

THEME E · NUCLEAR AND QUANTUM PHYSICS

SL & HL

≈ 30 min read

IB Physics E.5 Fusion and Stars — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). E.5 has **no additional higher level content**: everything on this page is examinable at both SL and HL. It draws on black-body radiation (B.1), the gas laws (B.3), spectra (E.1) and mass–energy (E.3, E.4).

 SL E.5 questions HL E.5 questions Flashcards Stars and HR diagram simulation

What this page covers

- ✓ Why a stable star neither collapses nor expands: the balance between outward radiation (and gas) pressure and inward gravity
- ✓ Nuclear fusion as the energy source of stars, and calculating the energy released
- ✓ Why fusion needs both a very high temperature and a very high density
- ✓ How the mass of a star decides how it evolves and how it ends
- ✓ Where main-sequence stars, red giants, supergiants and white dwarfs sit on the Hertzsprung–Russell (HR) diagram and what their properties are; where the instability strip and the lines of constant radius lie
- ✓ Measuring distance by stellar parallax, $d \text{ (parsec)} = \frac{1}{p \text{ (arc-second)}}$, and converting between AU, light years and parsecs
- ✓ Finding a star's surface temperature and composition from its spectrum, and its radius from its luminosity and surface temperature

In one minute

- A main-sequence star is in **equilibrium**: the outward force from radiation and gas pressure balances the inward gravitational force on every layer.
- The energy comes from **nuclear fusion** in the core: overall, four hydrogen nuclei become one helium nucleus, and about 0.7 % of the mass is released as energy ($E = mc^2$).
- Fusion needs a **high temperature** (nuclei fast enough to overcome their electrostatic repulsion) and a **high density** (collisions frequent enough).
- **Mass decides the life story**: stars up to about $8 M_{\odot}$ become red giants and end as white dwarfs; more massive stars become supergiants, explode as supernovae and leave neutron stars or black holes.
- HR diagram: luminosity up the vertical axis, surface temperature **decreasing** to the right. Main sequence, red giants, supergiants and white dwarfs occupy distinct regions.
- Distance: $d = 1/p$ (parsec, arc-second). Radius: $L = \sigma 4\pi R^2 T^4$, with T from Wien's law and $L = 4\pi d^2 b$.

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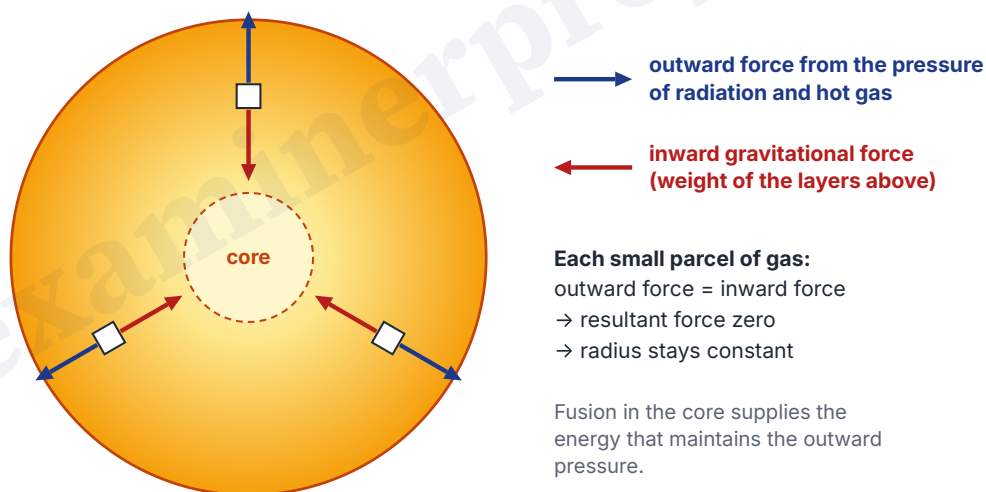
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Why does a star neither collapse nor fly apart?

A star is a huge ball of hot ionised gas (plasma) held together by its own gravity. Every layer is pulled towards the centre by the gravitational attraction of the mass inside it. If nothing opposed this, the star would collapse in less than an hour.

A star is stable when it is in equilibrium: the outward force due to radiation pressure (and the pressure of the hot gas) balances the inward gravitational force on every layer of the star.

- **Inward:** gravity. Each layer carries the weight of all the layers above it, so the pressure needed to hold it up is greatest at the centre.
- **Outward:** pressure. The energy released by fusion in the core flows outwards as radiation. Photons carry momentum, so they exert a **radiation pressure**; the very hot gas also exerts a large **gas (thermal) pressure**. Use the term radiation pressure, and always name it in an answer; you may add gas pressure.
- Because the two balance, the resultant force on each layer is zero and the star keeps a constant radius. This state is called **hydrostatic equilibrium** (the name is useful but not required).



Hydrostatic equilibrium. For every parcel of gas the outward force from pressure (blue) and the inward gravitational force (red) are equal in size and opposite in direction, so the arrows are drawn the same length.

Why is the equilibrium stable?

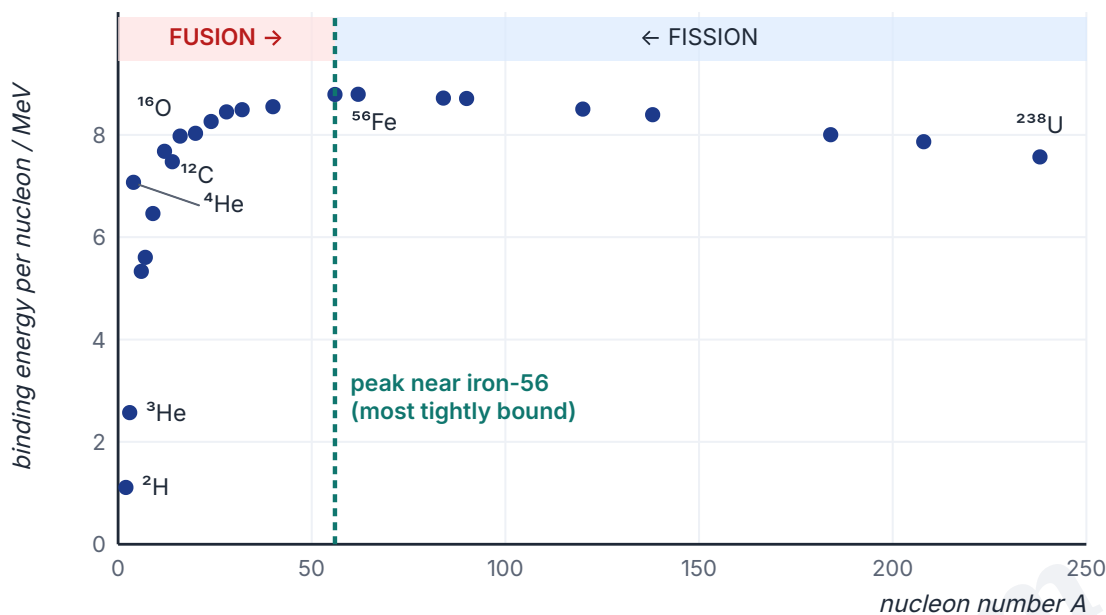
The balance corrects itself. If the fusion rate rises slightly, the extra energy raises the pressure, so the star expands a little. The expanding core cools and becomes less dense, the fusion rate falls, and the star settles back. If the fusion rate drops, gravity wins slightly, the core contracts and heats up, and the fusion rate rises again. This feedback keeps a main-sequence star almost unchanged for most of its life.

