

## HL Paper 3

Type Ia supernovae typically have a peak luminosity of around  $5 \times 10^5 L_s$ , where  $L_s$  is the luminosity of the Sun ( $3.8 \times 10^{26}$  W). A type Ia supernova is observed with an apparent peak brightness of  $1.6 \times 10^{-6}$  W m<sup>-2</sup>.

- a. Describe the formation of a type Ia supernova. [2]
- b.i. Show that the distance to the supernova is approximately  $3.1 \times 10^{18}$  m. [2]
- b.ii. State **one** assumption made in your calculation. [1]

- a.i. Derive, using the concept of the cosmological origin of redshift, the relation [2]

$$T \propto \frac{1}{R}$$

between the temperature  $T$  of the cosmic microwave background (CMB) radiation and the cosmic scale factor  $R$ .

- a.ii. The present temperature of the CMB is 2.8 K. This radiation was emitted when the universe was smaller by a factor of 1100. Estimate the temperature of the CMB at the time of its emission. [2]
- b. State how the anisotropies in the CMB distribution are interpreted. [1]

- a. Explain the evidence that indicates the location of dark matter in galaxies. [3]
- b. Outline why a hypothesis of dark energy has been developed. [3]

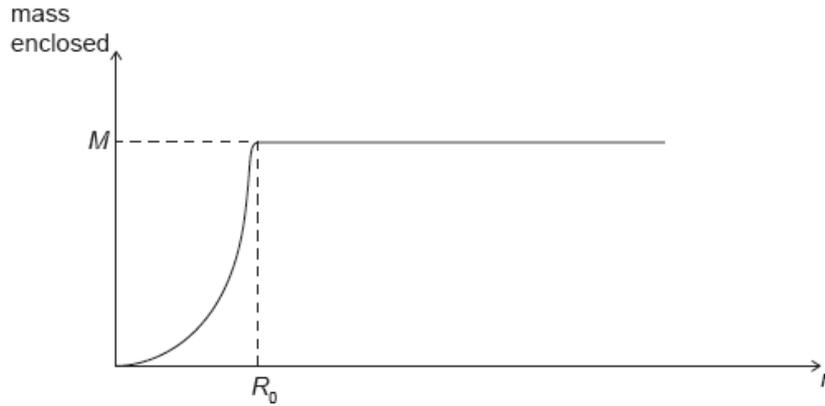
- a. The Sun is a second generation star. Outline, with reference to the Jeans criterion ( $M_J$ ), how the Sun is likely to have been formed. [4]
- b. Suggest how fluctuations in the cosmic microwave background (CMB) radiation are linked to the observation that galaxies collide. [3]
- c. Show that the critical density of the universe is [3]

$$\frac{3H^2}{8\pi G}$$

where  $H$  is the Hubble parameter and  $G$  is the gravitational constant.

- a. Outline, with reference to the Jeans criterion, why a cold dense gas cloud is more likely to form new stars than a hot diffuse gas cloud. [2]
- b. Explain how neutron capture can produce elements with an atomic number greater than iron. [2]

A galaxy can be modelled as a sphere of radius  $R_0$ . The distance of a star from the centre of the galaxy is  $r$ .

