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# Physics

## Higher level

### Paper 3

25 April 2024

Zone A afternoon | Zone B afternoon | Zone C afternoon

Candidate session number

1 hour 15 minutes

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#### 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

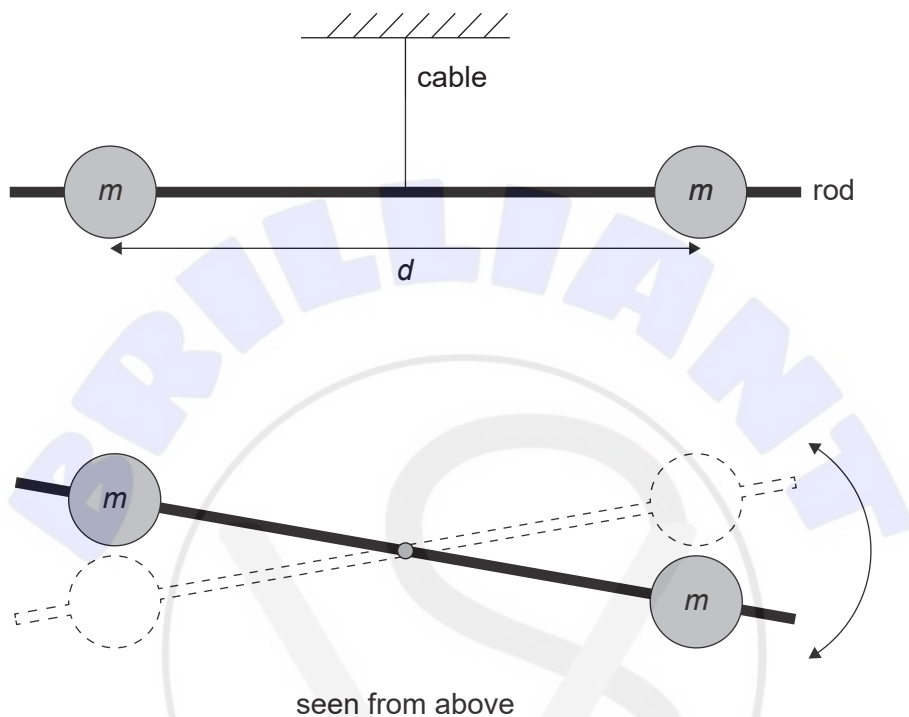
Section B	Questions
Answer all of the questions from one of the options.	
Option A — Relativity	3 – 7
Option B — Engineering physics	8 – 11
Option C — Imaging	12 – 16
Option D — Astrophysics	17 – 21



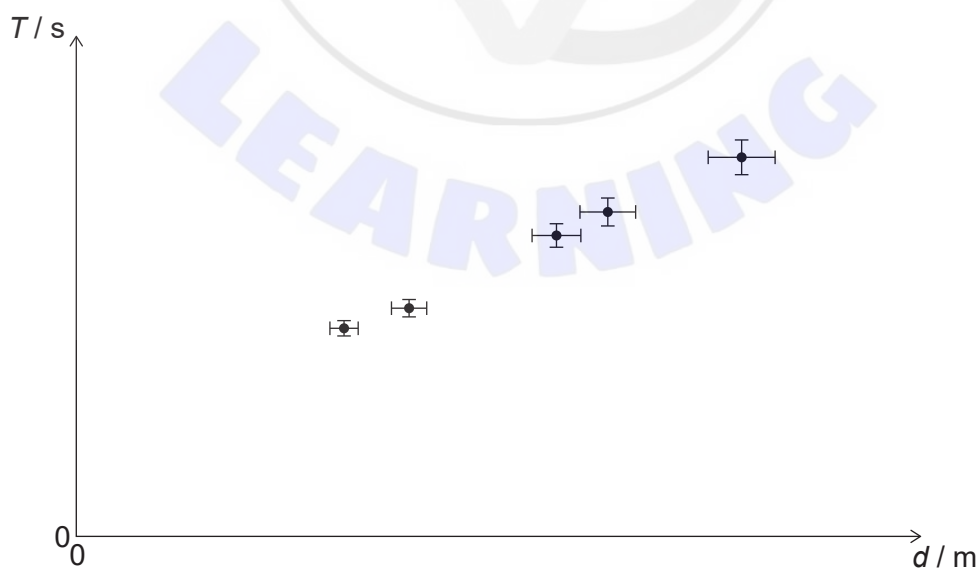
### Section A

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

1. A student performs an experiment with a rod that is free to oscillate in a horizontal plane. Two identical small spheres, each of mass  $m$ , are placed at equal distances from the centre of the rod. The student records values of the period of oscillation of the rod  $T$  in seconds for different values of the distance of separation of the spheres  $d$ , in metres.



The student plots the variation with  $d$  of  $T$ , keeping  $m$  constant.



(This question continues on the following page)



**(Question 1 continued)**

- (a) (i) Explain why  $m$  was kept constant. [1]

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- (ii) The student proposes the hypothesis that  $T$  is directly proportional to  $d$ .  
Outline whether the graph supports this model. [1]

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- (iii) State **one** other feature of the experiment that the student should keep constant. [1]

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- (b) The student proposes a new hypothesis such that

$$T^2 = Amd^2 + B$$

where  $A$  and  $B$  are constants.

After analysing the data for spheres of individual mass 40.0 g, the student proposes that

$$T^2 = 3.4d^2 + 1.5.$$

- Calculate  $A$ . State your answer with its fundamental SI unit. [2]

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**(This question continues on page 5)**





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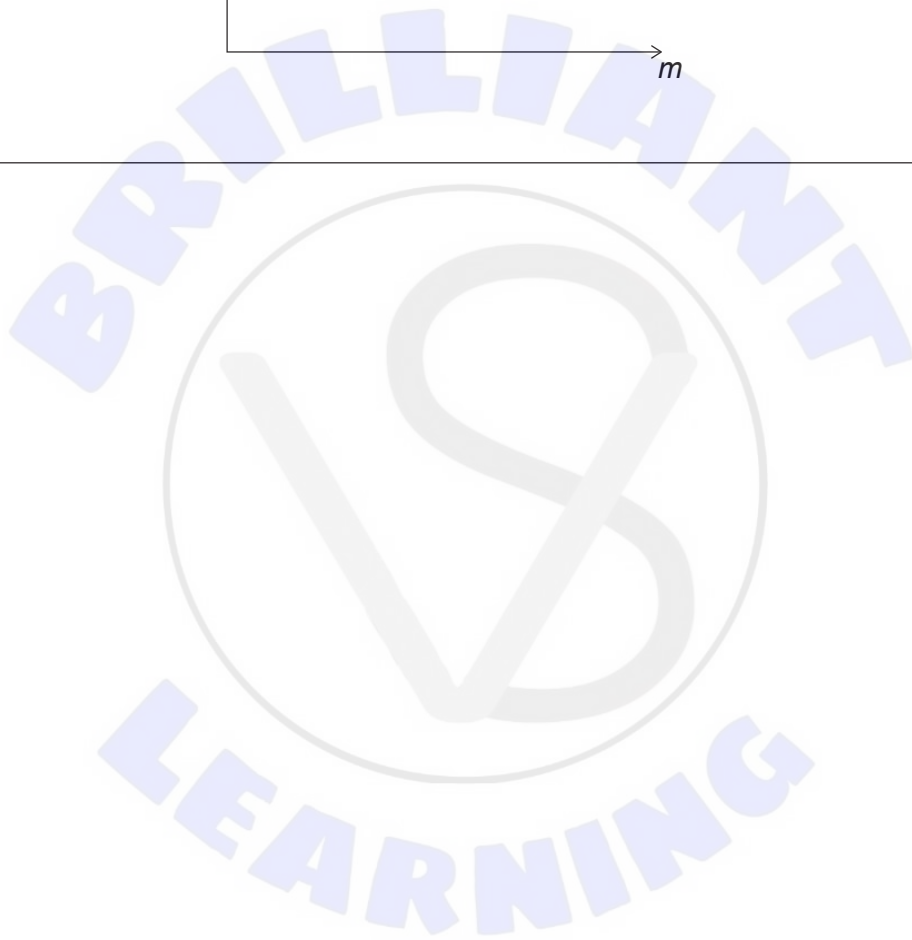
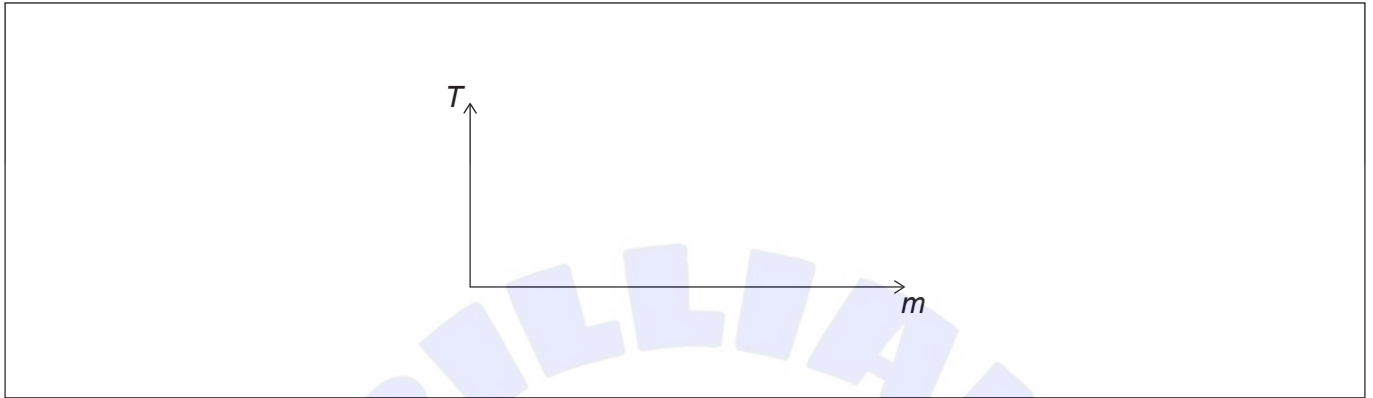