The equilibrium ends only when the core runs out of the nuclei it has been fusing. Then the outward pressure from the core falls, gravity wins, and the core contracts — the start of the changes described in section 4.

How does fusion supply a star's energy?

Nuclear fusion is the joining of two light nuclei to form a heavier nucleus. When the product has a greater binding energy per nucleon than the reactants, the total mass decreases and the mass difference is released as energy.

- Fusion of light nuclei releases energy because binding energy per nucleon **rises steeply** from hydrogen-2 to helium-4 and then, apart from a few dips, generally continues to rise up to the peak near iron-56 (E.3).
- The energy released is $E = mc^2$ applied to the **mass defect** of the reaction: (mass of reactants) – (mass of products). In atomic mass units, 1 u corresponds to 931.5 MeV (data booklet).
- Equivalently, energy released = (total binding energy of products) – (total binding energy of reactants).
- Most of the energy appears as kinetic energy of the products and as gamma-ray photons. It heats the core and eventually leaves the surface as the star's **luminosity**.

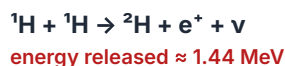


Binding energy per nucleon for selected stable nuclides (measured values). Fusing light nuclei moves up the steep left-hand side, so energy is released; fusion of nuclei heavier than about iron would absorb energy.

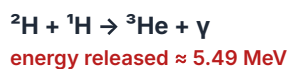
Hydrogen burning in the Sun

In the Sun, hydrogen is turned into helium mainly through the **proton–proton chain**. You do not need to recall every step, but you should know the overall change and that energy is released at each stage.

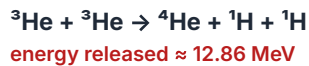
Stage 1 (happens twice)



Stage 2 (happens twice)



Stage 3



Overall: $4 ^1\text{H} \rightarrow ^4\text{He} + 2e^+ + 2\nu + 2\gamma$

total energy released = $2 \times \text{stage 1} + 2 \times \text{stage 2} + \text{stage 3}$ (see worked example 2)

proton neutron

Overview of the proton–proton chain. Stages 1 and 2 each happen twice for every helium-4 nucleus made. Two protons are returned in stage 3, so four protons are used overall. Energies are calculated from atomic masses, so the stage 1 value includes the energy from the annihilation of the positron.



- Charge is conserved: $+4e$ before, $+2e + 2e$ after. In stage 1 a proton changes into a neutron, emitting a positron and a neutrino — a β^+ process (E.3).
- The positrons quickly annihilate with electrons in the plasma, adding to the energy released.
- The neutrinos interact so weakly that they escape the Sun directly, carrying a few per cent of the energy with them.

EXAM TIP — WHICH MASSES TO USE

If a question gives **atomic** masses for the overall reaction $4 {}^1\text{H} \rightarrow {}^4\text{He}$, the electron masses take care of themselves: four hydrogen atoms contain four electrons, the helium atom contains two, and the two extra electrons annihilate the two positrons. If it gives **nuclear** masses, you must subtract the positron masses yourself. Read the stem carefully.

WORKED EXAMPLE 1 Medium · Show that / Calculate

The solar constant, the intensity of the Sun's radiation at the Earth, is $1.36 \times 10^3 \text{ W m}^{-2}$. The Earth–Sun distance is 1.00 AU.

(a) Show that the luminosity of the Sun is about $3.8 \times 10^{26} \text{ W}$. (b) Calculate the mass that the Sun loses every second because of the energy it radiates.

(a) The power spreads over a sphere of radius 1 AU = $1.50 \times 10^{11} \text{ m}$: $L = 4\pi d^2 b = 4\pi \times (1.50 \times 10^{11})^2 \times 1.36 \times 10^3 = \mathbf{3.85 \times 10^{26} \text{ W}} \approx 3.8 \times 10^{26} \text{ W}$

(b) Each second $E = 3.85 \times 10^{26} \text{ J}$ is radiated, so $m = \frac{E}{c^2} = \frac{3.85 \times 10^{26}}{(3.00 \times 10^8)^2} = \mathbf{4.3 \times 10^9 \text{ kg}}$ ($4.27 \times 10^9 \text{ kg}$) every second.

Context: with a solar mass of $2.0 \times 10^{30} \text{ kg}$, this is a fraction 6.7×10^{-14} of the Sun's mass per year — the Sun can shine for billions of years.

WORKED EXAMPLE 2 Medium · Calculate / Determine

Atomic masses: hydrogen-1 = 1.007825 u, helium-4 = 4.002603 u. Use the luminosity found in worked example 1.

(a) Calculate the energy, in MeV, released when four hydrogen-1 nuclei fuse to form one helium-4 nucleus. (b) Calculate the percentage of the initial mass converted to energy. (c) Determine the number of these fusion reactions taking place in the Sun every second.

(a) Mass defect = $4 \times 1.007825 - 4.002603 = 0.028697$ u.

$$E = 0.028697 \times 931.5 = \mathbf{26.7 \text{ MeV}} \text{ (26.73 MeV)}$$

Check with the stage energies in the proton–proton chain figure: $2 \times 1.44 + 2 \times 5.49 + 12.86 = 26.7$ MeV.

