Diploma Programme
Programme du diplôme
Programa del Diploma

Physics
Higher level
Paper 3

25 April 2024

Zone A afternoon | **Zone B** afternoon | **Zone C** afternoon

Candidate session number

1 hour 15 minutes

Instructions to candidates

- Write your session number in the boxes above.
- Do not open this examination paper until instructed to do so.
- Answers must be written within the answer boxes provided.
- A calculator is required for this paper.
- A clean copy of the **physics data booklet** is required for this paper.
- The maximum mark for this examination paper is **[45 marks]**.

Section A	Questions
Answer all questions.	1 – 2

Section B	Questions
Answer all of the questions from one of the options.	
Option A — Relativity	3 – 7
Option B — Engineering physics	8 – 12
Option C — Imaging	13 – 16
Option D — Astrophysics	17 – 20

37 pages

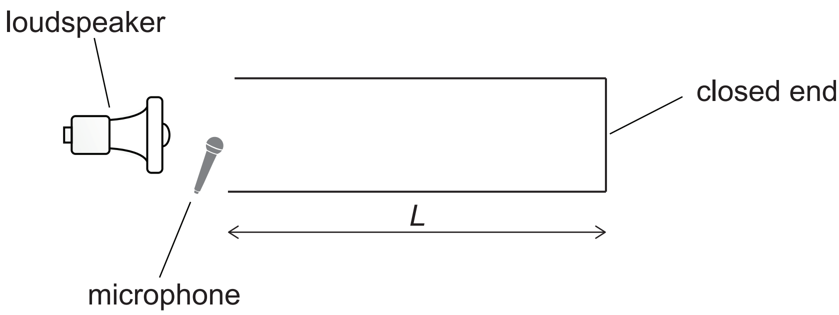
2224 – 6703

Section A

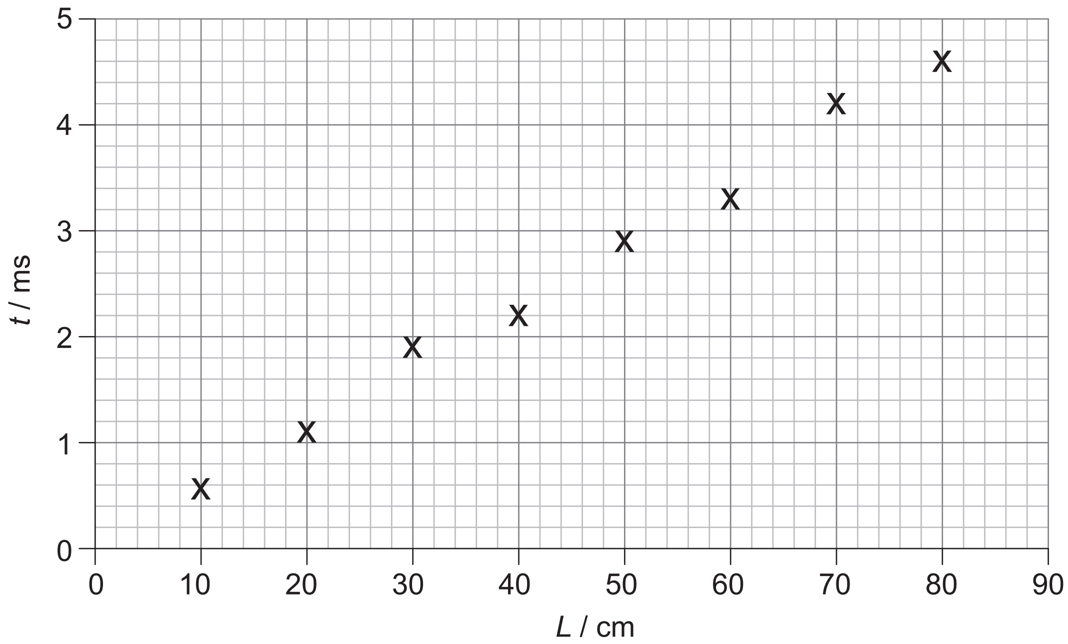
Answer **all** questions. Answers must be written within the answer boxes provided.

