IB DP PHYSICS · THEME E NUCLEAR AND QUANTUM PHYSICS · E.5 · ~6 MIN READ

E.5 Fusion and stars

Fusion and the conditions it needs, stellar equilibrium, the energy source of stars, stellar parallax, the Hertzsprung–Russell diagram, and the evolution of stars into white dwarfs, neutron stars and black holes.

Nuclear fusion | Conditions for fusion | Stellar equilibrium | Parallax & the parsec | HR diagram | Stellar evolution | White dwarfs, neutron stars, black holes

RS by Riyaz Sir
mentorriyaz.in

No tag = **SL and HL** HL ONLY HL students only DATA BOOKLET given in the exam

M1 A1 how marks are awarded highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

- **Fusion** joins light nuclei into heavier ones. The products have a higher binding energy per nucleon, so energy is released. Stars are powered by fusing hydrogen into helium.
- Fusion needs **very high temperature** (to overcome the electric repulsion) and **high density** (so collisions are frequent).
- A main-sequence star is stable because the inward pull of **gravity** balances the outward **radiation and gas pressure** from fusion.
- Stars are mapped on the **Hertzsprung–Russell diagram** (luminosity against temperature). Their mass decides their fate: white dwarf, neutron star or black hole.
- **E.5 is the same at SL and HL.**

BY THE END YOU CAN

- Explain why fusion releases energy and the conditions it needs.
- Explain the equilibrium of a main-sequence star.
- Measure stellar distances with parallax and the parsec.
- Read and interpret the HR diagram, including using luminosity and temperature to compare radii.
- Describe the evolution of low-mass and high-mass stars and their end points.

1 Fusion

$$4\,{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{0}_{+1}\mathrm{e} + 2\nu + \text{energy}$$

overall result of the proton–proton chain in the Sun (about 26.7 MeV)

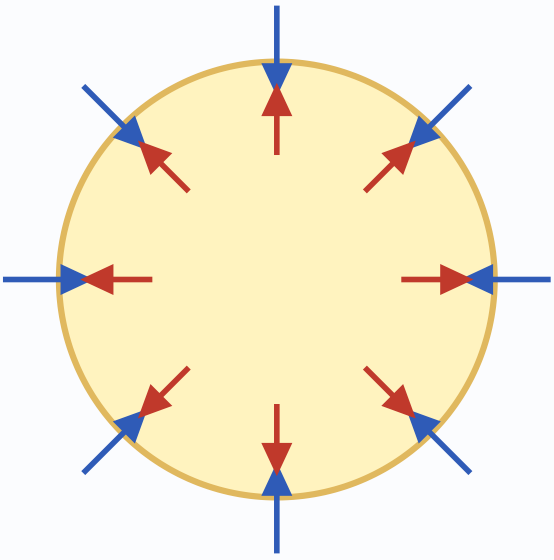
- **Why it releases energy:** on the binding-energy curve (E.3) light nuclei sit on the steep rising part, so building them up raises the binding energy per nucleon.
- **Conditions:** nuclei are positive and repel. They need enough kinetic energy to get within range of the strong force: temperatures of about 10^7 K, and high density for enough collisions. The Sun's core provides both; on Earth, magnetic confinement (tokamaks) is still experimental.

WORKED EXAMPLE

The Sun's luminosity is 3.8×10^{26} W. How much mass does it convert to energy each second?

1. $\Delta m = E/c^2 = 3.8 \times 10^{26}/(3.0 \times 10^8)^2$ M1
2. **$= 4.2 \times 10^9$ kg s^{-1}** A1

