

Markscheme

May 2024

Physics

Higher level

Paper 3

© International Baccalaureate Organization 2024

All rights reserved. No part of this product may be reproduced in any form or by any electronic or mechanical means, including information storage and retrieval systems, without the prior written permission from the IB. Additionally, the license tied with this product prohibits use of any selected files or extracts from this product. Use by third parties, including but not limited to publishers, private teachers, tutoring or study services, preparatory schools, vendors operating curriculum mapping services or teacher resource digital platforms and app developers, whether fee-covered or not, is prohibited and is a criminal offense.

More information on how to request written permission in the form of a license can be obtained from <https://ibo.org/become-an-ib-school/ib-publishing/licensing/applying-for-a-license/>.

© Organisation du Baccalauréat International 2024

Tous droits réservés. Aucune partie de ce produit ne peut être reproduite sous quelque forme ni par quelque moyen que ce soit, électronique ou mécanique, y compris des systèmes de stockage et de récupération d'informations, sans l'autorisation écrite préalable de l'IB. De plus, la licence associée à ce produit interdit toute utilisation de tout fichier ou extrait sélectionné dans ce produit. L'utilisation par des tiers, y compris, sans toutefois s'y limiter, des éditeurs, des professeurs particuliers, des services de tutorat ou d'aide aux études, des établissements de préparation à l'enseignement supérieur, des fournisseurs de services de planification des programmes d'études, des gestionnaires de plateformes pédagogiques en ligne, et des développeurs d'applications, moyennant paiement ou non, est interdite et constitue une infraction pénale.

Pour plus d'informations sur la procédure à suivre pour obtenir une autorisation écrite sous la forme d'une licence, rendez-vous à l'adresse <https://ibo.org/become-an-ib-school/ib-publishing/licensing/applying-for-a-license/>.

© Organización del Bachillerato Internacional, 2024

Todos los derechos reservados. No se podrá reproducir ninguna parte de este producto de ninguna forma ni por ningún medio electrónico o mecánico, incluidos los sistemas de almacenamiento y recuperación de información, sin la previa autorización por escrito del IB. Además, la licencia vinculada a este producto prohíbe el uso de todo archivo o fragmento seleccionado de este producto. El uso por parte de terceros —lo que incluye, a título enunciativo, editoriales, profesores particulares, servicios de apoyo académico o ayuda para el estudio, colegios preparatorios, desarrolladores de aplicaciones y entidades que presten servicios de planificación curricular u ofrezcan recursos para docentes mediante plataformas digitales—, ya sea incluido en tasas o no, está prohibido y constituye un delito.

En este enlace encontrará más información sobre cómo solicitar una autorización por escrito en forma de licencia: <https://ibo.org/become-an-ib-school/ib-publishing/licensing/applying-for-a-license/>.

Subject Details: Physics HL Paper 3 Markscheme

Candidates are required to answer **all** questions in Section A and **all** questions from **one** option in Section B. Maximum total = **45 marks**.

1. Each row in the “Question” column relates to the smallest subpart of the question.
2. The maximum mark for each question subpart is indicated in the “Total” column.
3. Each marking point in the “Answers” column is shown by means of a tick (✓) at the end of the marking point.
4. A question subpart may have more marking points than the total allows. This will be indicated by “**max**” written after the mark in the “Total” column. The related rubric, if necessary, will be outlined in the “Notes” column.
5. An alternative wording is indicated in the “Answers” column by a slash (/). Either wording can be accepted.
6. An alternative answer is indicated in the “Answers” column by “**OR**”. Either answer can be accepted.
7. An alternative markscheme is indicated in the “Answers” column under heading **ALTERNATIVE 1** etc. Either alternative can be accepted.
8. Words inside chevrons « » in the “Answers” column are not necessary to gain the mark.
9. Words that are underlined are essential for the mark.
10. The order of marking points does not have to be as in the “Answers” column, unless stated otherwise in the “Notes” column.
11. If the candidate’s answer has the same “meaning” or can be clearly interpreted as being of equivalent significance, detail and validity as that in the “Answers” column then award the mark. Where this point is considered to be particularly relevant in a question it is emphasized by **OWTTE** (or words to that effect) in the “Notes” column.
12. Remember that many candidates are writing in a second language. Effective communication is more important than grammatical accuracy.
13. Occasionally, a part of a question may require an answer that is required for subsequent marking points. If an error is made in the first marking point then it should be penalized. However, if the incorrect answer is used correctly in subsequent marking points then **follow through** marks should be awarded. When marking, indicate this by adding **ECF** (error carried forward) on the script. “ECF acceptable” will be displayed in the “Notes” column.
14. Do **not** penalize candidates for errors in units or significant figures, **unless** it is specifically referred to in the “Notes” column.