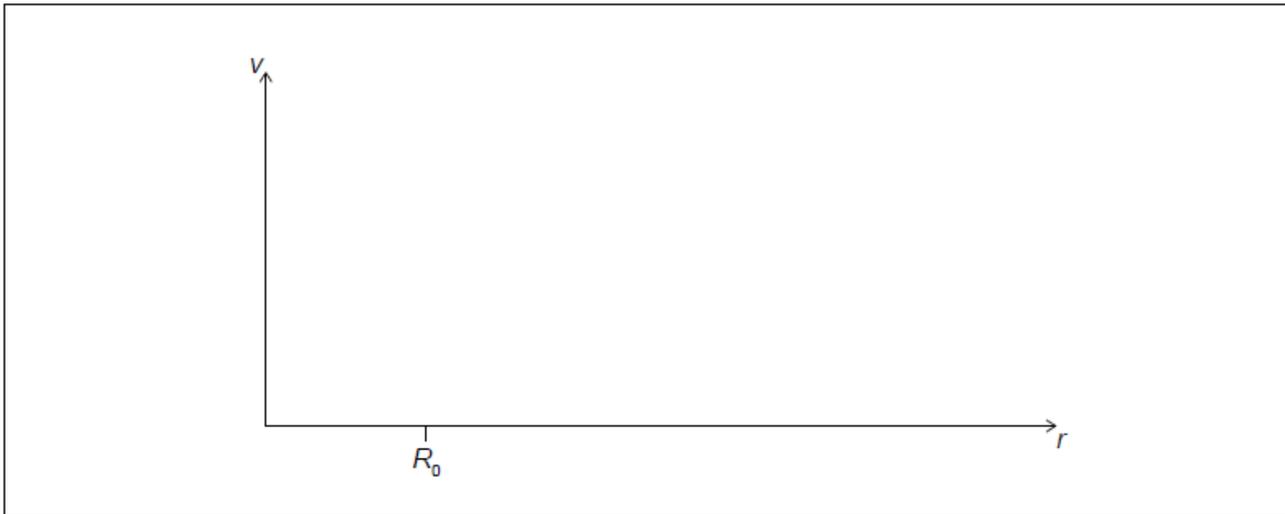


For this model the graph is a simplified representation of the variation with  $r$  of the mass of **visible matter** enclosed inside  $r$ .

- a. The mass of visible matter in the galaxy is  $M$ . [1]

Show that for stars where  $r > R_0$  the velocity of orbit is  $v = \sqrt{\frac{GM}{r}}$ .

- b. Draw on the axes the observed variation with  $r$  of the orbital speed  $v$  of stars in a galaxy. [2]



- c. Explain, using the equation in (a) and the graphs, why the presence of visible matter alone cannot account for the velocity of stars when  $r > R_0$ . [2]

This question is about Hubble's law.

a. Suggest why the two wavelengths are different. [3]

b. Determine the distance to this galaxy from Earth using a Hubble constant of  $74 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . [2]

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This question is about the Hubble constant.

A recent estimate for the value of the Hubble constant is  $70 \text{ km}^{-1} \text{ Mpc}^{-1}$ .

a. Estimate, in seconds, the age of the universe. [2]

b. The wavelength of the lines in the absorption spectrum of hydrogen is 656.3 nm when measured on Earth. Analysis of light from a distant galaxy [2]  
shows that the same line has a wavelength of 725.6 nm. Determine the recessional velocity of the distant galaxy.

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This question is about cosmic microwave background (CMB) radiation.

