InkPhysics

ANSWER BOOK

The HR diagram and stellar evolution

Astrophysics · Year 13

AQA 3.9.2.5, 3.9.2.6 · OCR A 5.5.1(a), 5.5.1(b), 5.5.1(c), 5.5.1(d), 5.5.1(e), 5.5.1(f), 5.5.1(g)

19 questions · 60 marks

NAVY EDITION

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SECTION A · Warm-up

A1 Absolute magnitude on the vertical axis, from about +15 at the bottom to -10 at the top, brighter upward on a reversed scale (1); temperature on the horizontal axis from about 50 000 K down to 2500 K left to right (1), often labelled instead by spectral class O B A F G K M. (If luminosity is plotted instead of magnitude, it increases upward normally on a log scale; only the temperature and magnitude scales run backwards.) (1) [3]

A2 The main sequence, a diagonal band from hot-bright (top left) to cool-dim (bottom right) (1); the red giants, above it on the cool side (1); and the white dwarfs, below it on the hot side (1). [3]

A3 It is fusing hydrogen in its core, the long stable phase of a star's life (1). The Sun sits partway down the main sequence, class G, absolute magnitude about +4.8 (1). [2]

A4 About 1.4 solar masses, the greatest mass electron degeneracy pressure can support as a white dwarf (1). A heavier core collapses further, to a neutron star or a black hole (1). [2]

A5 Any two of the following, one mark each (2): composed almost entirely of neutrons; massof order one to two solar masses; radius of order 10 km; density comparable with that of an atomic nucleus. [2]

A6 Electron degeneracy pressure, the quantum refusal of electrons to be squeezed into the same state (1). None: fusion has ended, so it only radiates its stored thermal energy, cooling and fading (1). [2]

SECTION B · Standard

B1 When core hydrogen runs low, fusion moves to a shell (1), the outer layers swell and the surface cools: the Sun leaves the main sequence and moves up and to the right, becoming a red giant (1). It then sheds its outer layers; the exposed core drops down and to the left as a white dwarf, no longer fusing (1), and slowly cools and fades (1). [4]

B2 $P = \sigma A T^4$: its lower temperature cuts the power per unit area (1), but its enormously larger surface area more than compensates (1). High luminosity at low temperature forces a huge radius, which is exactly what the giant region of the diagram encodes (1). [3]

B3 $m - M = 18.2 - (-19.3)$ (1) [4]
$m - M = 37.5$ (1)
$5 \log(d/10) = 37.5$, so $d = 10 \times 10^{7.5}$ (1)
$d = 3.2 \times 10^{8}$ pc (1)

B4 $V = (4/3)\pi r^3 = 7.2 \times 10^{12}$ m^3 (1) [3]
$\rho = M/V = 3.0 \times 10^{30}/(7.2 \times 10^{12})$ (1)
$\rho = 4.1 \times 10^{17}$ kg m^{-3} (1)

B5 The nebula collapses under its own gravity (1); the collapse heats the core, forming a protostar (1); when the core becomes hot enough, hydrogen fusion begins, and the star settles where the outward push of radiation and gas pressure balances gravity: it has joined the main sequence (1). [3]

B6 $M = R_s c^2/2G$ (1) $= 3.0 \times 10^4 \times (3.0 \times 10^8)^2/(2 \times 6.67 \times 10^{-11}) = 2.0 \times 10^{31}$ kg (1), which is $2.0 \times 10^{31}/(1.99 \times 10^{30}) \approx 10$ solar masses (1). [3]

B7 The event horizon is the radius at which the escape velocity reaches c (1). $\sqrt{(2GM/r)} = c$ gives $c^2 = 2GM/r$ (1), so $r = R_s = 2GM/c^2$ (1). [3]

SECTION C · Stretch

C1 $R_s \approx 2GM/c^2$ (1) [4]
$= 2 \times 6.67 \times 10^{-11} \times 1.19 \times 10^{31}/(3.0 \times 10^8)^2$ (1)
$R_s = 18$ km (1)
It is the radius of the event horizon, the boundary from inside which nothing, light included, can escape (1)

C2 Each is a white dwarf detonating in closely similar conditions, near the Chandrasekhar limit, so every one peaks at nearly the same absolute magnitude, about -19.3 (1); comparing with the observed peak apparent magnitude gives the distance (1). Distant ones proved fainter than their red shifts predicted, which within the standard cosmological model means the expansion of the universe is accelerating, driven by what is now called dark energy (1). The peaks are not truly identical: they scatter by a few tenths of a magnitude, and the measured rate of decline of each light curve is used to correct the peak, so a type Ia is a standardisable candle. [3]

C3 A steep rise over about two weeks to the peak near absolute magnitude -19.3 (1), then a decline lasting months, slower than the rise, the rate of that decline being what standardises the peak (1). A type Ia is a detonating white dwarf, not a massive star; some collapsing massive stars fire gamma-ray bursts, brief flashes of gamma radiation detectable across most of the universe (1). [3]

C4 $d = 40$ Mpc $= 4.0 \times 10^7$ pc (1). $m = M + 5 \log(d/10) = -19.3 + 5 \log(4.0 \times 10^6)$ (1) = +13.7 (1). Since +13.7 is brighter (smaller) than the +15 limit, the society could record the supernova (1). [4]

C5 With core hydrogen exhausted, the star swells to a giant, and its greater mass drives fusion on beyond helium (1). Its core ends more massive than the Chandrasekhar limit of about 1.4 solar masses (1), so electron degeneracy pressure cannot hold it up as a white dwarf, and the core collapses (1). The outer layers detonate as a supernova, briefly outshining the galaxy (a gamma-ray burst may accompany the collapse) (1). The collapsed core survives as a neutron star, its protons and electrons crushed together into neutrons (1). If the remnant is massive enough, it falls inside its own Schwarzschild radius and becomes a black hole; the Sun, far below these masses, ends instead as a white dwarf (1). [6]

C6 R_s is directly proportional to M (1), so $R_s = 3.0 \text{ km} \times 2 \times 10^9 \approx 6.0 \times 10^{12}$ m (1). That is about 40 times the Earth-Sun distance: the event horizon alone would swallow the whole planetary system (1). [3]