Section A

Question			Answers	Notes	Total
1.	a	i	identifies m as a controlled variable OR recognizes that «the variation of» m affects T OR identifies d as the independent variable OR relationship between d and T could not be found if m changes OR acknowledges that only one variable is to be changed at a time OR highlights the need of the same conditions throughout the experiment ✓	OWTTE.	1
	a	ii	no, as the fit does not go through the origin ✓		1
	a	iii	amplitude/angle of release / use of small angle OR number of oscillations OR any measurable feature of the cable, e.g. length or diameter OR any measurable feature of the rod OR cable holding the rod at its mid-point OR shape of masses ✓	Do not accept same cable/rod/ spheres without any other reference. Do not accept any environmental reference as e.g. temperature.	1
	b		«identifies $3.4 = Am$ so» $A = 85$ ✓ unit is $s^2 \text{ kg}^{-1} \text{ m}^{-2}$ ✓	Ignore unit and award [1] max for a final answer of 0.085.	2

c		correct shape of graph ✓  intercept on <i>T</i> axis is not zero ✓		2
----------	--	---	--	----------

Question		Answers	Notes	Total
2.	a	uncertainties are small / negligible OR variables can be measured precisely ✓	<i>Award [1] if the answer specifically refers to the specific heat capacity of water as known/constant value.</i>	1
	b	$(25 \pm 1 \text{ so}) 4\% \checkmark$		1
	c	$0.095 \times 4200 \times 25 = 0.025 \times (L + 4200 \times 20) \checkmark$ $L = \frac{0.095 \times 4200 \times 25}{0.025} - 4200 \times 20$ OR $L = 315000 \text{ «Jkg}^{-1}\text{»} \checkmark$	<i>MP2 scores MP1</i> <i>Do not apply ECF from MP1.</i> <i>Answer given, so award MP2 if candidates show a correct full expression for L OR the value with an extra significant figure.</i>	2
	d	$0.064 \times 3.2 \times 10^5 \text{ OR } 0.064 \times 3.15 \times 10^5 \text{ OR } 20480 \text{ OR } 20160\text{»} \checkmark$ $2 \times 10^4 \text{ «Jkg}^{-1}\text{»} \checkmark$	<i>For MP2, accept two significant figures for the answer, i.e. 2.0×10^4</i> <i>For MP2, accept a final answer of 20000.</i> <i>MP2 scores MP1</i>	2
	e	there is more thermal energy/mass/extra term in the L.H.S of the equation/thermal energy provided by the container OR	<i>MP1 can be expressed in a variety of ways.</i>	2

		<p>mass of container has made the final temperature higher/ΔT smaller ✓</p> <p>L should be greater than calculated / is an underestimate ✓</p>	<p><i>Award [1] max if they interpret that the container takes thermal energy, assuming it was at room temperature, regardless of the conclusion</i></p> <p><i>Do not accept MP2 if no reason given.</i></p> <p><i>Do not apply CON and award [1] if conclusion inconsistent with correct MP1</i></p>	
--	--	--	---	--

Section B

Option A — Relativity

Question		Answers	Notes	Total	
3.	a	there is no relative velocity/change in position between Y and the electron OR both move at the same velocity ✓		1	
	b	«electron experiences changing» magnetic field approaching thus creating a «changing» electric field ✓ no magnetic force on a stationary electron ✓ electric force on the electron ✓		2 max	
	c	i	correct use of relativistic addition of velocities formula e.g. $v = \frac{1.8 \times 10^8 - 1.5 \times 10^8}{1 - \frac{1.8 \times 10^8 \times 1.5 \times 10^8}{(3 \times 10^8)^2}} \text{ or } v = \frac{0.6c - 0.5c}{1 - \frac{0.6c \times 0.5c}{c^2}} \checkmark$ $= 0.14c \checkmark$	Award [2] for a BCA Ignore sign for MP2 Do not apply ECF for MP2	2
	c	ii	time/length is no longer absolute/depends on the frame of reference OR speed of light «in vacuum» is constant/ independent of the velocity of the source OR relative velocity between objects cannot be larger than c ✓	1	

Question			Answers	Notes	Total
4.	a		$\gamma = \frac{1}{(1-0.4^2)^{0.5}}$ <p>OR</p> $\gamma = 1.09 \checkmark$ $d = \llcorner 2.0 \times 10^8 / 1.09 \rceil \Rightarrow 1.8 \times 10^8 \llcorner \text{km} \rceil \checkmark$	<p>Allow ECF for MP2</p> <p>Allow BCA</p>	2
	b	i	$c \Delta t = d + v \Delta t, \llcorner \text{so } \Delta t = \frac{d}{c-v} \rceil \checkmark$ $\Delta t = \frac{3 \times 10^9}{0.6 \times 3 \times 10^8} \llcorner \text{s} \rceil$ <p>OR</p> $16.7 \llcorner \text{s} \rceil \checkmark$	<p>Answer of 17 s given, so award MP2 if candidates show a correct full substitution OR the value with an extra significant figure.</p>	2
	b	ii	<p>use of $\Delta t' = \gamma \left(\Delta t - \frac{v \Delta x}{c^2} \right) \checkmark$</p> $\Delta t' = 1.09 \times \left(16.7 - \frac{0.4c \times c \times 16.7}{c^2} \right) = 11 \llcorner \text{s} \rceil \checkmark$	<p>Award [2] for a BCA</p>	2