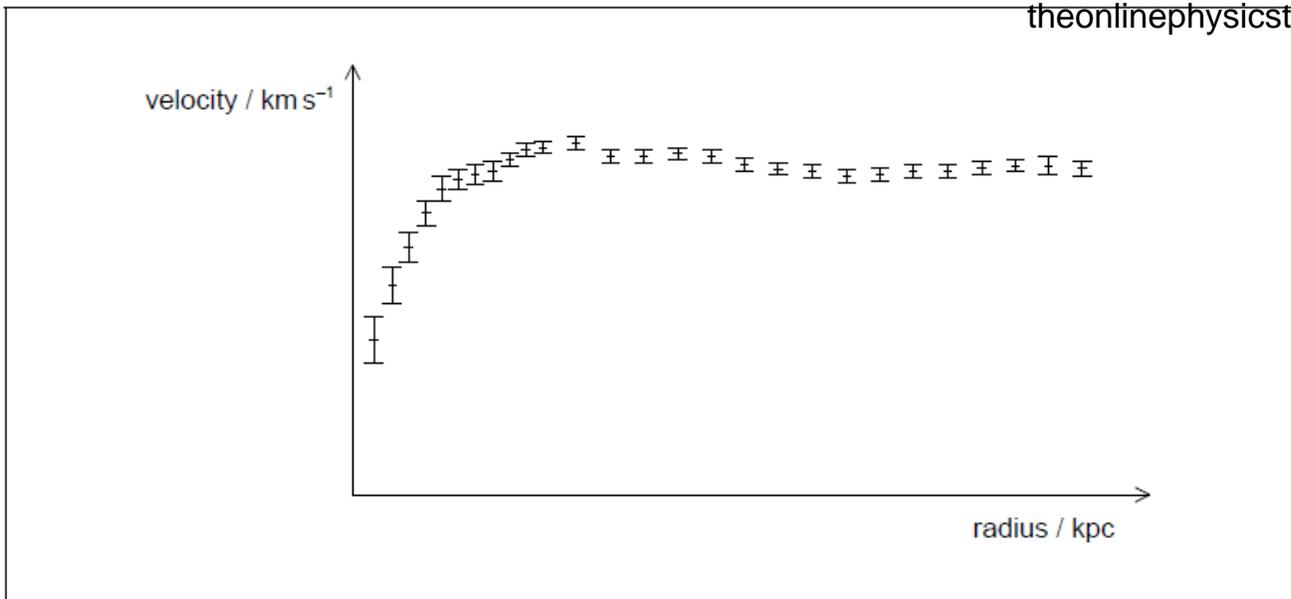
A line in the hydrogen spectrum is measured in the laboratory to have a wavelength of 656 nm. The same line from a distant galaxy is measured to have a wavelength of 730 nm. Assuming that the Hubble constant  $H_0$  is  $69.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,

b.i. calculate the distance of this galaxy from Earth. [2]

b.ii. discuss why different measurements of the Hubble constant do not agree with each other. [1]

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The graph shows the observed orbital velocities of stars in a galaxy against their distance from the centre of the galaxy. The core of the galaxy has a radius of 4.0 kpc.



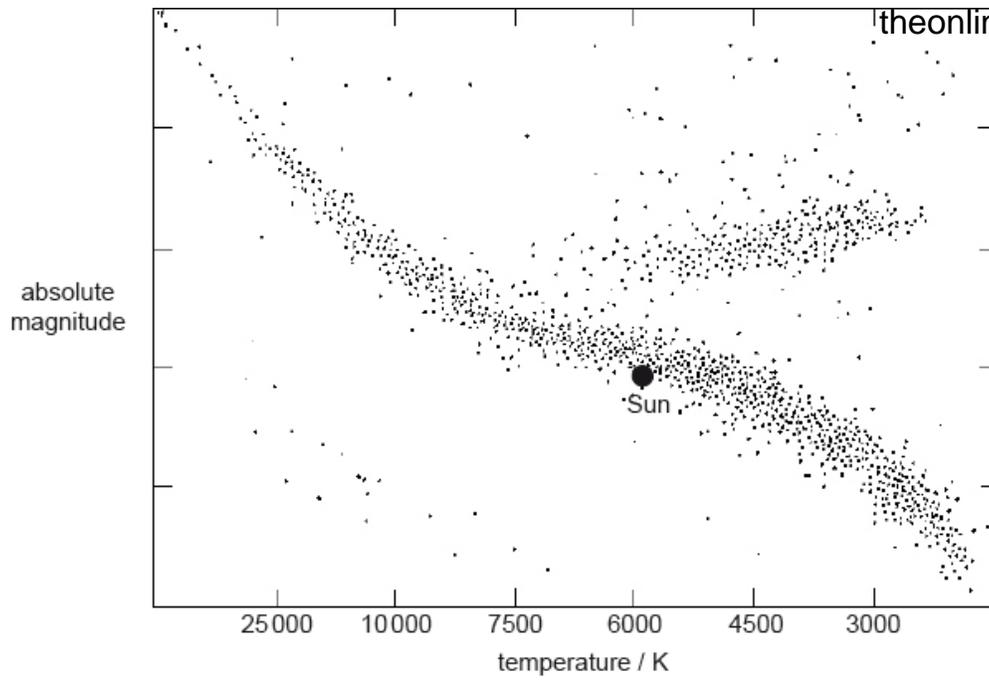
- a. Calculate the rotation velocity of stars 4.0 kpc from the centre of the galaxy. The average density of the galaxy is  $5.0 \times 10^{-21} \text{ kg m}^{-3}$ . [2]
- b. Explain why the rotation curves are evidence for the existence of dark matter. [2]

