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Centre number

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Candidate number

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Surname

StemUp Model Solution

Forename(s)

Candidate signature

I declare this is my own work.

A-level PHYSICS

Paper 3

Section B Astrophysics

Materials

For this paper you must have:

- a pencil and a ruler
- a scientific calculator
- a Data and Formulae Booklet
- a protractor.

Instructions

- Use **black** ink or **black ball-point** pen.
- **Fill** in the boxes at the top of this page.
- Answer **all** questions.
- You must answer the questions in the spaces provided. Do not write outside the box around each page or on blank pages.
- If you need extra space for your answer(s), use the lined pages at the end of this book. Write the question number against your answer(s).
- Do **all** rough work in this book. Cross through any work you do not want to be marked.
- Show **all** your working.

Information

- The marks for questions are shown in brackets.
- The maximum mark for this paper is 35.
- You are expected to use a scientific calculator where appropriate.
- A Data and Formulae Booklet is provided as a loose insert.

Time allowed: The total time for both sections of this paper is 2 hours. You are advised to spend approximately 50 minutes on this section.

For Examiner's Use	
Question	Mark
1	
2	
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4	
TOTAL	



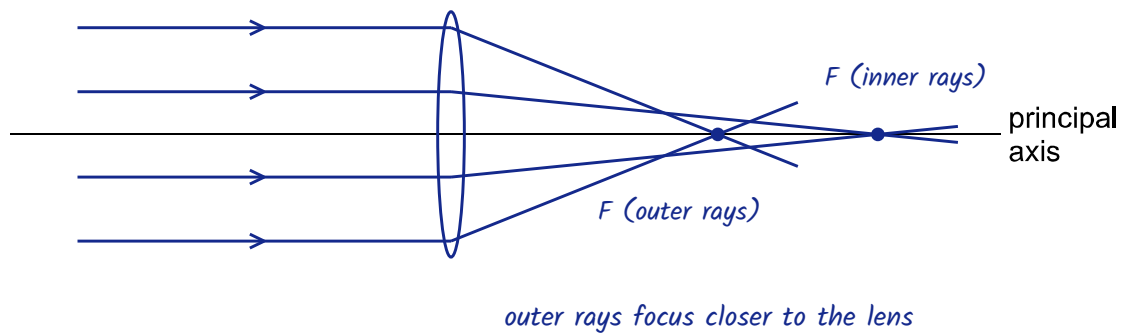
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Section B

Answer **all** questions in this section.

0 1 . 1 Draw a ray diagram to show how a converging lens can cause spherical aberration.

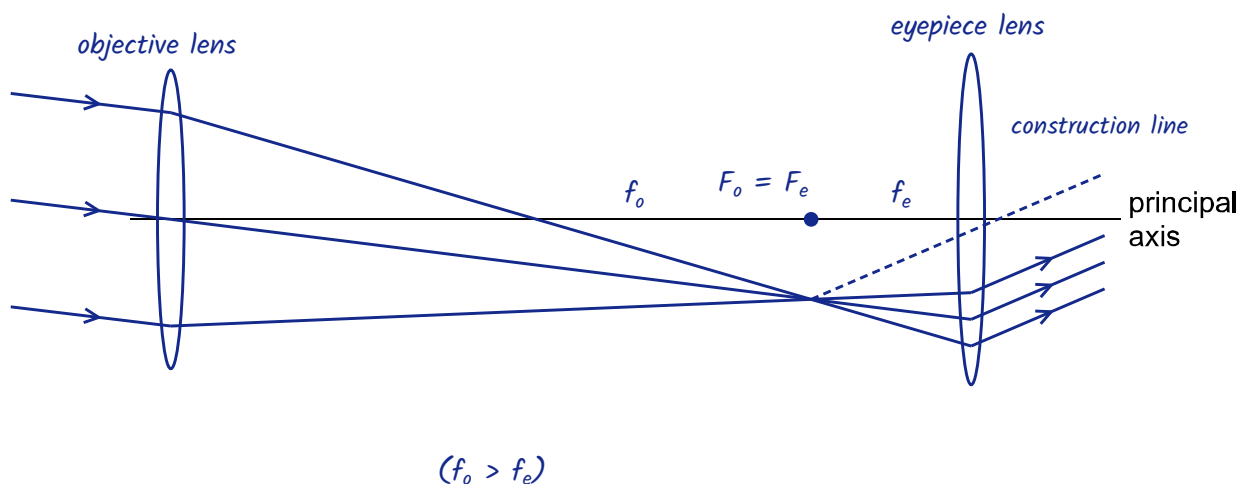
[1 mark]



0 1 . 2 Draw a labelled ray diagram for an astronomical refracting telescope in normal adjustment.