Question			Answers	Notes	Total
5.	a	i	<p>use of inverse of gradient of ct' axis \checkmark</p> $v = 0.6c \checkmark$	<p>Award [2] for a BCA</p>	2

	a	ii	draws axis x' through B and D ✓		1
	b		A and D ✓		1
	c		line shown parallel to x' ✓ through C ✓	<i>Accept answer C without working for MP2</i>	2
	d		shows 45° lines from A and D ✓ that meet on the ct' axis ✓		2

Question		Answers	Notes	Total
6.	a	total energy OR sum of rest and kinetic energy ✓		1
	b	attempt to use $E^2 = p^2c^2 + m_0^2c^4$ for any of the pions ✓ $(210 + 140)^2 = (pc)^2 + 140^2$ OR «p = » 321 « MeVc ⁻¹ » OR $(48 + 135)^2 = (pc)^2 + 135^2$ OR «p = » 124 «MeVc ⁻¹ » ✓ «applies conservation of momentum so» 312 - 124 «MeVc ⁻¹ » OR 197 «MeVc ⁻¹ » ✓		3
	c	attempt to use $E^2 = p^2c^2 + m_0^2c^4$ for the kaon ✓ «Rest energy of kaon» = $(533^2 - 197^2)^{0.5}$ OR 495 « MeVc ⁻² » ✓ « = $\frac{495 \times 10^6 \times 1.6 \times 10^{-19}}{(3 \times 10^8)^2}$ = »	MP2 can be 495 or 494 Award [3] for a BCA	3

			8.8×10^{-28} «kg» ✓	Allow ECF from MP2 to MP3	
--	--	--	------------------------------	---------------------------	--

Question		Answers	Notes	Total
7.	a	accelerated frames of reference are equivalent to frames in a gravitational field ✓	OWTTE	1
	b	mention of gravitational red shift OR clocks are at different positions «from a massive body » OR at a higher potential «than on Earth» ✓ there is a frequency/period shift OR clocks will run differently «than on Earth» OR clocks need to be adjusted ✓		2