- a. Describe how some white dwarf stars become type Ia supernovae. [3]
- b. Hence, explain why a type Ia supernova is used as a standard candle. [2]
- c. Explain how the observation of type Ia supernovae led to the hypothesis that dark energy exists. [3]

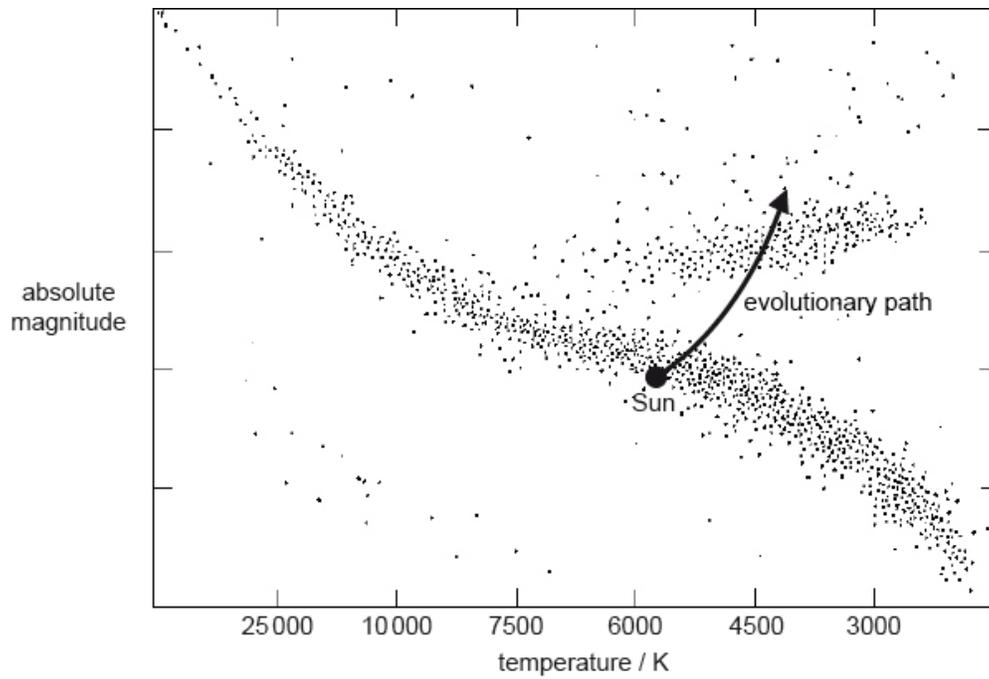
- a. Outline, with reference to star formation, what is meant by the Jeans criterion. [2]
- b. In the proton–proton cycle, four hydrogen nuclei fuse to produce one nucleus of helium releasing a total of  $4.3 \times 10^{-12} \text{ J}$  of energy. The Sun will spend  $10^{10}$  years on the main sequence. It may be assumed that during this time the Sun maintains a constant luminosity of  $3.8 \times 10^{26} \text{ W}$ .  
Show that the total mass of hydrogen that is converted into helium while the Sun is on the main sequence is  $2 \times 10^{29} \text{ kg}$ .
- c. Massive stars that have left the main sequence have a layered structure with different chemical elements in different layers. Discuss this structure by reference to the nuclear reactions taking place in such stars. [2]

This question is about the Hertzsprung–Russell (HR) diagram and the Sun.

