AQA

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A-level
PHYSICS

Paper 3
Section B Astrophysics

Thursday 15 June 2023 Morning

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.

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.

For Examiner's Use	
Question	Mark
1	
2	
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Section B

Answer **all** questions in this section.

0 1 . 1 Draw a labelled diagram to define the parsec (pc).

[1 mark]

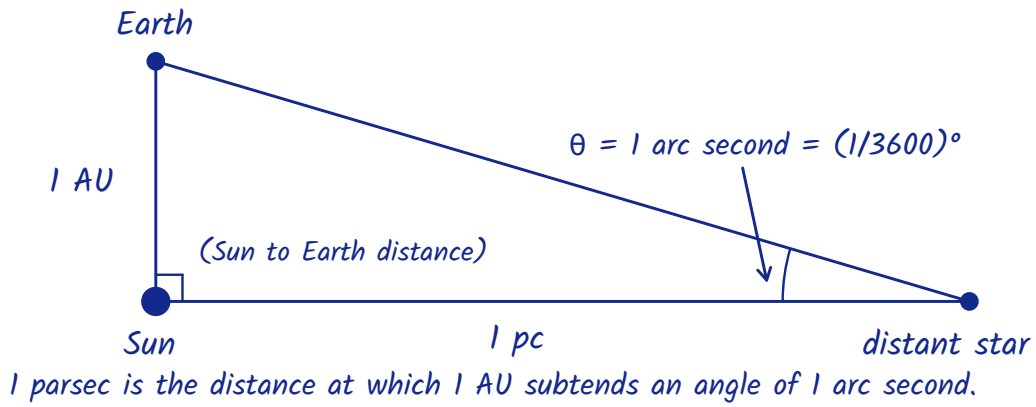

Table 1 shows data for two stars: Rigel and the Sun.

Table 1

Star	Surface temperature / K	Absolute magnitude	Mass / kg
Rigel	12 000	−7.84	3.6×10^{31}
Sun	5700	4.83	2.0×10^{30}

0 1 . 2 State the spectral class of Rigel.

[1 mark]

B

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0 1 . 3 The apparent magnitude of Rigel is 0.11

Calculate, in pc, the distance from Rigel to the Earth.

[2 marks]

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

$0.11 - (-7.84) = 7.95 = 5 \log(d/10)$

$\log(d/10) = 7.95/5 = 1.59$

$d = 10 \times 10^{1.59} = 389$ pc

distance = 390 pc

Question 1 continues on the next page

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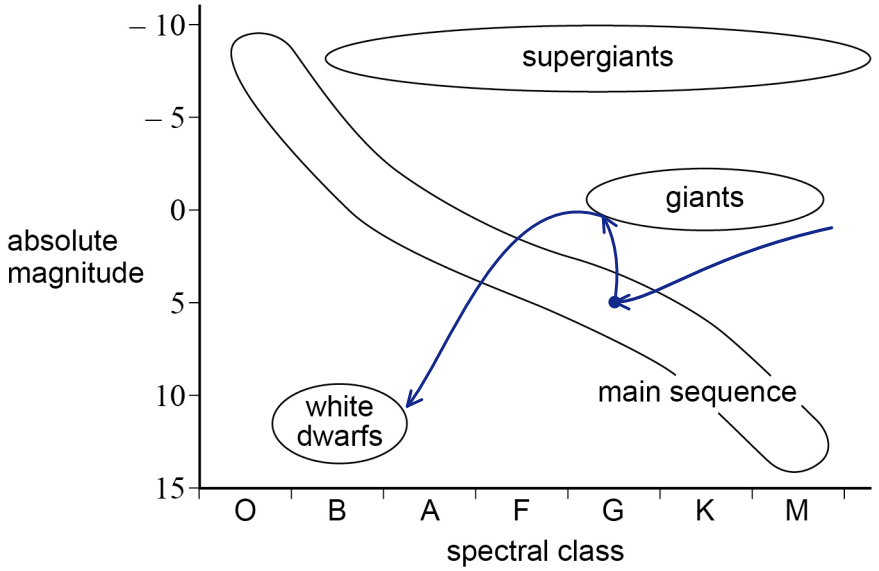
0 1 . 4 **Figure 1** shows a Hertzsprung–Russell (HR) diagram.

