....

Life cycle of a star

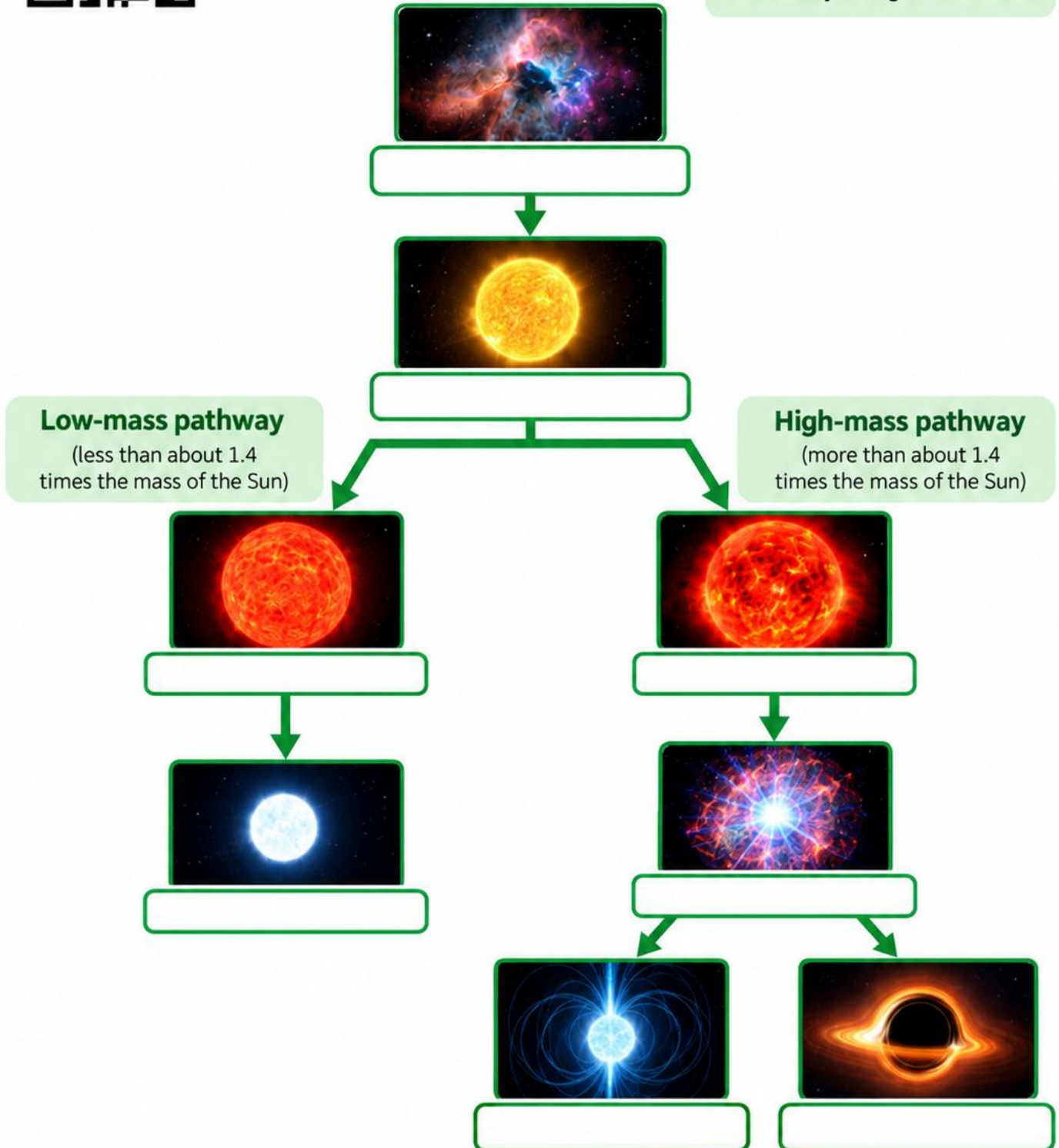


Watch the clip, then complete the diagram below.

<https://bit.ly/2IJnOIs>

Did you know?

A star's life cycle depends mainly on its mass. Low-mass stars end their lives very differently to high-mass stars.



Label the pictures with the correct stage names.

Electron degeneracy pressure

Electron degeneracy pressure is the pressure caused when electrons are squeezed so closely together that quantum effects stop them all occupying the same energy state. This creates a resistance to further compression and helps to support white dwarfs against gravitational collapse.

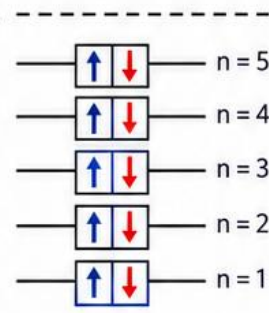
Pauli exclusion principle

No two electrons can occupy the same quantum state at the same time.

(Very simplified version)



Energy



Ionization (electron free)

Two electrons may share an energy level only if they have opposite spin.

Pauli exclusion principle: no two electrons can occupy the same quantum state.

1. What is electron degeneracy pressure?

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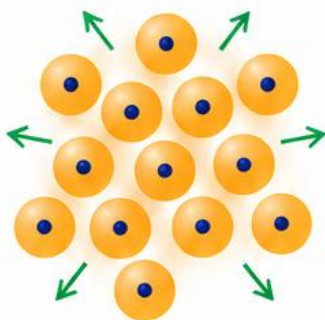
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2. Why does it prevent further collapse in a white dwarf?

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White dwarf



Electron degeneracy pressure

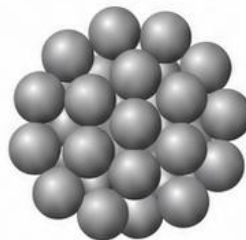
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Neutron star



Neutrons packed closely together
(neutron degeneracy pressure)

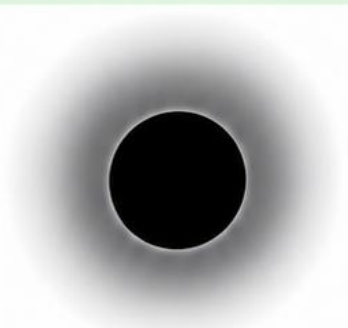
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Black hole



Gravity overcomes all
forms of support

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Stellar evolution questions

Use your knowledge of the life cycle of stars to answer the questions below.

Tick the correct answer and give brief explanations where asked.

- 1** Betelgeuse is a star in the constellation of Orion and astronomers think it could undergo a supernova explosion. What could Betelgeuse evolve into following the supernova stage?

- ☐ A. main sequence star
- ☐ B. neutron star
- ☐ C. planetary nebula
- ☐ D. red giant star

Explain your choice:

.....

.....

- 2** Which is the most likely evolution of a star which is 10 times more massive than our Sun?

- ☐ A. main sequence star → red supergiant → white dwarf → black dwarf
- ☐ B. main sequence star → supernova → red supergiant → neutron star
- ☐ C. main sequence star → red supergiant → supernova → neutron star
- ☐ D. main sequence star → red giant → neutron star → black hole

- 3** Some stars evolve into white dwarfs.
The mass of the Sun is 2.0×10^{30} kg. Which of the following **cannot** be the mass of a white dwarf?

- ☐ A. 1.2×10^{30} kg
- ☐ B. 2.0×10^{30} kg
- ☐ C. 2.7×10^{30} kg
- ☐ D. 3.2×10^{30} kg

Reminder:

Chandrasekhar limit ≈ 1.4 solar masses.

Show your working or give a brief explanation:

.....

.....

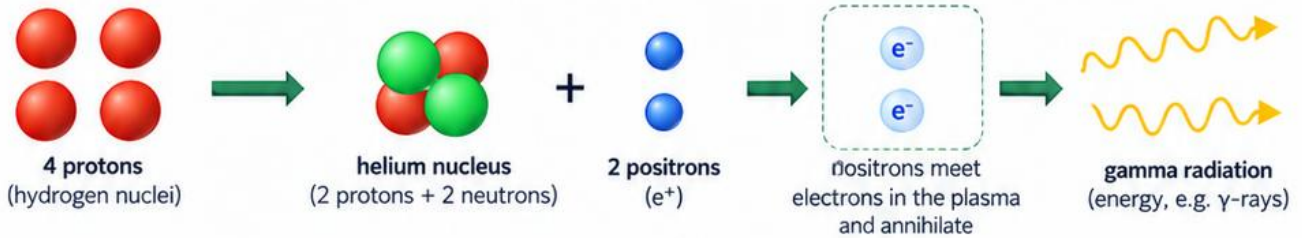
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Fusion, core burning and shell burning

Guided notes

1 Fusion in stars: the proton-proton chain

In the cores of stars, four hydrogen nuclei (protons) fuse to form a helium nucleus. This releases energy. The process also produces positrons, which annihilate with electrons from the surrounding plasma, producing gamma radiation.



The fuel at this stage is...

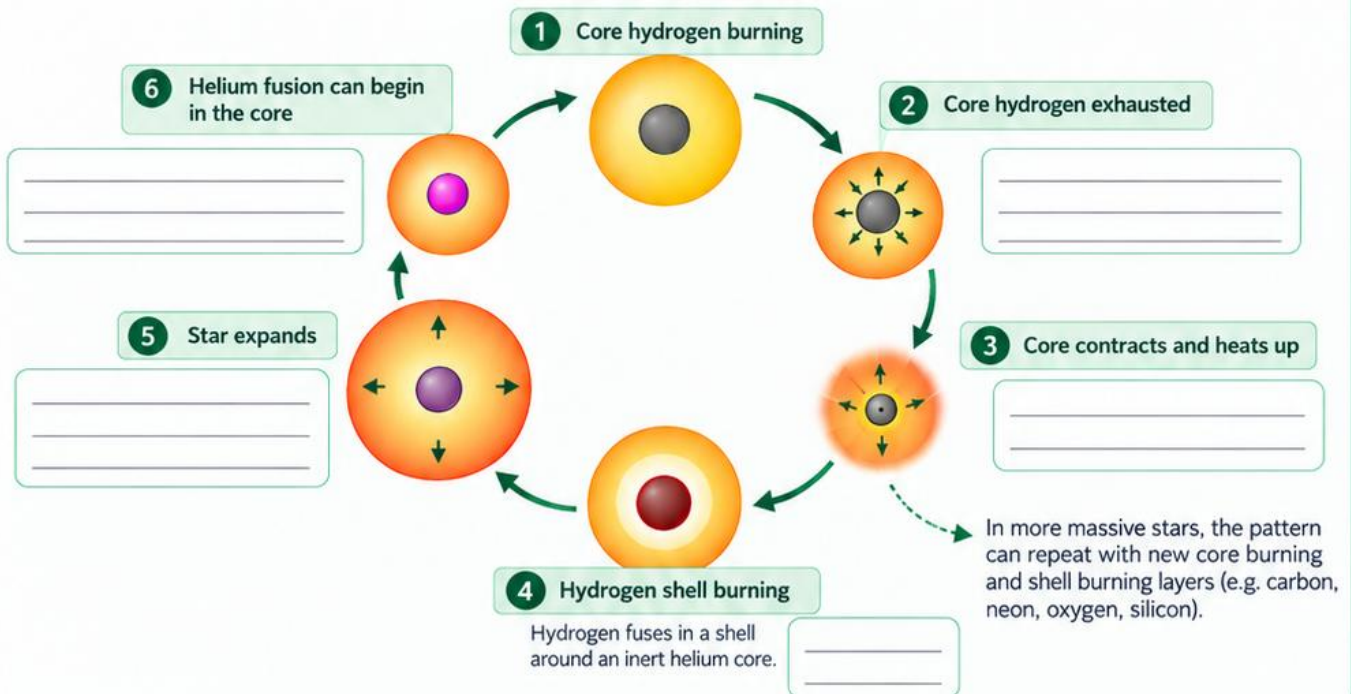
The main product is...

Fusion releases energy because...

Where does the annihilation happen?

2 From core burning to shell burning

When the fuel in the core is used up, the star changes. The diagram shows the cycle from core hydrogen burning to shell burning, and how the process can repeat in more massive stars.



Key idea

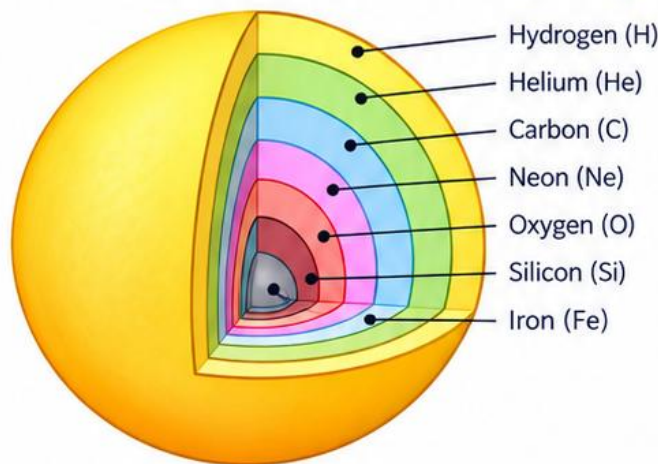
Stars are stable when inward gravitational force is balanced by outward pressure. When the fuel in the core is exhausted, the core contracts and heats up, leading to shell burning and, in more massive stars, further stages of fusion.

Nucleosynthesis and the Chandrasekhar Limit

Guided notes

1 Nucleosynthesis in massive stars

Massive stars fuse elements in a series of shells, building up heavier nuclei towards the centre.



Fusion in massive stars builds elements up to iron.

Elements heavier than iron are formed during supernova explosions.

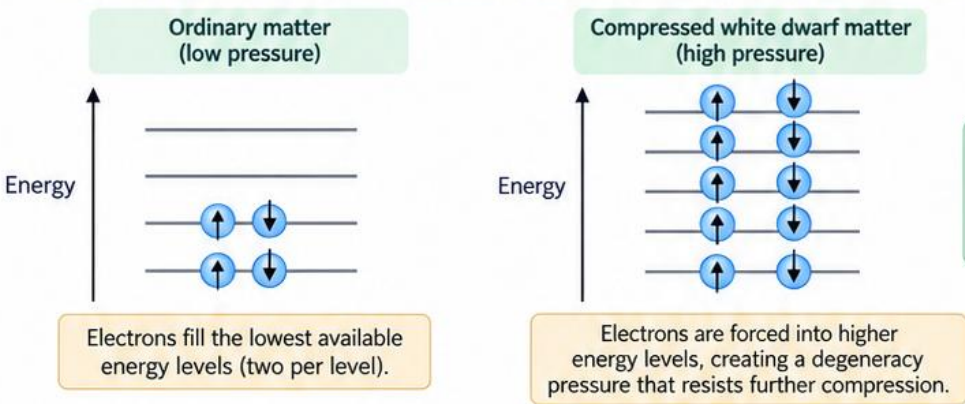
What does nucleosynthesis mean?