**(Question 1 continued)**

- (c) The student goes on to investigate the relationship proposed in (b) between  $T$  and  $m$ , keeping  $d$  constant.

Sketch the graph expected for this experiment on the axes provided.

[2]



2. In a series of trials to determine the specific latent heat of fusion of water  $L_{\text{water}}$ , crushed ice is added to an insulated container of negligible mass that contains water. The equilibrium temperature of the water is determined when all the ice has melted.

The following data are available:

Mass of water  $m_{\text{water}} = 0.095 \text{ kg}$

Mass of ice  $m_{\text{ice}} = 0.025 \text{ kg}$

Specific heat capacity of water  $c_{\text{water}} = 4200 \text{ J kg}^{-1} \text{ K}^{-1}$

Initial temperature of ice =  $0.0^\circ\text{C}$

Initial temperature of water =  $45.0^\circ\text{C}$

Average final equilibrium temperature of water =  $20 \pm 1^\circ\text{C}$

- (a) Suggest why some values of the experiment are stated without uncertainties in their measurements. [1]

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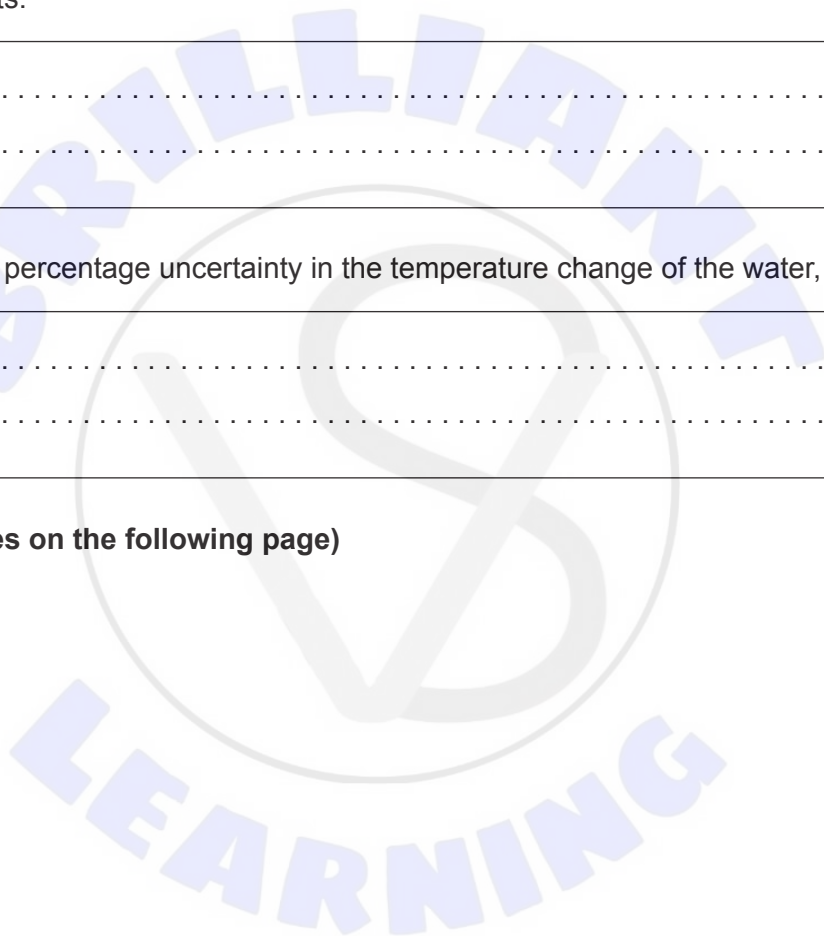
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- (b) Calculate the percentage uncertainty in the temperature change of the water,  $\Delta T_{\text{water}}$  [1]

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(This question continues on the following page)



**(Question 2 continued)**

The thermal energy exchanged is represented by the equation:

$$m_{\text{water}} c_{\text{water}} \Delta T_{\text{water}} = m_{\text{ice}} (L_{\text{water}} + c_{\text{water}} \Delta T_{\text{ice}}).$$

- (c) Show that the value of  $L_{\text{water}}$  for this experiment is  $3.2 \times 10^5 \text{ J kg}^{-1}$ . [2]

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- (d) The propagated percentage uncertainty in  $L_{\text{water}}$  is 6.4 %.
- Calculate its absolute uncertainty. State the value with an appropriate number of significant figures. [2]

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- (e) Discuss the effect of ignoring the mass of the container on the final calculated value of  $L_{\text{water}}$ . [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. An electron is moving towards a laboratory on Earth, where there is an observer X and a magnetic field. The observer X and the magnetic field are at rest with respect to the laboratory. The path of the electron is deflected by the interaction with the magnetic field. A second observer Y moves at the same velocity as the electron.

(a) Explain why observer Y is at rest in the reference frame of the electron. [1]

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(b) Outline how observer Y accounts for the deflection of the electron. [2]

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The electron approaches observer X at a speed of  $1.80 \times 10^8 \text{ ms}^{-1}$ . A second electron is approaching observer X from the same direction at a speed of  $1.50 \times 10^8 \text{ ms}^{-1}$ .

(c) (i) Calculate, in terms of  $c$ , the approaching speed of the second electron as measured by observer Y. [2]

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(ii) State **one** example of the paradigm shift resulting from the Lorentz transformations. [1]

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(Option A continues on the following page)



**(Option A continued)**

4. A spaceship travels from Earth to the orbit of Mars, at a constant velocity of  $0.4c$ . The distance travelled by the spaceship is  $2.0 \times 10^8$  km, as determined by an observer on Earth.

(a) Calculate, in km, the distance travelled as measured by an observer in the spaceship. [2]

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(b) While the spaceship is travelling, a radio signal is sent from Earth to the spaceship when it is at  $3.0 \times 10^6$  km, as measured from Earth.

