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SOLUTIONS

ATTEMPT CHECK CORRECT IMPROVE

OCR A A Level Astrophysics 2 spectra and stellar radiation solutions

Matching solutions and teaching prompts for the class review

Specification points covered

• 5.5.2(a) Describe electron energy levels in isolated atoms and recognise that bound-state energy levels have negative values.
• 5.5.2(b) Explain emission spectral lines from hot gases as photon emission during electron transitions between discrete energy levels.
• 5.5.2(c) Use $E = hf = hc / \lambda$ to calculate photon energy, frequency or wavelength.
• 5.5.2(d) Recognise that each element has a unique line spectrum and use this to identify elements in stars.
• 5.5.2(e) Describe continuous, emission line and absorption line spectra.
• 5.5.2(f) Use a transmission diffraction grating to determine wavelength using $n\lambda = d \sin \theta$.
• 5.5.2(g) Apply Wien's displacement law λ_{maxT} = constant to estimate stellar surface temperature.
• 5.5.2(h) Apply Stefan's law $L = 4\pi r^2 \sigma T^4$ and combine it with Wien's law to estimate stellar radius.

Teaching focus

Keep electron transitions, spectral evidence and thermal-radiation calculations linked but distinct.
In the grating work, halve a measured separation between symmetric maxima before finding θ, and convert lines per millimetre to lines per metre before taking the reciprocal.
For stellar radiation, λ_{max} fixes temperature through Wien's law; luminosity and temperature then determine radius through Stefan's law.

1. Atomic energy levels

1. The ionisation level of an isolated atom is assigned an energy of 0 eV. Explain why the atom's bound electron energy levels have negative values. [1 mark]

Answer / mark points: A bound electron has less energy than a free electron at the ionisation level. Energy must be supplied to remove it from the atom, so its energy is measured below zero.

Teacher prompt / common error: Negative energy does not mean the electron has negative kinetic energy. It records that the electron is bound and needs energy to reach the zero-energy ionisation level.

2. During calibration, an electron falls from an energy level of -1.85 eV to a level of -4.90 eV. Determine the photon energy in eV and state whether the photon is emitted or absorbed. [2 marks]

Answer / mark points: $\Delta E = (-1.85) - (-4.90) = 3.05$ eV. The electron moves to a lower energy level, so a photon is emitted.

Teacher prompt / common error: Subtract the two signed levels carefully. A transition down the energy diagram emits a photon; a transition up absorbs one.

3. Use the transition in Question 2 to calculate the wavelength of the photon. Give your answer in both metres and nanometres. Use $h = 6.63 \times 10^{-34}$ J s, $c = 3.00 \times 10^{8}$ m s^{-1} and 1 eV = 1.60×10^{-19} J. [3 marks]

Answer / mark points: $E = 3.05 \times 1.60 \times 10^{-19} = 4.88 \times 10^{-19}$ J. $\lambda = hc / E = (6.63 \times 10^{-34} \times 3.00 \times 10^{8}) / (4.88 \times 10^{-19}) = 4.08 \times 10^{-7}$ m = 408 nm.

Teacher prompt / common error: Require the eV-to-joule conversion before using SI values for h and c. Check that 4.08×10^{-7} m becomes 408 nm.