2 Stellar equilibrium

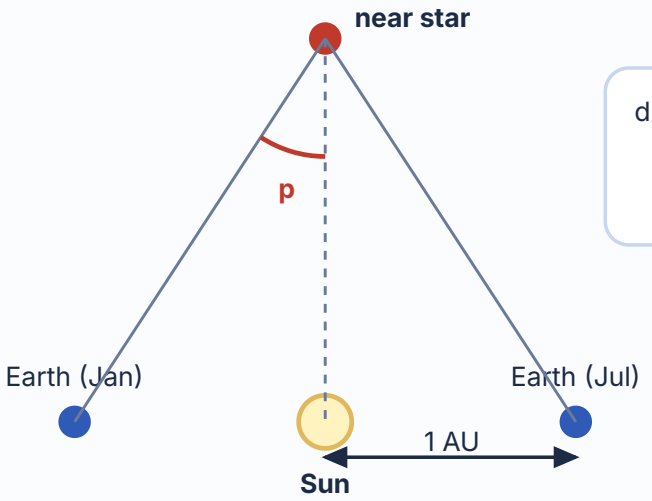


blue: gravity pulls inward
red: radiation and gas pressure from fusion push outward
balanced = stable star

Hydrostatic equilibrium: gravity in, pressure out.

- If fusion slowed, pressure would drop, the core would contract and heat up, and fusion would speed up again: the balance is self-correcting. When hydrogen in the core runs out, the balance shifts and the star changes stage.

3 Distances: parallax



d (pc) = 1/p (arcsec)

1 pc ≈ 3.26 ly

A near star seems to move against distant stars as the Earth orbits. The smaller the shift, the further the star.

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

1 pc ≈ 3.26 light-years ≈ 3.09×10^{16} m

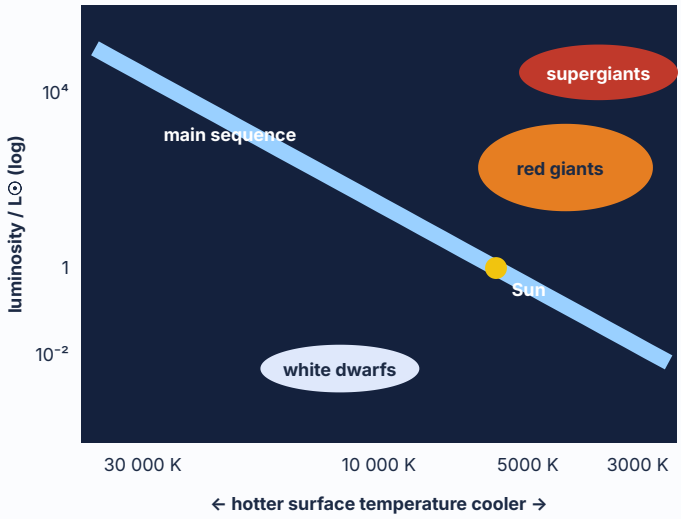
WORKED EXAMPLE

A star has a parallax angle of 0.20 arc-seconds. Find its distance.

1. d = 1/0.20 = **5.0 pc** A1
2. **= 5.0 × 3.26 = 16 light-years** A1

- **Limits:** parallax angles become too small to measure beyond a few hundred parsecs from the ground (further with satellites such as Gaia).

4 The Hertzsprung–Russell diagram



Most stars, including the Sun, are on the main sequence. Temperature increases to the LEFT.

- **Axes:** luminosity (log scale, often in solar luminosities) against surface temperature, decreasing to the right. Colour runs from blue (hot) on the left to red (cool) on the right.
- **Reading radius:** $L = \sigma(4\pi R^2)T^4$ (B.1). Red giants are cool but very luminous, so they must be huge; white dwarfs are hot but dim, so they must be tiny.

WORKED EXAMPLE

A red giant has the same surface temperature as a main-sequence star but 10 000 times its luminosity. Compare their radii.