Why does fusion stop at iron?

What happens to elements heavier than iron?

2 Electron degeneracy pressure and the Chandrasekhar limit

Electron degeneracy pressure is caused by electrons resisting being squeezed into the same quantum state.



Chandrasekhar limit ≈ 1.4 solar masses

How does electron degeneracy pressure resist collapse?

What is a white dwarf?

What happens if the core mass exceeds the Chandrasekhar limit?



Key ideas

- Massive stars fuse progressively heavier elements in shells.
- Iron marks the end of energy-releasing fusion.
- White dwarfs are supported by electron degeneracy pressure, but only up to about 1.4 solar masses.

19

Check for understanding: stellar evolution

3 multiple-choice questions to review the key ideas before extended writing.

OCR A Astrophysics | Stars

1 Which statement best explains what happens after the hydrogen in the core of a Sun-like star has been used up?

- A** The core contracts, hydrogen continues to fuse in a surrounding shell, the outer layers expand, and later the core becomes hot enough for helium to fuse.
- B** The core remains at a similar size, helium fuses in a shell around the core, and the star becomes hotter and more compact.
- C** Hydrogen fusion stops completely, the star immediately contracts to a white dwarf, and helium then fuses in the core.
- D** The core contracts and heats up, helium fusion starts immediately in the core, and there is no significant expansion of the outer layers.

2 Which statement about the Chandrasekhar limit is correct?

- A** A white dwarf is supported by electron degeneracy pressure, and if the remnant core mass exceeds about 1.4 solar masses it cannot remain a white dwarf.
- B** The Chandrasekhar limit is the maximum mass for a neutron star, above which electron degeneracy pressure can no longer support the star.
- C** The limit is set by the point at which radiation pressure from fusion can no longer support the star against gravity.
- D** If a white dwarf's mass is greater than about 1.4 solar masses, it becomes more stable due to stronger degeneracy pressure and can exist as a larger white dwarf.

3 Which statement about nucleosynthesis during stellar evolution is correct?

- A** Fusion in stars produces elements up to iron, while elements heavier than iron are formed mainly in supernova explosions and neutron-capture processes.
- B** Stars produce elements up to uranium during hydrostatic fusion, with the most massive stars forming the heaviest elements in their cores.
- C** Elements heavier than iron are formed mainly during the red giant phase through slow fusion in hydrogen and helium shells.
- D** Supernova explosions mainly produce elements up to iron, while heavier elements are formed in the cores of neutron stars by proton-capture reactions.

Essay link

These questions prepare you for explaining stellar evolution using ideas such as core₂₀ burning, shell burning, nucleosynthesis and the Chandrasekhar limit.

Extended writing

Write a clear and coherent account of the life cycle of stars, from their formation in interstellar dust and gas to their final remnants. Your explanation should include: formation from dust and gas, gravitational collapse, fusion, radiation pressure, the main sequence, what happens when core fuel runs out, core burning and shell burning, the different pathways for low-mass and high-mass stars, electron degeneracy pressure, supernovae, neutron stars, black holes and the Chandrasekhar limit where relevant.



nebula

gravitational collapse

protostar

fusion

hydrogen

helium

radiation pressure

main sequence

red giant

red supergiant

core burning

shell burning

white dwarf

electron degeneracy pressure

Chandrasekhar limit

supernova

neutron star

black hole

This image shows a single sheet of white paper with horizontal blue or grey ruling lines. The lines are evenly spaced and run across the width of the page. There are no margins, text, or other markings on the paper.

- ☐ defines the stages clearly
- ☐ explains why stars are stable
- ☐ explains what happens when core fuel runs out
- ☐ compares low-mass and high-mass stars
- ☐ uses specialist vocabulary accurately

Additional writing space

Hertzsprung–Russell (HR) diagram

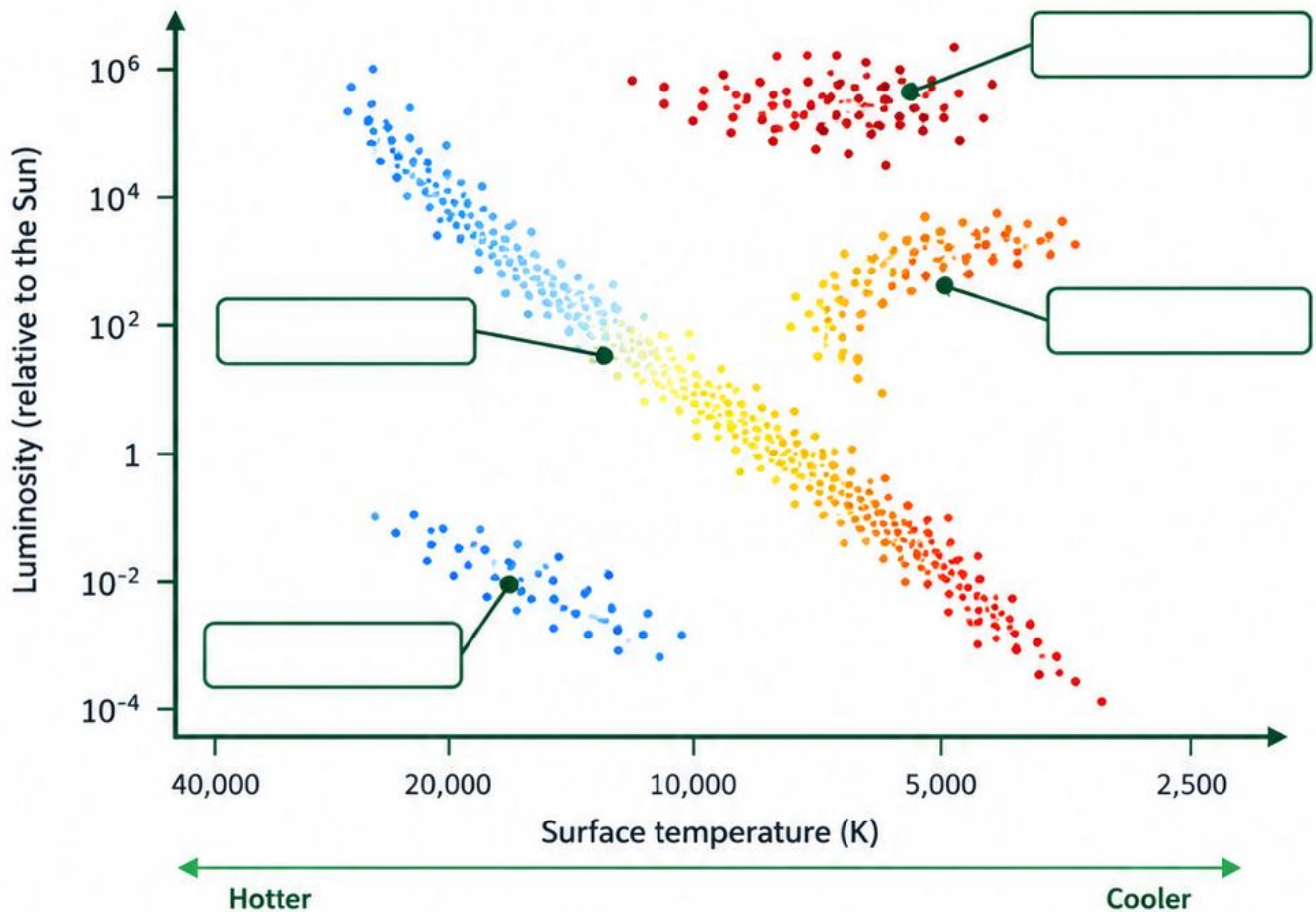


Watch the video

Scan the QR code or use the link below to recap HR diagrams.

<https://www.youtube.com/watch?v=SvaXfFgrKg4>

An HR diagram compares the luminosity and surface temperature of stars.



Word bank:

Main sequence

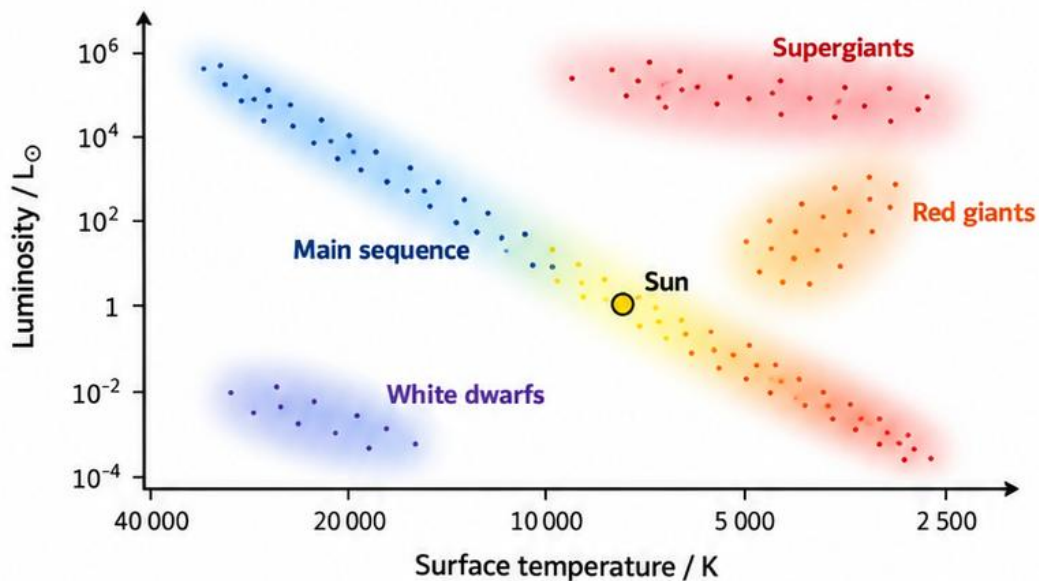
• Red giants

• Supergiants

• White dwarfs

1 Describe the relationship between temperature and luminosity along the main sequence.

2 How can a white dwarf be hot but have a low luminosity?



1 Which statement best describes the luminosity of a star?

- A** The total energy transferred (power radiated) by the star each second.
- B** The brightness of the star as seen from Earth.
- C** The surface temperature of the star.
- D** The energy emitted per unit area of the star's surface each second.

Your answer:

2 A Sun-like main-sequence star evolves into a red giant. Which change best describes its movement on the HR diagram?

- A** Its luminosity increases and its surface temperature decreases, so it moves upwards and to the right.
- B** Its luminosity increases and its surface temperature increases, so it moves upwards and to the left.
- C** Its luminosity decreases and its surface temperature decreases, so it moves downwards and to the right.
- D** Its luminosity decreases and its surface temperature increases, so it moves downwards and to the left.

Your answer:

3 A star is very hot but has low luminosity. Where is it most likely to be found on the HR diagram?

- A** In the white dwarf region.
- B** On the main sequence near the position of the Sun.
- C** In the red giant region.
- D** In the supergiant region.

Your answer:

Stellar evolution, HR diagrams and gravity

OCR A 5.5.1(g), 5.4.2 and 5.4.4 | Applied exam question | Total: 16 marks

An evolving star

A star moves from the main sequence (stage A) to a red giant (stage B). Its properties are modelled below.

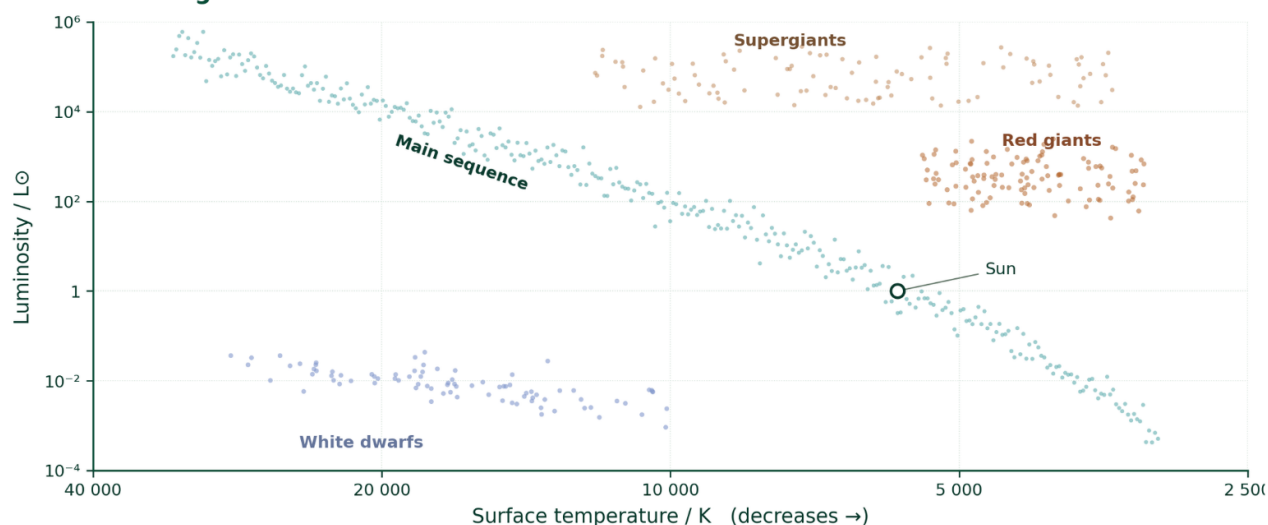
Stage	Mass	Radius	Temperature	Luminosity
A	$1.5 M_{\odot}$	$2.0 R_{\odot}$	7200 K	$10 L_{\odot}$
B	$1.2 M_{\odot}$	$75 R_{\odot}$	3500 K	$750 L_{\odot}$

Data: $G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$

$M_{\odot} = 2.0 \times 10^{30} \text{ kg}$

$R_{\odot} = 7.0 \times 10^8 \text{ m}$

Schematic HR diagram



(a) Plot stars A and B on the HR diagram and draw an arrow showing the direction of evolution. **[3]**

(b) Explain how the star can become more luminous even though its surface temperature falls. Refer to changes in its structure. **[3]**

(c) Calculate the surface gravitational field strength at A. Then determine the ratio g_B / g_A , using the two sets of stellar data. **[4]**

(d) Calculate the gravitational potential per unit mass at the surface of star B (zero at infinity). **[2]**

EXTENDED APPLICATION

(e) A parcel of gas leaves B at $6.0 \times 10^4 \text{ m s}^{-1}$. Assuming only gravity acts after launch, determine whether it can escape to infinity. Justify with an energy calculation. **[4]**

Additional working space

Stellar evolution, HR diagrams and gravity

TEACHER MARK SCHEME

16 MARKS

OCR A 5.5.1(g), 5.4.2 and 5.4.4 | Accept equivalent methods and rounding.