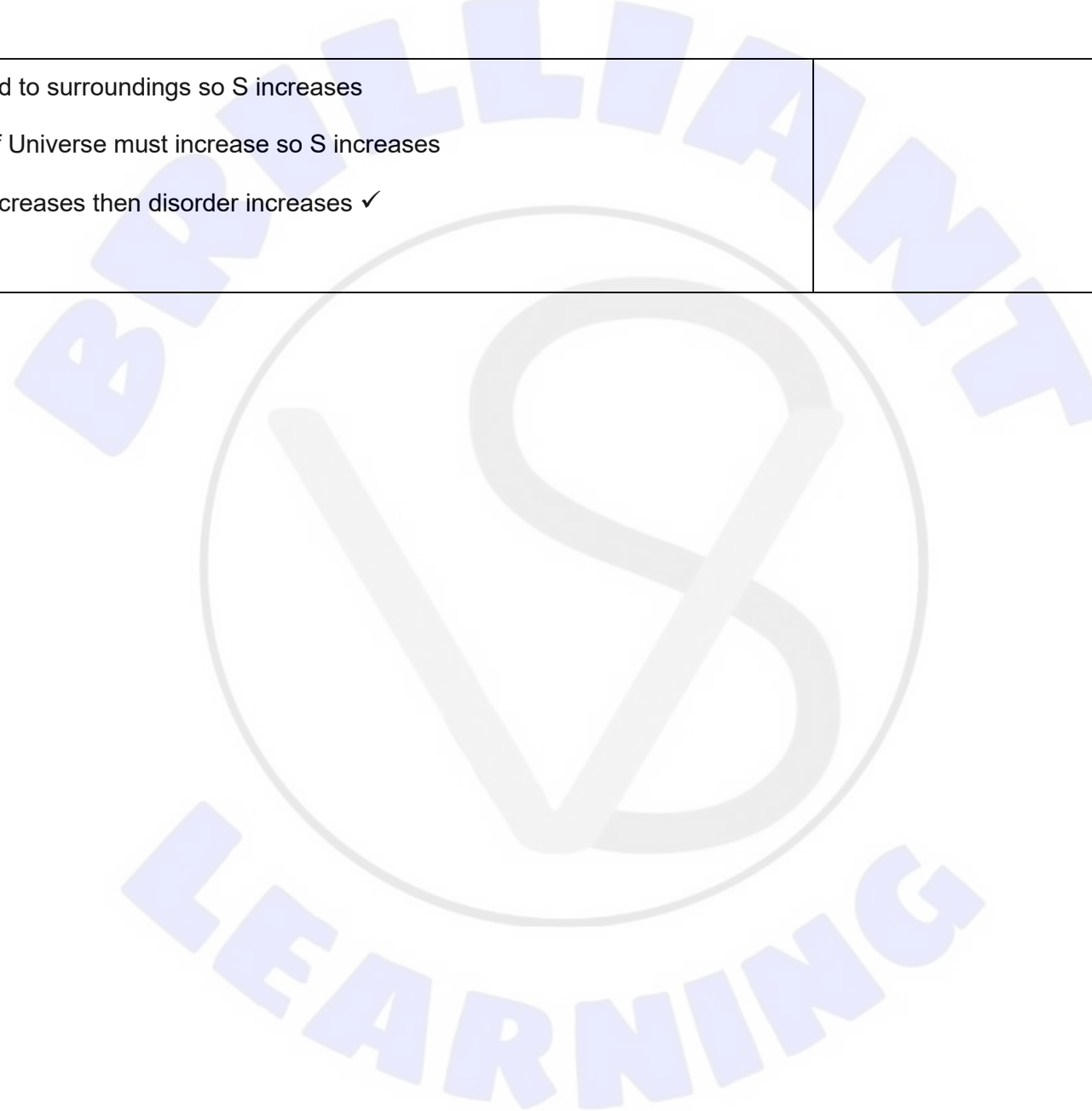
Option B — Engineering physics

Question			Answers	Notes	Total
8.	a	i	quotes $I = \Sigma mr^2$ with $r =$ «perpendicular» distance to axis OR resistance to change in rotation OR ratio of torque «applied» to angular acceleration OR analog to mass in rotational mechanics ✓	<i>In MP1, accept $r =$ radius.</i> <i>In MP2, do not accept resistance to rotation.</i> <i>In MP3 accept the expression as a formula if both symbols identified.</i>	1
	a	ii	Net torque/moment is zero ✓		1
	a	iii	$\frac{1}{12}2M(2L)^2 = \ll \frac{8}{12}ML^2 = \frac{2}{3}ML^2 \gg$ ✓		1
	b		$\frac{2}{3} \times 2.2 \times 0.6^2$ OR $\frac{1}{12} \times 4.4 \times 1.2^2$ OR 0.53 «kg m ² » ✓	<i>Answer of 0.5 kg m² given, so award the mark if candidates show a correct full substitution OR the value with an extra significant figure</i>	1
	c	i	«angular acceleration = $\frac{\text{torque}}{I} = \gg$ »	<i>Allow ECF from MP1</i> <i>Award [2] for a BCA</i>	2


		$\frac{140}{0.53} \quad \text{OR } 264 \text{ «rad/s» } \checkmark$ $t = \frac{\text{angular velocity}}{\text{angular acceleration}} = \frac{750}{264} = \text{» } 2.8 \text{ «s» } \checkmark$	
c	ii	$\ll \omega^2 = 2\alpha\theta \gg \theta = \frac{750^2}{2 \times 264}$ <p>OR 1065 «rad»</p> <p>OR $\ll r\theta = \frac{\omega}{2} \times t \gg = \frac{750}{2} \times 2.8$</p> <p>OR 1050 «rad» \checkmark</p> $n = \frac{1065}{2\pi} = 170 \checkmark$	<p><i>Follow the calculations as there can be other slight changes in the results, e.g. if they use 2.7 s.</i></p> <p><i>Allow ECF from MP1 and from c) i)</i></p> <p><i>Accept alternative methods through other rotational kinematics equations.</i></p> <p style="text-align: right;">2</p>
d		$\ll \alpha = \gg \frac{750}{5} \quad \text{OR } 150 \text{ «rad/s}^2\text{»}$ <p>OR «L = » 0.53 x 750 OR 398 «kg m²/s » \checkmark</p> <p>«torque = 0.53 x 150 =» 80 «Nm»</p> <p>OR « Rate of change in angular momentum =» 398/5 = 80 «Nm» \checkmark</p>	<p><i>Follow the calculations as there can be other slight changes in the results.</i></p> <p><i>Ignore sign of final answer</i></p> <p style="text-align: right;">2</p>