1. Student A conducts an experiment to determine the speed of sound in air using tubes of different lengths. Each tube is open at one end and closed at the other end.

A short pulse of sound is produced by a loudspeaker near the open end of each tube. A microphone is placed at the open end of each tube and detects the sound entering and leaving the tube.



The graph shows the variation with tube length L of the time t for the sound to travel along the tube and be reflected back.



The percentage uncertainty in each time measurement is 9 %. The uncertainty in L is negligible.

(This question continues on the following page)

(Question 1 continued)

(a) (i) For $L = 40\,\text{cm}$, calculate the absolute uncertainty in t. [1]

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(ii) For $L = 40\,\text{cm}$, draw the error bar on the graph for this data point only. [1]

(b) Draw the line of best fit. [1]

(c) Determine, using the graph, the speed of sound. State an appropriate unit for your answer. [3]

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(d) Student B conducts the same experiment and analysis but places the microphone 10 cm to the left of the open end of each tube.

Compare, with reference to the graphs drawn, the value for speed of sound obtained by student B to that of student A. [2]

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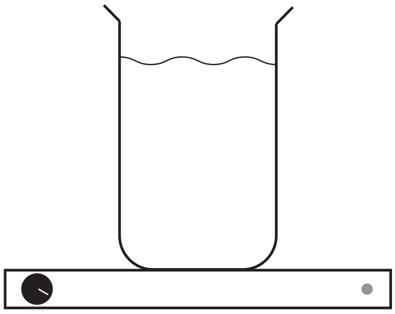
2. An experiment is conducted to measure the specific heat capacity of water. A mass of water is placed in a glass beaker and energy is transferred from an electric heater.



The data collected are:

Mass of water = (0.250 ± 0.002) kg
Change in temperature of the water = (14.0 ± 0.5) °C
Energy transferred from the electric heater = (16 000 ± 300) J

(a) (i) Calculate the specific heat capacity of water. [1]

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(ii) Determine the absolute uncertainty in the specific heat capacity of water. [3]

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(iii) Write down the specific heat capacity of water and its absolute uncertainty to the appropriate number of significant figures. [1]

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(This question continues on the following page)

(Question 2 continued)

(b) Outline **one** source of systematic error in the experiment and its effect on the calculated value of the specific heat capacity of water. [2]

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Section B

Answer **all** of the questions from **one** of the options. Answers must be written within the answer boxes provided.

Option A — Relativity

3. The length of a space station is measured to be 100 m according to observer A at rest in the space station.

Observer B is moving at 0.60*c* with respect to the space station.

(a) Write down the length of the space station according to Galilean relativity. [1]

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(b) (i) Define what is meant by proper length. [1]

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(ii) Calculate the length of the space station according to observer B, with reference to special relativity. [2]

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(c) Outline how the results in (b)(ii) contradict Newton's postulates concerning time and space. [2]

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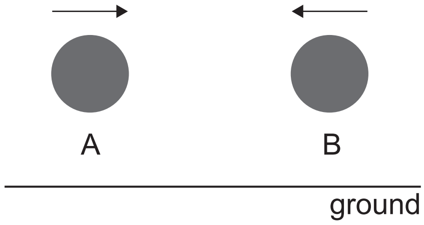
(Option A continues on the following page)

(Option A continued)

4. The diagram below shows two particles travelling in opposite directions above the ground.



The velocity with respect to the ground of particle A is 0.6*c* and the velocity of particle B with respect to the ground is –0.75*c*.

(a) Calculate the velocity of particle B according to particle A. [2]

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The particles were emitted at the same time according to observer X at rest with respect to the ground. Another observer, Y, is moving parallel to the ground.