DATA USED IN QUESTION

Stage	Mass	Radius	Temperature	Luminosity
A	1.5 M _⊙	2.0 R _⊙	7200 K	10 L _⊙
B	1.2 M _⊙	75 R _⊙	3500 K	750 L _⊙

a HR diagram: plotted stages and direction

[3]



1 A plotted at 7200 K, 10 L_⊙.

1 B plotted at 3500 K, 750 L_⊙.

1 Arrow correctly shown from A to B: upwards and rightwards.

b Why luminosity increases as the star cools

[3]

1 Hydrogen in the core becomes depleted; the core contracts and shell burning begins.

1 The star's outer layers expand substantially (radius increases from 2.0 to 75 R_⊙).

1 Increased emitting surface area more than compensates for the lower surface temperature: luminosity increases ($L \propto R^2 T^4$).

c Surface field strength at A and ratio g_B / g_A

[4]

1 Use $g = GM/r^2$ for stage A.

1 $g_A = (6.67 \times 10^{-11})(3.0 \times 10^{30}) / (1.40 \times 10^9)^2 = 1.02 \times 10^2 \text{ N kg}^{-1}$.

1 $g_B/g_A = (M_B/M_A)(R_A/R_B)^2 = (1.2/1.5)(2.0/75)^2$.

1 $g_B/g_A = 5.69 \times 10^{-4}$ (no units). [Equivalent: $g_B = 5.81 \times 10^{-2} \text{ N kg}^{-1}$.]

d Gravitational potential at the surface of B

[2]

1 Use $V_g = -GM/r$; the potential is negative because zero is at infinity.

1 $V_B = -(6.67 \times 10^{-11})(2.40 \times 10^{30}) / (5.25 \times 10^{10}) = -3.05 \times 10^9 \text{ J kg}^{-1}$.

e Extended application: can the gas escape?

[4]

1 Initial kinetic energy per unit mass = $\frac{1}{2}v^2 = \frac{1}{2}(6.0 \times 10^4)^2 = 1.80 \times 10^9 \text{ J kg}^{-1}$.

1 Gravitational energy needed per unit mass to reach infinity = $|V_B| = 3.05 \times 10^9 \text{ J kg}^{-1}$.

1 Total specific mechanical energy = $1.80 \times 10^9 - 3.05 \times 10^9 = -1.25 \times 10^9 \text{ J kg}^{-1}$.

1 Cannot escape: the total energy is negative. Alternatively, $v_{\text{esc}} = \sqrt{2GM/r} = 7.81 \times 10^4 \text{ m s}^{-1} > 6.0 \times 10^4 \text{ m s}^{-1}$.

5.5.2

Electromagnetic radiation from stars

EXPLORING THE UNIVERSE THROUGH LIGHT

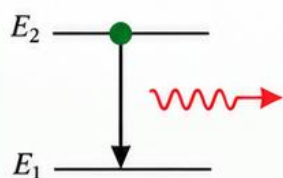


Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

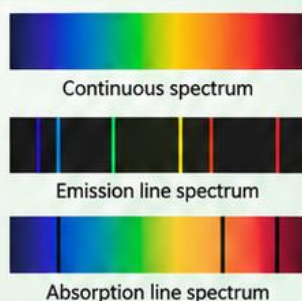
- (a) energy levels of electrons in isolated gas atoms
- (b) the idea that energy levels have negative values
- (c) emission spectral lines from hot gases in terms of emission of photons and transition of electrons between discrete energy levels
- (d) the equations $hf = \Delta E$ and $\frac{hc}{\lambda} = \Delta E$
- (e) different atoms have different spectral lines which can be used to identify elements within stars
- (f) continuous spectrum, emission line spectrum and absorption line spectrum
- (g) transmission diffraction grating used to determine the wavelength of light
- (h) the condition for maxima $d \sin \theta = n\lambda$, where d is the grating spacing
- (i) use of Wien's displacement law $\lambda_{\max} \propto \frac{1}{T}$ to estimate the peak surface temperature (of a star)
- (j) luminosity L of a star; Stefan's law $L = 4\pi r^2 \sigma T^4$ where σ is the Stefan constant
- (k) use of Wien's displacement law and Stefan's law to estimate the radius of a star.

Energy levels and emission

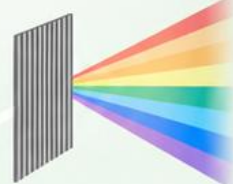


A transition between discrete energy levels emits a photon with energy $\Delta E = hf = hc/\lambda$.

Spectra from stars

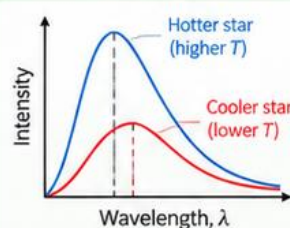


Diffraction grating



A transmission diffraction grating can be used to determine the wavelength of light.

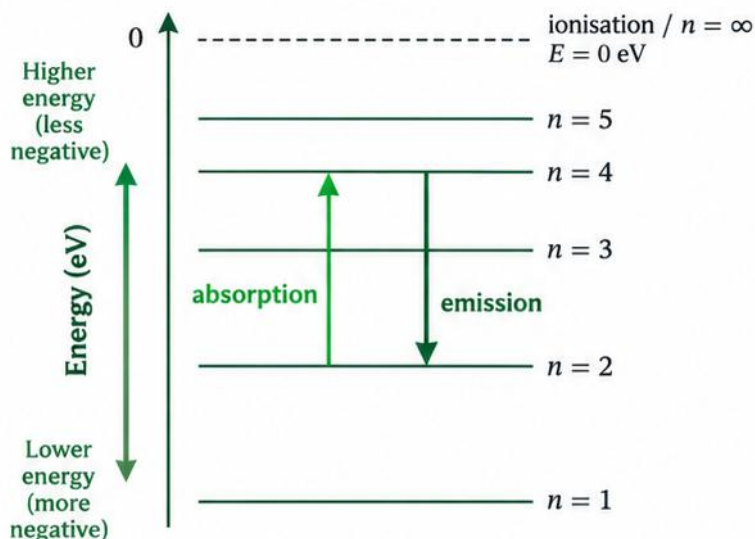
Stellar temperature and size



Wien's displacement law gives the peak temperature. Stefan's law can be used to find the radius of a star.

LIGHT REVEALS THE STARS

4. Energy levels in gas atoms



Energy levels in atoms are negative.
Ionisation corresponds to zero energy ($E = 0$ eV).

Key ideas

- Electrons in atoms can only occupy **discrete energy levels**.
- Electrons **absorb** energy to move to a **higher energy level**.
- Electrons **emit** a photon when they fall to a **lower energy level**.
- Energy levels in atoms are **negative** because work must be done to remove the electron from the atom.
- **Ionisation** occurs when the electron gains enough energy to escape from the atom.

Teacher model example

An electron in a hydrogen atom falls from $n = 3$ to $n = 2$. The energy levels are:

$$E_3 = -1.51 \text{ eV}$$

$$E_2 = -3.40 \text{ eV}$$

Calculate:

- the energy of the emitted photon
- the wavelength of the photon

Data and formulae

$$\Delta E = hf$$

$$c = f\lambda$$

$$\text{therefore } \lambda = \frac{hc}{\Delta E}$$

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

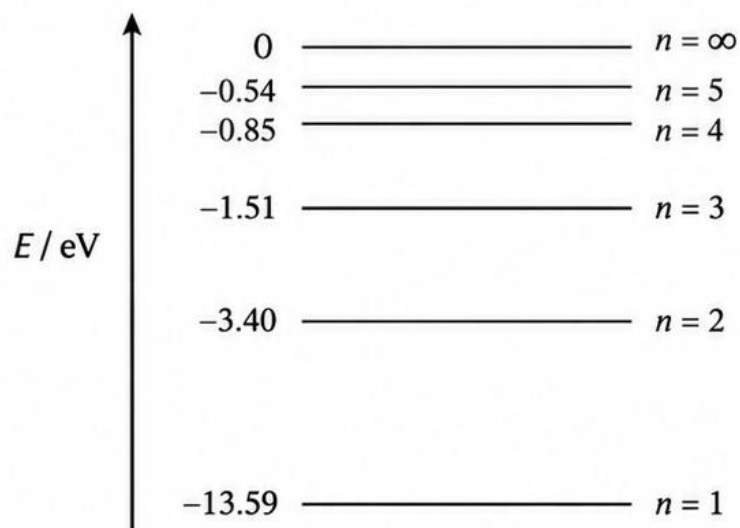
$$h = 6.63 \times 10^{-34} \text{ J s}$$

$$c = 3.00 \times 10^8 \text{ m s}^{-1}$$

Working / teacher model

Photon energy and electron transitions

The diagram shows some of the allowed energy levels for an electron in a hydrogen atom.



Data and constants

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

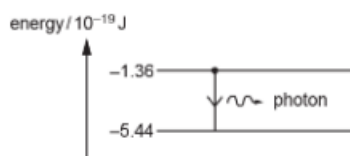
$$h = 6.63 \times 10^{-34} \text{ J s}$$

$$c = 3.00 \times 10^8 \text{ m s}^{-1}$$

Questions

- 1 State what is meant by a negative energy level for an electron in a hydrogen atom.
- 2 Convert the energy of the $n = 3$ level (-1.51 eV) into joules.
- 3 Calculate the minimum energy, in eV and in J, needed to ionise a hydrogen atom from the $n = 2$ level.
- 4 An electron falls from $n = 3$ to $n = 2$. Calculate the energy of the photon emitted, in eV and in J.
- 5 Calculate the wavelength of the photon emitted when an electron falls from $n = 4$ to $n = 2$.
- 6 Calculate the frequency of the photon emitted when an electron falls from $n = 3$ to $n = 1$.
- 7 A hydrogen atom in the $n = 2$ state absorbs a photon of energy 2.55 eV . Determine the new energy level reached by the electron.
- 8 A spectral line from hydrogen has wavelength $1.88 \times 10^{-6} \text{ m}$. Show that this corresponds to a transition from $n = 4$ to $n = 3$.
- 9 Explain, using conservation of energy, why a photon is emitted when an electron moves from a higher level to a lower level.

The diagram below shows two energy levels for the electron in the hydrogen atom.



The electron makes the transition shown by the arrow.

What is the wavelength of the photon emitted?

- A 293 nm
- B 366 nm
- C 488 nm
- D 1460 nm

Your answer

Spectra from stars

5.5.2 ELECTROMAGNETIC RADIATION FROM STARS



Brian Cox explains spectra from stars

Scan the QR code to watch
youtube.com/watch?v=n_KyYFYNvpl



Discharge lamp spectra demo

Scan the QR code to watch
youtube.com/watch?v=oae5fa-f0S0

Watch the videos, then explain how the spectra below are produced.

Hydrogen: visible spectral lines

EMISSION

Bright lines



ABSORPTION

Dark lines



The positions of the emission and absorption lines are matched.

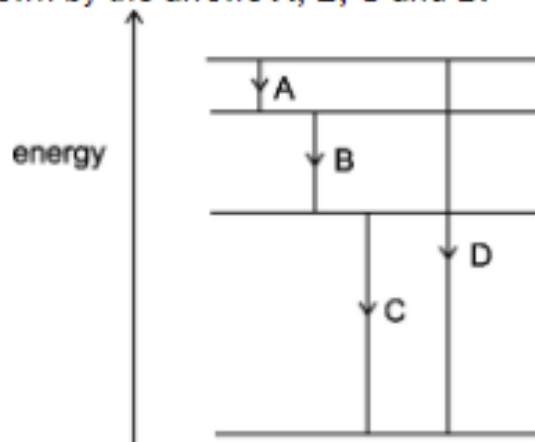
Explain the spectra

- 1 Explain how a hot, low-density hydrogen gas produces the bright emission lines shown. Refer to changes in electron energy levels and the photons emitted. [3]

- 2 Light from a hot star passes through cooler hydrogen gas in its atmosphere. Explain how the dark absorption lines are formed. Include an annotated electron energy-level diagram. [3]

- 3 Explain why the bright and dark lines occur at the same wavelengths, and how astronomers can use these lines to identify elements in a star. [3]

The four energy levels of an atom are shown below.
Four electron transitions are shown by the arrows A, B, C and D.



Which electron transition will give the longest wavelength of electromagnetic radiation?

A light source for an experiment is a discharge lamp containing excited atoms which emit light at several wavelengths. Fig. 8.1 shows the three lowest energy levels of one of these atoms, labelled $n = 1, 2$ and 3 .



Fig. 8.1

Electron transitions between these energy levels can produce three different wavelengths of radiation. The transition between $n = 2$ and $n = 1$ causes the 440 nm photons.

i. Photons at 590 nm are also emitted. Which transition causes these photons?

[1]

ii. Hence calculate the wavelength of the photons emitted by the third transition.