2. Spectral fingerprints

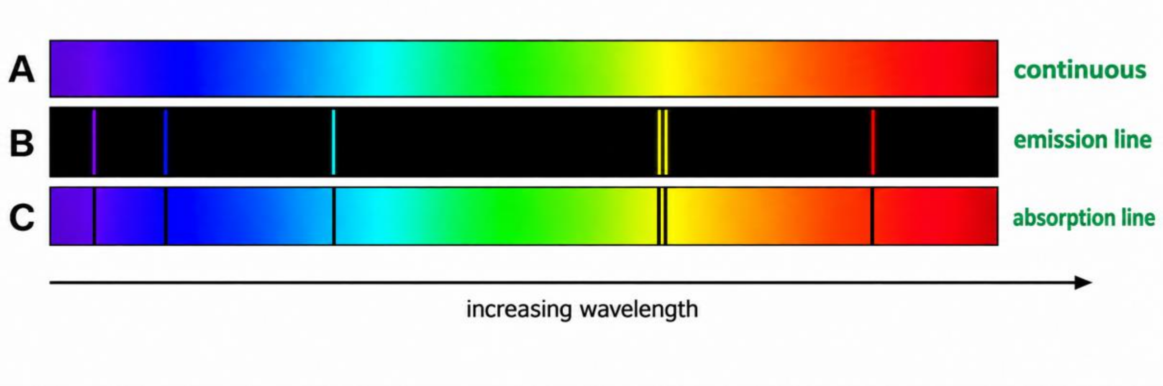

Figure 1 solution: continuous, emission line and absorption line spectra with the same wavelength ordering

4. Figure 1 shows three spectra recorded while the spectrograph is tested. Identify A, B and C as a continuous spectrum, an emission line spectrum or an absorption line spectrum. [3 marks]

Answer / mark points: A is a continuous spectrum. B is an emission line spectrum. C is an absorption line spectrum.

Teacher prompt / common error: Keep the three meanings distinct: continuous means all wavelengths, emission means bright isolated wavelengths and absorption means missing wavelengths from a continuum.

5. The calibration lamp contains a hot, low-pressure gas. Explain why it produces an emission line spectrum rather than every possible wavelength. [2 marks]

Answer / mark points: Collisions excite electrons in the gas to discrete higher energy levels. When electrons return to lower levels, they emit photons whose energies equal particular energy-level differences, so only discrete wavelengths are produced.

Teacher prompt / common error: The word discrete is important. The photon energies are fixed by differences between allowed electron energy levels.

6. Light from Nereid-T7 passes through the star's cooler outer atmosphere before reaching the telescope. Explain how the dark lines in its absorption spectrum are produced. [3 marks]

Answer / mark points: The dense, hot star produces an approximately continuous spectrum. Atoms in the cooler outer atmosphere absorb photons whose energies match allowed electron transitions. Photons are then re-emitted in random directions, so those wavelengths have reduced intensity along the line of sight and appear as dark lines.

Teacher prompt / common error: Avoid saying that black lines are emitted. The line of sight has reduced intensity because photons are absorbed and re-emitted in random directions.

7. After correcting the measured wavelengths for the radial motion of Nereid-T7, its dark lines are at 410.2, 434.0, 486.1, 589.0, 589.6 and 656.3 nm. Laboratory lines are: hydrogen 410.2, 434.0, 486.1 and 656.3 nm; sodium 589.0 and 589.6 nm; helium 447.1, 587.6 and 667.8 nm. Identify the elements detected and explain why a set of matching lines is stronger evidence than a single match. [3 marks]

Answer / mark points: Hydrogen and sodium are detected because all four listed hydrogen lines and both sodium lines match the corrected wavelengths. Helium is not supported. Several matching lines reproduce more of an element's unique spectral pattern and reduce the chance of an accidental or misidentified single-line match. A radial-motion correction scales every wavelength by one common Doppler factor rather than adding the same number of nanometres to every line.

Teacher prompt / common error: Identification should use a pattern of lines. A single apparent match may be a different element, a blend or a measurement uncertainty. If redshift is discussed, use one common fractional change: $\lambda_{observed} = (1 + z)\lambda_{rest}$.

3. Diffraction grating calibration

8. The calibration grating has 600 lines per millimetre. Calculate the separation d between adjacent grating lines in metres. [2 marks]

Answer / mark points: 600 lines mm^{-1} = 6.00×10^5 lines m^{-1}. Therefore $d = 1 / (6.00 \times 10^5) = 1.67 \times 10^{-6}$ m.

Teacher prompt / common error: The common error is treating 600 lines per millimetre as 600 lines per metre. Convert the line density before taking the reciprocal.