Question		Answers	Notes	Total																										
9.	a	$V = \frac{0.007 \times 8.31 \times 200}{120000}$ OR 9.7×10^{-5} «m ³ » ✓	Answer given, so award the mark if candidates show a correct full substitution OR the value with an extra significant figure	1																										
	b	$T = \frac{1.3 \times 10^{-4} \times 200}{9.7 \times 10^{-5}}$ OR $T = \frac{120 \times 10^3 \times 1.3 \times 10^{-4}}{0.007 \times 8.31}$ OR 268 «K» ✓	Accept 260 if 1×10^{-4} used Answer of 270 K given, so award the mark if candidates show a correct full substitution OR the value with an extra significant figure	1																										
	c	uses $PV^{5/3} = \text{constant}$ ✓ $V = 4.9 \times 10^{-5}$ «m ³ » ✓	Accept 4.95 or 5	2																										
	d	i	<table border="1"> <thead> <tr> <th></th> <th>Change in Q</th> <th>Change in U</th> <th>W</th> <th></th> </tr> </thead> <tbody> <tr> <td>A - B</td> <td>+</td> <td>+</td> <td>+</td> <td>✓</td> </tr> <tr> <td>B - C</td> <td>0</td> <td>+</td> <td>-</td> <td>✓</td> </tr> <tr> <td>C - D</td> <td>-</td> <td>-</td> <td>-</td> <td>✓</td> </tr> <tr> <td>D - A</td> <td>0</td> <td>-</td> <td>+</td> <td>✓</td> </tr> </tbody> </table>		Change in Q	Change in U	W		A - B	+	+	+	✓	B - C	0	+	-	✓	C - D	-	-	-	✓	D - A	0	-	+	✓	One mark per line	4
	Change in Q	Change in U	W																											
A - B	+	+	+	✓																										
B - C	0	+	-	✓																										
C - D	-	-	-	✓																										
D - A	0	-	+	✓																										
	d	ii	cycle is anticlockwise so work is negative OR work in BCD is larger than work in DAB OR work is negative so Q is negative/released «as $\Delta U = 0$ » ✓	1																										

	e	Q released to surroundings so S increases OR entropy of Universe must increase so S increases OR since S increases then disorder increases ✓		1
--	----------	--	--	----------



Question			Answers	Notes	Total
10.	a		$6\pi R\eta v = \frac{4}{3}\pi R^3 \rho g \checkmark$ manipulation to show \checkmark		2
	b		correct substitution \checkmark 0.0032 «Pa s» \checkmark	Award [1] if there is a POT error in the calculation Apply ECF from MP1	2
	c		Reynolds number = 33 or 35 \checkmark «comparison with limit for laminar flow» is laminar \checkmark	Allow ECF from b). Allow use of diameter in calculation of Reynolds number (R) so R is double. Allow ECF for MP2 with consistent conclusion.	2

Question			Answers	Notes	Total
11.	a		$Q = 2\pi \frac{1}{1-0.7} = 21 \checkmark$		1
	b	i	periodic curve with maxima every 1.5 s \checkmark decreasing height of peaks \checkmark	Example of the expected graph. Allow decreasing peaks by eye. 	2
	b	ii	$0.7^5 = 0.17 \text{ «m» } \checkmark$	Award [1] for a BCA	1

Option C — Imaging

Question			Answers	Notes	Total
12.	a	i	<p>«for the image to be smaller in a converging lens it must be inverted so»</p> $\left\langle M = \frac{h_i}{h_o} = - \right\rangle \frac{v}{u} = \left\langle - \right\rangle \frac{1}{2}$ <p>OR</p> $\frac{1}{f} = \frac{1}{u} + \frac{2}{u} \quad \checkmark$ $u = 3f \quad \checkmark$	<p>MP1 for $v = \frac{u}{2}$ or its use in the lens equation.</p> <p>MP2 scores MP1</p>	2
	a	ii	<p>one ray correct with object further than $2f$ ✓</p> <p>second ray drawn and image found smaller and inverted ✓</p>		2
	b	i	<p>erect OR virtual OR diminished OR image always on the same side as the object OR</p>	<p>Award [0] if more than one feature stated and any one is wrong.</p>	1

			v smaller than f OR v smaller than u ✓	
b	ii	$\llcorner M = \gg \frac{1}{2} = -\frac{v}{u}$ <p>OR</p> $v = \frac{-u}{2} \quad \checkmark$ $\llcorner - \gg \frac{1}{5} = \frac{1}{u} - \frac{2}{u}$ <p>OR</p> $\llcorner - \gg \frac{1}{f} = \frac{1}{u} - \frac{2}{u}$ <p>OR</p> <p>u = 5 «cm»</p> <p>OR</p> <p>u = f ✓</p>	<p><i>Ignore sign for MP2</i></p> <p><i>u = 5 scores MP2 only if MP1 scored.</i></p> <p><i>Answer is given in the question so check working carefully.</i></p>	2
b	iii	object at the focus, one ray correctly diverged ✓ another ray and image found of half the height ✓		2
c		new ray drawn towards the intermediate image through centre of diverging lens		2

OR

uses the ray coming from distant object originally entering parallel to principal axis, diverging it from the diverging lens parallel to principal axis and extends it back