A Hertzsprung–Russell (HR) diagram is shown.



The Sun will remain on the main sequence of the HR diagram for about another five billion years. After this time it will become a red giant, following the evolutionary path shown in the diagram.



e.i. Outline why the Sun will leave the main sequence, and describe the nuclear processes that occur as it becomes a red giant. [4]

e.ii. Describe **two** physical changes that the Sun will undergo as it enters the red giant stage. [2]

This question is about the characteristics of the stars Procyon A and Procyon B.

The star Betelgeuse is about five times the mass of Regulus. One possible outcome of the final stage of the evolution of Betelgeuse is for it to become a black hole. State the

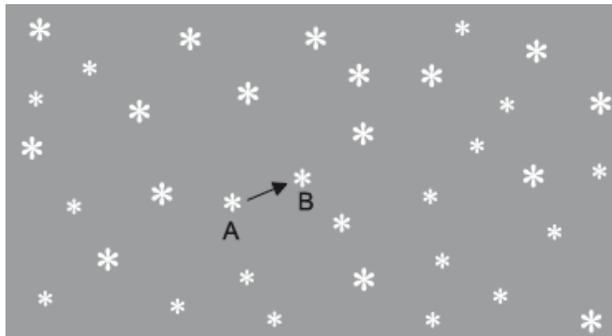
- i. The luminosity of the main sequence star Regulus is  $150 L_{\odot}$ . Assuming that, in the mass–luminosity relationship,  $n = 3.5$  show that the mass of Regulus is  $4.2 M_{\odot}$  where  $M_{\odot}$  is the mass of the Sun. [2]
- j. (i) other possible outcome of the final stage of the evolution of Betelgeuse. [2]  
 (ii) reason why the final stage in (j)(i) is stable.

This question is about Hubble's law.

- a. State Hubble's law. [1]
- b. Measured values of the Hubble constant can vary between  $40 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $90 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . State the reason for this wide variation in values. [1]
- c. The blue line in the spectrum of atomic hydrogen as measured in the laboratory is  $490 \text{ nm}$ . The same line in the spectrum of light from a galaxy has a wavelength of  $500 \text{ nm}$ . [3]
- Determine the distance of the galaxy from Earth. You may assume that the Hubble constant =  $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

This question is about determining the distance to a nearby star.

Two photographs of the night sky are taken, one six months after the other. When the photographs are compared, one star appears to have shifted from position A to position B, relative to the other stars.



Discuss whether Hubble's Law can be used to determine reliably the distance from Earth to this star.

This question is about the Big Bang model and red-shift.

- c. Many galaxies are a great distance from Earth. Explain, with reference to Hubble's law, how the measurement of the red-shift of light from such galaxies enables their distance from Earth to be determined. [3]
- d. State **one** problem associated with using Hubble's law to determine the distance of a galaxy a great distance from earth. [1]

This question is about Hubble's law.

- a. A galaxy a distance  $d$  away emits light of wavelength  $\lambda$ . Show that the shift in wavelength  $\Delta\lambda$ , as measured on Earth, is given by [1]

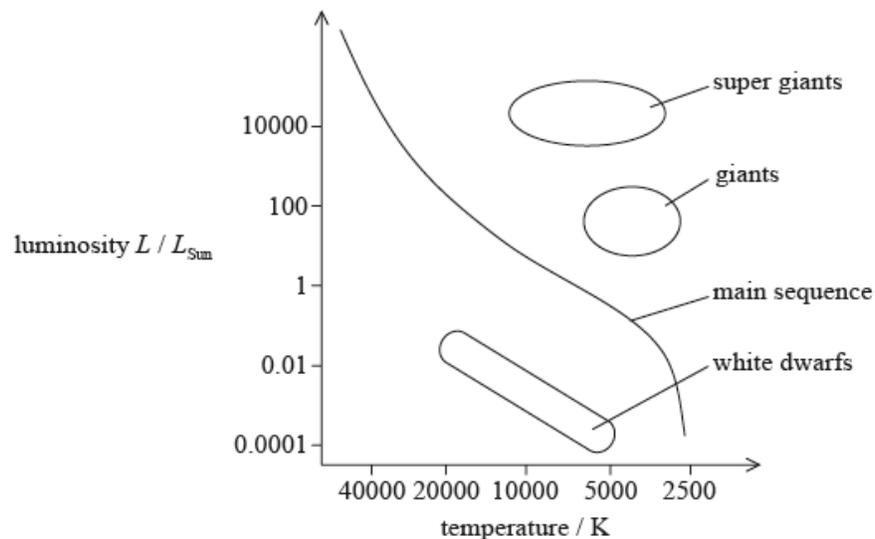
$$\Delta\lambda = \frac{H_0 d \lambda}{c}$$