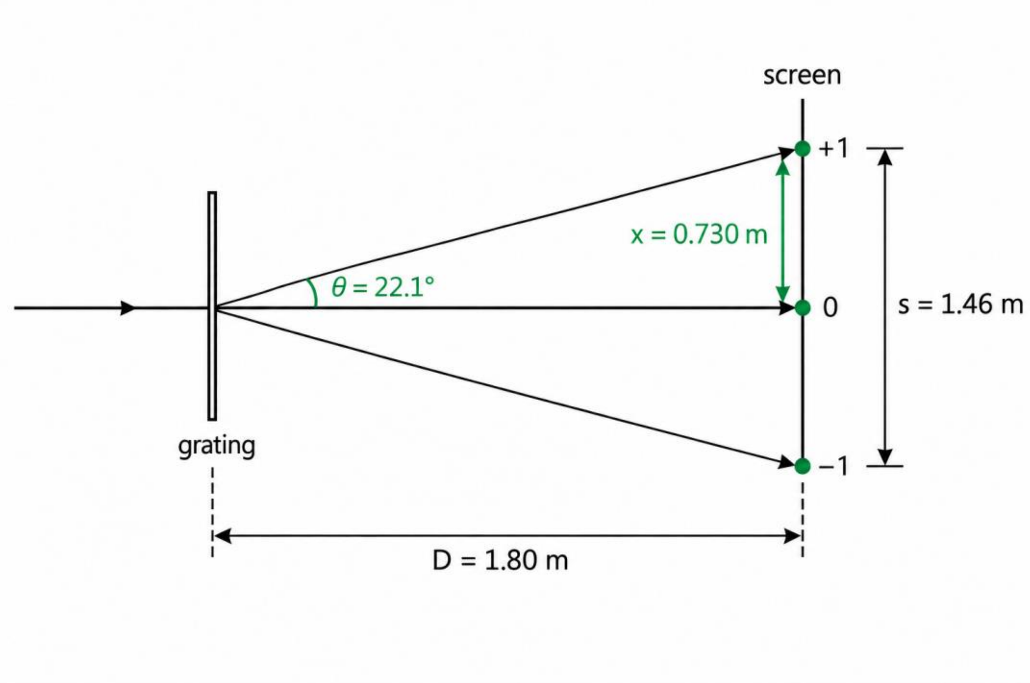

Figure 2 solution: half-separation and first-order angle

9. Figure 2 shows the first-order pattern made by one calibration line. Use the figure and your value of d to calculate the wavelength of the light. Give your answer to three significant figures. [4 marks]

Answer / mark points: The displacement to one first-order maximum is $x = 1.46 / 2 = 0.730$ m. $\tan \theta = x / D = 0.730 / 1.80$, so $\theta = 22.1°$. For $n = 1$, $\lambda = d \sin \theta = 1.67 \times 10^{-6} \times \sin 22.1° = 6.26 \times 10^{-7}$ m (626 nm).

Teacher prompt / common error: The 1.46 m dimension spans both first orders, so pupils must halve it. The trigonometric angle comes from $\tan \theta$; the grating equation then uses $\sin \theta$.

3. Diffraction grating calibration continued

10. Use your wavelength from Question 9 to determine the highest possible diffraction order and hence the total number of principal maxima that can be observed, including the central maximum. [2 marks]

Answer / mark points: n_{max} must satisfy $n\lambda \leq d$. $d / \lambda = 1.67 \times 10^{-6} / 6.26 \times 10^{-7} = 2.67$, so the highest whole-number order is 2. The pattern has orders -2, -1, 0, +1 and +2, giving five principal maxima.

Teacher prompt / common error: Only whole orders with $\sin\theta \leq 1$ exist. Once the maximum positive order is known, include the same negative orders and the central maximum.