Figure 1



Draw a line on **Figure 1** to show the evolution of the Sun from formation to white dwarf.

[1 mark]

0 1 . 5 One stage in the evolution of Rigel includes the emission of a gamma ray burst.

Outline the circumstances during which a gamma ray burst will be emitted by Rigel.

[2 marks]

When Rigel (a supergiant, as it is very massive) runs out of fuel, its core collapses suddenly (in a supernova).

The collapsing core forms a neutron star or a black hole, and the gamma ray burst is emitted during this collapse.

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0 2 . 1 State what is meant by normal adjustment when applied to an astronomical refracting telescope.

[1 mark]

The final image is formed at infinity (the principal focus of the objective coincides with the principal focus of the eyepiece, so the lenses are $f_o + f_e$ apart).

0 2 . 2 Which combination of lenses gives the largest angular magnification when used as an astronomical telescope in normal adjustment?

Tick (✓) **one** box.

[1 mark]

Objective lens		Eyepiece lens		
Focal length / cm	**Type**	**Focal length / cm**	**Type**	
5	diverging	100	converging	
5	converging	100	converging	
100	diverging	5	converging	
100	converging	5	converging	✓

V1031 and WASP-82 are two stars in the constellation Orion.
V1031 appears 40 times brighter than WASP-82 when viewed from Earth.
The apparent magnitude of V1031 is 6.0

0 2 . 3 Calculate the apparent magnitude of WASP-82.

[2 marks]

Each magnitude step = brightness ratio of 2.51

$2.51^x = 40$

$x = \log 40 / \log 2.51 = 4.0$

$m = 6.0 + 4.0 = 10.0$ (WASP-82 is fainter)

apparent magnitude = 10.0

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0 2 . 4 V1031 is just visible to the naked eye of an astronomer when her pupil diameter is 7 mm.

Suggest whether she can observe WASP-82 using a telescope with an objective diameter of 60 mm.
Support your answer with a calculation.

[2 marks]

Collecting power ∝ D^2: $(60/7)^2$ = 73, so the telescope collects 73 times more light than her eye.

73 > 40, so WASP-82 (40 times fainter than V1031, which is just visible) will be seen: yes, she can observe it.

0 2 . 5 CCDs are often connected to telescopes.

Explain **two** reasons why this improves the ability of astronomers to observe dim stars.

[3 marks]

1 CCDs have a much higher quantum efficiency (about 80% compared with about 1% for the eye), so a greater proportion of the incident photons are detected.

2 A CCD can be exposed for a long time (or many images added together), so more light / photons from the dim star are collected, giving better image contrast.

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0 3 . 1 State the defining property of a black hole.

[1 mark]

Its gravitational field is so strong that its escape velocity is greater than the speed of light, so light cannot escape from it.

0 3 . 2 In 2019, astronomers linked several radio telescopes to produce a single telescope called the EHT. The resolution of the EHT is the same as the resolution that a telescope with an aperture equal to the diameter of the Earth could achieve.

Table 2 shows data about the EHT and the Hubble telescope.

Table 2

	Aperture	Operating wavelength
EHT	1.3×10^7 m	1.3 mm
Hubble	2.4 m	410 nm

Galaxy M87 is 5.3×10^7 light years from Earth. The supermassive black hole at the centre of M87 has a mass 6.5×10^9 times the mass of the Sun.

The radius of the event horizon is R.

The astronomers propose to use either the EHT or the Hubble telescope to observe stars whose distance from the centre of the black hole is less than $1000R$.

Discuss, with calculations, which telescope is more suitable for this observation.