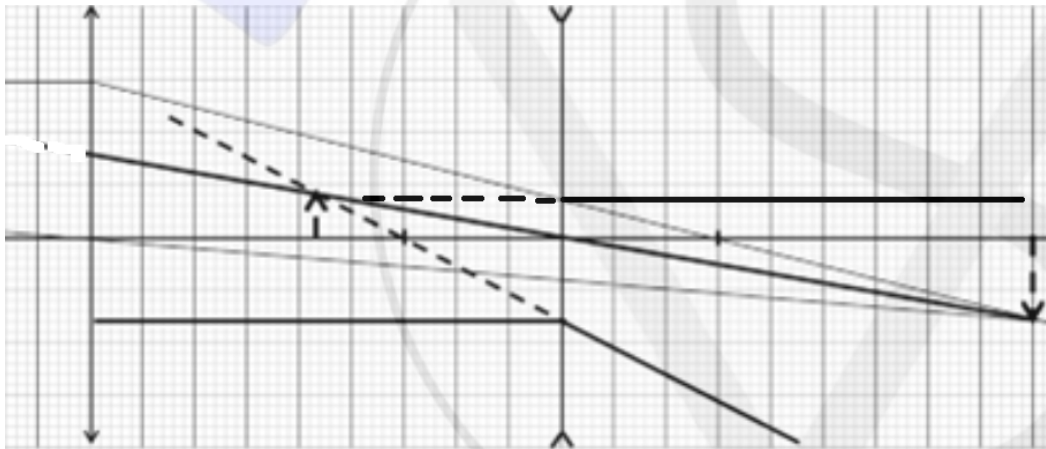
OR

draws a new ray aiming at intermediate image, parallel to principal axis and diverged away from the focus and extends it back ✓