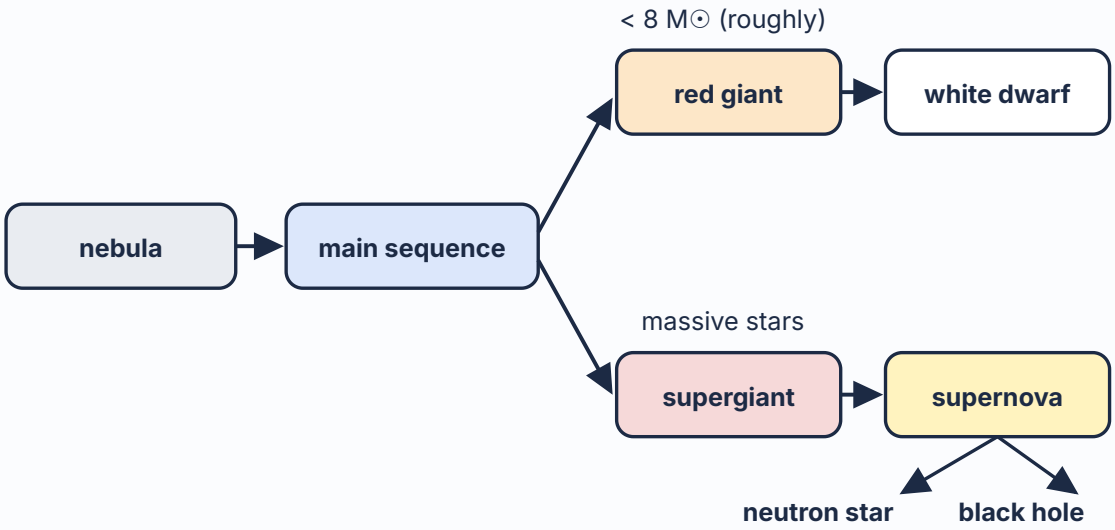
1. $L \propto R^2T^4$; same T, so $L \propto R^2$ M1
2. **R ratio = √10 000 = 100** A1

COMMON MISTAKE

Reading the temperature axis the wrong way round. On an HR diagram hot stars are on the **left**.

Riyaz Sir

5 Stellar evolution



The mass of the star when it forms decides everything that follows.

- **Low and medium mass (like the Sun):** main sequence (hydrogen fusion) → red giant (helium fusion in the core, outer layers swell) → planetary nebula, leaving a **white dwarf** that slowly cools.
- **High mass:** main sequence (much shorter, because they burn fuel fast) → red supergiant (fusion up to iron) → **supernova** → a **neutron star**, or a **black hole** if the remaining core is massive enough.
- **Elements:** fusion in stars makes elements up to iron; heavier elements form in supernovae and neutron-star mergers. The atoms in your body were made in stars.

EXAM TIP

"Explain why fusion stops at iron": iron-56 has the highest binding energy per nucleon, so fusing it further would absorb energy instead of releasing it.

LINKING QUESTION

Stellar spectra (E.1), redshift (C.5), black-body radiation (B.1) and gravity (D.1) all come together here: astronomy is how physicists test their models on the largest scales.

IDEA FOR YOUR IA / EXPLORATION

Use public data (for example a star catalogue or Gaia data) to build your own HR diagram for a star cluster and estimate the cluster's age from where its main sequence turns off.

Test yourself — cover the answers first

QUICK CHECK

1. Why does fusion need high temperatures?
2. What keeps a main-sequence star stable?
3. Define the parsec.
4. Where are the hottest stars on an HR diagram?
5. What will the Sun eventually become?
6. Why are white dwarfs dim even though they are hot?

EXAM-STYLE

7. Star A is at 10 pc and star B at 40 pc. They have the same luminosity. Compare their apparent brightness.

8. A white dwarf at 20 000 K has luminosity 0.010 L☉. The Sun is at 5800 K. Find its radius in solar radii.

Show answers

1. nuclei must move fast enough to overcome their electric repulsion
2. gravity inward balanced by radiation and gas pressure outward
3. the distance at which a star has a parallax angle of one arc-second
4. on the left
5. a red giant, then a white dwarf
6. they are very small (small surface area)
7. $b \propto 1/d^2$
   $b_A/b_B = (40/10)^2$
   A is **16 times brighter**
8. $R/R_\odot = \sqrt{(L/L_\odot)} \times (T_\odot/T)^2$
   $= \sqrt{0.010} \times (5800/20\,000)^2$
   $= 0.10 \times 0.0841 =$ **0.0084 R☉** (about the size of the Earth)

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