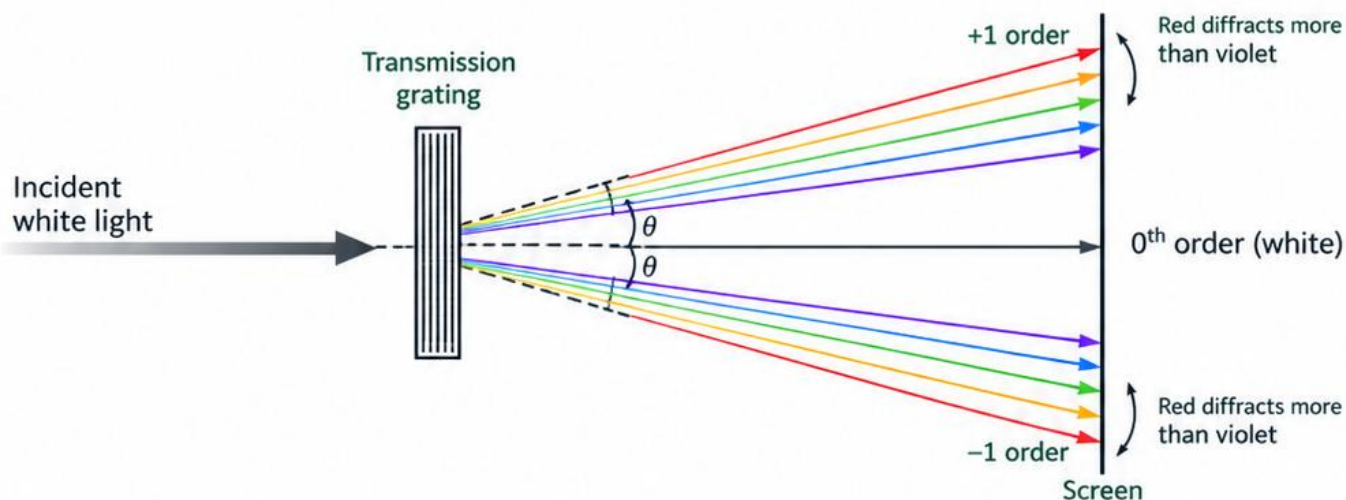
wavelength = ... m [3]

5. Transmission diffraction gratings



Video: How transmission diffraction gratings work

youtube.com/watch?v=fIPSbngdLwI



1 Write the diffraction grating equation for maxima and explain the meaning of d , θ , n and λ .

2 Explain why a white-light source produces a central white maximum and coloured spectra on both sides.

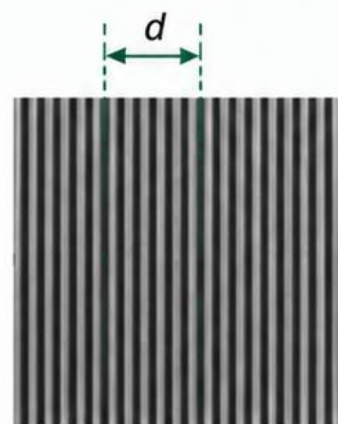
3 A diffraction grating has 500 lines per mm. Monochromatic light has a wavelength of 600 nm. Calculate the first-order diffraction angle.

Diffraction gratings – Multiple choice questions

1

A transmission diffraction grating has 300 lines per mm. What is the separation distance between adjacent lines on the grating?

- A $3.3 \times 10^{-6} \text{ m}$
- B $3.3 \times 10^{-5} \text{ m}$
- C $1.0 \times 10^{-6} \text{ m}$
- D $1.0 \times 10^{-5} \text{ m}$

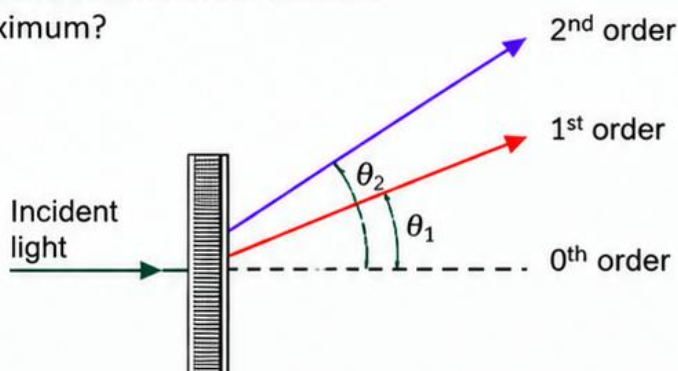


Close-up of a transmission grating

2

A beam of monochromatic light with wavelength 530 nm is incident normally on a diffraction grating with 300 lines per mm. What is the angle between the first and second order maxima on the same side of the central maximum?

- A 14.6°
- B 17.3°
- C 31.9°
- D 34.6°

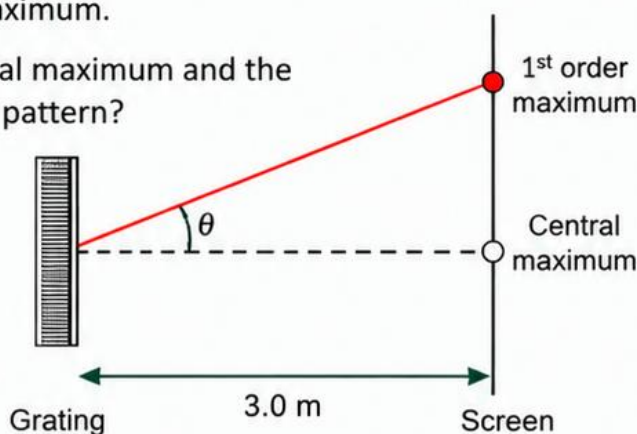


3

A diffraction grating with 300 lines per mm is illuminated with light of wavelength 530 nm. A screen is placed 3.0 m from the grating, perpendicular to the central maximum.

What is the distance between the central maximum and the first order maximum on one side of the pattern?

- A 0.28 m
- B 0.52 m
- C 0.91 m
- D 1.6 m



An astronomer uses a spectrometer and diffraction grating to view a hydrogen emission spectrum from a star. The light is incident normally on the grating.

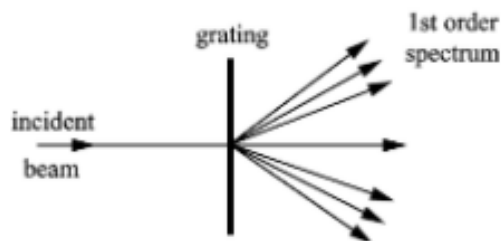


Fig. 6.1

First order diffraction maxima are observed at angles of 12.5° , 14.0° and 19.0° to the direction of the incident light as shown in Fig. 6.1.

Two of the wavelengths are $4.33 \times 10^{-7} \text{ m}$ and $4.84 \times 10^{-7} \text{ m}$.

Calculate the wavelength of the third line.

wavelength = ... m [2]

Laser light of wavelength of 640 nm is incident normally at a diffraction grating. The separation between adjacent lines (slits) is $3.3 \times 10^{-6} \text{ m}$.

What is the **total** number of bright spots that can be observed in the diffraction pattern?

- A 5
- B 6
- C 10
- D 11

☐

Your answer

[1]

A light source for an experiment is a discharge lamp containing excited atoms which emit light at several wavelengths. Fig. 8.1 shows the three lowest energy levels of one of these atoms, labelled $n = 1, 2$ and 3 .



Fig. 8.1

Electron transitions between these energy levels can produce three different wavelengths of radiation. The transition between $n = 2$ and $n = 1$ causes the 440 nm photons.

i. Photons at 590 nm are also emitted. Which transition causes these photons?

[1]

ii. Hence calculate the wavelength of the photons emitted by the third transition.

wavelength = ... m [3]

Wien's law

Black-body radiation |
peak wavelength |
temperature

Key ideas

- Stars are approximately black bodies, so their thermal radiation follows Wien's law.
- The peak wavelength of the emitted radiation is inversely proportional to the absolute temperature.
- Hotter stars have shorter peak wavelengths.
- Cooler stars have longer peak wavelengths.
- Wien's law can be used to estimate the surface temperature of a star.

Important equation

Wien's displacement law

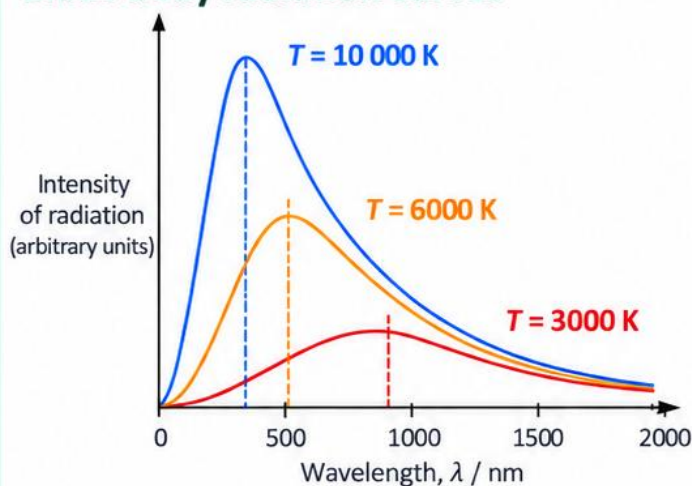
$$\lambda_{max} = \frac{b}{T}$$

λ_{max} = peak wavelength (m)

T = absolute temperature (K)

$b = 2.90 \times 10^{-3} \text{ m K}$

Black-body radiation curves

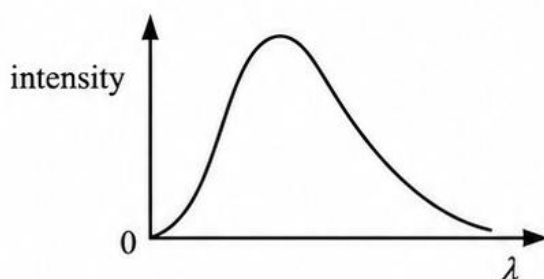


Check for understanding

- 1 A star has a higher surface temperature than another star. How does its peak wavelength compare?
- 2 A star has a peak wavelength of 500 nm. Estimate its surface temperature.

Teacher model

1. The Sun emits a peak wavelength of 500 nm and has a surface temperature of 5500 K. A star has a peak wavelength of 400 nm. What is the temperature of the star?
- A 4400 K
B 5500 K
C 6900 K
D 7600 K
2. Stars emit electromagnetic radiation. The graph below shows the intensity against wavelength λ for a main-sequence star.



Which statement is correct as the main-sequence star evolves into a red giant?

- A The peak wavelength does not change.
B The peak wavelength moves towards the origin.
C The peak wavelength moves to the left (to a shorter wavelength).
D The peak wavelength moves to the right (to a longer wavelength).
3. The intensity–wavelength graph of an object at 750 °C peaks at a wavelength λ . The temperature is increased to 960 °C.

What is the new peak wavelength in terms of λ ?
(Compare the temperatures in kelvin.)

- A 0.78λ
B 0.83λ
C 1.2λ
D 1.3λ

Key ideas

- The total power radiated per unit area by a black body is proportional to the fourth power of its absolute temperature.
- Hotter objects emit much more radiation.
- A star's luminosity depends on both its surface area and temperature.
- For stars of the same radius, luminosity increases strongly with temperature.
- Stefan's law can be used to estimate the luminosity or radius of a star.

Important equation

Stefan–Boltzmann law

$$L = 4\pi R^2 \sigma T^4$$

L = luminosity (W)

R = radius (m)

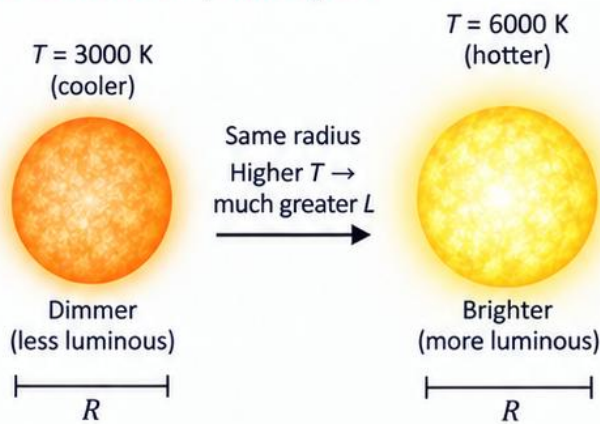
T = absolute temperature (K)

$\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$

Remember

- For the same radius, luminosity is proportional to T^4 .

How luminosity changes



Check for understanding

- 1 Two stars have the same radius. One star has twice the surface temperature of the other. How many times greater is its luminosity?
- 2 Two stars have the same surface temperature. One star has three times the radius of the other. Compare their luminosities.

Teacher model

Work through a relevant example here (e.g. comparing luminosities or finding radius).

Check for understanding

Answer these questions in your book.

1

A star has a surface temperature of 5800 K. Calculate the peak wavelength of the radiation it emits. State the region of the electromagnetic spectrum.

[2]

2

A star has a peak wavelength of 250 nm. Calculate its surface temperature.

[2]

3

A star has twice the radius of the Sun and the same surface temperature. By what factor is its luminosity greater than the Sun's?

[2]

4

Explain why hotter stars appear bluer and more luminous than cooler stars, referring to the shape of the black-body radiation curve and Stefan's law.

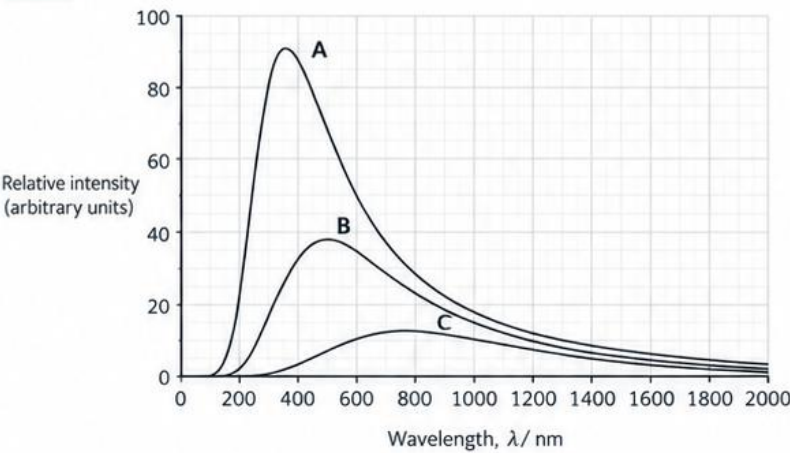
[3]

Stars: Wien's law, Stefan's law and applications

Black-body radiation
Stellar properties
Problem solving

1

The graph shows the black-body radiation curves for three stars, A, B and C.