(b) Show that the particles are **not** emitted simultaneously in the frame of observer Y, according to the Lorentz transformation equations. [2]

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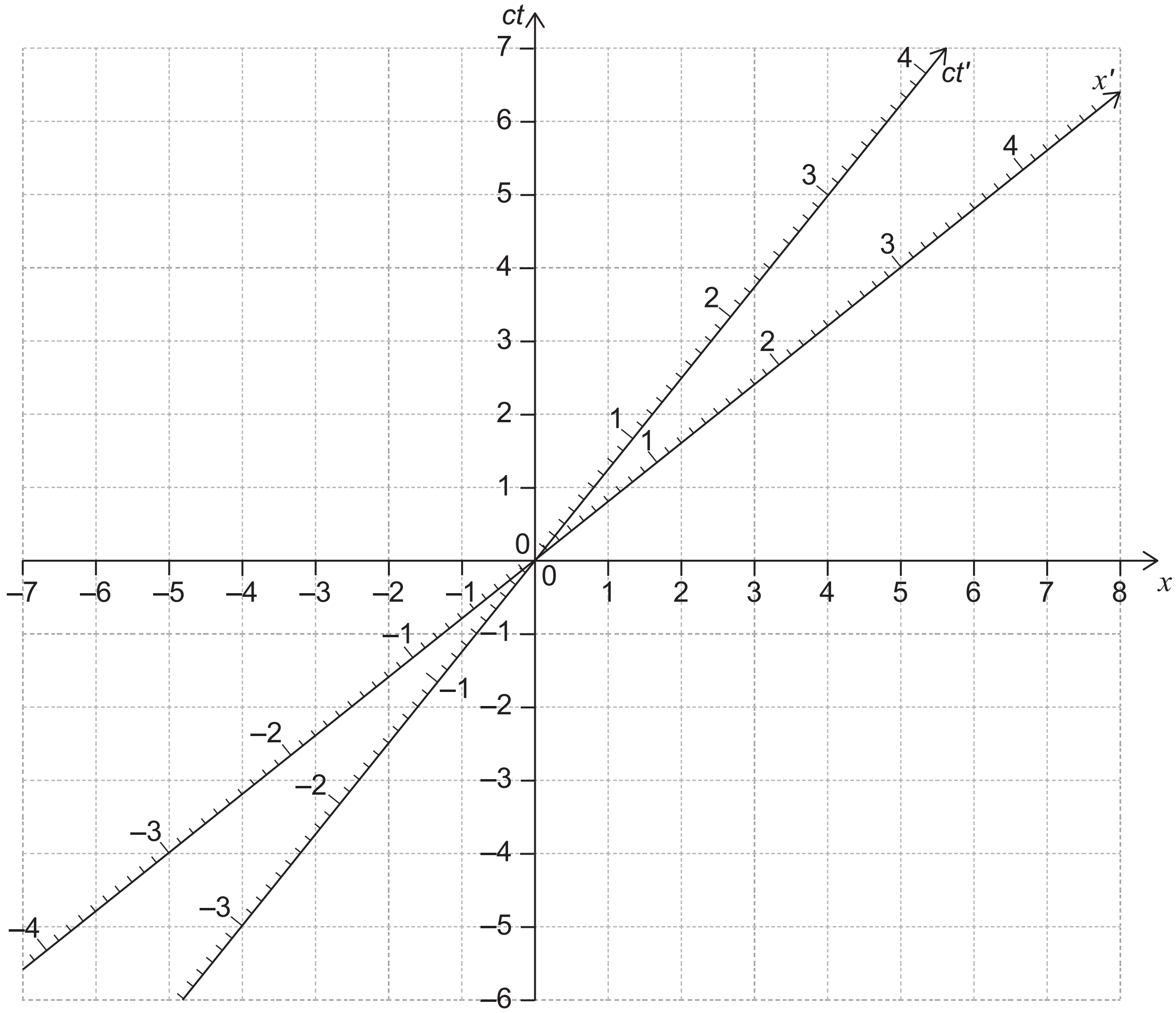
(Option A continues on the following page)

(Option A continued)

5. The spacetime diagram gives the *ct*-x axes for observer A. The worldline and x' axis for observer B are also shown. When observer A and observer B were at the origin of the spacetime diagram their clocks were synchronized.



(a) Calculate the speed of observer B with respect to observer A. [2]

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(Option A continues on the following page)

(Option A, question 5 continued)

(b) For observer A an event has spacetime coordinate $x = 3$ and $ct = 1$.