(i) Show that, according to an Earth observer, the time taken for the signal to reach the spaceship is about 17 s. [2]

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(ii) Determine, according to an observer in the spaceship, the time taken for the signal to reach the spaceship. [2]

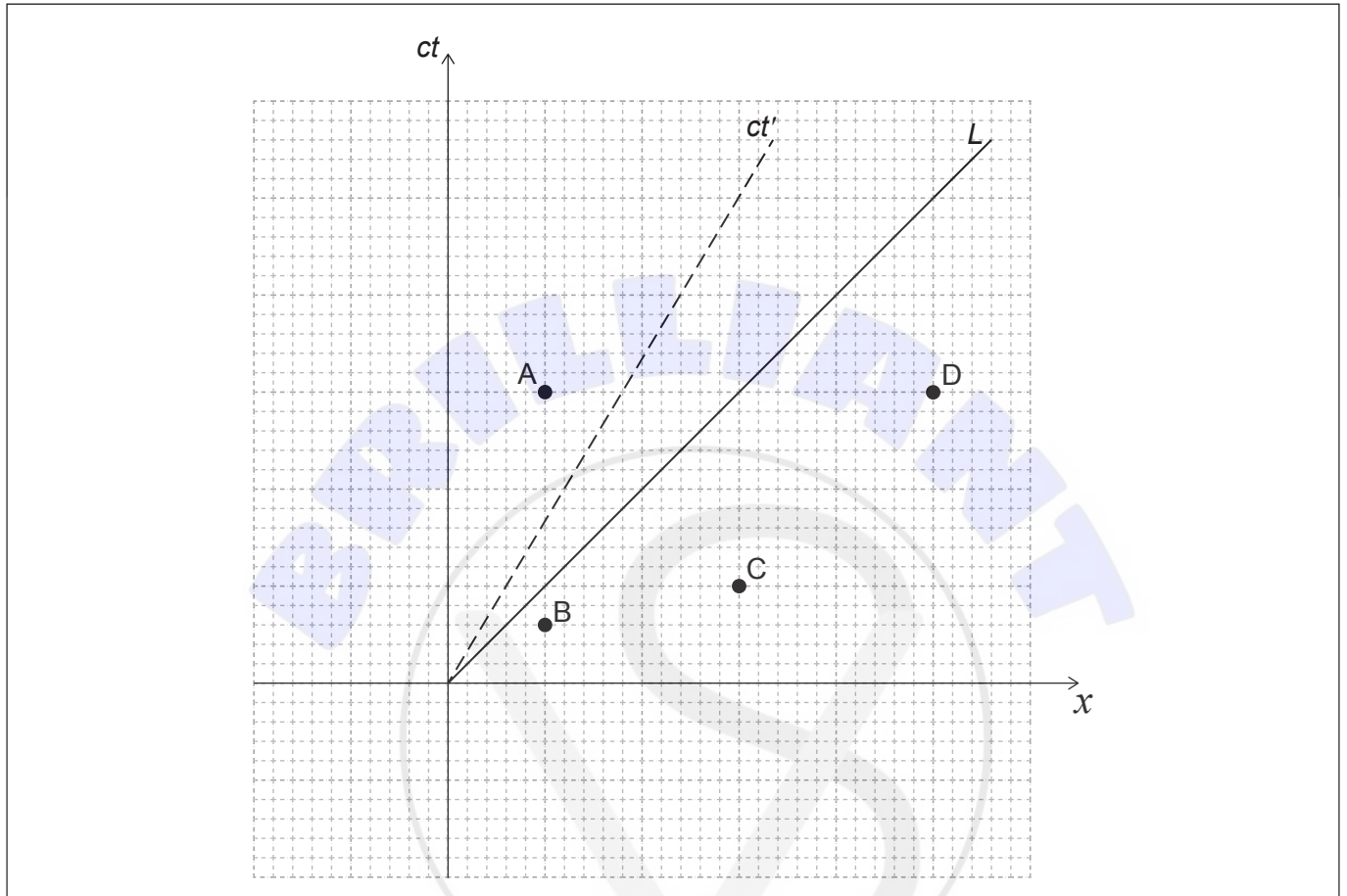
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**(Option A continues on the following page)**



**(Option A continued)**

5. Four events, A, B, C and D are plotted on the spacetime diagram. The  $ct - x$  axes are drawn in the reference frame of observer P. Observer Q is moving with respect to P. The  $ct'$  axis for observer Q and the path of a beam of light  $L$  are shown. The scale on both axes is the same.



- (a) (i) Determine the speed of observer Q with respect to observer P. [2]

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- (ii) Draw and label the  $x'$  axis for observer Q. [1]

**(Option A continues on the following page)**



**(Option A, question 5 continued)**

- (b) List the events that occur simultaneously, according to observer P. [1]

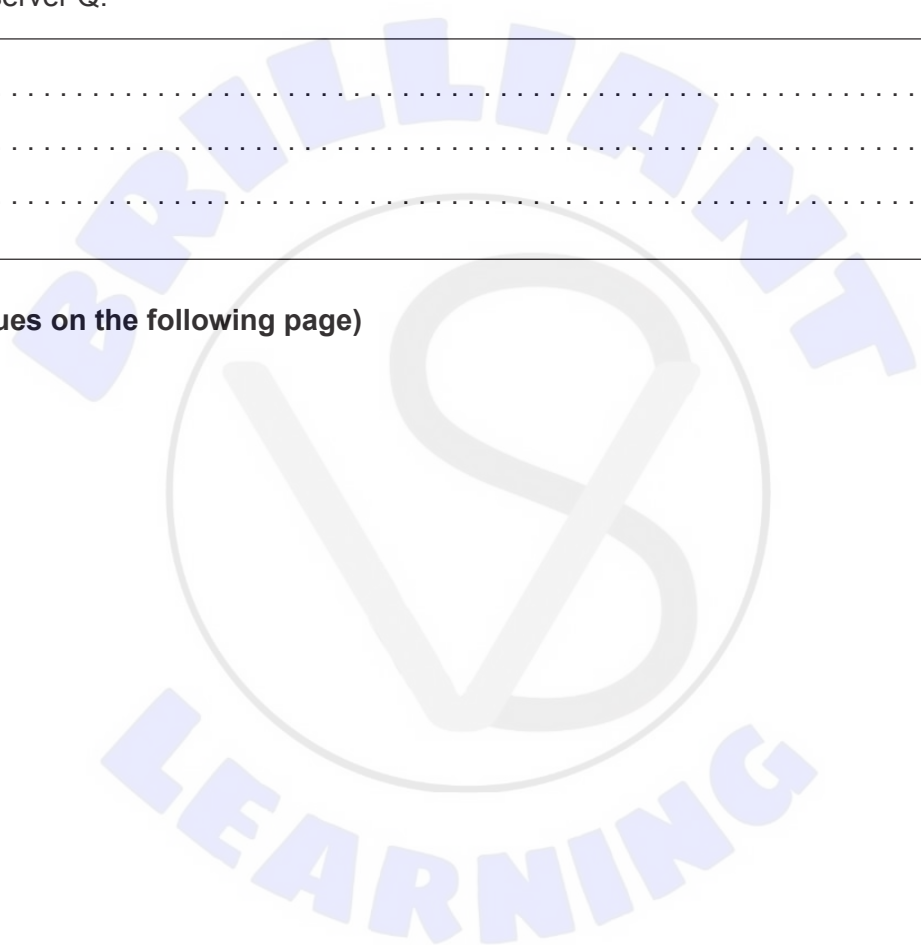
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- (c) Identify, by annotating the diagram, which event occurs first according to Q. [2]

- (d) Explain, using the diagram, why light from events A and D is received simultaneously by observer Q. [2]

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**(Option A continues on the following page)**



**(Option A continued)**

6. A kaon decays into two pions, pion A and pion B, that can be used to determine the rest mass of the kaon. After the decay, pion A has a kinetic energy of 210 MeV and pion B moves in the opposite direction to that of pion A with a kinetic energy of 48 MeV.

The following data are available:

Rest energy of pion A = 140 MeV

Rest energy of pion B = 135 MeV

- (a) In the energy - momentum relation,

$$E^2 = (pc)^2 + (m_0c^2)^2$$

identify the term  $E$ .

[1]

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- (b) Show that the total momentum of the system is about  $200 \text{ MeVc}^{-1}$ .

[3]

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**(Option A continues on the following page)**



**(Option A, question 6 continued)**

- (c) Calculate, in kg, the rest mass of the kaon. [3]

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**7. Global positioning systems (GPS) rely on the accuracy of clocks on satellites that orbit the Earth.**

- (a) State the equivalence principle. [1]

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- (b) Special and general relativistic effects must be considered when correcting signals from these clocks for GPS applications. Explain, in relation to general relativity, why these corrections need to be applied. [2]

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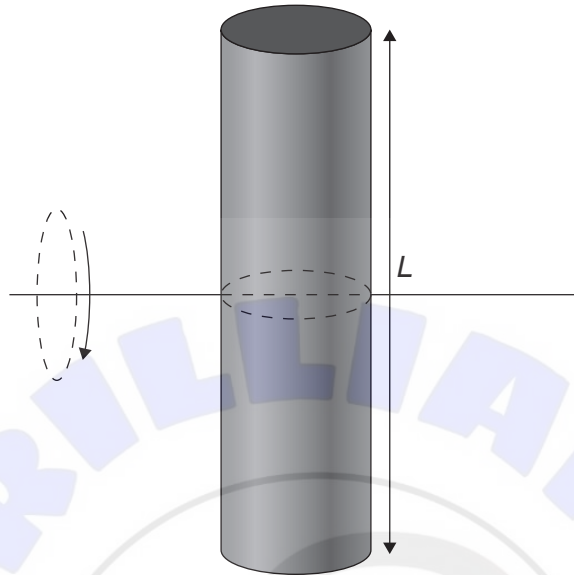
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**End of Option A**



**Option B — Engineering physics**

8. A uniform cylinder, of mass  $M$  and length  $L$ , has a moment of inertia of  $\frac{1}{12}ML^2$  when rotated about an axis through its centre.