- (a) Use the graph to determine the peak wavelength for each star. [3]
- (b) Rank the stars in order of their surface temperature, from highest to lowest. Give a reason for your answer. [2]
- (c) Star B has a luminosity of 2.0×10^{26} W. Star C has a luminosity of 1.0×10^{26} W. By what factor is the radius of star C larger than the radius of star B? [3]

2

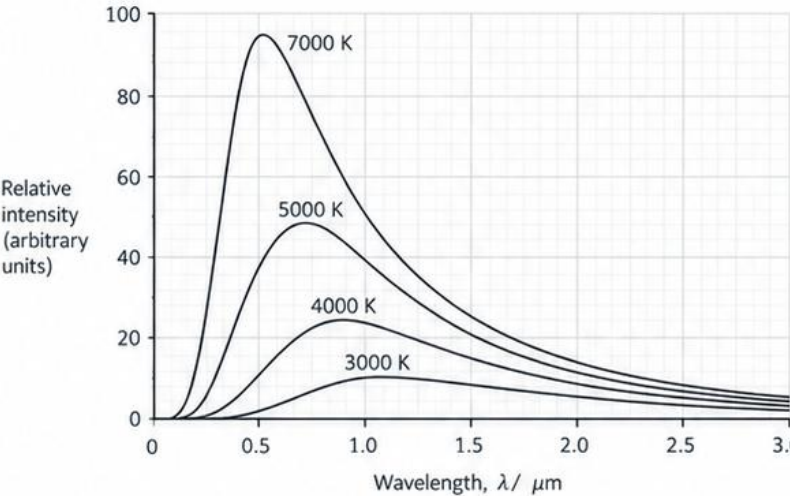
The Sun and a distant star X are both approximately black bodies. Information about the two stars is given below.

Star	Peak wavelength / nm	Luminosity / W
Sun	500	3.85×10^{26}
Star X	310	$10 \times (\text{Sun's luminosity})$

- (a) Use the data to determine the surface temperature of star X. (Do not use the value of Wien's constant. Use a suitable ratio method.) [2]
- (b) Show that the radius of star X is approximately 8.4×10^8 m ($\approx 840,000$ km). [4]

3

A star has a peak wavelength of $0.94 \mu\text{m}$ and a luminosity of 4.0×10^{25} W. It is assumed to radiate approximately as a black body.



- (a) Use the graph below to determine the surface temperature of the star. [2]
- (b) Hence calculate the radius of the star. [3]
- (c) State two assumptions made in this calculation and suggest how each might affect the accuracy of the value for the radius. [2]

Stars emit electromagnetic radiation. A graph of intensity against wavelength λ for a main sequence star is shown.



Which statement is correct as the main sequence star evolves into a red giant?

- A. the peak wavelength does not change
- B. the peak wavelength moves towards the origin
- C. the peak wavelength moves to the left
- D. the peak wavelength moves to the right

A star has surface temperature $3000\text{ }^{\circ}\text{C}$ and luminosity L . Another star of identical size has a surface temperature of $2500\text{ }^{\circ}\text{C}$.

What is the luminosity of this second star in terms of L ?

- A. $0.48L$
- B. $0.52L$
- C. $0.83L$
- D. $0.85L$

Your answer

A hot metal emits a black-body spectrum. The luminosity of the metal at $800\text{ }^{\circ}\text{C}$ is L .

What is the luminosity of the metal when at $1000\text{ }^{\circ}\text{C}$?

- A. $1.2L$
- B. $1.3L$
- C. $2.0L$
- D. $2.4L$

Your answer

5.5.3

Cosmology

MEASURING SPACE • AN EXPANDING UNIVERSE • ITS ORIGINS

OCR A Physics | Learning outcomes

By the end of this section, you should be able to:

Measuring astronomical distances

a–c

- a** distances measured in astronomical units (AU), light-years (ly) and parsecs (pc)
- b** stellar parallax; distances expressed in parsecs (pc)
- c** $p = 1/d$, where p is the parallax in arcseconds and d is the distance in parsecs

The expanding Universe

d–i

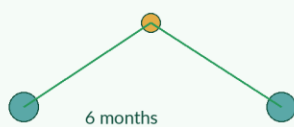
- d** the Cosmological Principle: the Universe is homogeneous and isotropic, and physical laws are universal
- e** the Doppler effect; Doppler shift of electromagnetic radiation
- f** the Doppler approximation $\Delta\lambda/\lambda \approx \Delta f/f \approx v/c$ (magnitudes of small shifts)
- g** Hubble's law $v \approx H_0 d$ for receding galaxies; H_0 is the Hubble constant
- h** evidence for an expanding Universe from galactic redshift
- i** the Hubble constant H_0 in $\text{km s}^{-1} \text{Mpc}^{-1}$ and s^{-1}

The Big Bang and the composition of the Universe

j–o

- j** the Big Bang theory
- k** evidence from the cosmic microwave background radiation at 2.7 K
- l** the idea that the Big Bang gave rise to the expansion of space-time
- m** estimating the age of the Universe using $t \approx H_0^{-1}$
- n** the evolution of the Universe after the Big Bang to the present
- o** current ideas: the Universe contains dark energy, dark matter and a small percentage of ordinary matter

Stellar parallax



Different viewing angles

Galactic redshift

Reference spectrum

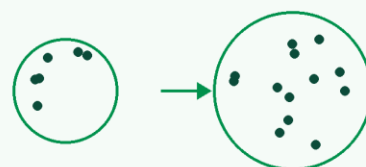


Distant galaxy



Lines shifted to longer λ

From Big Bang to today



CMB: temperature $\approx 2.7 \text{ K}$

Astronomical distances

AU • LIGHT-YEARS

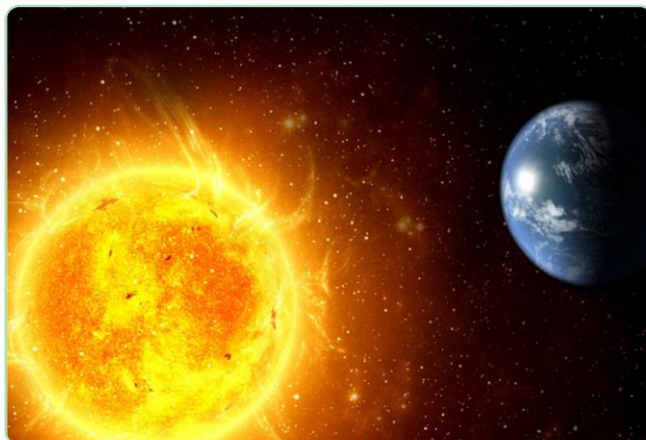
OCRA 5.5.3(a) | Measuring distances in astronomy

1 Astronomical unit (AU)

An astronomical unit is the average distance between Earth and the Sun.

$$1 \text{ AU} = 1.496 \times 10^{11} \text{ m}$$
$$= 149.6 \text{ million km}$$

Useful for comparing distances within our Solar System.



Sun and Earth (not to scale)

2 Light-year (ly)

A light-year is a unit of distance: the distance light travels through a vacuum in one year.

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

$$\text{Take 1 year} = 365 \text{ days}$$

Calculate the distance of one light-year in metres.

Show how you convert years into seconds.

3 Quick check • Application MCQ

A spacecraft is 4.0 AU from the Sun. Approximately how long does sunlight take to reach it?

Choose the best answer.

A 8.3 minutes

B 17 minutes

C 33 minutes

D 66 minutes

Key ideas

- The parsec (pc) is a unit of distance used in astronomy, based on stellar parallax.
- It is the distance at which a star would have a parallax angle of 1 arcsecond (1").
- $1 \text{ pc} = 3.09 \times 10^{16} \text{ m}$
= 3.26 light years
= 206,000 AU

Space for diagram and notes

Discussion

State any problems or limitations with measuring astronomical distances using the parsec.

Check for understanding

Choose the best answer (A–D).

1

Which of the following is the correct definition of one parsec?

- A** The distance light travels in one year.
- B** The distance at which a star has a parallax angle of 1 arcsecond.
- C** The distance from the Earth to the Sun.
- D** The distance at which a star has a parallax angle of 1 degree.

2

A star has a parallax angle of 0.25 arcseconds. What is its distance in parsecs?

- A** 0.25 pc
- B** 2 pc
- C** 4 pc
- D** 40 pc

Stellar parallax

Three challenging multiple-choice questions

OCR A Physics 5.5.3(a)-(c) | Each question is worth 1 mark

Useful information

Parallax angle p in arcseconds; distance d in parsecs:

$$p = 1 / d$$

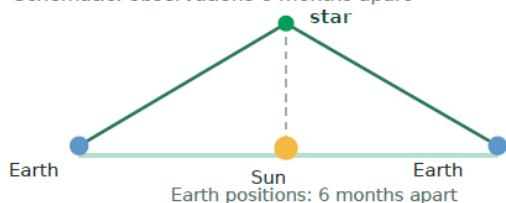
1 pc = 3.26 light-years

1 AU = mean Earth-Sun distance

1 Interpreting parallax observations

Relative to distant background stars, a nearby star shifts through a total angle of 0.40 arcseconds between observations six months apart. What is the distance to the star?

Schematic: observations 6 months apart



A 2.5 pc

B 5.0 pc

C 10 pc

D 20 pc

2 From parallax to light-years

A different star has a measured parallax angle of 0.347 arcseconds. What is its approximate distance from Earth, in light-years?

A 0.94 ly

B 2.9 ly

C 9.4 ly

D 30.6 ly

3 Comparing distances to two stars

Two stars lie almost along the same line of sight. Star A has a parallax angle of 0.156 arcseconds and star B has a parallax angle of 0.347 arcseconds. Approximately how much farther away is A than B?



A 3.5 ly

B 9.4 ly

C 11.5 ly

D 30.3 ly

Astronomical distances – exam style questions

AU | light years |
parsecs | parallax

- 1 (a) Define the **parsec**. Draw a labelled diagram to illustrate your answer.

[3]

- (b) The mean distance from the Earth's centre to the Sun's centre is $1 \text{ AU} = 1.496 \times 10^{11} \text{ m}$.
Express this distance in light-years.

[2]

.....
.....

- 2 Sirius is a very bright star in the night sky. It has a parallax angle of 0.38 arc seconds.

- (a) Calculate the distance to Sirius in parsecs (pc). [2]

.....
.....

- (b) Express this distance in light-years (ly). [1]

.....
.....

Useful information

$$1 \text{ pc} = 3.09 \times 10^{16} \text{ m}$$

$$1 \text{ pc} = 3.26 \text{ ly}$$

$$1 \text{ AU} = 1.496 \times 10^{11} \text{ m}$$

$$1 \text{ ly} = 9.46 \times 10^{15} \text{ m}$$

- 3 A distant star has a parallax angle of 0.93 arc seconds.

- (a) Calculate the distance to this star in light-years. [2]

.....
.....

- (b) Which of the following is the greatest astronomical distance?
Tick (✓) one box.

[1]

A 1.0 pc ☐

B 2.0 ly ☐

C $3.0 \times 10^5 \text{ AU}$ ☐

D $4.0 \times 10^{13} \text{ km}$ ☐

- (c) In astronomy, distance can be measured in different units.
Which one of the following distances is the largest?

[1]

A $4.22 \times 10^{16} \text{ m}$ ☐

B 1.91 pc ☐

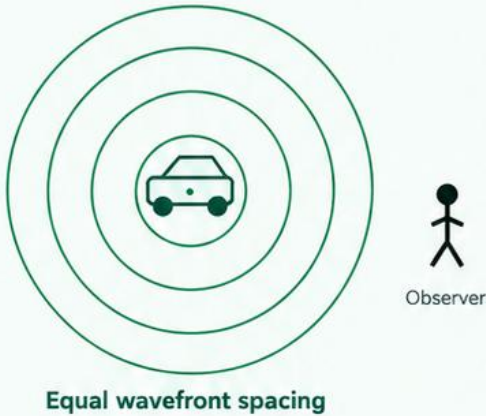
C 3.42 ly ☐

D 59 934 AU ☐

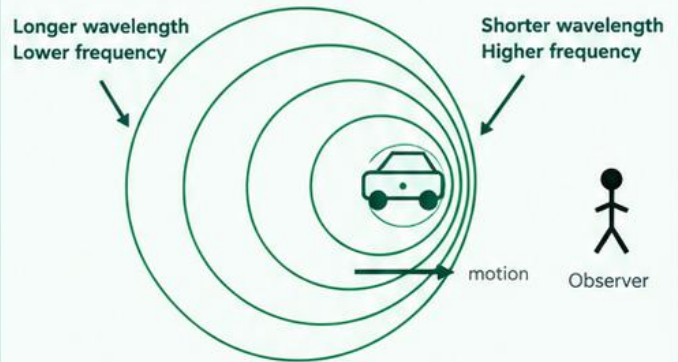
Doppler effect

When a source moves relative to an observer, the observed wavelength and frequency change.

Source at rest



Source moving to the right



For light (astronomy)

Approaching source → **blueshift** (shorter wavelength, higher frequency)

Receding source → **redshift** (longer wavelength, lower frequency)

Teacher modelling and pupil notes

- Label how wavelength changes
- State what happens to frequency
- Add the Doppler equation for light
- Explain redshift and blueshift

Useful data

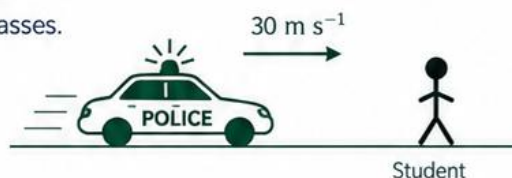
Speed of sound in air $c = 340 \text{ m s}^{-1}$

Use $f = c/\lambda$.

1 Passing siren

A police car travels at 30 m s^{-1} and emits a siren of frequency 720 Hz .

A student stands on the pavement as the car approaches and then passes.

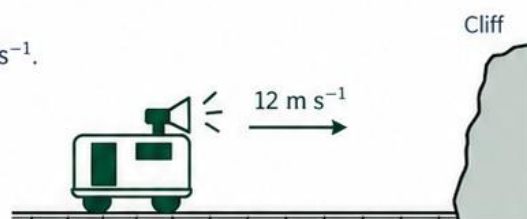


- (a) Show that the wavelength of the sound in front of the car is 0.431 m . [2]
- (b) Calculate the frequency heard by the student as the car approaches. [2]
- (c) Calculate the frequency heard by the student immediately after the car has passed and is moving away. [2]
- (d) Explain why the student hears a sudden drop in pitch as the car passes. [2]

2 Echo from a cliff

A maintenance trolley moves directly towards a vertical cliff at 12 m s^{-1} .

A horn on the trolley emits sound of frequency 600 Hz . The sound reflects from the cliff and returns to the trolley.



- (a) Calculate the frequency of the sound received at the cliff. [2]
- (b) The cliff reflects the sound without changing its frequency. Calculate the frequency of the echo heard back on the trolley. [3]
- (c) Explain why the returned echo has a higher frequency than the sound emitted by the horn. [2]
- (d) State one assumption made in this model of sound propagation. [1]

Galactic redshift

Cosmology | Doppler shift of electromagnetic radiation | Hubble expansion

Notes and modelling

Key ideas

- Spectral lines from a galaxy can be compared with laboratory (rest) wavelengths of the same element.
- If the lines are shifted towards longer wavelengths (the red end), the light is redshifted.
- A redshift indicates that the galaxy is moving away from the observer.
- A larger fractional wavelength shift means a greater recession speed.
- The redshift of distant galaxies provides evidence that the universe is expanding.