(i) Plot the point corresponding to the event on the diagram. Label the point E. [1]

(ii) According to observer B, event E occurs before observer A and observer B meet. Justify this statement using the spacetime diagram. [2]

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(iii) Determine the spacetime coordinates of the event according to observer B. [3]

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(iv) Show that the spacetime interval between the clock synchronization and the event is invariant. [2]

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(Option A continues on the following page)

(Option A continued)

6. An electron is accelerated from rest by a potential difference in a laboratory.

(a) Calculate the potential difference required to accelerate the electron to a speed corresponding to a Lorentz factor $\gamma = 2.0$ with respect to the laboratory. [2]

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(b) A baryon is moving with respect to both the laboratory and the electron.

Laboratory reference frame:
Momentum of the baryon: 450 MeVc^{-1}
Energy of the baryon: 1100 MeV

Electron reference frame:
Energy of the baryon: 1700 MeV

Determine the momentum of the baryon in the reference frame of the electron. [3]

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(Option A continues on the following page)

(Option A continued)

7. (a) Explain the path followed by light near massive objects. [3]

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An experiment is to be conducted on Earth to investigate gravitational redshift. A beam of gamma photons of energy 14 keV is to be emitted and then detected at a height of 10 m above the emission.

(b) Calculate the expected change in the frequency of a gamma photon due to the gravitational redshift. [2]

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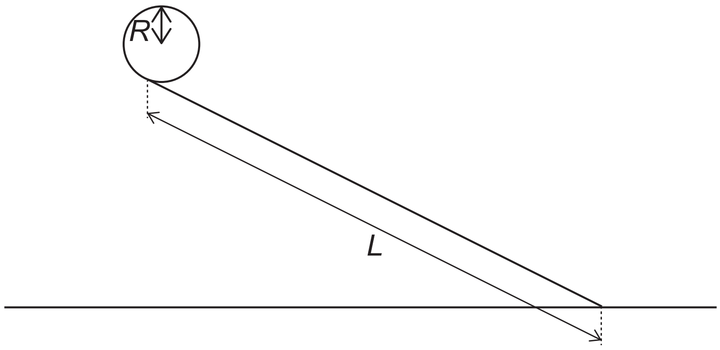
End of Option A

Option B — Engineering physics

8. A solid disk, initially at rest, rolls without slipping down an inclined plane. The disk has a radius $R = 5.5\,\text{cm}$. The length of the inclined plane is $L = 1.5\,\text{m}$.



(a) The time taken for the disk to roll down the inclined plane is $t = 0.96\,\text{s}$.

(i) State, for this disk, the relationship between linear displacement, L, and angular displacement, θ. [1]

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(ii) Calculate the angular acceleration of the disk. [3]

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(Option B continues on the following page)

(Option B, question 8 continued)

(b) The disk and a ring, with the same mass and radius, are released from the top of the slope at the same time. Explain, **without** numerical calculation, which one will reach the bottom of the inclined plane first. [3]

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(Option B continues on page 15)

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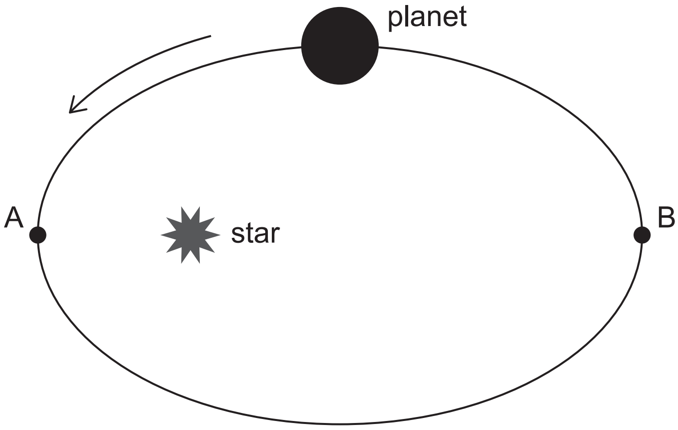
(Option B continued)

9. A planet orbits around a star in an elliptical orbit as shown below.



At point A the planet is closest to the star and at point B it is furthest from the star.
As the planet orbits the star it has a moment of inertia $I = mr^2$ where m is the mass of the planet.