Show **three** non-axial rays passing through both lenses.
Label the principal foci of the lenses.

[3 marks]



0 1 . 3

The James Lick telescope is an astronomical refracting telescope. When in normal adjustment, the distance between the lenses of the telescope is 17.4 m and the angular magnification is 750

Calculate the focal length of the eyepiece lens.

[2 marks]

$$M = f_o / f_e = 750 \text{ so } f_o = 750 f_e$$

$$f_o + f_e = 17.4 \text{ m so } 750 f_e + f_e = 751 f_e = 17.4$$

$$f_e = (f_o + f_e) / 751 = 17.4 / 751 = 0.0232 \text{ m}$$

focal length = 2.32×10^{-2} m

0 1 . 4

The James Lick telescope can be used to identify binary stars.

Two techniques are available using this telescope:

- using a processed image from a CCD, and
- direct observation using the naked eye.

Compare the use of a CCD with the use of the naked eye to observe binary stars with this telescope.

[3 marks]

Resolution is limited by the diameter of the objective, so it makes no difference to which close binary stars can be resolved.

A CCD has a higher quantum efficiency (80% vs 1%) and can be exposed for a long time, so dimmer or more distant binaries can be observed.

A CCD detects a wider range of wavelengths (e.g. IR and UV), enabling the observation of more binary pairs.

CCD images can be stored and analysed on a computer, so images at different times can be compared to see the stars orbit.

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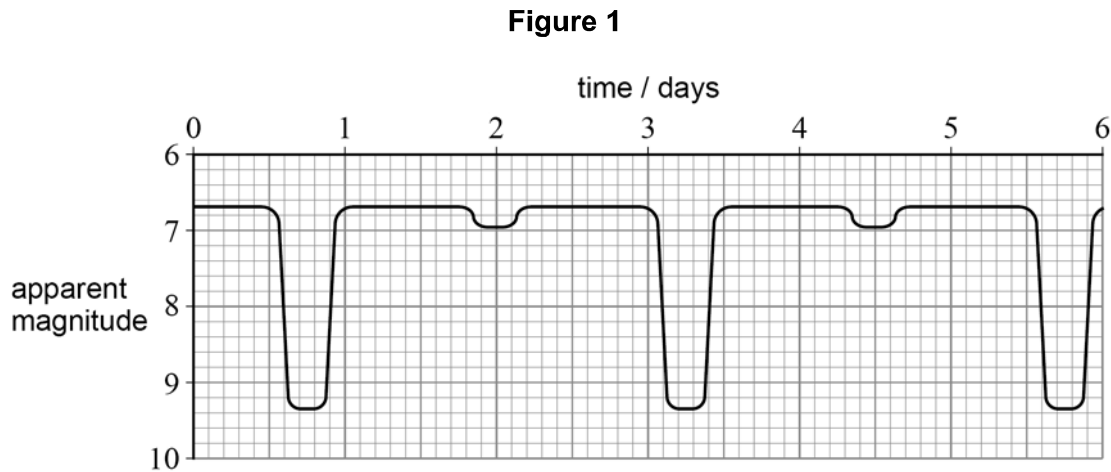


0 2

U Cephei is an eclipsing binary system consisting of two stars that orbit their common centre of mass.

The primary star is class B; the secondary star is class G.

Figure 1 shows the variation of apparent magnitude of U Cephei with time as observed from Earth.



0 2 . 1

Explain the shape of the graph in **Figure 1**.

[2 marks]

The minima (dips) are caused when one star passes in front of the other, so less light reaches us and the apparent magnitude increases.

The deeper minima are caused by the cooler (class G) star passing in front of the hotter (class B) star, blocking more of the light; the shallow dips are when the hotter star passes in front of the cooler star.

Question 2 continues on the next page

Turn over ►



A particular spectral line has a wavelength of 486.136 nm when measured from a source in the laboratory.