Doppler relation for light (non-relativistic)

$$\frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$$

$\Delta\lambda$ = change in wavelength (m)

λ = laboratory (rest) wavelength (m)

v = recession speed of the source (m s^{-1})

c = speed of light ($\approx 3.0 \times 10^8 \text{ m s}^{-1}$)

Laboratory spectrum



Galaxy A (small redshift)



→ Lines shifted to longer wavelength (redshift)

Galaxy B (larger redshift)



→ Lines shifted to longer wavelength (redshift)

Teacher model

A spectral line has wavelength 656.4 nm in the laboratory and 658.1 nm in the light from a distant galaxy. Show how this indicates that the galaxy is moving away, and estimate its speed.

Step 1: Compare wavelengths

Step 2: Calculate $\Delta\lambda / \lambda$

Step 3: Find v and interpret

Challenge MCQs

- 1** An absorption line from a distant galaxy is observed at a longer wavelength than in the laboratory. Which statement is best supported by this observation?

- ☐ A The galaxy is moving away from us and this provides evidence that the universe may be expanding.
- ☐ B The galaxy is moving towards us.
- ☐ C The galaxy is hotter than the laboratory source.
- ☐ D The line is from a different element in the galaxy than in the laboratory.

- 2** The same absorption line is observed in two galaxies. In the laboratory the wavelength is 500.0 nm. In galaxy X it is measured at 502.5 nm, and in galaxy Y at 506.0 nm. Which galaxy is receding faster?

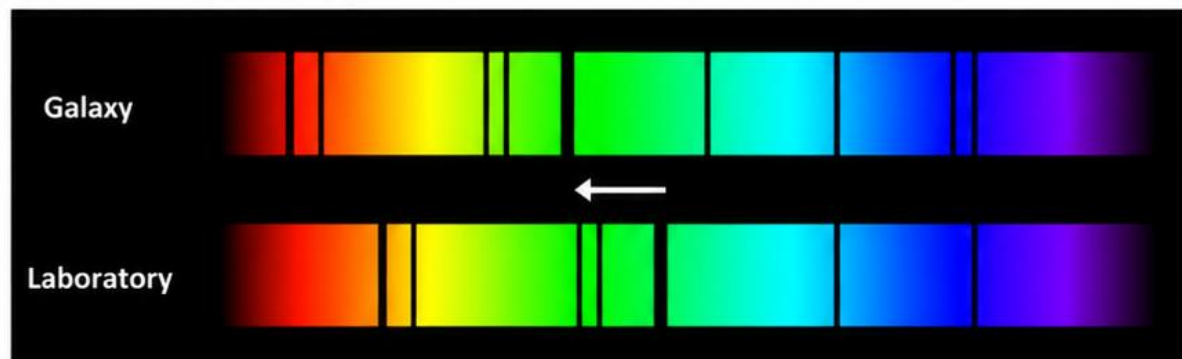
- ☐ A Galaxy X, because the redshift is smaller.
- ☐ B Galaxy Y, because the redshift is larger.
- ☐ C Both galaxies are receding at the same speed.
- ☐ D There is not enough information to tell.

Redshift and the Doppler effect

Doppler effect
Spectral lines
Redshift
Galaxies

1

Light from distant galaxies has spectral lines shifted towards the red end of the spectrum. The diagram shows the same absorption line from a galaxy compared with the position of the line measured in a laboratory.



- (a) What does the observation that the spectral lines are redshifted tell us about the motion of distant galaxies relative to us? [2]

.....

.....

.....

- (b) Suggest how measuring the red shift of many galaxies allows us to determine the speed of galaxies and to provide evidence for the expansion of the universe. [2]

.....

.....

.....

2

An absorption line is measured in the laboratory at 656.4 nm. The same absorption line is observed in a distant galaxy at 658.1 nm.

- (a) Calculate the speed at which the galaxy is moving away from us. [3]

Use the Doppler equation ($v \ll c$): $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$

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

$\Delta\lambda = \lambda_{\text{observed}} - \lambda_{\text{original}}$

- (b) Another galaxy has an absorption line measured in the laboratory with a frequency of $5.12 \times 10^{14} \text{ Hz}$. The same line is observed in the galaxy with a frequency of $4.98 \times 10^{14} \text{ Hz}$. Calculate the speed at which this galaxy is moving and state whether it is moving towards or away from us. [3]

Hubble's law

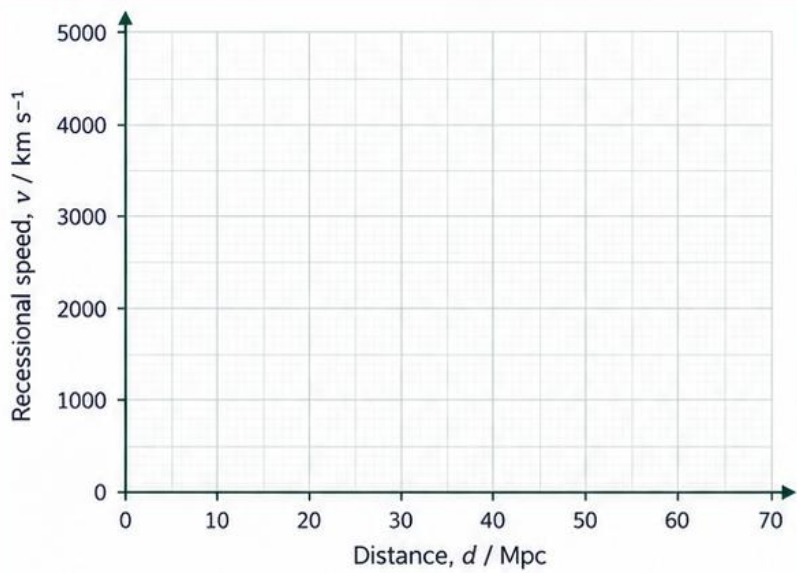
OCR A 5.5.3 COSMOLOGY | REDSHIFT | RECESSIONAL SPEED | DISTANCE

Key idea

- Light from many distant galaxies is redshifted.
- This tells us those galaxies are moving away from us.
- The greater the distance to a galaxy, the greater its recessional speed tends to be.



Plot the data



Galaxies to plot

Galaxy	Distance, d / Mpc	Recessional speed, v / km s^{-1}
A	10	720
B	20	1380
C	35	2470
D	50	3490
E	65	4580

Task

Plot the five galaxies and draw a line of best fit. What trend do you notice?

Teacher modelling / class discussion

Think

If the graph is a straight line, what might the gradient mean?

2. Gradient, units and the age of the universe

COSMOLOGY | HUBBLE'S LAW | AGE OF UNIVERSE

Key ideas

- On a graph of recession speed v against distance d , the gradient is H_0 .
- Hubble's law can be written as $v = H_0 d$.
- A steeper gradient means a larger Hubble constant.
- If H_0 is converted into s^{-1} , then $1/H_0$ has units of seconds.
- This gives an estimate for the age of the universe: $t \approx 1/H_0$.

Cosmological principle

- On the largest scales, the universe is assumed to be homogeneous and isotropic.
- This helps justify using a single large-scale expansion trend when interpreting Hubble graphs.
- Nearby galaxies can show blue shift or scatter because of local motion, even though the overall large-scale trend is expansion.

Important equations

$$v = H_0 d$$

$$H_0 = \frac{\Delta v}{\Delta d}$$

$$t \approx \frac{1}{H_0}$$

Gradient of a v - d graph = H_0

Teacher model: finding the gradient

- Choose two well-spaced points on the best-fit line.
- Calculate Δv and Δd .
- Write the gradient with units.

Teacher model: converting units

- Start with H_0 in $\text{km s}^{-1} \text{Mpc}^{-1}$.
- Convert km to m and Mpc to m.
- Show why the final unit is s^{-1} .

Teacher model: estimating the age of the universe

- Use $t \approx 1/H_0$ once H_0 is in s^{-1} .
- Give the answer in seconds.
- Convert seconds into years.

Check for understanding

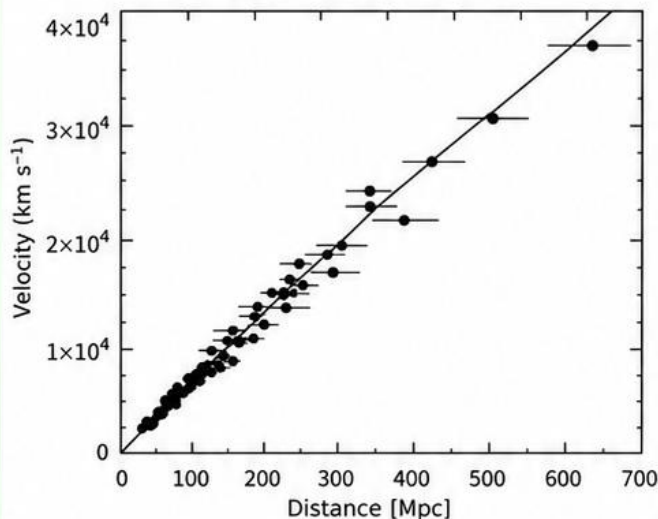
- Why does $1/H_0$ have units of time?
- Why might some nearby galaxies not fit the overall Hubble trend perfectly?

Hubble's law: historical and modern data

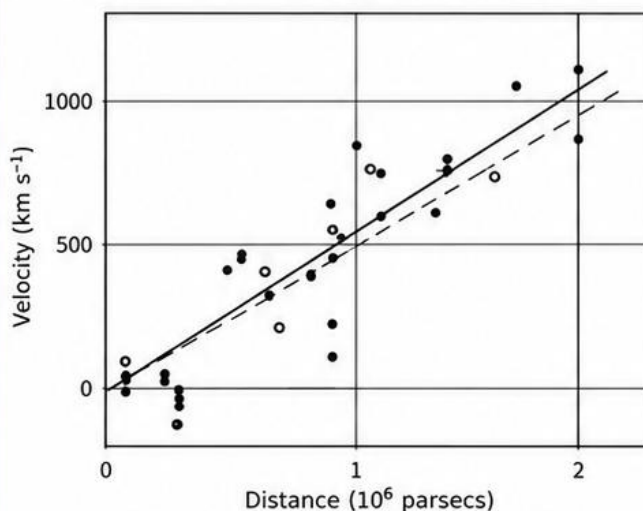
OCR A 5.5.3(g), (i) and (m) | Exam-style worksheet | Total: 16 marks

Use the two Hubble-law graphs below to compare early and modern measurements of the expansion of the universe.

Modern data: Type Ia supernovae



Historical data: Hubble's early observations



Useful data

$$1 \text{ Mpc} = 3.09 \times 10^{22} \text{ m}$$

$$1 \text{ year} = 3.15 \times 10^7 \text{ s}$$

$$1 \text{ km} = 10^3 \text{ m}$$

$$\text{Age of universe estimate: } t \approx \frac{1}{H_0}$$

- (a) Using the modern data graph, determine a value for the Hubble constant H_0 in $\text{km s}^{-1} \text{ Mpc}^{-1}$. [2]

- (b) Use your answer to (a) to estimate the age of the universe in seconds and in years. [4]

Age in seconds: _____

Age in years: _____

- (c) Using the historical data graph, determine a value for the Hubble constant H_0 in $\text{km s}^{-1} \text{ Mpc}^{-1}$. [2]

- (d) Use your answer to (c) to estimate the age of the universe in seconds and in years. [4]

Age in seconds: _____

Age in years: _____

- (e) Compare the two estimates of the age of the universe. [1]

- (f) Suggest **two** reasons why the historical value of H_0 may differ from the modern value. [3]

1. _____

2. _____

Hubble's law – multiple choice

Redshift
Hubble's law
Cosmology
The Universe

1

The current accepted value of Hubble's constant is

$$H_0 = 2.2 \times 10^{-18} \text{ s}^{-1}$$

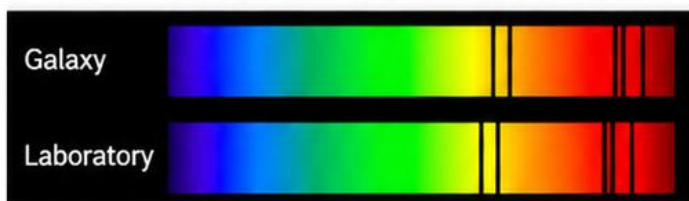
A galaxy is receding from us at $160\,000 \text{ m s}^{-1}$. What is its distance from us?
($1 \text{ Mpc} = 3.09 \times 10^{22} \text{ m}$)

- A $7.3 \times 10^{20} \text{ m}$ (0.024 Mpc)
- B $2.2 \times 10^{21} \text{ m}$ (0.071 Mpc)
- C $7.3 \times 10^{22} \text{ m}$ (2.4 Mpc)
- D $2.2 \times 10^{23} \text{ m}$ (7.1 Mpc)

[1]

2

Hydrogen lines are observed in a distant galaxy. In a laboratory the wavelength of a particular line is 626.9 nm . The same line is observed in the galaxy at 642.5 nm .



The galaxy is 28 Mpc from Earth. What is the best estimate for the age of the universe?
Use $c = 3.00 \times 10^8 \text{ m s}^{-1}$.

- A $4.6 \times 10^8 \text{ years}$
- B $1.4 \times 10^9 \text{ years}$
- C $6.8 \times 10^9 \text{ years}$
- D $1.4 \times 10^{10} \text{ years}$

[1]

3

Which of the following statements best explains why Hubble's original estimate of the age of the universe ($\sim 2 \text{ billion years}$) was much lower than modern estimates ($\sim 14 \text{ billion years}$)?

- A Hubble used the relativistic Doppler effect, which is only valid at low speeds.
- B Hubble significantly underestimated the distances to galaxies due to calibration errors in the method used (e.g. Cepheid variables).
- C The early data included many galaxies with blueshifts due to gravitational attraction.
- D The value of the speed of light used by Hubble was too low.