(a) State what r represents in this situation. [1]

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(b) Show, using conservation of angular momentum, that the linear speed of the planet is greater at A than at B. [2]

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(c) Suggest why, in this situation, the magnitude of the linear momentum of the planet is not conserved whereas the magnitude of its angular momentum is conserved. [2]

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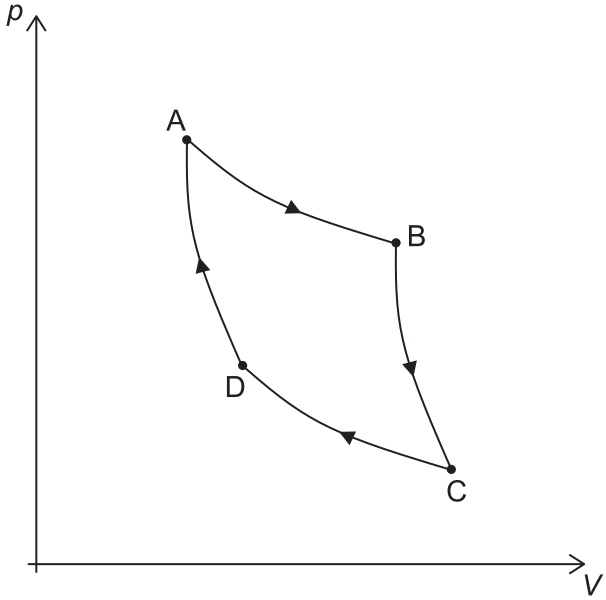
(Option B continues on the following page)

(Option B continued)

10. The pressure *p* and volume *V* diagram represents a Carnot cycle for an ideal monatomic gas.



(a) Show, using the first law of thermodynamics, that during the process from A to B energy is supplied to the gas. [3]

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(Option B continues on the following page)

(Option B, question 10 continued)

(b) The following data are given:

Volume of the gas at A: $2.2 \times 10^{-3}\,m^3$
Pressure of the gas at A: $4.3 \times 10^5\,Pa$
Pressure of the gas at D: $1.7 \times 10^5\,Pa$

(i) Show that the volume of the gas at D is about $4 \times 10^{-3}\,m^3$. [2]

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(ii) Calculate the efficiency of this Carnot cycle. [3]

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(Option B continues on page 19)

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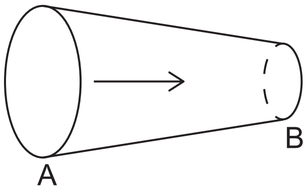
(Option B continued)

11. An ideal fluid is travelling through a pipe that has a large diameter at one end A and a smaller diameter at the other end B.



(a) Outline why the speed of the fluid is larger at B than at A. [2]

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The fluid enters the pipe at A at a rate of 2.3 kg s^{-1}. The smaller radius at B is 1.2 cm and the density of the fluid is 900 kg m^{-3}.

(b) Calculate the speed of the fluid at B. [3]

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(Option B continues on the following page)

(Option B continued)

12. A mass is attached to a horizontal spring. The mass is displaced so that it is at a position x_0 from the equilibrium. The mass is released from rest and starts oscillating. After one complete oscillation the amplitude is measured to be x_1. The *Q* factor for the system is 200.

(a) Show that $\frac{x_1}{x_0}$ is about 0.98. [3]

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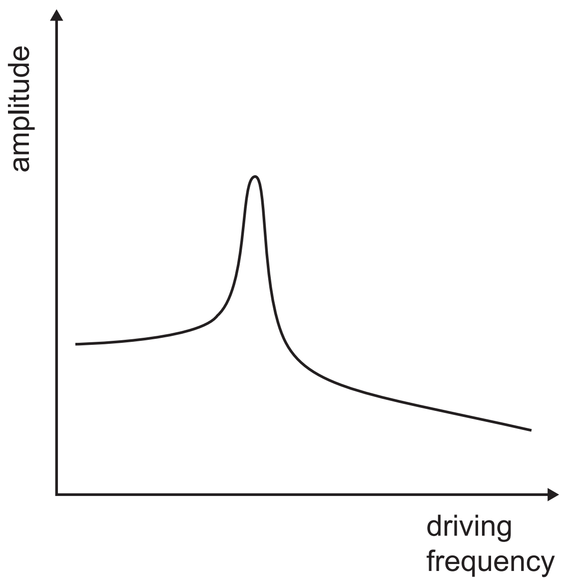
The spring is now connected to an oscillator that drives the oscillations.