Another one of the above rays drawn

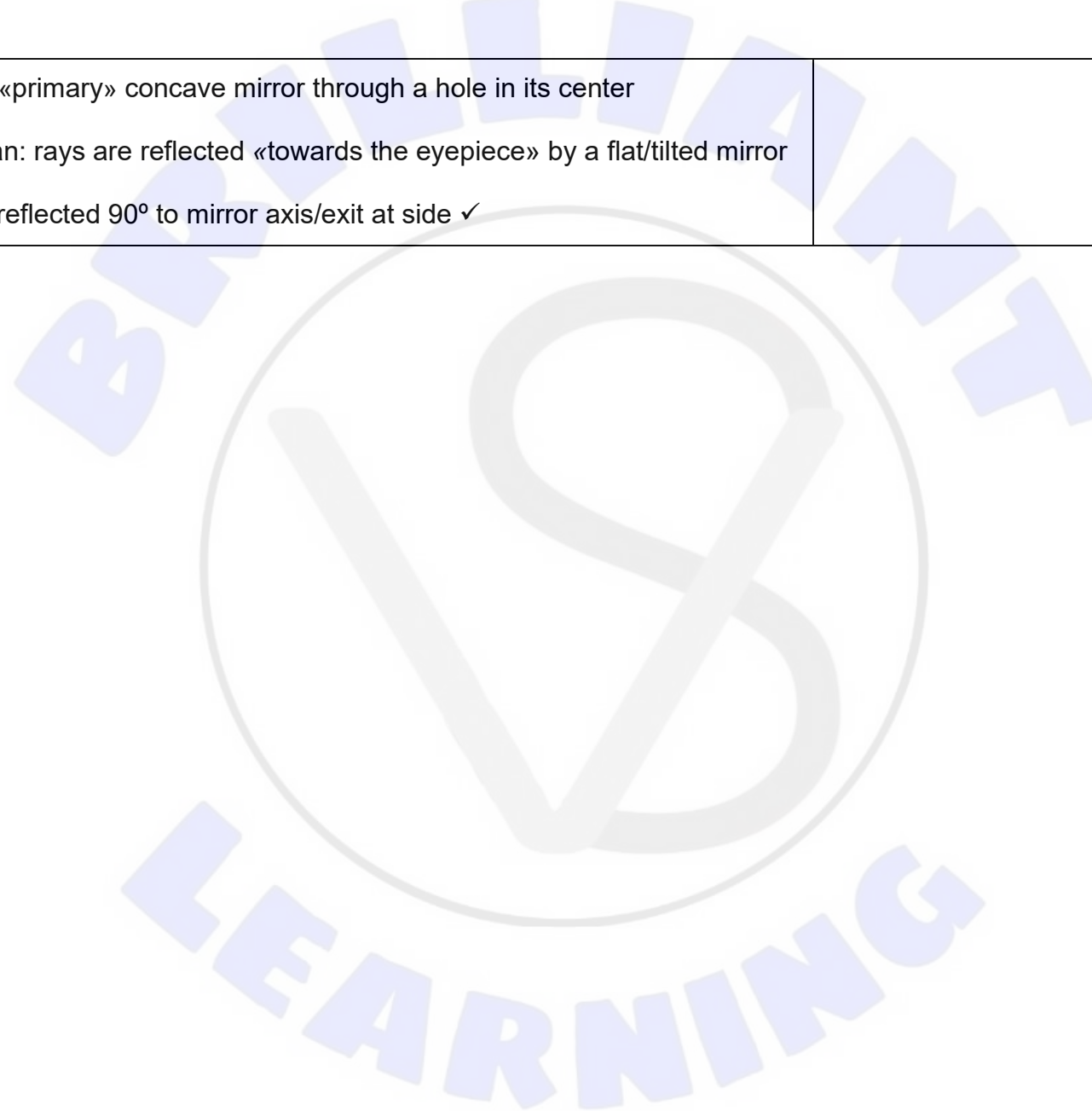
OR

image identified within the central square (about half-way between the lenses) and not taller than 1 square ✓



Question		Answers	Notes	Total	
13.	a	<p>M «= angular magnification» = $\frac{0.34}{\theta_{moon}}$ OR $\frac{0.34}{\frac{3500}{380000}}$</p> <p>OR</p> <p>M = 37 ✓</p> <p>« = $M = \frac{f_o}{f_e} = \frac{1100}{f_e} = 37$ so » $f_e = 30$ «mm» ✓</p>	Allow ECF for MP2	2	
	b	i	<p>have increased our ability to collect information of «celestial» objects</p> <p>OR</p> <p>detect «celestial» objects not visible «to the naked eye»</p> <p>OR</p> <p>allow for the analysis of light/radiation to determine distance/luminosity/temperature/velocity/structure of «celestial» objects</p> <p>OR</p> <p>Mention of any large astronomical reflecting telescope, e.g. Hubble/James Webb/Planck/WMAP ✓</p>	<p>For MP1, MP2 and MP3 accept the reference to any specific celestial object</p> <p>For MP4 accept an example of a telescope working on any wavelength.</p> <p>Accept other sensible answers</p>	1
	b	ii	<p>there is dispersion / chromatic aberration at the lenses in refracting telescope</p> <p>OR</p> <p>there is no dispersion/chromatic aberration at the mirror</p> <p>OR</p> <p>there is only dispersion/chromatic aberration at eyepiece of reflecting telescope</p> <p>OR</p> <p>no refraction in mirror telescopes ✓</p>		1
	b	iii	<p>Cassegrain: rays are reflected «towards the eyepiece» by a convex mirror</p> <p>OR</p> <p>rays are axial to mirror/exit along mirror axis</p> <p>OR</p>	Allow a sketch which illustrates either telescope.	1

			rays exit «primary» concave mirror through a hole in its center OR Newtonian: rays are reflected «towards the eyepiece» by a flat/tilted mirror OR rays are reflected 90° to mirror axis/exit at side ✓	
--	--	--	--	--



Question		Answers	Notes	Total
14.	a	refractive index/velocity varies with wavelength OR wavelengths/colors arrive at different times OR mentions pulse broadening or chromatic dispersion ✓	<i>Allow reference to change in critical angle so increased refractive losses</i>	1
	b	uses transit time = $\llcorner = \frac{d}{\left(\frac{c}{n}\right)} \gg$ ✓ $t = \frac{10\,000(1.45298 - 1.45264)}{3 \times 10^8} = 11 \text{ ns}$ OR $t = 10000 \times 1.45298 / 3 \times 10^8 = 4.84327 \times 10^{-5}$ OR $t = 10000 \times 1.45264 / 3 \times 10^8 = 4.84213 \times 10^{-5}$ ✓ 11 ns + 1 ns = 12 «ns» ✓		3

Question		Answers	Notes	Total
15.	a	20 keV attenuation/coefficients quite different «for muscle and bone» OR 100 keV attenuation/coefficients almost the same ✓ «hence » better contrast with 20 keV ✓	<i>Accept reverse conclusion</i>	2
	b	$d = \frac{\ln 2}{7.2}$ OR 0.096 «cm» OR	<i>Answer of 1 mm given, so award the mark if candidates show a correct full substitution OR the value with an extra significant figure</i>	1

		$\frac{I}{I_0} = e^{-0.1 \times 7.2}$ OR $\frac{I}{I_0} = 0.49 \quad \checkmark$	
c	i	one decay expression correct i.e. $e^{-2 \times 0.24}$ or $e^{-2 \times 0.21} \quad \checkmark$ $\ll \frac{I}{I_0} = e^{2(-0.24-0.21)} = \frac{I}{I_0} = \gg 0.41$ OR $\ll \frac{I}{I_0} = \gg 41\%$ \checkmark	2
c	ii	two exponential decays «with the overall change in the first 2 cm section smaller than the second 2 cm section by eye» \checkmark	1

Question		Answers	Notes	Total
16.	a	high frequencies have better resolution ✓ high frequencies have lower penetration ✓ high frequencies are more attenuated ✓	<i>Or reverse argument for low frequencies</i>	2 max
	b	gel removes/fills air gap/cancels acoustic differences/makes densities similar ✓ prevents reflection/improves transmission ✓	<i>OWTTE</i>	2

