inkPhysics

ANSWER BOOK

Quasars and exoplanets

Astrophysics · Year 13

AQA 3.9.3.3, 3.9.3.4

18 questions · 54 marks

NAVY EDITION

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SECTION A · Warm-up

A1 Quasi-stellar radio source (1): they were identified in the early 1960s as strong radio sources whose optical counterparts looked like faint star-like points, not galaxies (1). [2]

A2 Its star outshines it by a factor of order a billion (1), and at interstellar distances the angular separation between planet and star is below the diffraction-limited resolving power of telescopes (1). [2]

A3 The fractional dip equals $(r_p/r_s)^2$, the squared ratio of planet radius to star radius, so it measures the planet's relative size (1). The interval between dips is the planet's orbital period (1). [2]

A4 An active supermassive black hole, of millions to billions of solar masses, fed by infalling matter (1). At the centres of galaxies in the early universe, at very large distances (1). [2]

A5 A more massive planet drags its star through a faster counter-orbit about their common centre of mass, so the Doppler shift is larger (1); a close orbit makes the star's speed higher still and the period short, so the wobble is easiest to detect (1). [2]

A6 A transit is seen only when the orbit lies edge-on to us, so that the planet crosses the star's disc along our line of sight (1). [1]

SECTION B · Standard

B1 $v = zc = 0.40 \times 3.0 \times 10^8 = 1.2 \times 10^8$ m s^{-1} (1). $d = v/H = 120\,000/65 \approx 1800$ Mpc (1). [4]
Both $v = zc$ and $d = v/H$ are low red shift approximations, valid for v much less than c (1); at $z = 0.40$ the relativistic Doppler speed is 0.32c, so $v = zc$ runs about 23 per cent high, and the distance should not be quoted to more than two figures (1).

B2 An object cannot brighten as a whole faster than light crosses it (1) [3]
size $\leq ct = 3.0 \times 10^8 \times 3 \times 86\,400 \approx 7.8 \times 10^{13}$ m (1)
Comparable with the size of the solar system despite a galaxy-scale power output (1)

B3 The fractional dip equals $(r_p/r_s)^2$ (1) [3]
$r_p/r_s = \sqrt{(2.5 \times 10^{-3})} = 0.050$ (1)
$r_p = 0.050 \times 6.96 \times 10^8 = 3.5 \times 10^7$ m (1)

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B4 $\Delta\lambda = \lambda v/c$ (1) [3]
$\Delta\lambda = 656.3 \times 55/(3.0 \times 10^8)$ (1)
$\Delta\lambda = 1.2 \times 10^{-4}$ nm (1)

B5 Fractional dip = $(r_p/r_s)^2$ (1). Giant: $(7.0 \times 10^7/(6.96 \times 10^8))^2 = 1.0 \times 10^{-2}$, well above the threshold (1). Rocky planet: $(6.37 \times 10^6/(6.96 \times 10^8))^2 = 8.4 \times 10^{-5}$, below 1.0×10^{-4} (1). Only the gas giant is detected (1). [4]

B6 $N = 4.0 \times 10^{39}/(3.8 \times 10^{26})$ (1) $= 1.1 \times 10^{13}$ (1). That is around a hundred times the star count of a large galaxy: the quasar alone outshines its entire host galaxy (1). [3]

B7 $v = c\Delta\lambda/\lambda = 3.0 \times 10^8 \times 2.6 \times 10^{-4}/656.3$ (1) $= 119$ m s^{-1} (1). The star is being swung round the centre of mass it shares with an unseen orbiting companion, a planet (1). [3]

SECTION C · Stretch

C1 $M = m - 5\log(d/10\text{ pc}) = 16.1 - 5\log(1.8 \times 10^8)$ (1) $= -25.2$ (1). That is 4.2 magnitudes brighter than the galaxy: a factor of $2.51^{4.2} \approx 47$ (1). The distance itself came from low red shift approximations that are already strained at $z = 0.40$, and $m - M = 5\log(d/10)$ assumes flat Euclidean space with no expansion between source and observer, so treat M as good to a few tenths of a magnitude at best (1). [4]

C2 Matter spiralling towards the black hole heats by friction to millions of kelvin (1) and radiates fiercely before crossing the event horizon, releasing energy far more efficiently than fusion (1), so a galaxy's worth of power is possible (1). The engine is only as big as the hole and its inner disc, a solar-system-scale region, consistent with the rapid brightness variation (1). [4]

C3 The transit dip gives the planet's size, through $(r_p/r_s)^2$, and its interval gives the orbital period (1). The radial velocity wobble confirms the period (1) and its size reflects the planet's mass, since a heavier planet drags its star through a faster counter-orbit (1). [3]

C4 $r_p = r_s\sqrt{(1.1 \times 10^{-4})}$ (1) $= 6.8 \times 10^6$ m (1). $V = (4/3)\pi r_p^3 = 1.3 \times 10^{21}$ m^3 (1). $\rho = M/V = 7.3 \times 10^{24}/(1.3 \times 10^{21}) = 5.5 \times 10^3$ kg m^{-3} (1). This matches the Earth's mean density, so the planet is rocky rather than gaseous (1). [5]

C5 V: $v = 3.0 \times 10^8 \times 3.2 \times 10^{-4}/550 = 175$ m s^{-1} (1). W: $v = 44$ m s^{-1} (1). With similar stars and orbits, a faster stellar counter-orbit about the centre of mass means a heavier planet dragging it (1). Star V moves about four times faster, so V's planet is the more massive (1). [4]

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