(b) $\frac{0.028697}{4 \times 1.007825} \times 100 = \mathbf{0.71 \%}$ — less than 1 % of the mass becomes energy.

(c) $26.73 \text{ MeV} = 26.73 \times 10^6 \times 1.60 \times 10^{-19} = 4.28 \times 10^{-12} \text{ J}$.

$$\text{Reactions per second} = \frac{3.85 \times 10^{26}}{4.28 \times 10^{-12}} = \mathbf{9.0 \times 10^{37} \text{ s}^{-1}}$$

This uses up about 6.0×10^{11} kg of hydrogen every second; only the 0.71 % mass decrease ($4.3 \times 10^9 \text{ kg s}^{-1}$) is radiated away.

What conditions does fusion need?

Fusion needs a very high temperature, so that nuclei collide fast enough to overcome their electrostatic repulsion, and a very high density, so that collisions happen often enough to sustain a significant rate of fusion.

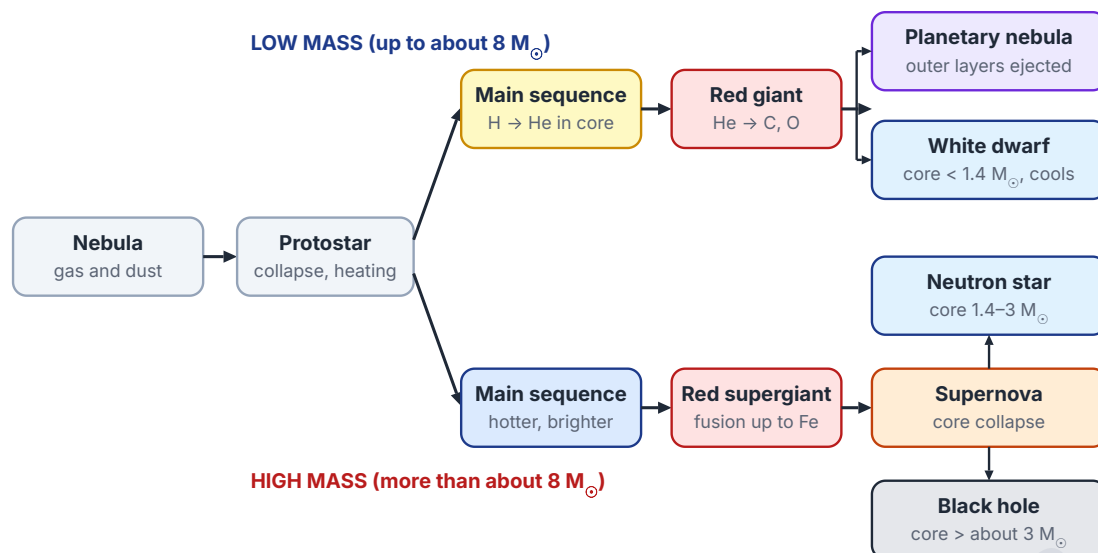
- **Temperature.** All nuclei are positively charged and repel each other. Only if they approach at very high speed do they get close enough (about 10^{-15} m) for the strong nuclear force to bind them. The mean kinetic energy of a particle is $\bar{E}_k = \frac{3}{2}k_B T$ (B.1), so a high kinetic energy needs a high temperature: the Sun's core is about $1.5 \times 10^7 \text{ K}$.

- **Density.** At a given temperature, only a tiny fraction of collisions lead to fusion. A very high density (more nuclei per unit volume) makes collisions frequent enough to release energy at the rate needed to support the star.
- **Gravity provides both.** When a cloud of gas and dust (a nebula) collapses under gravity, gravitational potential energy is transferred to the kinetic energy of the particles, so the gas heats up and becomes denser. When the core of the protostar becomes hot and dense enough, hydrogen fusion begins and the star joins the main sequence.
- Heavier nuclei have more charge, so they repel more strongly: fusing helium, carbon and oxygen needs progressively **higher core temperatures**. This is why only massive stars can fuse elements beyond carbon.

Quick estimate. At 1.5×10^7 K, $\bar{E}_k = \frac{3}{2} \times 1.38 \times 10^{-23} \times 1.5 \times 10^7 = 3.1 \times 10^{-16}$ J ≈ 1.9 keV. At the Sun's surface (5800 K) it is only 0.75 eV — far too little, which is why fusion happens only in the core.

How does a star's mass decide its evolution?

A star spends about 90 % of its life on the main sequence, fusing hydrogen into helium in its core. Its **mass** controls everything that follows. A more massive star has stronger gravity, so its core is hotter and denser, its fusion rate is far higher and its luminosity is much greater. It therefore uses up its hydrogen much faster: **massive stars have shorter lives**, even though they start with more fuel.



$M_{\odot}$ = mass of the Sun. Boundaries are approximate; it is the mass of the remnant core that decides the end point.

Evolutionary paths. All stars form from a collapsing nebula. After the main sequence, the path depends on mass: low-mass stars end as white dwarfs; high-mass stars explode as supernovae and leave a neutron star or a black hole.

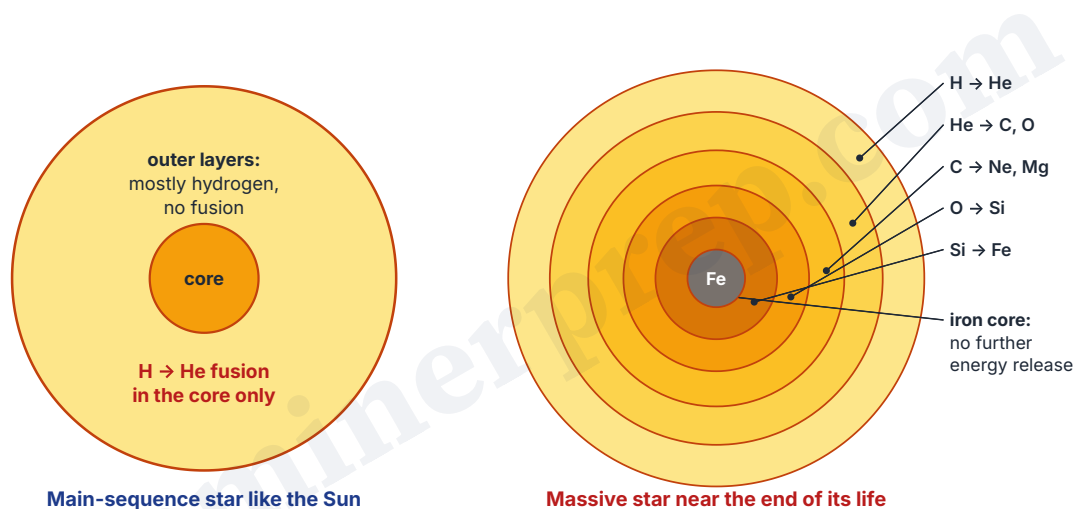
Low-mass stars (up to about 8 solar masses), including the Sun

