Name	Date started	Target end date

GCE A LEVEL — ORBITS & THE WIDER UNIVERSE QUESTION PACK

1324-01 (Legacy PH4)

REVISE
.wales

PHYSICS — UNIT 4 TOPIC 3

Orbits & the wider universe — Kepler, Doppler, Hubble & dark matter

Cosmology questions drawn from legacy WJEC PH4 papers (January 2010 – June 2014) that are not already covered by the new-spec U3 T1 circular-motion pack.

LEGACY 2008 SPECIFICATION · PH4.5 MAPS TO NEW UNIT 4 TOPIC 3

Estimated time for entire question pack: ~35 minutes

*Derived from the legacy PH4 pace of **~1.3 min/mark** (80 marks in 1¾ hours).*

*You are advised to **not** attempt to complete all of this in one sitting.*

For Examiner's use only

Q	Source	Max	Mark
1	Jan 10 Q7	4	
2	Jan 13 Q6	10	
3	Jan 10 Q8	13	
Total		27	

ABOUT THIS QUESTION PACK

This is a **focused practice pack**, not a single mock paper. It collects the legacy WJEC PH4 questions on **Doppler shift in stellar spectra** and **dark matter** — the parts of new-spec U4 T3 that are not already covered by the circular-motion booklet (U3 T1).

Pure orbital-circular-motion questions (Kepler-radius / centre-of-mass orbits, e.g. Jun 2012 Q7 with its Kepler-3rd-law verification) are deliberately not duplicated here.

INSTRUCTIONS

Use black ink or black ball-point pen. Answer all questions in the spaces provided.

A calculator is required. The Data Booklet is allowed.

Unit 4 Topic 3 — Orbits & the wider universe

WJEC GCE A Level Physics (from 2015) · Unit 4 Assessment Unit *Fields and Options*. Drawn from legacy PH4.5 “Application to Orbits in the Solar System & Universe”.

Kepler’s laws A

- **K1:** orbits are ellipses with the Sun at one focus.
- **K2:** the line from Sun to planet sweeps equal areas in equal times.
- **K3:** $T^2 \propto r^3$ for orbits around the same primary.

Satellites & orbital period A

- Gravity supplies the centripetal force: $\frac{GMm}{r^2} = \frac{mv^2}{r} = m\omega^2 r$.
- Hence $T^2 = \frac{4\pi^2}{GM} r^3$ (Kepler-3 derived).
- Geostationary: $T = 24$ h, equatorial, west-to-east.

Doppler effect & stellar spectra A

- For $v \ll c$: $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$.
- Red shift ↔ source receding ($\Delta\lambda > 0$).
- Blue shift ↔ source approaching ($\Delta\lambda < 0$).
- Used to detect exoplanets via radial-velocity wobble of a star.

Hubble’s law & the universe B

- $v = H_0\, d$ — recession speed proportional to distance.
- Evidence for an expanding universe (Big Bang).
- Estimated age of the universe: $t \approx 1/H_0$.
- $H_0 \approx 70$ km s^{-1} Mpc^{-1} $\approx 2.3 \times 10^{-18}$ s^{-1}.

Big Bang evidence B

- Galactic red shifts: galaxies recede from us in all directions.
- **Cosmic microwave background** at ~ 2.7 K: relic radiation, cooled by expansion.
- Observed light-element abundances (H, He, Li).

Dark matter & critical density B

- Galaxy rotation curves stay flat at large r, instead of falling as $v \propto 1/\sqrt{r}$.
- Implies extra unseen mass (**dark matter**) extending beyond the visible disk.
- Critical density ρ_c: density that gives a flat, just-bound universe.

Section index for this question pack

Why is this pack short? The legacy PH4 papers contain only a handful of questions that focus on Doppler / dark-matter content rather than direct circular-motion derivations. Questions where the dominant physics is $\frac{GMm}{r^2} = \frac{mv^2}{r}$ (e.g. Jun 11 Q5, Jun 12 Q7, Jan 13 Q5, Jan 14 Q7, Jun 14 Q3 & Q7) are placed in the U3 T1 Circular Motion pack to avoid duplication, even where they touch on Kepler’s laws or red shift.

Orbits & the wider universe in one page

Quick-reference notes — revisit before each question.