This line is also present in the absorption spectrum of the primary star of U Cephei. When observed from Earth, the wavelength of the primary star's absorption line varies as shown in **Table 1**.

Table 1

	Wavelength / nm
maximum value	486.498
minimum value	485.672

- 0 2 . 2** State why the average of the values in **Table 1** is different from the laboratory value. **[1 mark]**

The average (486.085 nm) is lower, so the light is blue shifted: the system is moving towards us (Doppler effect).

- 0 2 . 3** Show that the orbital speed of the primary star is about 250 km s⁻¹. **[3 marks]**

$$\Delta\lambda = (486.498 - 485.672) / 2 = 0.413 \text{ nm}$$

$$\text{average wavelength} = (486.498 + 485.672) / 2 = 486.085 \text{ nm}$$

$$z = \Delta\lambda / \lambda = 0.413 / 486.085 = 8.50 \times 10^{-4}$$

$$v = zc = 8.50 \times 10^{-4} \times 3.00 \times 10^8$$

$$v = 2.55 \times 10^5 \text{ m s}^{-1} = 255 \text{ km s}^{-1} \text{ (about 250 km s}^{-1}\text{)}$$



0 2 . 4

Calculate the orbital radius of the primary star.

[2 marks]

Period $T = 2.5$ days (time between deep minima, from Figure 1)

$$T = 2.5 \times 24 \times 3600 = 2.16 \times 10^5 \text{ s}$$

$$v = 2\pi R / T \text{ so } R = vT / 2\pi$$

$$R = 2.55 \times 10^5 \times 2.16 \times 10^5 / 2\pi = 8.76 \times 10^9 \text{ m}$$

orbital radius = 8.76×10^9 m

0 2 . 5

Which absorption lines would be most prominent in the spectrum of the primary star?
Tick (✓) **one** box.

[1 mark]

hydrogen

☐

hydrogen and helium

☒

ionised metals

☐

neutral metals

☐

0 2 . 6

A different eclipsing binary star system is thought to consist of a white dwarf star and a neutron star.

Discuss how astronomers could confirm this.

[2 marks]

*White dwarf: hot (class O or B, H and He absorption lines) but with a dim absolute magnitude. Neutron star: detected by its radio emissions (pulsar).**They must be coincident in space: the radio emission from the neutron star is periodically blocked by the white dwarf, and the white dwarf's spectral lines show a periodic Doppler shift.*

0 3

3C 273 was the first quasar to be discovered.
IC 1101 is one of the largest galaxies known.
Table 2 shows some information about these objects.

Table 2

	Absolute magnitude	Apparent magnitude	Distance / Mpc
quasar 3C 273	X	12.8	760
galaxy IC 1101	-22.8	14.7	320

0 3

1

State the property of the quasar that led to its discovery.

[1 mark]

It is a very powerful (high power) radio emitter.

0 3

2

Show that the absolute magnitude X of quasar 3C 273 is about -27

[2 marks]

$$m - M = 5 \log (d / 10)$$

$$M = m - 5 \log (d / 10)$$

$$d = 760 \text{ Mpc} = 760 \times 10^6 \text{ pc}$$

$$M = 12.8 - 5 \log (760 \times 10^6 / 10)$$

$$M = 12.8 - 39.4 = -26.6 \text{ (about -27)}$$



0 3 . 3

Assume that the quasar and the galaxy are both viewed from the same distance.

Explain which would be the brighter object.

Go on to calculate the ratio $\frac{\text{brightness of brighter object}}{\text{brightness of dimmer object}}$.

[3 marks]

The quasar is brighter, because it has the more negative absolute magnitude (-26.6 compared with -22.8), so it would be brighter at the same distance.

$$\text{difference in absolute magnitudes} = 26.6 - 22.8 = 3.8$$

each magnitude is a brightness ratio of 2.51

$$\text{ratio} = 2.51^{3.8} = 33$$

$$\text{ratio} = \underline{\quad 33 \quad}$$

0 3 . 4

The black hole at the centre of IC 1101 has a mass of $7.1 \times 10^{11} M_{\text{S}}$ where M_{S} is the mass of the Sun.

Calculate the average density within the event horizon of the black hole.