- When the core hydrogen runs out, fusion in the core stops and gravity makes the core **contract and heat up**. Hydrogen continues to fuse in a shell around the core.
- The outer layers **expand enormously and cool**: the star becomes a **red giant** — larger, more luminous and with a lower surface temperature than before.
- The core becomes hot enough to fuse **helium into carbon** (and some oxygen). In a star like the Sun, the core never becomes hot enough for carbon fusion.
- The outer layers drift away as a **planetary nebula**, leaving the hot, exposed core: a **white dwarf**. No fusion occurs in a white dwarf; it is held up against gravity by electron pressure (a quantum effect) and simply cools over billions of years. A white dwarf can be stable only if its mass is below about **$1.4 M_{\odot}$** (the Chandrasekhar limit).

High-mass stars (more than about 8 solar masses)

- After the main sequence the star becomes a **red supergiant**. Its core reaches temperatures high enough to fuse successively heavier nuclei: helium $\rightarrow$ carbon and oxygen $\rightarrow$ neon and magnesium $\rightarrow$ silicon $\rightarrow$ iron, each stage in a shell surrounding the next.

- **Iron** sits at the peak of the binding-energy curve: fusing it would *absorb* energy. Once the core is iron, no energy is released to support it, so it **collapses** in a fraction of a second.
- The collapse rebounds as a **supernova** explosion that ejects the outer layers. Many nuclei heavier than iron are made by neutron capture during this explosion, and the products are scattered into space to form new stars and planets.
- The remnant core becomes a **neutron star** if its mass is between about $1.4 M_{\odot}$ and about $3 M_{\odot}$, or a **black hole** if it is larger.



Not to scale: the shells sit deep inside a red supergiant whose envelope is hundreds of times wider.

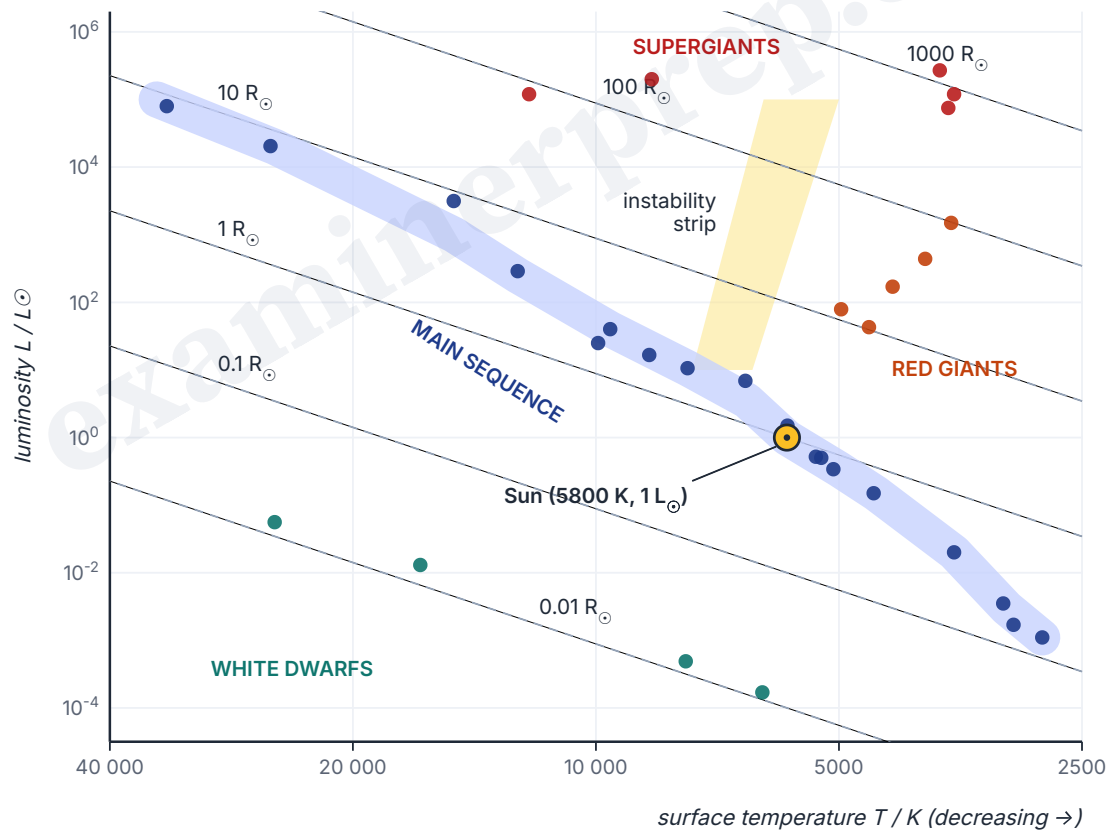
Cross-sections (not to scale). Left: a main-sequence star like the Sun fuses hydrogen only in its core. Right: near the end of its life a massive star has nested shells, each fusing a heavier nucleus, around an inert iron core.

Main-sequence mass	After the main sequence	Heaviest nucleus fused	End point
up to about $8 M_{\odot}$ (e.g. the Sun)	red giant → planetary nebula	carbon/oxygen (from helium fusion)	white dwarf (core $< 1.4 M_{\odot}$)
more than about $8 M_{\odot}$	red supergiant → supernova	iron	neutron star (core about $1.4\text{--}3 M_{\odot}$) or black hole (core above about $3 M_{\odot}$)

What does the Hertzsprung–Russell diagram show?

The Hertzsprung–Russell (HR) diagram is a graph of the luminosity of stars against their surface temperature, with temperature decreasing from left to right. Stars are not scattered at random but fall into distinct regions that reflect their stage of evolution.