The graph shows the variation of the amplitude of oscillations with the driving frequency.

(b) (i) Draw on the graph above how the amplitude would vary for a system with a much larger *Q* factor. [1]

(Option B continues on the following page)

(Option B, question 12 continued)

(ii) Justify the curve drawn in (b)(i). [1]

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End of Option B

Option C — Imaging

13. (a) The thin lens equation models rays passing through the centre of a lens as undeflected. Outline why a ray passing through the centre of the lens can be assumed to be straight. [2]

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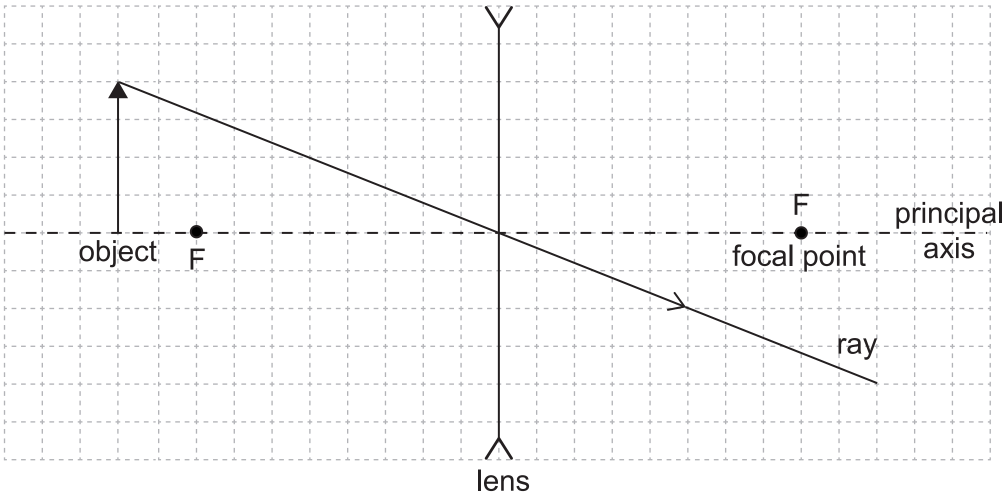
A ray diagram for a thin **diverging** lens is shown.



(b) The lens forms an image of the object. Draw the image and the rays from the object to show the formation of the image. [2]

(c) Estimate the linear magnification of the lens. [2]

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(Option C continues on the following page)

(Option C, question 13 continued)

(d) Explain how spherical aberration arises for real lenses and how it can be reduced. [2]

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(Option C continues on the following page)

(Option C continued)

14. An optical compound microscope in normal adjustment is composed of an objective lens of focal length 0.82 cm and an eyepiece lens of focal length 2.9 cm.

An object is placed 0.91 cm from the objective lens. The image is formed at the near point 25 cm from the eye.

(a) Show that the angular magnification of the microscope is about –90. [3]

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(b) The final image through the eyepiece is magnified. State **two** other characteristics of the final image. [1]

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(Option C continues on the following page)

(Option C continued)

15. (a) Explain why the refractive index of the cladding in a step-index optical fibre is **only slightly less** than the refractive index of the core. [2]

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(b) Explain how a graded-index fibre reduces the effects of waveguide dispersion. [3]

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(c) An optic fibre has an attenuation per unit length of $1.1\,\text{dB km}^{-1}$. Determine the maximum length of the fibre so that at least 4.0 % of the initial power transmitted reaches the end of the fibre. [3]