[4 marks]

$R = 2GM/c^2 = (2 \times 6.67 \times 10^{-11} \times 6.5 \times 10^9 \times 1.99 \times 10^{30}) / (3.00 \times 10^8)^2$

$R = 1.9 \times 10^{13}$ m

Region diameter $= 2 \times 1000R = 3.83 \times 10^{16}$ m

Distance $d = 5.3 \times 10^7 \times 9.46 \times 10^{15} = 5.0 \times 10^{23}$ m

Angle subtended $= 3.83 \times 10^{16} / 5.0 \times 10^{23} = 7.6 \times 10^{-8}$ rad

Minimum resolvable angle $\theta \approx \lambda/D$:

EHT: $\theta = 1.3 \times 10^{-3} / 1.3 \times 10^7 = 1.0 \times 10^{-10}$ rad

Hubble: $\theta = 410 \times 10^{-9} / 2.4 = 1.7 \times 10^{-7}$ rad

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The EHT's minimum resolvable angle (1.0×10^{-10} rad) is much smaller than 7.6×10^{-8} rad, so the EHT can resolve stars within 1000R. Hubble's (1.7×10^{-7} rad) is larger than 7.6×10^{-8} rad, so it cannot. The EHT is more suitable.

0 3 . 3 A star is orbiting the black hole in M87. The star is observed in the plane of its orbit. The wavelength of a spectral line observed in the light emitted from the star varies between a maximum and a minimum value.

maximum value observed = 374.96 nm
minimum value observed = 373.53 nm

Calculate the orbital speed of the star.

[3 marks]

$\Delta\lambda = (374.96 - 373.53)/2 = 0.715$ nm

λ (rest) $= (374.96 + 373.53)/2 = 374.245$ nm

$\Delta\lambda/\lambda = v/c$ so $v = 0.715/374.245 \times 3.00 \times 10^8$

$v = 5.7 \times 10^5$ m s^{-1}

orbital speed = 5.7×10^5 m s^{-1}

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0 4

M40 A and M40 B are two stars that appear very close to each other when viewed from Earth.
There are two possible reasons for this:

- they are an orbiting binary system
- they are distant from each other and only appear in the same line of sight.

In an orbiting binary system, the difference between the apparent magnitude and the absolute magnitude for each star is similar.

Table 3 shows data about these two stars.

Table 3

	Temperature / K	Radius of star / m	Apparent magnitude
M40 A	6000	6.3×10^{9}	9.7
M40 B	4700	1.1×10^{10}	10.1

Discuss the appearance of the two stars to an astronomer on the Earth.
In your answer you should:

- compare the colour of the stars
- compare the brightness of the stars
- deduce, with a calculation, whether the stars form an orbiting binary system.

[6 marks]

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

A: $\lambda_{max} = 2.9 \times 10^{-3}/6000 = 4.8 \times 10^{-7}$ m; B: $2.9 \times 10^{-3}/4700 = 6.2 \times 10^{-7}$ m

Brightness: $\Delta m = 10.1 - 9.7 = 0.4$; ratio $= 2.51^{0.4} = 1.5$

Power: $P = \sigma A T^4 = \sigma 4\pi r^2 T^4$

$P_A = 5.67 \times 10^{-8} \times 4\pi \times (6.3 \times 10^9)^2 \times 6000^4 = 3.7 \times 10^{28}$ W

$P_B = 5.67 \times 10^{-8} \times 4\pi \times (1.1 \times 10^{10})^2 \times 4700^4 = 4.2 \times 10^{28}$ W

Same distance (binary) ⇒ intensity ∝ P, so B would appear brighter:

I_B/I_A would be 4.2/3.7 = 1.15, so m_B would be about 0.15 less than m_A.

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Colour: M40 A (6000 K) is hotter than M40 B (4700 K), so its peak wavelength is shorter. M40 A is a class F/G star and appears yellow-white (white/yellow), while M40 B is a class K star and appears orange, so M40 B looks redder than M40 A because it is cooler.