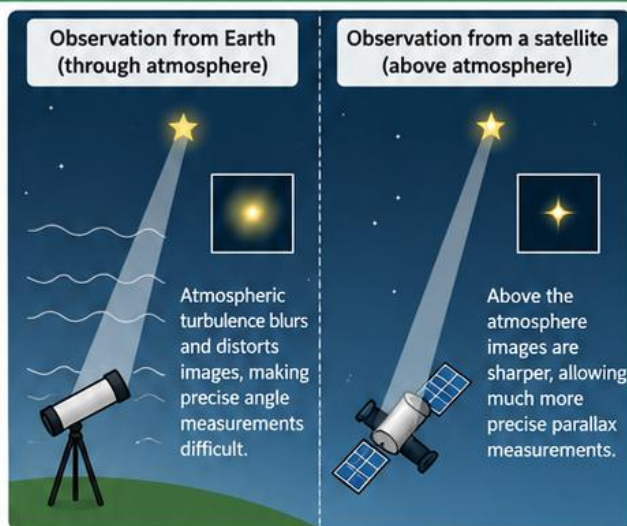
Difficulties with measuring Hubble's constant

Hubble's law states that recession speed is proportional to distance: $v = H_0 d$.

To determine H_0 accurately, astronomers need reliable measurements of both recession speed and distance.

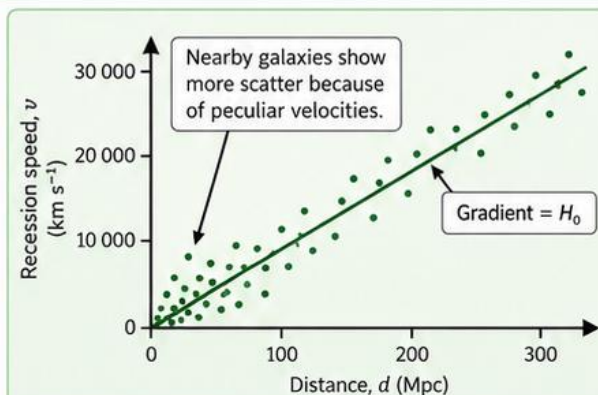
1. Measuring distance is difficult

- Nearby stars can be measured using **stellar parallax**.
- A star at **1 parsec** has a parallax angle of **1 arcsecond**.
- Beyond about 100 pc, the parallax angle is **smaller than about 0.01 arcseconds**, so the apparent shift becomes extremely tiny.
- From Earth, **turbulence in the atmosphere** blurs images and makes precise angle measurements difficult.
- This is why **satellites above the atmosphere** are needed. Space missions such as **Hipparcos** and **Gaia** can measure much smaller parallax angles far more accurately.
- For more distant stars and galaxies, astronomers must use indirect methods such as **standard candles**, which introduce additional uncertainty.



2. Recession speed is not the only motion

- **Redshift** is used to calculate radial speed.
- However, galaxies also have **local motions** caused by gravity, and stars and gas inside galaxies **rotate**.
- These extra motions are called **peculiar velocities**.
- For nearby galaxies, peculiar velocity can be a **large fraction** of the total measured speed.
- Some nearby galaxies may even be **blueshifted**.
- This adds **scatter to a Hubble graph** and makes H_0 harder to determine.



3. Why values of H_0 have changed

- Early measurements used **small data sets** and less accurate distance estimates.
- Modern telescopes, satellites, **better detectors**, and **improved calibration** have greatly increased accuracy.
- Different measurement methods can still give **slightly different results**.
- Measuring H_0 remains an **important area of cosmology**.

4. What H_0 tells us

- On a graph of recession speed against distance, the **gradient is H_0** .
- Its common units are **$\text{km s}^{-1} \text{Mpc}^{-1}$** .
- The quantity **$1/H_0$** gives an estimate of the **age of the universe**.
- H_0 describes the **present-day expansion rate** of the universe.



Key idea

Accurate values of Hubble's constant depend on two things: precise distances and reliable recession speeds. Both are difficult to measure, especially for nearby galaxies and very distant objects.

The Big Bang: research assessment

From the hot early Universe to the cosmos we observe today

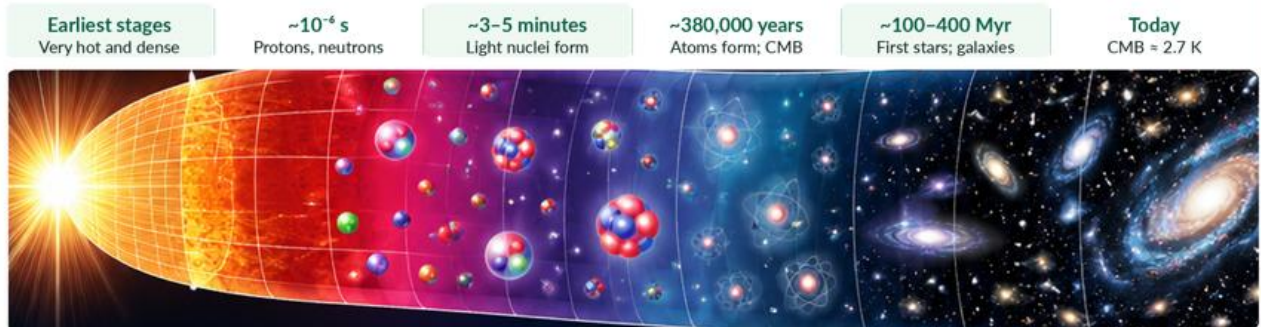
20 MARKS

OCR A Physics • 5.5.3 (j–o) • Complete all answers in your exercise book

Use the video and reliable scientific sources to explain how the Universe developed. Include key times, temperatures, evidence and accurate physics vocabulary.

A visual timeline of the Universe

Follow the stages in order. Illustrative timeline — NOT to scale.



Schematic, not to scale: expansion of space, not an explosion into existing space.

Research sources

WATCH • READ • CHECK

01 VIDEO



Moments after the Big Bang

bit.ly/35mQAXf

02 OCR A



Official H556 specification

Cosmology 5.5.3

03 NASA



Universe overview

Timeline and evidence

1 Chronology

[8]

Build a timeline of at least six milestones, from the hot early Universe to the first stars and galaxies.

Give estimated times for at least four stages and temperatures for at least three. Explain how expansion and cooling allowed particles, nuclei and neutral atoms to form.

Include the present age of the Universe and connect it to $t \approx 1/H_0$.

2 Cosmic microwave background

[5]

Explain why the early Universe was opaque, and why light could travel freely after neutral atoms formed.

Explain why this radiation is now observed as a microwave background of about 2.7 K.

Describe how the CMB supports the hot Big Bang model.

3 Expansion of space-time

[3]

Use galactic redshift and Hubble's law to explain the evidence that the Universe is expanding.

Explain why the Big Bang describes expansion of space, not an explosion into pre-existing empty space.

4 The Universe today

[4]

Research the approximate percentages of ordinary matter, dark matter and dark energy.

Explain how each contributes to the present-day Universe, including the roles of gravity and accelerated expansion.

Check your work

- ☐ At least six stages; specific times and temperatures
- ☐ Clear link between galactic redshift and expansion

- ☐ CMB origin, redshift and ≈ 2.7 K explained
- ☐ Composition explained; reliable sources used

Research note: Some early times are model-dependent. Use approximate values and name the source.





Fig. 23.1 gives some data on the wavelength of a hydrogen spectral line for light received from the Andromeda galaxy and the Virgo cluster of galaxies.

	wavelength of hydrogen line from galaxy / nm	wavelength of hydrogen line on Earth / nm
Andromeda galaxy	485.6	486.1
Virgo cluster	489.8	486.1

Fig. 23.1

- i. The Virgo cluster is 16.5 Mpc from the Earth.

Estimate the age of the Universe using data from Fig. 23.1.

age = _____ s [3]

- ii. Suggest why hydrogen spectral lines might often be used to measure a star's velocity.

.....

.....

.....

..... [2]

Answer: *Level 3 (5–6 marks)

Expect T1 and T2 for the Big Bang Theory
Expect full discussion of red shift points R1, 2, 3 and 4
Expect at least B1 and B2 for the Blue Shift
Expect C1 and any three from C2, C3, C4, C5 for CMBR

There is a well-developed line of reasoning which is clear and logically structured. The information presented is relevant and substantiated.

Level 2 (3–4 marks)

Expect T1 and T2 for the Big Bang Theory
Expect R1 and R2; red shift identified but no explanation why it implies an expanding Universe
Expect B1 and B2; blue shift identified with no explanation of cause
Expect any three from C1, 2, 3, 4 and 5; CMBR evidence recalled but linked to the Big Bang

There is a line of reasoning presented with some structure. The information presented is in the most-part relevant and supported by some evidence.

Level 1 (1–2 marks)

Expect T1 or T2 for the Big Bang Theory
Expect R1, R2 or B1, B2; red shift or blue shift identified but without explanation or link to Big Bang Theory
Expect at least one from C1, 2, 3, 4 and 5; CMBR evidence recalled but not linked to the Big Bang

Guidance: Big Bang Theory (T)

1. Predicts that all galaxies will be receding.
2. Galaxy velocity proportional to distance from Earth.

Red Shift (R)

1. Radiation from Virgo shows increase in wavelength or red shift
2. Change in wavelength caused by motion of galaxy or reference to Doppler Effect
3. Evidence that Virgo is receding from Earth.
4. Support for Big Bang theory.

Blue Shift (B)

1. Andromeda shows blue shift
2. Andromeda approaching Earth
3. Caused by gravitational attraction.

CMBR (C)

1. Formed as gamma radiation at Big Bang
2. Galactic red shift to microwave wavelength
3. Intensity is uniform in all directions
4. Corresponds to a temperature of 2.7K
5. (Very small) ripples in intensity corresponding to formation of first stars or galaxies.

*The Big Bang theory explains the origin and the evolution of the early Universe.
The table below shows the distance d and recession velocity v of some galaxies close to our own galaxy.

Galaxy	d / Mpc	$v / \text{km s}^{-1}$
NGC-5357	0.45	200
NGC-3627	0.90	650
NGC-4151	1.7	960
NGC-4472	2.0	850

Discuss the evidence for the Big Bang theory of the Universe. Use data in the table and your knowledge of electromagnetic radiation in your answer.

$$1 \text{ pc} = 3.1 \times 10^{16} \text{ m}$$

[6]

The chemical composition of the stars in our galaxy can be determined by analysing in the laboratory the absorption spectral lines for these stars.

The closest star to us is the Sun. The wavelength of the hydrogen-beta spectral line from the Sun is 486 nm.

- i. Use the information from the table to calculate the **observed** wavelength λ of the hydrogen-beta spectral line from a star in the galaxy NGC-4151.

$$\lambda = \text{-----} \text{ nm [3]}$$

- ii. A diffraction grating with 800 lines per mm is used to observe and analyse the light from the Sun in the laboratory.

A narrow beam of light from the Sun is incident normally at the diffraction grating.

Calculate the angle θ between the central beam of light through the grating and the hydrogen-beta spectral line in the **second** order spectrum.

$$\theta = \text{-----}^\circ \text{ [2]}$$

Answer: *Level 3 (5-6 marks)

Clear use of data and discussion of MBR.

There is a well-developed line of reasoning which is clear and logically structured. The information presented is relevant and substantiated.

Level 2 (3-4 marks)

Some use of data and discussion of MBR.

There is a line of reasoning presented with some structure. The information presented is in the most-part relevant and supported by some evidence.

Level 1 (1-2 marks)

Limited use of data or limited discussion of MBR.

The information is basic and communicated in an unstructured way. The information is supported by limited evidence and the relationship to the evidence may not be clear.

0 marks

No response or no response worthy of credit.

Marks: B1x6

Guidance:

Indicative scientific points may include:

Use of data

- The table of values for d and v support the idea of an expanding Universe.
- Calculate of H_0 more than once using data.
- $\text{age} = t = \frac{1}{H_0}$ used correctly to calculate t .
- Age calculated correctly in s or in y.
- Furthest galaxies travelling faster.
- Space expanding in all directions.
- Use data to plot graph of v against d to determine H_0 / graph of d against v to find t .
- More data needed since anomalies in the table.

Discussion of MBR (microwave background radiation)

- Early Universe extremely hot / very dense.
- High energy gamma photons existed in the early Universe.
- As space expanded the wavelength of these photons / waves 'stretched' out.
- We now observe this as microwave background radiation.
- Temperature of the Universe is now 2.7 K

$$\Delta\lambda = \frac{\lambda v}{c} = \frac{486 \times 10^{-9} \times 960 \times 10^3}{3.00 \times 10^8}$$

Answer: i)

i) $\Delta\lambda = 1.56 \text{ (nm)}$

i) $\lambda = 486 + 1.56 = 488 \text{ (nm)}$

ii) $d = 1.25 \times 10^{-6} \text{ m}$

$$\theta = \sin^{-1}\left(\frac{2 \times 488 \times 10^{-9}}{1.25 \times 10^{-6}}\right)$$

ii) $\theta = 51^\circ$

Marks: i) C1

i) C1

i) A1

ii) C1

ii) A1

Guidance: i)

i)

i)

ii)

ii) **Allow** 1 mark $\theta = \sin^{-1}\left(\frac{2 \times 488 \times 10^{-9}}{1.25 \times 10^{-6}}\right) = 51^\circ$; incorrect

488 nm used instead of 486 nm.

Additional challenge

The table gives data about the supergiant star Melnick 34 and the Sun.

Name	Radius / m	Surface temperature / K
Melnick 34	1.4×10^{10}	53 000
Sun	7.0×10^8	5 700

- (a) Calculate $\frac{\text{power output of Melnick 34}}{\text{power output of the Sun}}$.

answer = _____ (2)

- (b) Discuss why the evolution of a supergiant star in the local part of our galaxy could be dangerous for life on Earth.

(2)
(Total 4 marks)

Antares is a red supergiant star in the constellation of Scorpio. It has a mass about 18 times that of the Sun.

Eventually the star will become a supernova, leaving behind a core that could form a neutron star or a black hole.

- (a) State what is meant by a supernova.

(1)

- (b) State the defining properties of a neutron star.

(2)

- (c) To become a black hole it is likely that the core would have to have a mass at least twice that of the Sun.

Calculate the Schwarzschild radius of a black hole with a mass twice that of the Sun.

radius = _____ m

(2)

- (d) Some scientists are concerned about the consequences for the Earth of a supernova occurring in a nearby part of the galaxy.

Explain the cause of this concern.

(2)

(Total 7 marks)

NGC 3842 is a galaxy which contains one of the biggest black holes ever discovered.