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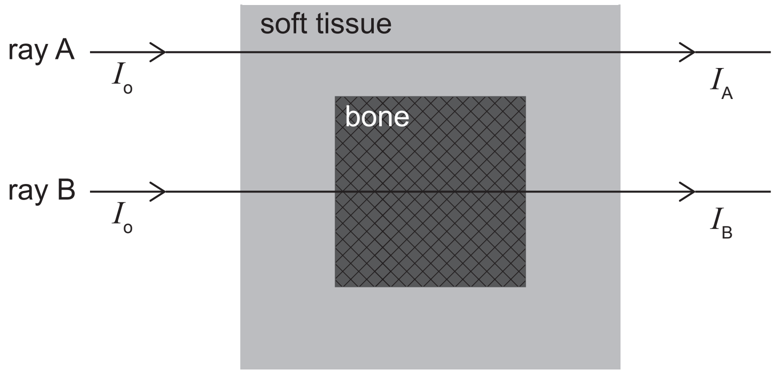
(Option C continues on the following page)

(Option C continued)

16. An X-ray image is taken of a patient's leg. Part of the beam, ray A, passes through soft tissue only and leaves the leg with an intensity I_A. The remainder of the beam, ray B, passes through soft tissue and bone and leaves the leg with an intensity I_B.

The diagram shows a simplified model of a cross-section of the leg.



The following data are given:

Width of the leg: 20 cm
Width of the bone: 9 cm
Attenuation coefficient of soft tissue: 0.13 cm^{-1}
Attenuation coefficient of bone: 0.59 cm^{-1}

(a) Determine the ratio $\frac{I_A}{I_B}$. [3]

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(b) The same leg is to be imaged using ultrasound. State what is meant by acoustic impedance. [1]

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(Option C continues on the following page)

(Option C, question 16 continued)

(c) When the ultrasound passes from soft tissue to bone, some of the ultrasound is reflected. The fraction of reflected ultrasound is given by:

$$\frac{(Z_2 - Z_1)^2}{(Z_1 + Z_2)^2}$$

where Z_1 is the acoustic impedance of soft tissue and Z_2 is the acoustic impedance of bone.

The following data are given:

Density of soft tissue: $1100\,\text{kg}\,\text{m}^{-3}$
Speed of sound in soft tissue: $1600\,\text{m}\,\text{s}^{-1}$
Density of bone: $1950\,\text{kg}\,\text{m}^{-3}$
Speed of sound in bone: $4100\,\text{m}\,\text{s}^{-1}$

Calculate the fraction of ultrasound reflected at the soft tissue–bone boundary. [2]

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(d) State **one** advantage and **one** disadvantage of using X-ray over ultrasound for a medical image. [2]

Advantage:

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Disadvantage:

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(Option C continues on page 29)

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(Option C, question 16 continued)

(e) Explain, with reference to the protons, how nuclear magnetic resonance (NMR) imaging can distinguish between bone and soft tissue. [2]

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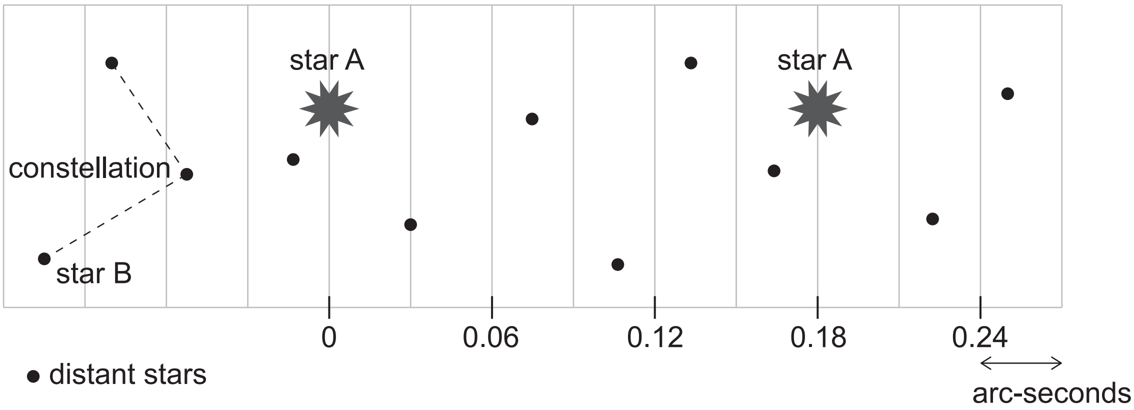
End of Option C

Option D — Astrophysics

17. The diagram shows the extreme positions of star A six months apart as seen from Earth. The black dots are the fixed positions of distant stars. The horizontal scale is in arc-seconds.