Kepler's three laws

- **1.** Planets move on ellipses with the Sun at one focus.
- **2.** A line from Sun to planet sweeps out equal areas in equal times ⇒ the planet speeds up near perihelion, slows near aphelion.
- **3.** $T^2 \propto r^3$ (mean orbital radius).

Deriving Kepler 3

For a circular orbit, gravity = centripetal:

$$\frac{GMm}{r^2} = m\omega^2 r = m\frac{4\pi^2}{T^2}r$$

Rearranging:

$$T^2 = \frac{4\pi^2}{GM}r^3$$

Orbital speed

For a body of mass $m \ll M$ on circular orbit:

$$v = \sqrt{\frac{GM}{r}}$$

- Used to predict galactic rotation curves.
- If the measured v is larger than this predicts, additional mass (dark matter) is implied.

Doppler formula (light)

For source moving with speed $v \ll c$ along line of sight:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

- $\Delta\lambda > 0$: **red shift**, source recedes.
- $\Delta\lambda < 0$: **blue shift**, source approaches.
- Used to find a star's radial velocity, hence its orbital motion.

Radial-velocity wobble

A planet pulls its star around their *centre of mass*. Over one orbit, the star's radial velocity oscillates sinusoidally about a mean.

- From the graph: *period* T and *amplitude* v_{star}.
- Hence orbital radius of the star: $r_{\text{star}} = v_{\text{star}}\,T/(2\pi)$.
- Centre-of-mass: $M_{\text{star}}\,r_{\text{star}} = m_{\text{planet}}\,r_{\text{planet}}$.

Hubble's law

Distant galaxies recede with

$$v = H_0\,d$$

- $H_0 \approx 2.3 \times 10^{-18}$ s^{-1} (or ≈ 70 km s^{-1} Mpc^{-1}).
- Plot v against d for many galaxies → gradient = H_0.

Age of the universe

If expansion has been steady:

$$t \approx \frac{1}{H_0} \approx 4.4 \times 10^{17}\ \text{s} \approx 14\ \text{Gyr}$$

- Each galaxy at distance d left us at speed v, so $t = d/v = 1/H_0$.

Big Bang evidence

- **Red shift** of distant galaxies (Hubble's law).
- **Cosmic microwave background** at ~ 2.7 K: smooth, relic radiation cooled by expansion since recombination.
- Observed abundances of ^{1}H, ^{4}He, ^{7}Li.

Dark matter

Outer stars/dust in a spiral galaxy rotate *faster* than $v = \sqrt{GM_{\text{vis}}/r}$ predicts using only the visible mass.

- Extra unseen mass (dark matter) must lie beyond the visible disk.
- Does not emit or absorb light; detected gravitationally.

Critical density

Density at which the universe's expansion just halts at $t = \infty$:

$$\rho_c = \frac{3H_0^2}{8\pi G}$$

- $\rho > \rho_c$: closed, recollapses.
- $\rho < \rho_c$: open, expands forever.

Strategy — Doppler Qs

1. Read graph: pick v (amplitude) and T (period).
2. $\Delta\lambda = \lambda\,v/c$ for the wavelength shift.
3. For wobble: $r_{\text{star}} = vT/(2\pi)$, then centre of mass for planet mass.

Strategy — rotation curves

1. Predict $v(r) = \sqrt{GM_{\text{vis}}/r}$ ⇒ falls off at large r.
2. Compare to observed flat curve.
3. Discrepancy ⇒ dark matter must be present.

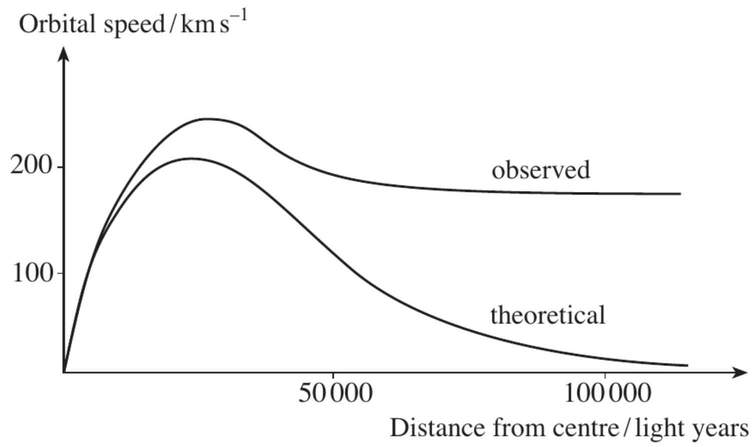
SECTION A

Doppler shift & dark matter

Questions 1 – 3 · 27 marks

7. The graphs below refer to the orbital speeds of objects in a spiral galaxy. The visible disk of the galaxy extends to about 35 000 light years from the centre. Explain briefly how such graphs are thought to give evidence for the existence of Dark Matter.