- (a) (i) Outline what is meant by moment of inertia. [1]

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- (ii) State the condition for rotational equilibrium. [1]

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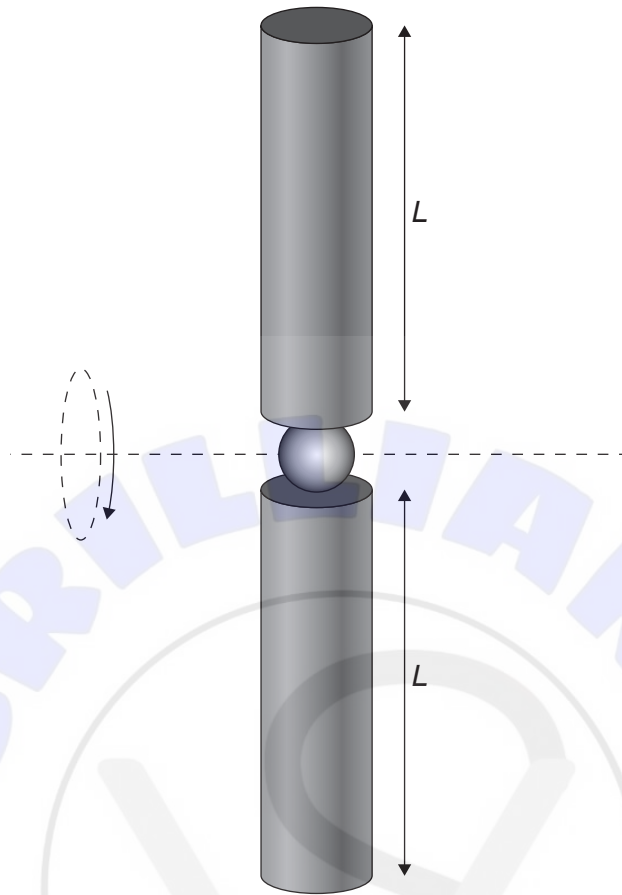
- (iii) Two identical cylinders, each of mass  $M$  and length  $L$ , are connected end to end. Show that the moment of inertia when these cylinders are rotated about their combined centre is  $\frac{2}{3}ML^2$ . [1]

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**(Option B continues on the following page)**



(Option B, question 8 continued)



(b) A two-blade propeller can be modelled using the two-cylinder arrangement in (a)(iii).

The following data for the two-blade propeller are available:

Length of each blade: 0.60 m

Mass of each blade: 2.2 kg

Show that the moment of inertia of the two-blade propeller is about  $0.5 \text{ kg m}^2$ .

[1]

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(Option B continues on page 17)





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**(Option B, question 8 continued)**

(c) The two-blade propeller is initially at rest. When a constant torque of 140 N m acts on the two-blade propeller it reaches an angular speed of  $750 \text{ rad s}^{-1}$ . Ignore any frictional torque.

(i) Calculate the time taken for the two-blade propeller to reach the angular speed of  $750 \text{ rad s}^{-1}$ . [2]

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(ii) Calculate the number of revolutions of the two-blade propeller to reach the angular speed of  $750 \text{ rad s}^{-1}$ . [2]

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(d) The propeller is brought to rest in 5.0 s. Determine the average value of the external torque applied. [2]

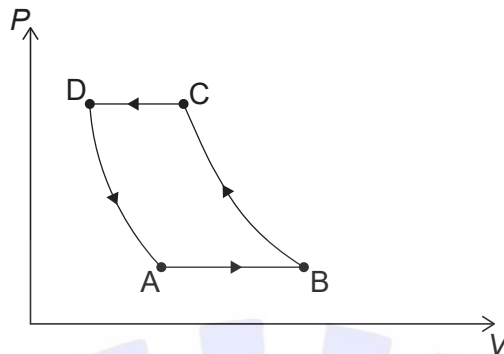
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**(Option B continues on the following page)**



(Option B continued)

9. A closed system contains 0.0070 mol of an ideal monatomic gas. The gas undergoes a cycle of four steps, represented below, consisting of two isobaric and two adiabatic processes.



Initially, at A, the gas is at a pressure of 120 kPa and a temperature of 200 K.

- (a) Show that the volume of the system at A is about  $1.0 \times 10^{-4} \text{ m}^3$ . [1]

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- (b) The gas undergoes an isobaric process from A to B reaching a volume of  $1.3 \times 10^{-4} \text{ m}^3$ . Show that the temperature of the gas at B is about 270 K. [1]

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- (c) The gas now undergoes an adiabatic compression from B to C. For this compression, the ratio of the pressures is

$$\frac{\text{Pressure at C}}{\text{Pressure at B}} = 5.0.$$

Determine the volume of the gas at C. [2]

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(Option B continues on the following page)



**(Option B, question 9 continued)**

- (d) (i) Identify the nature of the thermal energy transferred,  $Q$ , the change in internal energy of the gas,  $\Delta U$ , and the work done,  $W$ , for each step of the cycle. Insert, in the table below, “+” to identify a positive value, “-” to identify a negative value or “0” when the quantity does not change. Three values are given. [4]

	Change in $Q$	Change in $U$	$W$
<b>A-B</b>			+
<b>B-C</b>	0		
<b>C-D</b>			
<b>D-A</b>		-	

- (ii) Deduce, without performing any calculation, that during the cycle ABCDA there is a net output of thermal energy. [1]

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- (e) Discuss, in terms of entropy changes, the impact of this cycle on the surroundings. [1]

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**(Option B continues on the following page)**



**(Option B continued)**

10. A bubble of gas is rising at constant speed in a container filled with a liquid.

(a) Show that the speed  $v$  of the bubble can be estimated as

$$v = \frac{2 R^2 \rho g}{9 \eta}$$

where  $R$  is the radius of the bubble,  $\rho$  is the density of the liquid and  $\eta$  is the viscosity of the liquid. Assume the weight of the bubble is negligible.

[2]

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(b) The velocity of the bubble is measured to be  $18 \text{ cm s}^{-1}$ . The radius of the bubble is  $0.45 \text{ mm}$  and the density of the liquid is  $1300 \text{ kg m}^{-3}$ .

Calculate, in Pas, the viscosity of the liquid.

[2]

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(c) Justify, with a calculation, that laminar flow applies in this situation.

[2]

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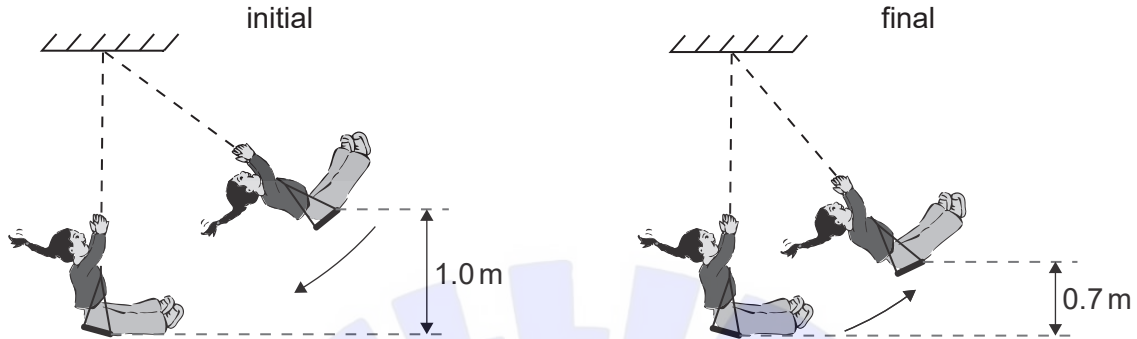
**(Option B continues on the following page)**



**(Option B continued)**

11. A child is on a swing. The child is displaced to one side through a vertical height  $h$  of 1.0 m above the rest position of the swing.