Option D — Astrophysics

Question		Answers	Notes	Total
17.	a	mention of spectrum/spectral lines ✓ lines/wavelengths/transitions are specific for an element ✓	OWTTE	2
	b	502 «nm» ✓	Accept 501 or 500 5.02 x 10 ⁻⁷ scores [1] if unit (m) stated.	1
	c	(most) orbits of planets are nearly circular/slightly elliptical OR orbits of comets highly/more elliptical ✓	OWTTE	1
	d	stellar nucleosynthesis/fusion in stars «for elements up to iron» ✓ supernovae/neutron capture for elements heavier than iron ✓	OWTTE	2

Question		Answers	Notes	Total	
18.	a	addition of Alpha Centauri B to the luminosity/brightness of the binary star system OR combined luminosity/brightness of the binary stars ✓	OWTTE	1	
	b	i	$d = \frac{1}{0.76}$ OR 1.3 «pc» ✓ $d = \frac{3.26 \times 9.46 \times 10^{15}}{0.76}$ OR $d = 4.1 \times 10^{16}$ «m» ✓	MP2 scores MP1. Answer given, so award MP2 if candidates show a correct full substitution OR the value with an extra significant figure	2
	b	ii	$\ll b = \frac{5.7 \times 10^{26}}{4\pi(4.1 \times 10^{16})^2} \Rightarrow 2.7 \times 10^{-8}$ «W/m» ✓	Accept use of 4×10^{16}	1
	b	iii	Use of $L = M^{3.5}$ ✓ $M = \left(\frac{5.7}{3.8}\right)^{\frac{1}{3.5}} M_{\odot}$ OR $M = 1.12 M_{\odot}$ ✓	Answer given, so award MP2 if candidates show a correct full substitution OR the value with an extra significant figure	2
	c	i	position of A correct (just above and to the left of the Sun) ✓	Allow a position from the Sun up to the second drawn star to its left.	1
	c	ii	loop via red giants to white dwarves OR line towards red giants, then white dwarves ✓ red giants and white dwarves' approximate regions labelled ✓	Allow areas on the upper right-hand and lower left-hand region.	2
	d		« $L = E/t$ and E proportional to M so» t inversely proportional to $M^{2.5}$ OR	Award [1] for a correct but incomplete reason, e.g. larger luminosity, or smaller mass, with the correct conclusion.	2

		$\frac{t_P}{t_\alpha} = \left(\frac{1.12}{0.12}\right)^{2.5}$ <p>OR faster fusion rate to hydrogen available in Alpha Centauri A ✓</p> <p>Proxima Centauri stays longer on main sequence OR $t_P = 270 t_\alpha$ ✓</p>	
e		type I a supernovae form when a white dwarf in a binary star system accretes mass from companion ✓	1
f		reference to standard candles OR mention of constant/peak luminosities ✓ «allow calculation of distance from apparent brightness»	1

Question		Answers	Notes	Total
19.	a	isotropic/uniform/homogeneous/appears to come from everywhere ✓ tiny fluctuations «in temperature» ✓ black body radiation «spectrum» ✓ «radiation of a body at» 3 K/2.7(6)K ✓ «radiation with a» wavelength of 2 mm ✓	OWTTE	1 max
	b	Big Bang model predicted the existence of CMB radiation ✓ «discovery of» CMB radiation provides evidence for the BB model ✓ CMB radiation left by the BB/originated when Universe was hot/small ✓ wavelength increased/T decreased as Universe expanded/cooled down ✓		2 max
	c	red-shift ✓ as space is being stretched / «distant» galaxies are moving away ✓ OR «relative» abundance of elements/H/He ✓ as Big Bang model predicts the ratio «of H/He as observed in all stars» ✓ OR «large scaled» structure of universe ✓ as Big Bang model predicts influence of gravity to create structures/relates structures to anisotropies ✓		2

Question		Answers	Notes	Total
20.		$\frac{R}{R_0} = z + 1 = 8.5. \checkmark$ $R_0 = \frac{1}{8.5}R$ OR 0.118 OR 11.8% ✓	Allow reverse argument, from 12% to a z value of 7.33 Answer 12% given, so award MP2 if candidates show a correct full substitution OR the value with an extra significant figure	2

Question		Answers	Notes	Total
21.	a	<p>corresponds to the critical density/flat «model» ✓</p> <p>density of the Universe = critical density OR the curve becomes asymptotic to time axis OR Universe expands to limiting value OR expansion slows down ✓</p>	OWTTE	2
	b	<p>D ✓</p> <p>identified as accelerated Universe OR stretching of space/expansion speeding up mentioned OR need for energy not observed identified OR dark energy postulated to account for this «model/observations» ✓</p>		2