where  $H_0$  is the Hubble constant.

- b. Light of wavelength 620 nm is emitted from a distant galaxy. The shift in wavelength measured on Earth is 35 nm. Determine the distance to the galaxy using a Hubble constant of  $68 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . [1]

This question is about the Hertzsprung–Russell (HR) diagram and stellar evolution.

The star Phi-1 Orionis is a large star on the main sequence with a mass of approximately 18 solar masses.



- a. Calculate the luminosity of Phi-1 Orionis in terms of the luminosity of the Sun. Assume that  $n = 3.5$  in the mass–luminosity relation. [2]
- b. The Sun is expected to have a lifespan of around  $10^{10}$  years. With reference to the equilibrium between radiation pressure and gravitational pressure, discuss why Phi-1 Orionis will use up its hydrogen at a faster rate than the Sun. [2]

c.i. Using the HR diagram on page 6, draw the evolutionary path of Phi-1 Orionis as it leaves the main sequence. [1]

c.ii. Outline, with reference to the Oppenheimer–Volkoff limit, the fate of Phi-1 Orionis. [1]

This question is about stellar distances.

b. The star Sirius A is 3 pc from Earth. The apparent brightness of Sirius A is  $1.2 \times 10^{-7} \text{ W m}^{-2}$ . Determine the luminosity of Sirius A. [2]

c. The luminosity of the Sun is  $3.8 \times 10^{26} \text{ W}$ . Determine the mass of Sirius A relative to the mass of the Sun. (Assume that  $n=3.5$  in the mass–luminosity relation.) [2]

This question is about stellar evolution.

a. The mass of a main sequence star is two solar masses. Estimate, in terms of the solar luminosity, the range of possible values for the luminosity of this star. [2]

b. The star in (a) will eventually leave the main sequence. [3]

State

(i) the condition that must be satisfied for this star to eventually become a white dwarf.

(ii) the source of the energy that the white dwarf star radiates into space.

(iii) **one** likely element, other than hydrogen and helium, that may be found in a white dwarf.

c. Explain why a white dwarf maintains a constant radius. [2]

This question is about the mass–luminosity relation.

Star X is  $1.5 \times 10^5$  more luminous than the Sun and has a mass 30 times that of the Sun.

a. Identify whether star X is on the main sequence. Assume that  $n = 3.5$  in the mass–luminosity relation. [2]

b. (i) State the evolution of star X. [3]

(ii) Explain the eventual fate of star X.

a. State the Jeans criterion for star formation.

- b. Describe **three** differences between type Ia and type II supernovae. [3]
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This question is about Hubble's law and the age of the universe.

- a. (i) State Hubble's law. [2]
- (ii) State why Hubble's law cannot be used to determine the distance from Earth to nearby galaxies, such as Andromeda.
- b. (i) Show that  $\frac{1}{H_0}$  is an estimate of the age of the universe, where  $H_0$  is the Hubble constant. [3]
- (ii) Assuming  $H_0 = 80 \text{ km s}^{-1}\text{Mpc}^{-1}$ , estimate the age of the universe in seconds.
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This question is about some of the properties of the star Aldebaran and also about galactic distances.