- **Luminosity** L is the total power radiated by a star (W). It is often given in units of the Sun's luminosity, $L_{\odot}$. Both axes are usually **logarithmic** because the values range over many orders of magnitude.
- Surface temperature runs from about 40 000 K on the left to about 2500 K on the right. Hot stars appear blue-white; cool stars appear red.



HR diagram plotted from measured temperatures and luminosities of well-known stars (blue: main sequence; orange: red giants; red: supergiants; green: white dwarfs). The Sun is marked $\odot$. Dashed lines are lines of constant radius from $L = \sigma 4\pi R^2 T^4$; the yellow band is the instability strip.

Region	Position on HR diagram	Main properties
Main sequence	diagonal band from hot and luminous (top left) to cool and dim (bottom right)	fusing hydrogen into helium in the core; in equilibrium; position set by mass — more massive stars are hotter, more luminous, larger and shorter-lived. Radii from about $0.1 R_{\odot}$ to about $10 R_{\odot}$.
Red giants	above and to the right of the main sequence	cool surface (about 3000–5000 K) but luminous (about 10 – $1000 L_{\odot}$) because very large (about 10 – $100 R_{\odot}$); core hydrogen exhausted; hydrogen fusing in a shell around the core, and later helium fusing in the core.
Supergiants	across the top of the diagram	the most luminous stars (about 10^4 – $10^6 L_{\odot}$); radii up to about $1000 R_{\odot}$; evolved high-mass stars fusing heavier elements; may be red or blue.
White dwarfs	bottom left	hot surface (often $> 10\,000$ K) but very dim (about 10^{-4} – $10^{-2} L_{\odot}$) because tiny (about $0.01 R_{\odot}$, the size of the Earth); no fusion; cooling remnant cores of low-mass stars.
Instability strip	near-vertical band rising from the main sequence (at about 6500–7500 K) towards the supergiants, leaning slightly towards lower temperatures	stars that pulsate: they expand and contract periodically, so their luminosity varies with a regular period.

Lines of constant radius

From the Stefan–Boltzmann law, $L = \sigma 4\pi R^2 T^4$. For stars of the same radius, $L \propto T^4$, so on log–log axes every line of constant radius is a **straight line**, sloping down from upper left to lower right. Moving up and to the *right* on the diagram means a larger star: cool but very luminous stars must be giants. Moving down and to the *left* means a smaller star: hot but dim stars must be tiny.

A star's track across the diagram shows its evolution. The Sun will move up and to the right as it becomes a red giant, then down and to the left to become a white dwarf.

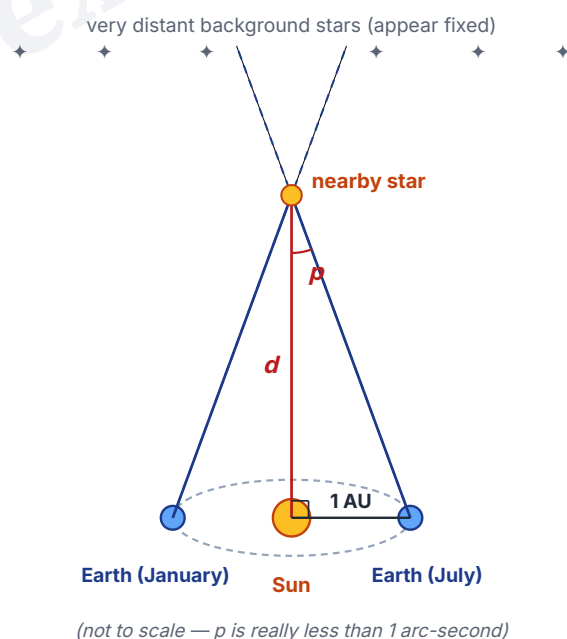
TRY IT YOURSELF

E.5 Stars and HR diagram simulation: change a star's temperature and luminosity, see where it sits on the HR diagram and how its radius changes, and follow the evolutionary paths of stars of different masses.

How is stellar parallax used to measure distance?

As the Earth orbits the Sun, a nearby star appears to move against the background of much more distant stars. Measuring this shift six months apart gives the star's distance by simple geometry.

The parallax angle p of a star is half the angular shift of the star against the distant background over six months; it is the angle subtended at the star by a baseline of 1 AU. A star with a parallax angle of one arc-second is at a distance of one parsec.



View through the telescope:
the nearby star shifts against the background by an angle $2p$ over six months

$$d \text{ (parsec)} = 1 / p \text{ (arc-second)}$$

Stellar parallax. Observations six months apart (January and July) use the diameter of the Earth's orbit as a baseline. The parallax angle p is the angle at the star subtended by 1 AU, the Earth–Sun distance.

$$d (\text{parsec}) = \frac{1}{p (\text{arc-second})}$$

- d = distance to the star (pc), p = parallax angle (arc-seconds). In the data booklet. The equation works **only** with these units.
- $1 \text{ arc-second} = \frac{1}{3600}$ of a degree. Because p is tiny, $\tan p \approx p$ (in radians), so $d = \frac{1 \text{ AU}}{p}$ — this is what defines the parsec.
- Smaller parallax angle means a more distant star. Ground-based telescopes can measure angles down to roughly $0.01''$ (about 100 pc); space telescopes above the atmosphere measure far smaller angles and reach thousands of parsecs.

Unit	Definition	Value (data booklet)
astronomical unit (AU)	mean distance from the Earth to the Sun	$1 \text{ AU} = 1.50 \times 10^{11} \text{ m}$
light year (ly)	distance travelled by light in a vacuum in one year	$1 \text{ ly} = 9.46 \times 10^{15} \text{ m}$ ($\approx 63\,000 \text{ AU}$)
parsec (pc)	distance at which 1 AU subtends an angle of 1 arc-second	$1 \text{ pc} = 3.26 \text{ ly}$ ($\approx 3.08 \times 10^{16} \text{ m} \approx 2.06 \times 10^5 \text{ AU}$)

WORKED EXAMPLE 3 Easy · Calculate

The parallax angle of a star is measured to be 0.286 arc-seconds.