The swing is released and reaches  $h = 0.70$  m after a complete oscillation.

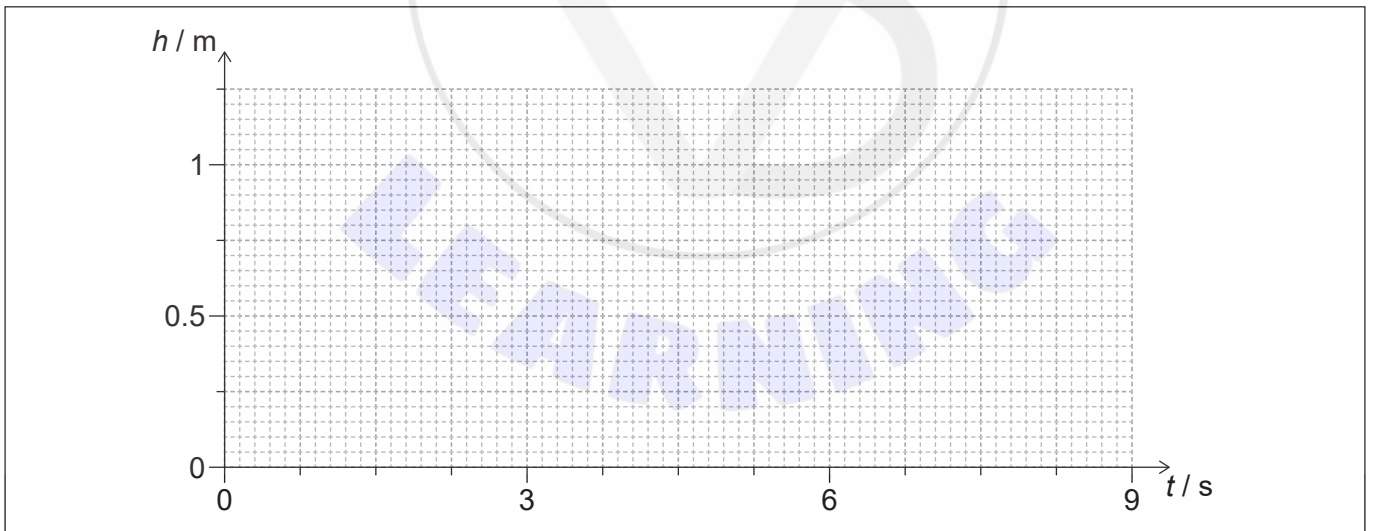


- (a) Determine the Q factor. [1]

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- (b) The period of the swing is 3.0 s.  
 (i) Draw the variation with time  $t$  of the height  $h$  for the first **two** complete oscillations. [2]



- (ii) Estimate the height  $h$  reached by the swing after 15.0 s from start. [1]

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**End of Option B**



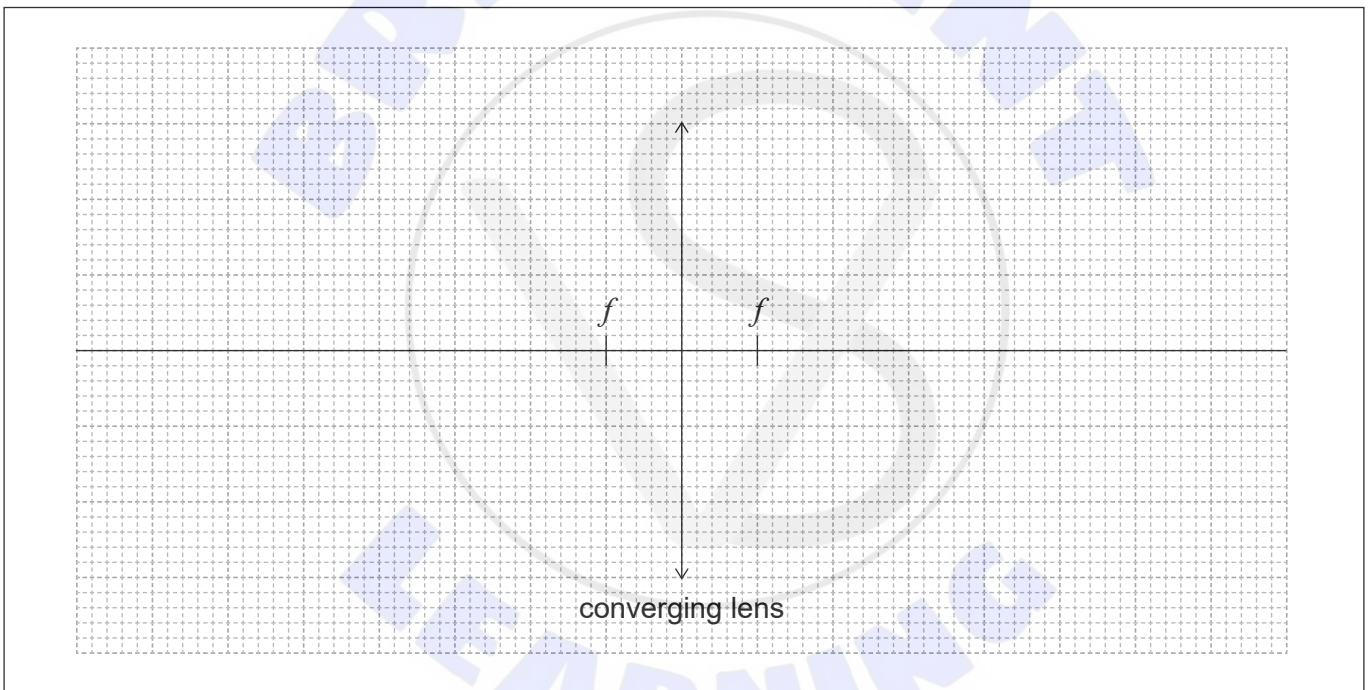
**Option C — Imaging**

12. In one arrangement an image that is half the height of a real object is produced by a lens of focal length  $f$ .

- (a) (i) Deduce, by calculation and in terms of  $f$ , the position of the object when a **converging lens** is used. [2]

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- (ii) Draw a ray diagram to show the arrangement described in (a)(i). [2]



(Option C continues on the following page)



(Option C, question 12 continued)

(b) A **diverging lens** of focal length 5.0 cm is now used to produce an image that is half the height of the object.

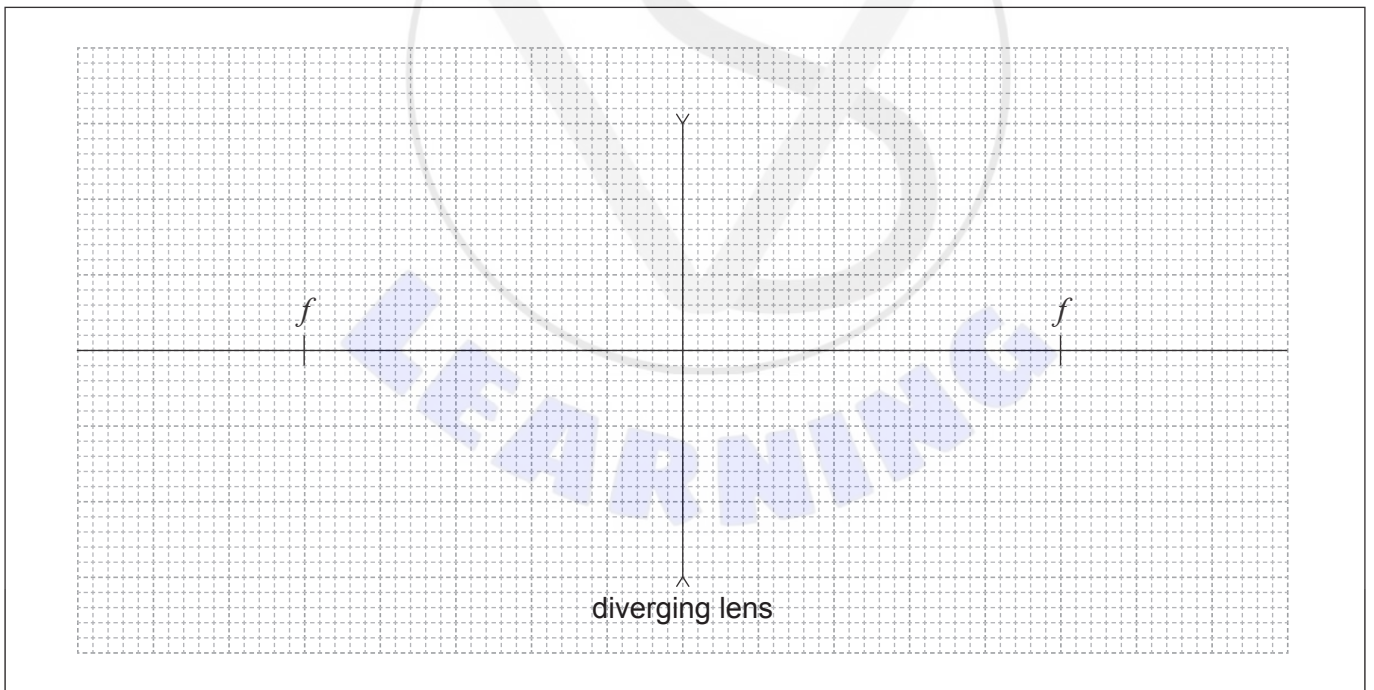
(i) State the nature of all images formed by a diverging lens. [1]