The equation $v = \sqrt{\frac{GM}{r}}$ may assist you in your explanation. [4]



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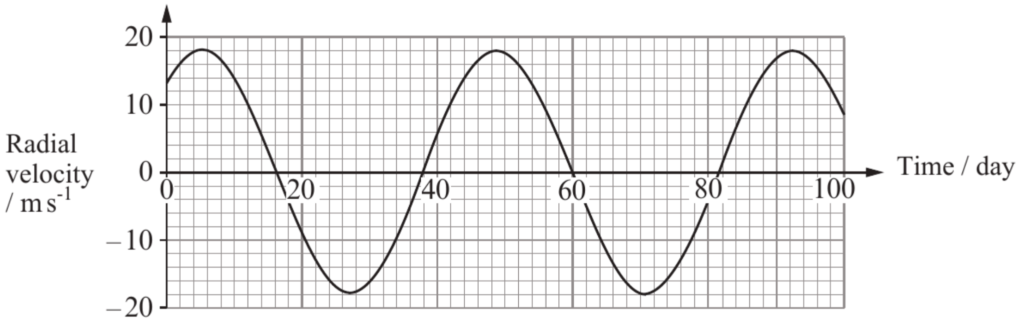
Examiner only

6. The light spectrum from a star 41 light years from Earth was analysed. It was found that this light was Doppler shifted due to the star orbiting the mutual centre of mass of the star and a nearby planet. The following graph is derived from the data obtained.



(a) From the graph, calculate the period of the orbit in **seconds**. [2]

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(b) Show that the radius of orbit of the star about the centre of mass is approximately 1.1×10^7 m. [2]

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(c) The mass of the star is 1.9×10^{30} kg. Calculate the distance between the star and the planet, ensuring that you state any approximation that you make. [3]

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Examiner only

(d) Using the centre of mass equation, or otherwise, estimate the mass of the planet and compare its mass with that of the Earth ($M_E = 5.9 \times 10^{24}$ kg). [3]

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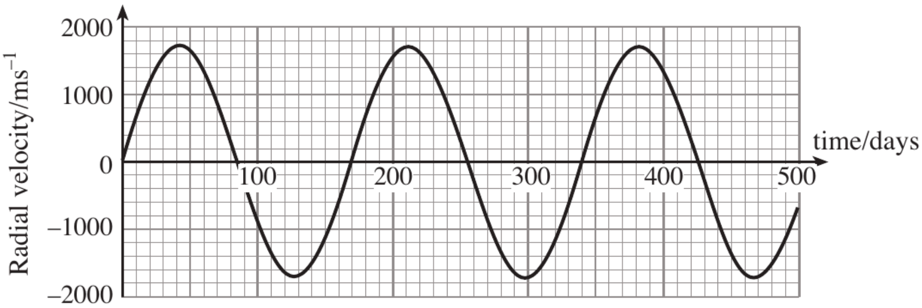
8. In 2008, a brown dwarf star was discovered orbiting a larger star using the following data obtained from spectral observations of the larger star. The graph shows the large star's radial velocity versus time (here, radial velocity is the component of the star's velocity towards the Earth).



(a) With the use of a diagram, explain why this variation in radial velocity occurs. [3]

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(b) (i) From the graph write down the orbital speed of the larger star. .... [1]

(ii) The wavelength of light used to obtain this data via Doppler shift was 600 nm. Calculate the maximum wavelength shift corresponding to the above results. [2]

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(c) (i) From the graph write down the period of orbit. .... [1]

(ii) From your answers to *(b)*(i) and *(c)*(i), show that the radius of the orbit of the larger star is approximately 4×10^9 m. [2]

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(d) The mass of the larger star is $8{\cdot}0 \times 10^{29}$ kg and you may assume that this is far greater than that of the brown dwarf. Use your answer to *(c)*(i) to show that the distance, d, between the larger star and the brown dwarf is around 7×10^{10} m. [2]

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(e) Calculate the mass of the brown dwarf. [2]

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