- (a) Calculate the distance to the star in parsecs, in light years and in metres.
 (b) State the parallax angle of a star twice as far away.

$$\text{(a)} \quad d = \frac{1}{0.286} = \mathbf{3.50 \text{ pc}}$$

$$3.50 \times 3.26 = \mathbf{11.4 \text{ ly}}$$

$$11.4 \times 9.46 \times 10^{15} = \mathbf{1.08 \times 10^{17} \text{ m}}$$

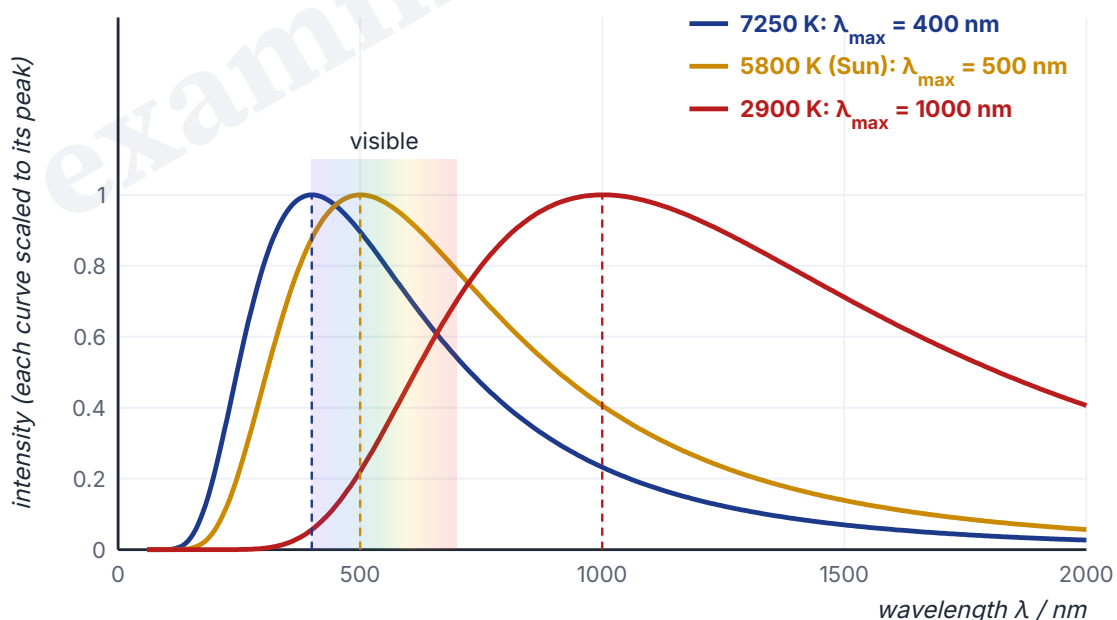
$$\text{(b)} \quad p \propto \frac{1}{d}, \text{ so the angle halves: } \mathbf{0.143 \text{ arc-seconds}}$$

Light from this star takes 11.4 years to reach us — the distance in light years tells you the travel time in years.

How do we find a star's temperature, composition and radius?

Information from the spectrum

- **Surface temperature.** A star radiates approximately as a black body (B.1). The wavelength at which the intensity peaks gives the surface temperature through **Wien's displacement law**, $\lambda_{\text{max}} T = 2.9 \times 10^{-3} \text{ m K}$ (data booklet). Hotter stars peak at shorter wavelengths and look bluer.
- **Composition.** The continuous spectrum is crossed by dark **absorption lines**. Atoms in the cooler outer layers absorb photons whose energies match differences between their energy levels (E.1). Each element has its own pattern of lines, so the lines identify the elements present in the star's **outer layers**.



Black-body spectra (each scaled to its own peak) for surface temperatures of 7250 K, 5800 K and 2900 K. The peak wavelength is inversely proportional to the temperature, so $\lambda_{\text{max}} = 400 \text{ nm}$, 500 nm and 1000 nm : halving the temperature doubles the peak wavelength. The visible band is shaded.

Luminosity, apparent brightness and radius

$$L = \sigma AT^4 = \sigma 4\pi R^2 T^4 \qquad b = \frac{L}{4\pi d^2}$$

- L = luminosity (W), σ = Stefan–Boltzmann constant $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$, A = surface area (m^2), R = radius of the star (m), T = surface temperature (K), b = apparent brightness (W m^{-2}), d = distance (m).
- $L = \sigma AT^4$ and $b = \frac{L}{4\pi d^2}$ are in the data booklet (B.1). The surface area of a sphere, $A = 4\pi R^2$, is **not**, so learn it.
- **Apparent brightness** is what we measure at the Earth; **luminosity** is the power the star emits. A dim-looking star may be very luminous but far away.

To determine a stellar radius: find the distance (parallax), measure the apparent brightness and use $L = 4\pi d^2 b$; find the surface temperature from

$$\lambda_{\text{max}}; \text{ then } R = \sqrt{\frac{L}{4\pi\sigma T^4}}.$$

Comparing with the Sun avoids the constants. Dividing $L = \sigma 4\pi R^2 T^4$ for the star by the same equation for the Sun:

$$\frac{R}{R_{\odot}} = \sqrt{\frac{L}{L_{\odot}}} \left(\frac{T_{\odot}}{T} \right)^2$$

This ratio form is not in the data booklet; it follows directly from $L = \sigma AT^4$. Solar values ($L_{\odot}$, $R_{\odot}$, $T_{\odot}$) are given in a question when they are needed.

WORKED EXAMPLE 4 Medium · Determine (HR diagram) / Explain

A star has a luminosity of $0.010 L_{\odot}$ and a surface temperature of 11 600 K. The surface temperature of the Sun is 5800 K and its radius is $6.96 \times 10^8 \text{ m}$.

- (a) Determine the radius of the star in terms of the Sun's radius, and in metres. (b) Calculate the wavelength at which the star's emission peaks. (c) Identify the region of the HR diagram in which the star lies and explain why it is so dim despite being hot.

$$(a) \frac{R}{R_{\odot}} = \sqrt{0.010} \times \left(\frac{5800}{11\,600} \right)^2 = 0.10 \times 0.25 = \mathbf{0.025 R_{\odot}}$$

$R = 0.025 \times 6.96 \times 10^8 = \mathbf{1.7 \times 10^7 \text{ m}}$ ($1.74 \times 10^7 \text{ m}$) — less than three times the radius of the Earth.

$$(b) \lambda_{\max} = \frac{2.9 \times 10^{-3}}{11\,600} = \mathbf{2.5 \times 10^{-7} \text{ m}}$$
 (250 nm, ultraviolet)

(c) High temperature and low luminosity place it at the **bottom left**: it is a **white dwarf**. Each square metre of its surface emits $2^4 = 16$ times as much power as the Sun's, but its surface area is only $0.025^2 = 6.25 \times 10^{-4}$ of the Sun's, so its total luminosity is small.