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(ii) Show that the position of the object is at the focus of the lens. [2]

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(iii) Construct a scaled ray diagram to show the situation described in (b)(ii). [2]

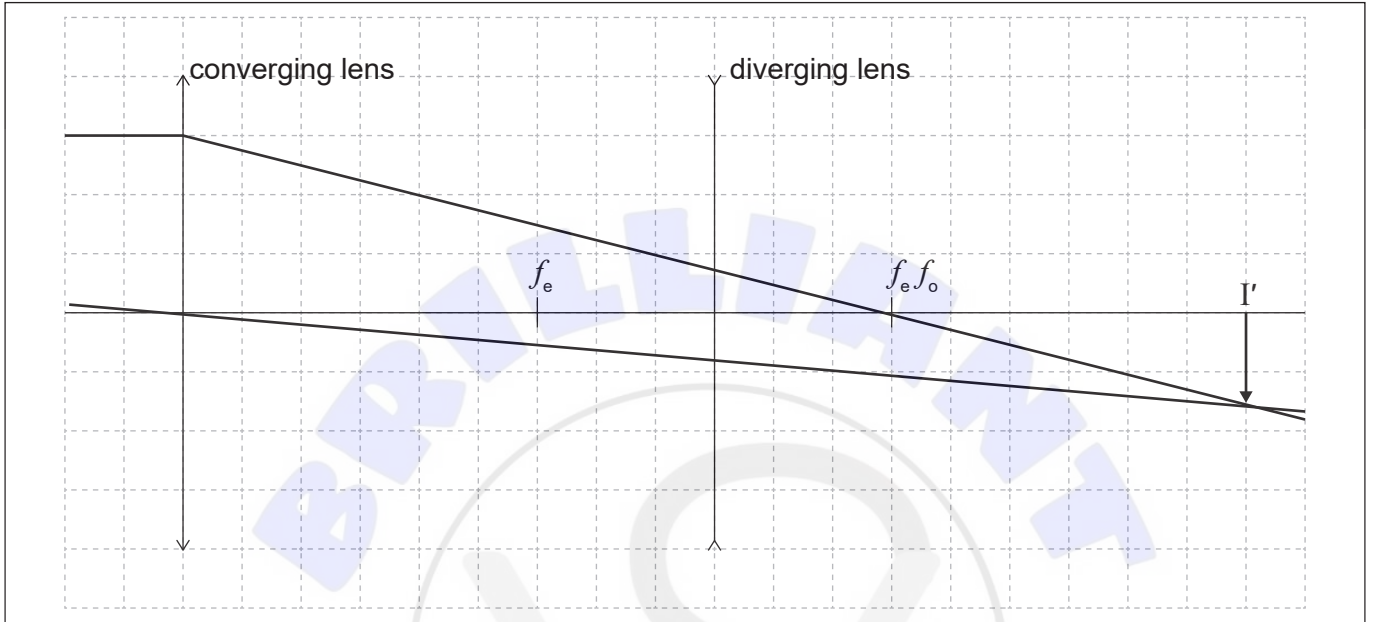


(Option C continues on the following page)



(Option C, question 12 continued)

- (c) A converging lens and a diverging lens are combined to form a virtual image of a distant object. The focal point of the converging lens and the focal point of the diverging lens coincide. The diagram shows two rays from the distant object and the formation of the intermediate image  $I'$  by the converging lens. Construct two other rays to show that the final image is upright (erect). [2]



(Option C continues on the following page)



**(Option C continued)**

13. (a) The focal length of the objective lens of a refracting telescope is 1.1 m. The telescope is used to observe the Moon. The image observed subtends an angle of 0.34 rad.

The following data are available:  
Distance to the Moon: 380 000 km  
Diameter of the Moon: 3500 km

Calculate, in mm, the focal length of the eye piece. [2]

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- (b) Large optical telescopes are usually reflecting telescopes.

- (i) State **one** example of how large reflecting telescopes have led to scientific discoveries. [1]

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- (ii) Outline why chromatic aberration is less significant in reflecting telescopes than in refracting telescopes. [1]

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- (iii) Distinguish between the paths of the light rays in Newtonian mounting and Cassegrain mounting telescopes. [1]

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**(Option C continues on page 27)**





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**(Option C continued)**

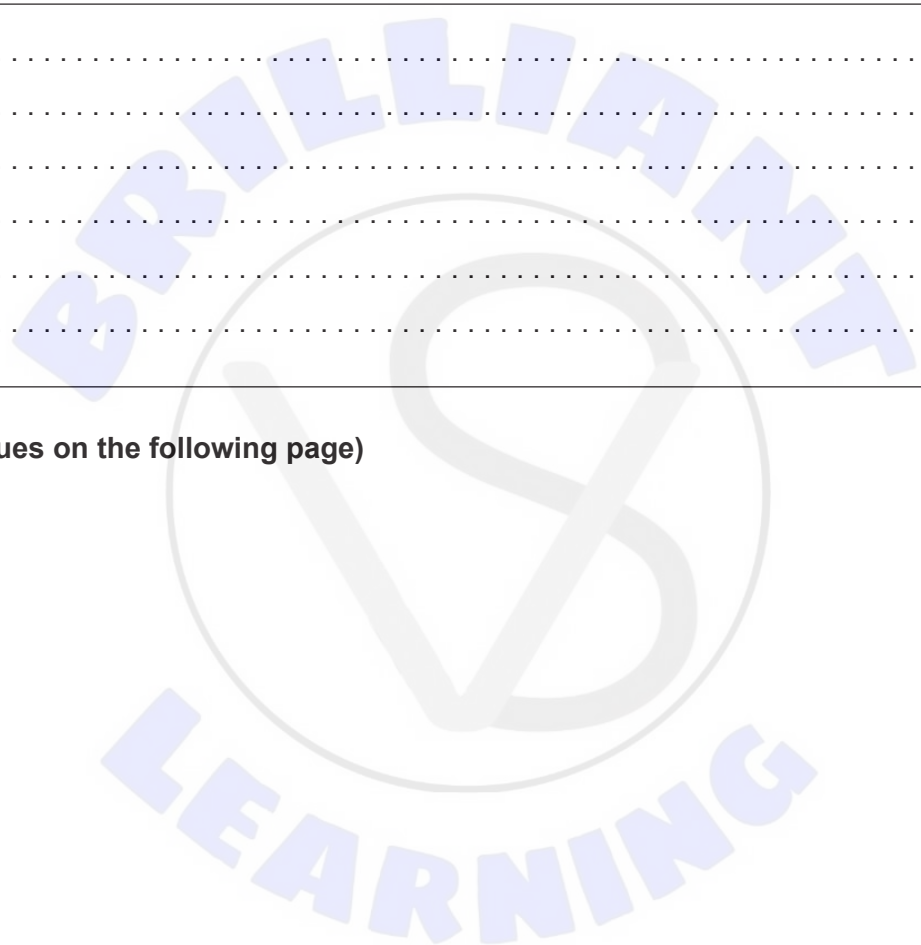
**14. (a)** Outline how dispersion affects the transmission of light in an optic fibre. [1]

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**(b)** The glass in a 10 km optic fibre has a refractive index that varies between 1.45298 to 1.45264. A pulse of duration 1.0 ns is transmitted through this optic fibre. Determine the minimum received pulse duration. [3]

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**(Option C continues on the following page)**



**(Option C continued)**

15. The linear absorption coefficients  $\mu_{20}$  and  $\mu_{100}$  for bone and muscle are shown for two incident X-ray energies of 20 keV and 100 keV.