- (a) State what is meant by a black hole.

(1)

- (b) The mass of the black hole in NGC 3842 is believed to be 1.0×10^{10} times greater than that of the Sun.

Calculate the radius of its event horizon.

radius = _____ m

(2)

- (c) NGC 3842 is 3.3×10^8 light years from the Earth, and is receding at a velocity of 6.3×10^4 m s⁻¹.

Estimate, using these data, an age in seconds for the Universe.

age of Universe = _____ s

(3)

(Total 6 marks)

- (a) Use of $P = \sigma AT^4$ ✓

$$\text{Ratio} = \frac{\sigma A_M T_M^4}{\sigma A_S T_S^4} =$$

$$\frac{(1.4 \times 10^{10})^2 \times 53000^4}{(7.0 \times 10^8)^2 \times 5700^4} = 3.0 \times 10^6 \checkmark$$

Award mp 1 for substituting data for either the Sun or Melnick 34

2

- (b) Star will undergo supernova collapse or

Star will form a neutron star/black hole ✓

which produces a gamma ray burst

and

consequence for life or reference to being highly collimated ✓

Examples of consequence for life: kills cells / damages DNA.

2

[4]

- (a) An object that produces a rapid increase in brightness ✓

Allow lowering in value of absolute magnitude

1

- (b) Extremely dense ✓

Ignore descriptions of Neutron star surface

1

Made up of neutrons ✓

Ignore refs to spinning or producing radio waves

1

- (c) Use of $R_s = 2GM / c^2$

To give

$$R_s = 2 \times 6.67 \times 10^{-11} \times 2 \times 2 \times 10^{30} / (3 \times 10^8)^2 \checkmark$$

First mark is for substitution

1

$$= 5.9 \times 10^3 \text{ m} \checkmark$$

Second mark for answer

1

- (d) Collapsing star can produce gamma ray bursts with energy similar to total output of Sun ✓

First mark is for gamma ray burst and an idea of the amount of energy

1

Highly collimated – if in direction of Earth, could cause mass extinction event ✓

Second mark is for consequence.

1

[7]

- (a) an object with an escape velocity greater than the speed of light ✓

Ignore references to singularity and density etc.

Allow gravity so strong light cannot escape.

1

- (b) mass of black hole = $1 \times 10^{10} \times 1.99 \times 10^{30} = 2 \times 10^{40}$ kg ✓

M correct for the first mark

Use of

$$R = 2GM / c^2$$

$$= 2 \times 6.67 \times 10^{-11} \times 2 \times 10^{40} / (3.00 \times 10^8)^2$$

$$= 3 \times 10^{13} \text{ m} \checkmark \quad \text{allow 2.9 or 2.95 etc.}$$

Final answer correct for the second mark.

Allow ce for the mass.

No sf penalty.

2

- (c) $V = Hd$
 $v \text{ (in kms}^{-1}\text{)} = 6300$

$$D \text{ (in MPc)} = 3.3 \times 10^8 / 3.26 \times 10^6$$

$$= 101 \checkmark$$

$$H = v / d = 6300 / 101 = 62 \text{ kms}^{-1} \text{ Mpc}^{-1} \checkmark$$

Alternatively.

$$\text{Age of universe} = 1 / H$$

$$= D / v$$

$$= 3.3 \times 10^8 \times 9.47 \times 10^{15} \checkmark / 6.3 \times 10^6 \checkmark$$

$$= 5.0 \times 10^{17} \text{ s} \checkmark$$

$$\begin{aligned} \text{age of Universe} &= 1 / H \\ &= 1 / 62 \\ &= 1.6 \times 10^{-2} \text{ Mpc s km}^{-1} \end{aligned}$$

$$\begin{aligned} &= 1.6 \times 10^{-2} \times 3.1 \times 10^{16} \times 10^6 / 10^3 \\ &= 5.0 \times 10^{17} \text{ s} \checkmark \end{aligned}$$

The first mark is for calculating D, the second for substituting correctly to find H

The third is for determining 1 / H in seconds.

If other value of H used, 1 mark max.

3

[6]

Consolidation: Stars

OCR A Physics | 5.5.1 (a)–(g) • Complete answers in your exercise book

Specification confidence check		R / A / G	Next step
(a)	Planets, satellites, comets, solar systems, galaxies and the Universe	☐ ☐ ☐	_____
(b)	Formation of stars: gravitational collapse, fusion and pressure balance	☐ ☐ ☐	_____
(c)	Low-mass stars: red giants, planetary nebulae and white dwarfs	☐ ☐ ☐	_____
(d)	White dwarfs: electron degeneracy and the Chandrasekhar limit	☐ ☐ ☐	_____
(e)	Massive stars: red supergiants, supernovae and compact remnants	☐ ☐ ☐	_____
(f)	Characteristics of neutron stars and black holes	☐ ☐ ☐	_____
(g)	Interpret HR diagrams: luminosity, temperature and star populations	☐ ☐ ☐	_____

Mixed application questions26 marks

- 1

Order planet, solar system, galaxy and Universe from smallest to largest. Explain how a comet differs from a planetary satellite.

[3]
- 2

Explain how the collapse of an interstellar gas cloud can produce a stable main-sequence star. Refer to heating, hydrogen fusion, gravity and gas/radiation pressure.

[4]
- 3

Explain how a Sun-like star evolves into a white dwarf after core hydrogen is exhausted. Include shell burning, red giant and planetary nebula stages.

[4]
- 4

A white dwarf approaches 1.4 solar masses. Explain how electron degeneracy pressure supports it and why this mass limit is important.

[3]
- 5

A high-mass star becomes a red supergiant. Explain how a supernova can leave behind either a neutron star or a black hole.

[4]
- 6

Compare neutron stars and black holes: what prevents further collapse, and can light escape?

[2]

7 HR diagram application[6]

Luminosity (relative to Sun)

Surface temperature / K (decreases →)

(a) Identify the four populations labelled A–D on the HR diagram.

(b) Explain how a white dwarf can have a high surface temperature but low luminosity.

Use the positions on the diagram to support your explanation.

Consolidation: Radiation from stars

OCR A Physics | 5.5.2 (a)–(k) • Complete answers in your exercise book

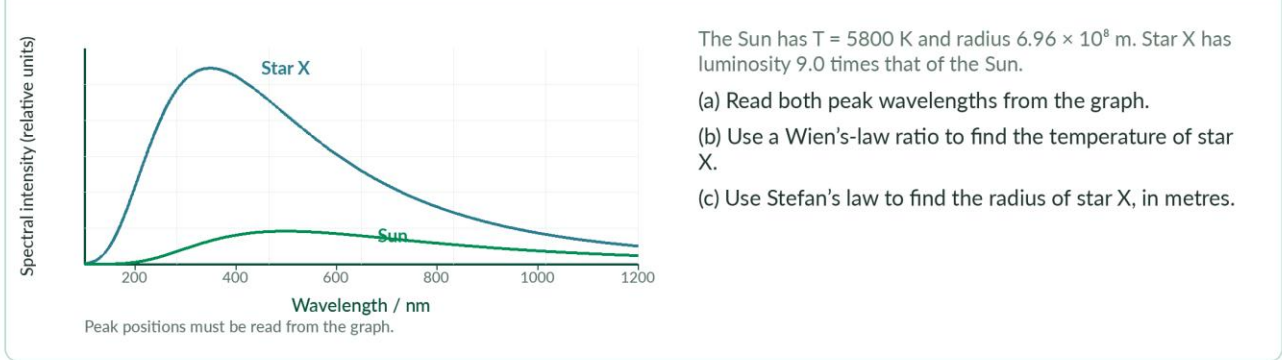
Specification confidence check		R / A / G	Next step
(a)	Discrete electron energy levels in isolated gas atoms	☐ ☐ ☐	_____
(b)	Negative energy levels and ionisation (zero energy at infinity)	☐ ☐ ☐	_____
(c)	Emission lines: electron transitions and photons	☐ ☐ ☐	_____
(d)	Photon energy: $hf = \Delta E = hc/\lambda$	☐ ☐ ☐	_____
(e)	Elements identified using characteristic spectral lines	☐ ☐ ☐	_____
(f)	Continuous, emission-line and absorption-line spectra	☐ ☐ ☐	_____
(g)	Transmission diffraction gratings measure wavelength	☐ ☐ ☐	_____
(h)	Grating maxima: $d \sin \theta = n\lambda$	☐ ☐ ☐	_____
(i)	Wien's law: peak wavelength and stellar surface temperature	☐ ☐ ☐	_____
(j)	Stefan's law: luminosity $L = 4\pi r^2 \sigma T^4$	☐ ☐ ☐	_____
(k)	Use Wien's and Stefan's laws to estimate stellar radius	☐ ☐ ☐	_____

Mixed application questions28 marks

Useful data: $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$ $h = 6.63 \times 10^{-34} \text{ J s}$ $c = 3.00 \times 10^8 \text{ m s}^{-1}$

- 1In an isolated hydrogen atom, an electron has energy -3.40 eV . Explain why this energy is negative and calculate the energy needed to ionise it from this state.[3]
- 2An electron falls from -1.51 eV to -3.40 eV . Explain why a photon is emitted and calculate its wavelength in nm.[4]
- 3Compare continuous, emission-line and absorption-line spectra. Explain how astronomers use absorption lines to identify elements in a star.[4]
- 4Light passes through a grating with $600 \text{ lines mm}^{-1}$. A first-order maximum is at 23.2° . Calculate the wavelength in nm and explain one use of this method in astronomy.[4]
- 5Two equal-radius stars have peak wavelengths 400 nm and 800 nm . Use Wien's and Stefan's laws to find their surface-temperature and luminosity ratios.[3]
- 6A very hot white dwarf can be much less luminous than a cooler red giant. Explain this using Stefan's law and the stars' sizes.[3]

7 Stellar temperature and radius[7]



Consolidation: Cosmology

OCR A Physics | 5.5.3 (a)–(o) • Complete answers in your exercise book

Specification confidence check		R / A / G	Next step
(a)	Distances: astronomical units (AU), light-years (ly) and parsecs (pc)	☐ ☐ ☐	_____
(b)	Stellar parallax and the distance defined by one parsec	☐ ☐ ☐	_____
(c)	Parallax calculation: $p = 1/d$ (arcsec and pc)	☐ ☐ ☐	_____
(d)	Cosmological principle: homogeneous, isotropic, universal laws	☐ ☐ ☐	_____
(e)	Doppler shift of electromagnetic radiation	☐ ☐ ☐	_____
(f)	Fractional wavelength / frequency shift and radial velocity	☐ ☐ ☐	_____
(g)	Hubble's law: recession speed proportional to galaxy distance	☐ ☐ ☐	_____
(h)	An expanding Universe supported by galactic redshift	☐ ☐ ☐	_____
(i)	Hubble constant in $\text{km s}^{-1} \text{Mpc}^{-1}$ and s^{-1}	☐ ☐ ☐	_____
(j)	The Big Bang model	☐ ☐ ☐	_____
(k)	Cosmic microwave background radiation at about 2.7 K	☐ ☐ ☐	_____
(l)	Expansion of space-time following the Big Bang	☐ ☐ ☐	_____
(m)	Estimating the age of the Universe: $t \approx 1/H_0$	☐ ☐ ☐	_____
(n)	Evolution of the Universe from the Big Bang to today	☐ ☐ ☐	_____
(o)	Ordinary matter, dark matter and dark energy	☐ ☐ ☐	_____

Mixed application questions30 marks

- Useful data: $c = 3.00 \times 10^8 \text{ m s}^{-1}$ $1 \text{ pc} = 3.26 \text{ ly}$ $1 \text{ Mpc} = 3.09 \times 10^{22} \text{ m}$ $1 \text{ year} = 3.15 \times 10^7 \text{ s}$
- 1

Define an astronomical unit and a light-year. A star has parallax $p = 0.20$ arcsec. Calculate its distance in pc and ly. Explain why measuring the parallax of distant stars is difficult.

[5]
- 2

The Universe contains galaxies and clusters. Explain how it can nevertheless satisfy the cosmological principle. Refer to homogeneity, isotropy and the laws of physics.

[3]
- 3

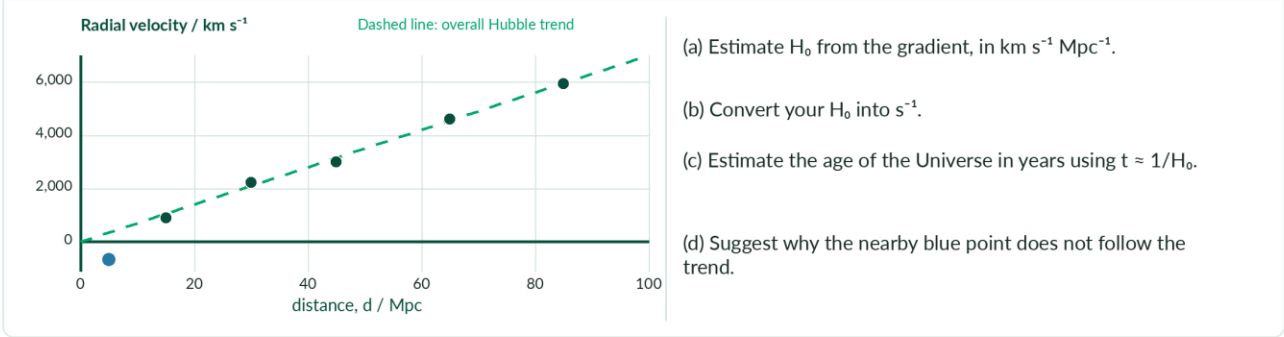
An absorption line is at 656.3 nm in the laboratory but 669.4 nm in a distant galaxy. Calculate the fractional redshift and radial speed. Explain the direction of motion and how the observed frequency changes.

[4]
- 4

A nearby galaxy has blueshifted absorption lines. Explain why this does not contradict the overall expansion of the Universe and why nearby galaxies can distort a Hubble graph.

[3]

5 Hubble graph: gradient and age7



- 6

Starting with a hot, dense early Universe, outline the formation of light nuclei, neutral atoms and eventually galaxies. Explain how the 2.7 K cosmic microwave background and galactic redshift support the Big Bang model of expanding space-time.

[5]
- 7

Ordinary matter forms only a small part of the Universe. Distinguish the roles of dark matter and dark energy in its structure and evolution.

[3]

Additional notes

★

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