WORKED EXAMPLE 5 Medium · Determine (binding energy) / Explain

Near the end of its life, the core of a massive star is hot enough for oxygen-16 nuclei to fuse with each other: ${}^{16}_8\text{O} + {}^{16}_8\text{O} \rightarrow {}^{28}_{14}\text{Si} + {}^4_2\text{He}$. Binding energies per nucleon: oxygen-16 = 7.976 MeV, silicon-28 = 8.448 MeV, helium-4 = 7.074 MeV.

(a) Determine the energy released in this reaction. (b) Explain why the core of a massive star cannot continue to release energy by fusing iron-56.

(a) Total binding energies: two O-16: $2 \times 16 \times 7.976 = 255.232 \text{ MeV}$; Si-28: $28 \times 8.448 = 236.544 \text{ MeV}$; He-4: $4 \times 7.074 = 28.296 \text{ MeV}$.

Energy released = $(236.544 + 28.296) - 255.232 = \mathbf{9.61 \text{ MeV}}$

(b) Iron-56 has (close to) the **greatest binding energy per nucleon**. Fusing iron would produce nuclei with a *lower* binding energy per nucleon, so the products would have more mass than the reactants and energy would have to be **supplied**, not released. With no energy release to maintain the outward pressure, the iron core collapses.

WORKED EXAMPLE 6 Hard · Determine / Suggest

Measurements of a star give: parallax angle 0.0250 arc-seconds; apparent brightness $6.0 \times 10^{-9} \text{ W m}^{-2}$; peak wavelength of its spectrum 750 nm. Data for the Sun: $L_{\odot} = 3.83 \times 10^{26} \text{ W}$, $R_{\odot} = 6.96 \times 10^8 \text{ m}$.

(a) Calculate the distance to the star in metres. (b) Determine the luminosity of the star in W and in terms of $L_{\odot}$. (c) Determine the radius of the star in terms of $R_{\odot}$. (d) Suggest, with a reason, the stage of evolution of the star.

$$\text{(a)} \quad d = \frac{1}{0.0250} = 40.0 \text{ pc} = 40.0 \times 3.26 \times 9.46 \times 10^{15} = \mathbf{1.23 \times 10^{18} \text{ m}}$$

$$\text{(b)} \quad L = 4\pi d^2 b = 4\pi \times (1.234 \times 10^{18})^2 \times 6.0 \times 10^{-9} = \mathbf{1.1 \times 10^{29} \text{ W}} \quad (1.15 \times 10^{29} \text{ W})$$

$$\frac{L}{L_{\odot}} = \frac{1.15 \times 10^{29}}{3.83 \times 10^{26}} = \mathbf{300 L_{\odot}}$$

$$\text{(c)} \quad T = \frac{2.9 \times 10^{-3}}{750 \times 10^{-9}} = \mathbf{3870 \text{ K}}.$$

$$R = \sqrt{\frac{L}{4\pi\sigma T^4}} = \sqrt{\frac{1.15 \times 10^{29}}{4\pi \times 5.67 \times 10^{-8} \times 3870^4}} = \mathbf{2.68 \times 10^{10} \text{ m}}$$

$$\frac{R}{R_{\odot}} = \frac{2.68 \times 10^{10}}{6.96 \times 10^8} = \mathbf{39 R_{\odot}} \quad (\text{accept } 38\text{--}39)$$

(d) Cool surface (3870 K), high luminosity ($300 L_{\odot}$) and large radius (about $40 R_{\odot}$) place it above and to the right of the main sequence: a **red giant**. Its core hydrogen is exhausted, so it has left the main sequence: hydrogen now fuses in a shell around the core, and the core fuses (or will soon fuse) helium.

Exam tips for E.5

EXAM TIP 1 — SAY "SURFACE" OR "CORE"

When comparing stars, always state **which** temperature you mean. A red giant has a **lower surface temperature** but a **higher core temperature** than the Sun. "The red giant is cooler" is ambiguous and is not credited.

EXAM TIP 2 — LUMINOSITY IS NOT BRIGHTNESS

Luminosity is the total **power** emitted (unit W, or J s^{-1}); apparent brightness is the power received **per unit area** at the Earth (W m^{-2}). Write “more luminous”, not “brighter”, when you mean the star emits more power.

EXAM TIP 3 — EQUILIBRIUM NEEDS DIRECTION

For the stability of a star, name **both** forces and their directions: outward force due to radiation (gas) pressure, inward gravitational force, and say they are **balanced / equal in magnitude**. “Pressure balances gravity” on its own loses marks if the direction or the word “force” is missing from the comparison.

EXAM TIP 4 — UNITS IN PARALLAX AND RADIUS PROBLEMS

$d = 1/p$ gives parsecs only when p is in arc-seconds. Before using $L = 4\pi d^2 b$ or $L = \sigma 4\pi R^2 T^4$, convert to **metres** (1 pc = 3.26 ly, 1 ly = 9.46×10^{15} m). For radius ratios, the ratio method avoids conversions — but remember to **square** the temperature ratio and take the **square root** of the luminosity ratio.

EXAM TIP 5 — SKETCHING AN HR DIAGRAM

Label the axes “luminosity” (vertical) and “surface temperature” (horizontal) with temperature **increasing to the left**. Put the main sequence as a diagonal band from top left to bottom right, red giants above-right of it, supergiants across the top, white dwarfs bottom left. Mark the Sun on the main sequence at about 5800 K and $1 L_{\odot}$.

Common misconceptions

Misconception	Why it is wrong	Correct idea
Stars shine because they are burning (chemical combustion).	Even the best chemical fuels release about ten million times less energy per kilogram than hydrogen fusion — a chemically burning Sun would last less than ten thousand years.	Stars are powered by nuclear fusion in the core.
Massive stars live longer because they have more fuel.	Their luminosity is enormously greater, so they use fuel much faster.	The more massive the star, the shorter its main-sequence lifetime.
A white dwarf is dim because it is cold.	White dwarfs have high surface temperatures, often above 10 000 K.	They are dim because their surface area is tiny (about the size of the Earth).
Red giants are red because they are hot.	Red light means the black-body peak is at long wavelengths, i.e. a low surface temperature.	Red giants have cool surfaces but are very luminous because they are very large.
The parallax angle is the whole shift of the star over six months.	The whole shift corresponds to a 2 AU baseline.	p is half the total angular shift; it is the angle subtended by 1 AU.
Stars fuse elements all the way up to uranium.	Beyond iron, fusion absorbs energy, because binding energy per nucleon decreases.	Fusion in stars stops at iron; heavier elements are made by neutron capture, much of it in supernovae.