	$\mu_{20} / \text{cm}^{-1}$	$\mu_{100} / \text{cm}^{-1}$
<b>bone</b>	7.2	0.24
<b>muscle</b>	0.96	0.21

(a) Discuss, with reference to the contrast in the final image, the difference between the use of 20 keV or 100 keV X-rays. [2]

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(b) Show that the intensity of the 20 keV X-rays is halved when travelling through 1 mm of bone. [1]

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**(Option C continues on the following page)**



(Option C, question 15 continued)

(c) A 100 keV X-ray beam goes through 2 cm of muscle and then 2 cm of bone. The intensity after passing through both layers is  $I$ .

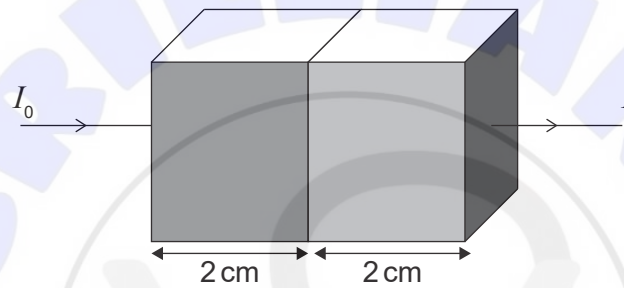
(i) Calculate the intensity ratio  $\frac{I}{I_0}$ . [2]

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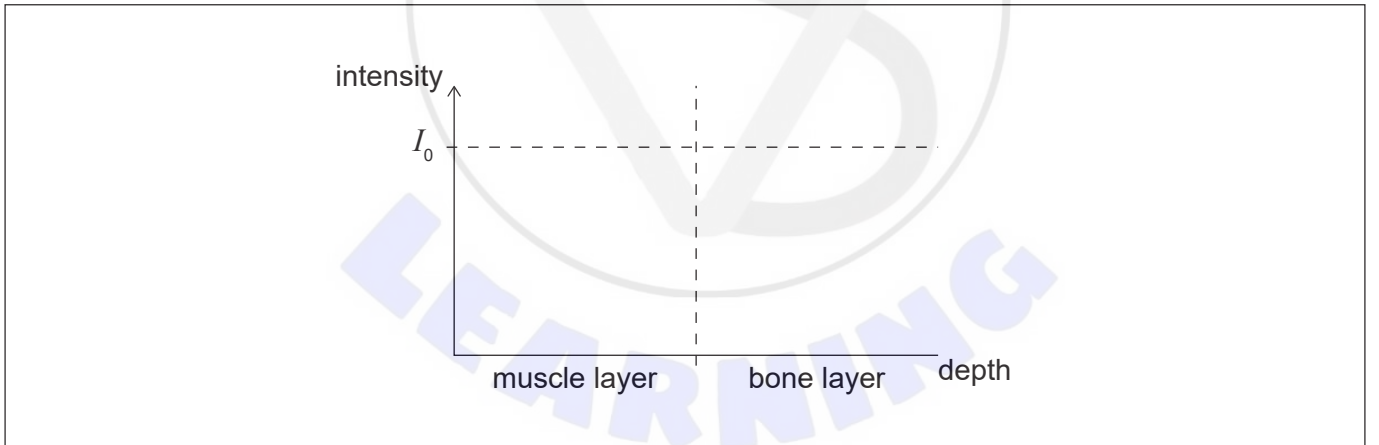
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(ii) Draw the variation in intensity of the beam with layer depth. [1]



(Option C continues on the following page)



**(Option C continued)**

**16.** Ultrasound imaging is usually performed at frequencies in the range of 2–20 MHz.

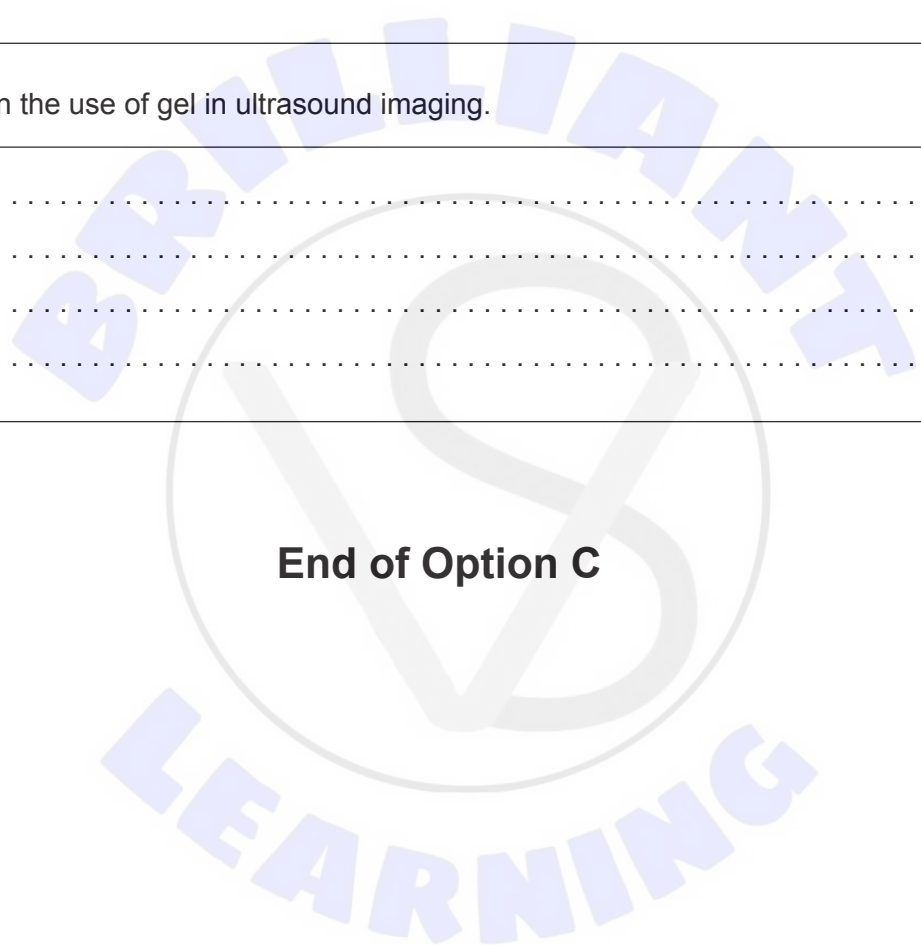
(a) Outline why frequencies of 2.5 MHz are used to image structures deep in the body while frequencies of 15 MHz are used for structures close to the skin. [2]

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(b) Explain the use of gel in ultrasound imaging. [2]

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**End of Option C**



**Option D — Astrophysics**

17. Over 60 elements, apart from hydrogen, have been identified in the composition of the Sun.

(a) Explain how elements present in the Sun are identified. [2]

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(b) The temperature of the surface of the Sun is 5780K. Calculate, in nm,  $\lambda_{\text{max}}$  for the spectrum of the Sun. [1]

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(c) Planets and comets orbit the Sun. Distinguish, with reference to their orbits, between planets and comets. [1]

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(d) Elements heavier than hydrogen and helium exist in the universe. Outline how these heavier elements were formed. [2]

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(Option D continues on the following page)



**(Option D continued)**

18. Alpha Centauri A and B form the closest binary star system to the Earth. This binary star system is the third brightest stellar object in the night sky.

- (a) Arcturus is the fourth brightest star in the night sky. Its apparent brightness is slightly greater than that of the star Alpha Centauri A.

Outline why the binary star system Alpha Centauri appears brighter than Arcturus. [1]

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- (b) Alpha Centauri A is a main sequence star.