- c. Betelgeuse in the constellation of Orion is a red supergiant star. [5]
- (i) Compare the fate of Aldebaran to that of Betelgeuse.
- (ii) Outline, with reference to the Chandrasekhar limit, the circumstances under which the final state of Betelgeuse could be the same as the final state of Aldebaran.
- d. Distances to galaxies may be determined by using Cepheid variable stars. [5]
- By considering the nature and properties of Cepheid variable stars, explain how such stars are used to determine galactic distances.
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This question is about Hubble's law.

- a. The fractional change in the wavelength  $\lambda$  of light from the galaxy Hydra is  $\frac{\Delta\lambda}{\lambda} = 0.204$ . The distance to Hydra is 820 Mpc. [2]
- Estimate in  $\text{km s}^{-1} \text{Mpc}^{-1}$  a value for the Hubble constant.
- b. An estimate of the age of the universe is  $\frac{1}{H}$  where  $H$  is the Hubble constant. Suggest why  $\frac{1}{H}$  overestimates the age of the universe. [2]
- 

This question is about the structure of the universe.

- a. (i) State, in terms of the arrangement of galaxies, the present large-scale distribution of mass in the universe. [2]
- (ii) State how the separation of distant galaxies is changing with time.
- b. State and explain the observational evidence for your answer to (a)(ii). [3]

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This question is about the life history of stars.

- a. Outline, with reference to pressure, how a star on the main sequence maintains its stability. [3]
- b. A star with a mass equal to that of the Sun moves off the main sequence. Outline the main processes of nucleosynthesis that occur in the core of this star before and after this change. [2]
- c. Compare the fate of the star in (b) with that of a star of much greater mass. [3]

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- b. Beta Centauri is a star in the southern skies with a parallax angle of  $8.32 \times 10^{-3}$  arc-seconds. Calculate, in metres, the distance of this star from Earth. [2]
  - c. Outline why astrophysicists use non-SI units for the measurement of astronomical distance. [1]

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This question is about the Hubble constant.

- a. Outline the measurements that must be taken in order to determine a value for the Hubble constant. [3]
- b. One estimate of the Hubble constant is  $60 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . Cygnus A is a radio galaxy at a distance of  $6.0 \times 10^8$  ly from Earth. Calculate, in  $\text{km s}^{-1}$ , the recessional speed of Cygnus A relative to the Earth. [2]

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This question is about Hubble's law.

- a. State Hubble's law. [1]
- b. The wavelength of a line in the spectrum of atomic hydrogen, as measured in the laboratory, is 656 nm. The same line in the spectrum of light from a distant galaxy is measured to be 790 nm. The galaxy is 940 Mpc from Earth. [6]
  - (i) Show that the recessional speed of the galaxy is  $6.13 \times 10^4 \text{ km s}^{-1}$ .
  - (ii) Determine, using your answer to (b)(i), a value for the Hubble constant.
  - (iii) Show, using your answer to (b)(ii), that the age of the universe is of the order of  $10^{17}$  s. (1 pc =  $3.1 \times 10^{13}$  km)

This question is about Hubble's law.

- a. State [2]
- (i) Hubble's law.
  - (ii) the significance of the reciprocal of the Hubble constant.
- b. The wavelength of a certain line in the hydrogen spectrum is measured to be 434 nm in the laboratory. The same line in the hydrogen spectrum of the galaxy 3C-273 is measured on Earth to be 504 nm. [2]
- Determine the distance of 3C-273 from Earth using a Hubble constant of  $72 \text{ kms}^{-1} \text{ Mpc}^{-1}$ .
- 

This question is about stellar evolution.

Achernar may evolve to become a neutron star.

- a. Achernar is a main sequence star with a mass that is eight times the mass of the Sun. Deduce that Achernar has a greater temperature than the Sun. [2]
- b. Outline why Achernar will spend less time on the main sequence than the Sun. [2]
- c. (i) State the condition relating to mass that must be satisfied for Achernar to become a neutron star. [3]
- (ii) Some neutron stars rotate about their axes and have strong magnetic fields. State how these stars may be detected.
- 

This question is about the evolution of stars.