Brightness: M40 A has the smaller apparent magnitude (9.7 compared with 10.1, a difference of 0.4), so M40 A appears brighter, about $2.51^{0.4}$ = 1.5 times as bright as M40 B. Both are dimmer than magnitude 6, so neither can be seen with the naked eye; a telescope is needed.

Binary or not: from Stefan's law, the power output of M40 A is 3.7×10^{28} W, which is less than the 4.2×10^{28} W of M40 B. If they were a binary they would be the same distance from Earth, so M40 B (more powerful) would appear brighter and have the smaller apparent magnitude, and m − M would be similar for both.

But M40 A appears brighter even though it emits less power, so M40 A must be closer to the Earth than M40 B. The values of m − M are therefore different, so the stars are not an orbiting binary system: they are at different distances and only appear in the same line of sight.

6

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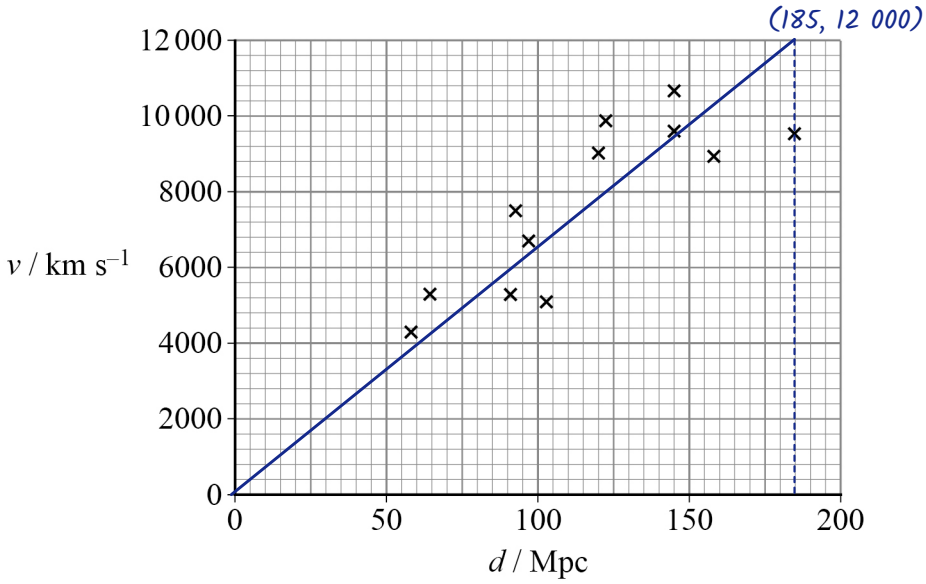
0 5 **Figure 2** shows, for some galaxies, how their recession speed v varies with distance d from the Earth.

Figure 2



0 5 . 1 Estimate, using **Figure 2**, the age in seconds of the Universe.

[3 marks]

H_0 = gradient = v/d = 12 000 / 185 = 65 km s^{-1} Mpc^{-1}

$H_0 = 6.49 \times 10^4$ m s^{-1} / 3.08×10^{22} m = 2.1×10^{-18} s^{-1}

age ≈ $1/H_0$ = 1 / 2.1×10^{-18}

age = 4.7×10^{17} s

age of Universe = 4.7×10^{17} s

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0 5 . 2 The estimate in Question **05.1** assumes that the Universe has expanded at a constant rate. Measurements involving type 1a supernovae that are at large distances from Earth caused astronomers to make a modification to this assumption.

State:

- the modification
- the explanation that was proposed to account for this modification.

[2 marks]

The modification: the expansion of the Universe is accelerating (the rate of expansion is increasing), because distant type Ia supernovae appeared dimmer, so further away, than expected.

The explanation proposed is dark energy, which acts against gravity and pushes the Universe apart.

5

END OF QUESTIONS

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