[3 marks]

$$M = 7.1 \times 10^{11} \times 1.99 \times 10^{30} = 1.41 \times 10^{42} \text{ kg}$$

$$R_{\text{S}} = 2GM / c^2 = 2 \times 6.67 \times 10^{-11} \times 1.41 \times 10^{42} / (3.00 \times 10^8)^2$$

$$R_{\text{S}} = 2.09 \times 10^{15} \text{ m}$$

$$V = \frac{4}{3} \pi R_{\text{S}}^3 = \frac{4}{3} \times \pi \times (2.09 \times 10^{15})^3 = 3.85 \times 10^{46} \text{ m}^3$$

$$\rho = \text{mass} / \text{volume} = 1.41 \times 10^{42} / 3.85 \times 10^{46}$$

$$\rho = 3.7 \times 10^{-5} \text{ kg m}^{-3}$$

$$\text{average density} = \underline{\quad 3.7 \times 10^{-5} \quad} \text{ kg m}^{-3}$$

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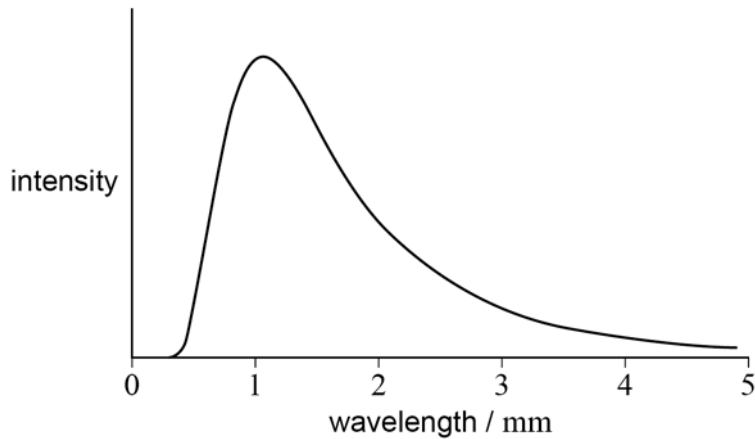


0 4

In the middle of the 20th century, there were two competing theories of the Universe. In 1964, electromagnetic radiation was observed coming from all directions in space. **Figure 2** shows the distribution of this radiation as observed from Earth.

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Figure 2



The graph provides evidence for one of these theories of the Universe.

Discuss the main features of this theory of the Universe.

In your answer, you should include:

- the main predictions and evidence for the theory, and
- a suitable calculation.

[6 marks]

Calculation (Wien's law): peak of Figure 2 at $\lambda_{max} \approx 1.07 \text{ mm}$

$$\lambda_{max} T = 2.9 \times 10^{-3} \text{ m K}$$

$$T = 2.9 \times 10^{-3} / 1.07 \times 10^{-3} = 2.7 \text{ K}$$

$$\text{Age of Universe} \approx 1 / H_0 = 1 / 2.27 \times 10^{-18} \text{ s}^{-1}$$

$$= 4.4 \times 10^{17} \text{ s} \approx 1.4 \times 10^{10} \text{ years}$$

$$(H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} = 2.27 \times 10^{-18} \text{ s}^{-1})$$

The graph supports the Big Bang theory: the Universe began in a very small, very hot and dense state and has been expanding and cooling ever since.

Prediction 1, cosmic microwave background radiation (CMBR): the theory predicts that radiation left over from the Big Bang should fill the



Universe and have been stretched by the expansion into black body radiation at microwave wavelengths, about 3 K.

Figure 2 shows exactly this: the radiation comes from all directions, it peaks in the microwave region (about 1 mm) and the curve has the shape of a black body curve. Using Wien's law the peak gives a temperature of about 2.7 K, matching the prediction. This shows the Universe was once very small and hot. The CMBR is not predicted by the competing Steady State theory.

Prediction 2, red shift: the theory predicts that distant galaxies are all moving away from us. Light from distant galaxies is observed to be red shifted, and Hubble's law ($v = H_0 d$) shows that the further away a galaxy is, the faster it is receding, so the Universe is expanding.

Running the expansion backwards gives an age of about $1 / H_0$, roughly 14 billion years.

Prediction 3, hydrogen to helium ratio: the theory predicts that nuclear fusion in the hot early Universe produced hydrogen and helium in a ratio of about 3 : 1 by mass. This ratio is observed in deep space (gas clouds away from stars), which supports the Big Bang theory.

END OF QUESTIONS



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