How this topic connects

Fusion and fission side by side: shared principles, opposite directions

Alike: in both, the products have a greater binding energy per nucleon than the reactants, so the mass decreases and energy $E = \Delta mc^2$ is released, mostly as

kinetic energy of the products (E.4). **Unlike:** fusion joins light nuclei (left of the iron peak) whereas fission splits very heavy nuclei (right of the peak). Fusion releases more energy per unit mass of fuel (about 0.7 % of the mass, compared with about 0.1 % for uranium fission), needs extremely high temperatures and densities rather than a critical mass, and its main product, helium, is not radioactive. Fission is triggered by neutron absorption and can run as a chain reaction at ordinary temperatures, which is why it, not fusion, powers today's nuclear power stations.

Stars as black bodies: temperature and radius from their radiation

Treating a star as a black body (B.1) lets us read its **surface temperature** from the peak wavelength of its spectrum using Wien's law. Combined with its **luminosity** (from apparent brightness and distance), the Stefan–Boltzmann law $L = \sigma 4\pi R^2 T^4$ then gives its **radius**, which no telescope could measure directly. The same laws produce the lines of constant radius on the HR diagram and explain why the colour of a star indicates its temperature.

A star as an ideal gas: modelling stellar stability with the gas laws

The plasma in a star behaves approximately as an ideal gas (B.3), $PV = nRT$: the pressure depends on the temperature and the density. This simple model explains the self-regulation of a star — if the core contracts, its temperature and density rise, the pressure rises and pushes back. It also explains why a collapsing nebula heats up (work done on the gas by gravity increases its internal energy). The model is approximate: at the very high densities of white dwarfs and neutron stars the ideal-gas model fails and quantum effects provide the pressure — a reminder that models have limits of validity.

Tools & NOS — observing stars and classifying them

- **Technology and data:** the Earth's atmosphere blurs images and absorbs ultraviolet and infrared. Space telescopes avoid both and have measured parallax angles hundreds of times smaller than ground-based instruments can, extending distance measurements from about 100 pc to thousands of parsecs. CCD cameras and spectrometers record brightness and spectra digitally.

- **Uncertainty:** the percentage uncertainty in d equals the percentage uncertainty in p . For distant stars p is so small that its uncertainty dominates, which is why parallax works only for relatively nearby stars.
- **Classification and patterns (NOS):** plotting thousands of stars on the HR diagram revealed a pattern — most lie on the main sequence — that pointed to an underlying cause (hydrogen fusion and the role of mass). Classification also guides other areas of physics: the types of nuclear radiation (alpha, beta, gamma) in E.3, and the phases of matter in B.1.
- **Indirect measurement:** almost nothing about a star is measured directly. Temperature, composition, radius and distance are all *inferred* from light using physical laws, so the reliability of each conclusion rests on the validity of those laws.

Key equations

Equation	Use	In data booklet?
$d(\text{parsec}) = \frac{1}{p(\text{arc-second})}$	distance from parallax	yes (E.5)
1 pc = 3.26 ly; 1 ly = 9.46×10^{15} m; 1 AU = 1.50×10^{11} m	distance conversions	yes (unit conversions)
$E = mc^2$; 1 u = 931.5 MeV c ⁻²	energy released in fusion from the mass defect	yes (E.3, constants)
$L = \sigma AT^4$	luminosity from radius and surface temperature	yes (B.1)
$A = 4\pi R^2$	surface area of a spherical star	no — learn it
$b = \frac{L}{4\pi d^2}$	apparent brightness at distance d	yes (B.1)
$\lambda_{\text{max}}T = 2.9 \times 10^{-3} \text{ m K}$	surface temperature from the spectrum	yes (B.1)
$\frac{R}{R_{\odot}} = \sqrt{\frac{L}{L_{\odot}}} \left(\frac{T_{\odot}}{T} \right)^2$	radius compared with the Sun	no — from $L = \sigma AT^4$
$\bar{E}_k = \frac{3}{2}k_B T$	mean kinetic energy of particles in a hot core	yes (B.1)

Check your understanding

1. A star is 4.2 ly from the Earth. Calculate its distance in parsecs and its parallax angle.

$$d = \frac{4.2}{3.26} = 1.29 \text{ pc (1.3 pc)}. p = \frac{1}{d} = \frac{1}{1.29} = 0.78 \text{ arc-seconds.}$$

2. Explain why a main-sequence star does not collapse under its own gravity.

Fusion in the core releases energy that maintains a high outward radiation (and gas) pressure. The resulting outward force on each layer is equal and opposite to the inward gravitational force, so the resultant force is zero and the star stays the same size.

3. A star has the same surface temperature as the Sun but 400 times its luminosity. Determine its radius in terms of the Sun's radius and suggest what type of star it is.

Same T , so $L \propto R^2$: $\frac{R}{R_{\odot}} = \sqrt{400} = 20$. A star of $20 R_{\odot}$ at a Sun-like temperature lies above the main sequence: a **giant**.

4. A main-sequence star has a mass of 20 solar masses. Outline the stages of its evolution after the main sequence and state its likely end point.

Its core hydrogen runs out and it becomes a red supergiant, fusing successively heavier elements in shells up to iron. The iron core cannot release energy by fusion and collapses, producing a supernova. The remnant core becomes a **neutron star**, or a **black hole** if the remnant mass exceeds about $3 M_{\odot}$.

5. The spectrum of a star peaks at 290 nm. Calculate its surface temperature and state one piece of information that the dark lines in its spectrum provide.

$T = \frac{2.9 \times 10^{-3}}{290 \times 10^{-9}} = 1.0 \times 10^4 \text{ K}$. The absorption lines identify the **elements present** in the star's outer layers (its composition), since each element absorbs at its own characteristic wavelengths.

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Original Paper 1A, 1B and 2 questions on fusion and stars, with full mark schemes. Tick the questions you want and print them as your own test.

SL E.5 questions

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