The following data are available:

Parallax angle of Alpha Centauri A = 0.76 arcsec

Luminosity of Alpha Centauri A =  $5.7 \times 10^{26}$  W

Luminosity of the Sun  $L_{\odot} = 3.8 \times 10^{26}$  W

- (i) Show that the distance from Alpha Centauri A to our solar system is about  $4 \times 10^{16}$  m. [2]

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- (ii) Calculate the apparent brightness of Alpha Centauri A. [1]

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- (iii) Show that the mass of Alpha Centauri A is  $1.1 M_{\odot}$ , where  $M_{\odot}$  is the mass of the Sun. [2]

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(Option D continues on the following page)

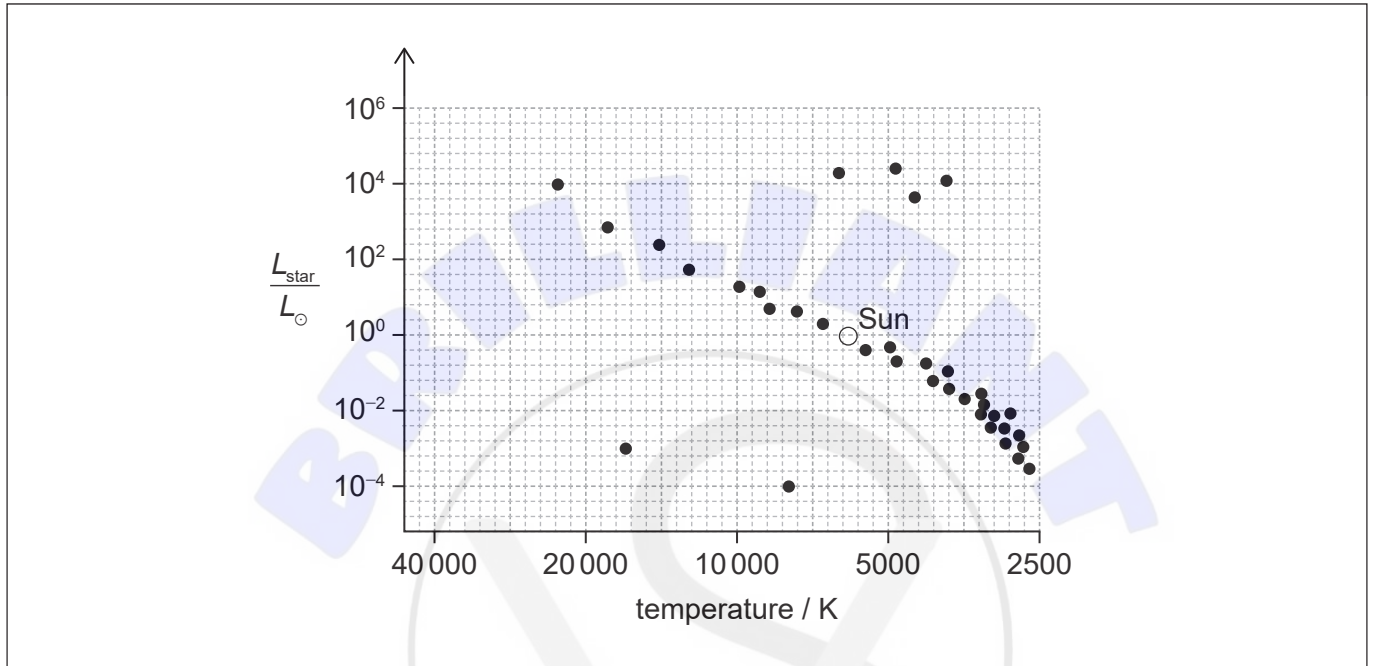


**(Option D, question 18 continued)**

(c) On the Hertzsprung-Russell (HR) diagram,

(i) plot, with an X, the position of Alpha Centauri A; [1]

(ii) draw the most likely future evolutionary path of Alpha Centauri A, labelling the two main regions of this path. [2]



(d) Proxima Centauri is a main sequence star with a mass of  $0.12 M_{\odot}$ .

Compare the times for which Proxima Centauri and Alpha Centauri A are main sequence stars. [2]

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**(Option D continues on the following page)**



**(Option D, question 18 continued)**

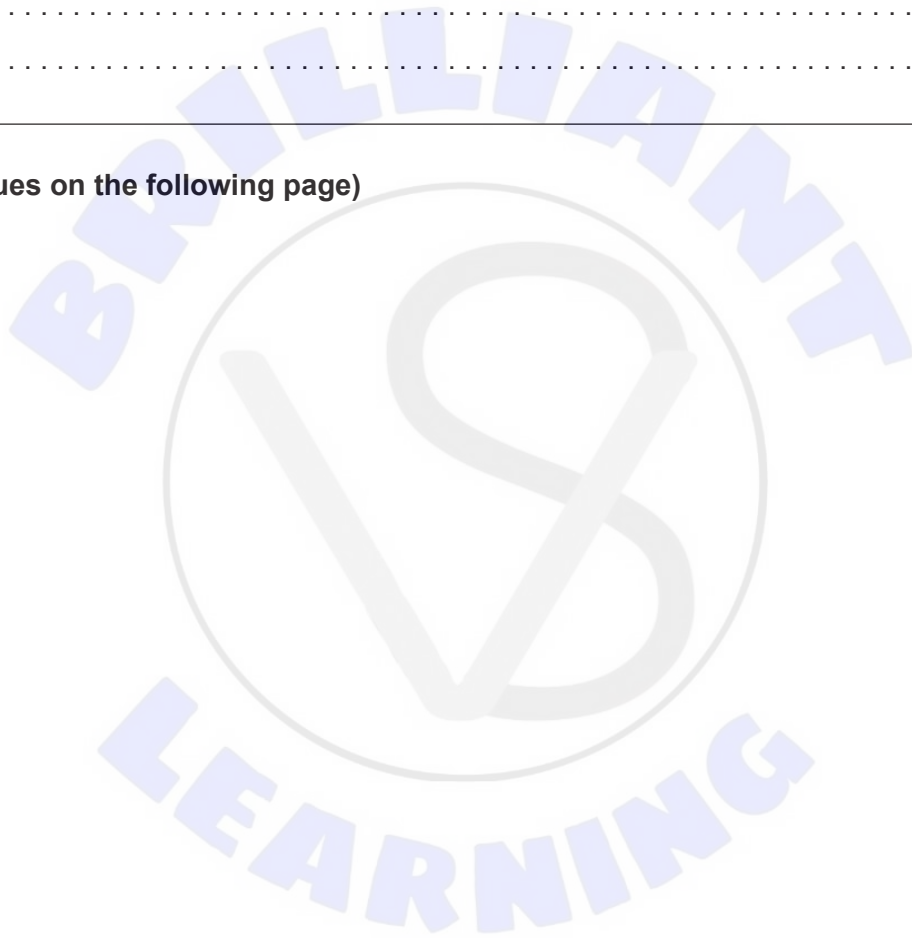
(e) Explain the relationship between binary star systems and type Ia supernovae. [1]

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(f) Outline how type Ia supernovae can be used to measure very large astronomical distances. [1]

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**(Option D continues on the following page)**



**(Option D continued)**

**19.** Cosmic microwave background (CMB) radiation was discovered more than 50 years ago.

(a) State **one** characteristic of CMB radiation. [1]

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(b) Outline the significance of CMB radiation in relation to the Big Bang model. [2]

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(c) State and explain **one** additional piece of evidence for the Big Bang model. [2]

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**20.** Quasars are bright celestial objects which show very large red-shifts.

Show that the light from a quasar with a red-shift of 7.5 was emitted when the universe was about 12% of its current size. [2]

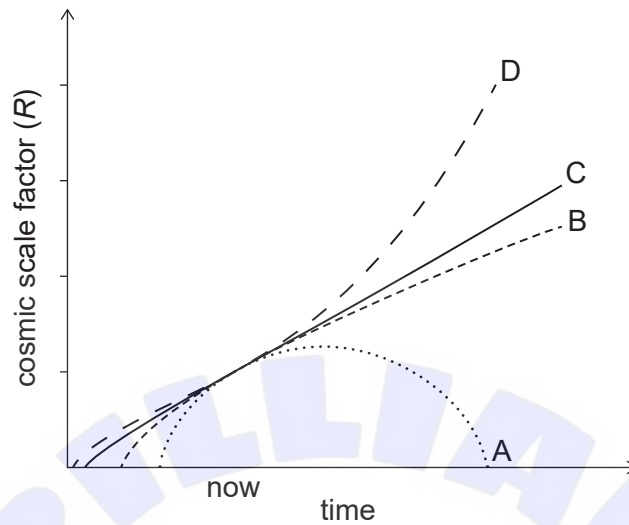
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**(Option D continues on the following page)**



(Option D continued)

21. The graph shows possible models for the fate of the universe.



(a) Comment on the value of the density of the universe for line B. [2]

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(b) State and explain which line is related to the concept of dark energy. [2]

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**End of Option D**

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**References:**

21. NASA/WMAP Science Team. Available at: <https://map.gsfc.nasa.gov/media/990350/990350b.jpg>. Source adapted.

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