(a) (i) Show that the distance to star A is about 10 pc. [2]

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(ii) Calculate the ratio $\dfrac{\text{distance to star A}}{\text{distance from Earth to the Sun}}$. [2]

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(Option D continues on the following page)

(Option D, question 17 continued)

(b) Star B is part of a constellation. Outline what is meant by a constellation. [2]

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(c) The analysis of the stellar spectrum of star B shows that it has a surface temperature of 9900 K. Star B is a main sequence star with a luminosity of $25L_{\odot}$, where $L_{\odot}$ is the luminosity of the Sun.

(i) Outline how the temperature of a star can be determined from its stellar spectrum. [2]

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(ii) Predict the likely **final stage** in the stellar evolution of star B. [2]

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(d) Another star in the constellation is a Cepheid variable. Outline the reason for the variation in brightness of this star. [2]

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(Option D continues on the following page)

(Option D continued)

18. The cosmic microwave background (CMB) radiation is observed to be largely isotropic with a temperature of about 2.76 K.

(a) Explain how these features of the CMB provide evidence for a Hot Big Bang model. [2]

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(b) A galaxy is observed to have a redshift of 0.01. Hubble's constant can be assumed to be $70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$.

(i) Calculate, in Mpc, the distance to the galaxy. [3]

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(ii) Determine the age of the universe, in seconds, corresponding to the above value of Hubble's constant. Give your answer to at least 2 significant figures. [2]

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(Option D continues on the following page)

(Option D, question 18 continued)

(c) Explain how the observation of type Ia supernovae provides evidence for an accelerated expansion of the universe. [1]

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(Option D continues on page 35)

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(Option D continued)

19. In the core of a red giant star, helium fusion occurs for about one billion years before the star enters the next stage of its stellar evolution. However, a super red giant fuses the helium in its core in about one million years.

(a) Deduce the cause of the difference in times. [2]

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(b) Some super red giants evolve into supernovae. Elements heavier than iron can be produced through the r process in a supernova. Describe the r process and the conditions in a supernova that allow the r process to occur. [3]

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(Option D continues on the following page)

(Option D continued)

20. (a) Show, using Newton's universal law of gravitation, that the rotational speed of stars near the centre of the galaxy, V_{rot}, is proportional to the distance of each star from the centre of the galaxy, *d*. Assume the mass density near the centre of the galaxy to be constant and that the galaxy is spherical. [2]

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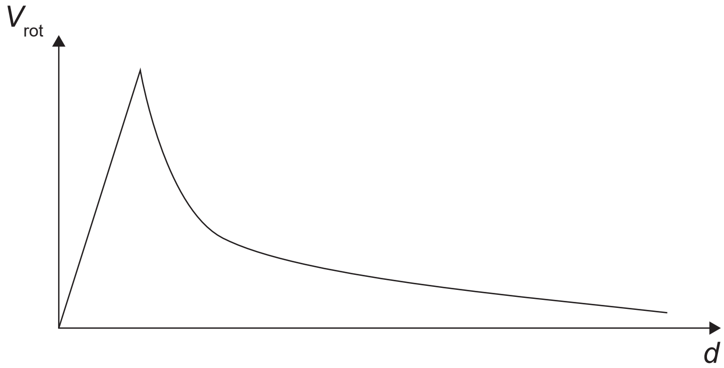
(Option D, question 20 continued)



The graph shows how V_{rot} was originally predicted to vary with d.

(b) (i) Sketch the observed relationship on the same axes. [1]

(ii) Outline **one** current hypothesis which supports your answer to (b)(i). [2]

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End of Option D

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