11. Describe how the bench arrangement in Figure 2 can be used to determine an unknown wavelength. Include the measurements, how θ is obtained, how the grating spacing is found and one way to reduce the percentage uncertainty. [4 marks]

Answer / mark points: Measure the perpendicular grating-screen distance D. Measure the separation s between equal-order maxima on opposite sides of the centre and use $x = s / 2$. Calculate θ from $\tan\theta = x / D$. Convert the grating line density to lines per metre and use $d = 1 / N$, then use $n\lambda = d \sin\theta$. Measuring symmetric maxima, repeating and averaging, using a larger D or using a higher visible order can reduce percentage uncertainty.

Teacher prompt / common error: Insist on normal incidence, a perpendicular screen distance and symmetric measurements. A larger separation improves percentage uncertainty but does not change the diffraction angle.

12. A trainee moves the screen further from the grating and claims that the diffraction angle increases. Evaluate the claim and state one measurement advantage of increasing the grating-screen distance. [2 marks]

Answer / mark points: The diffraction angle is fixed by $n\lambda = d \sin\theta$, so changing the screen distance does not change θ. A larger distance increases the linear separation of the maxima, reducing the percentage uncertainty in the position or separation measurement.

Teacher prompt / common error: Separate angular position from linear screen position. The angle stays the same while the spots move further apart on a more distant screen.

4. Stellar temperature and radius

13. The corrected intensity curve for Nereid-T7 has a peak wavelength of 462 nm. Calculate the star's surface temperature using Wien's constant 2.90×10^{-3} m K. [2 marks]

Answer / mark points: $T = 2.90 \times 10^{-3} / (462 \times 10^{-9}) = 6.28 \times 10^{3}$ K.

Teacher prompt / common error: Convert nanometres to metres. A shorter λ_{max} corresponds to a hotter surface.

14. The luminosity of Nereid-T7 is 3.40×10^{28} W. Use Stefan's law to calculate its radius. Express the result in metres and as a multiple of the Sun's radius. Use $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} and solar radius = 6.96×10^{8} m. [4 marks]

Answer / mark points: $L = 4\pi r^2\sigma T^4$, so $r = \sqrt{(L / (4\pi\sigma T^4))}$. Using $L = 3.40 \times 10^{28}$ W and $T = 6.28 \times 10^{3}$ K gives $r = 5.54 \times 10^{9}$ m. The radius ratio is $5.54 \times 10^{9} / 6.96 \times 10^{8} = 7.97$, approximately 8.0 solar radii.

Teacher prompt / common error: The fourth power applies to temperature, while radius is squared. Pupils should rearrange before substituting and then compare with the supplied solar radius.

15. A second star has the same surface temperature as Nereid-T7 but nine times its luminosity. Determine the ratio of the second star's radius to the radius of Nereid-T7. [2 marks]

Answer / mark points: At the same T, Stefan's law gives $L \propto r^2$. Therefore $r_2 / r_1 = \sqrt{(L_2 / L_1)} = \sqrt{9} = 3$.

Teacher prompt / common error: For equal temperatures, luminosity depends on surface area. Nine times the luminosity means three times the radius, not nine times.

16. A later calibration shows that the true peak wavelength of Nereid-T7 is longer than 462 nm while its luminosity is unchanged. State how the corrected temperature and calculated radius compare with the original values. Explain both changes. [2 marks]

Answer / mark points: Wien's law gives $T \propto 1 / \lambda_{max}$, so a longer peak wavelength gives a lower temperature. For unchanged luminosity, Stefan's law gives $r \propto 1 / T^2$, so the lower corrected temperature requires a larger radius.

Teacher prompt / common error: Ask for linked reasoning: longer λ_{max} means lower T by Wien, then unchanged L means larger r by Stefan.

Language and model check

Electrons move to higher or lower energy levels; energy levels themselves do not move.
A dark absorption line means reduced intensity at that wavelength. It is not a black wavelength emitted by the star.
For one redshift, every wavelength is multiplied by the same factor (1 + z). Longer wavelengths therefore have a larger absolute change in wavelength; do not add the same nanometre shift to every line.
Increasing the screen distance increases linear separation, not diffraction angle.
A star has a higher or lower surface temperature and a larger or smaller radius. Luminosity itself is not hot or cold.