- a. State what is meant by the [2]
- (i) Chandrasekhar limit.
  - (ii) Oppenheimer–Volkoff limit.
- b. Suggest how your answers in (a) can be used to predict the fate of a main sequence star. [3]
- 

This question is about the main sequence star Khad (Phi Orionis).

The luminosity of Khad is  $2.0 \times 10^4 L_S$ , where  $L_S$  is the luminosity of the Sun.

- a. Assuming that the exponent  $n$  in the mass–luminosity relation is 3.5, show that the mass of Khad is about 17 solar masses. [2]

b. Outline the likely evolution of the star Khad after it leaves the main sequence.

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This question is about Hubble's law.

a. State Hubble's law.

[1]

b. Light from the galaxy M31 received on Earth shows a blue-shift corresponding to a fractional wavelength shift  $\frac{\Delta\lambda}{\lambda}$  of 0.001.

[5]

(i) Calculate the velocity of M31 relative to Earth.

(ii) The distance to M31 from Earth is 0.77 Mpc. Estimate, using the answer to (b)(i), a value of the Hubble constant.

(iii) Comment on your answer to (b)(ii).

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This question is about red-shift.

The wavelengths of radio signals from galaxy A are found to be red-shifted from the wavelengths that would be observed from sources at rest relative to Earth.

The fractional change in wavelength of the radio signals from galaxy A is  $9.4 \times 10^{-3}$ .

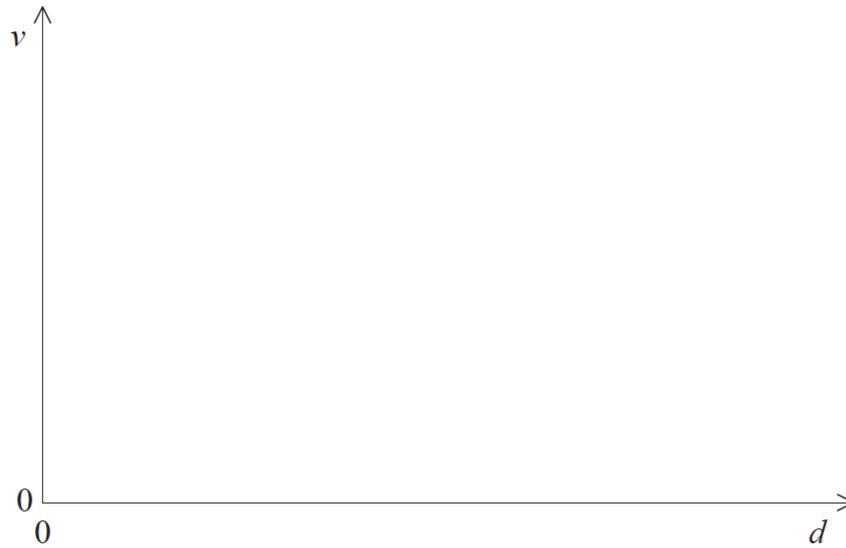
Calculate, in  $\text{km s}^{-1}$ , the average velocity of galaxy A relative to Earth.

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This question is about red-shift.

a. (i) On the axes, sketch a graph to show how the recessional speed  $v$  of a galaxy varies with distance  $d$  from the Earth.

[3]



(ii) Outline how the graph in (a)(i) can be used to determine the age of the universe.

b. Astronomers use the factor  $z$  to report the red-shift of an object relative to Earth where

[2]

$$z = \frac{\text{shift in wavelength detected by Earth observer}}{\text{wavelength of light emitted by object}}$$

Quasar 3C273 is thought to be the closest quasar to Earth and has  $z=0.18$ . Assuming that the Hubble constant is  $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , determine the distance of this object from Earth.

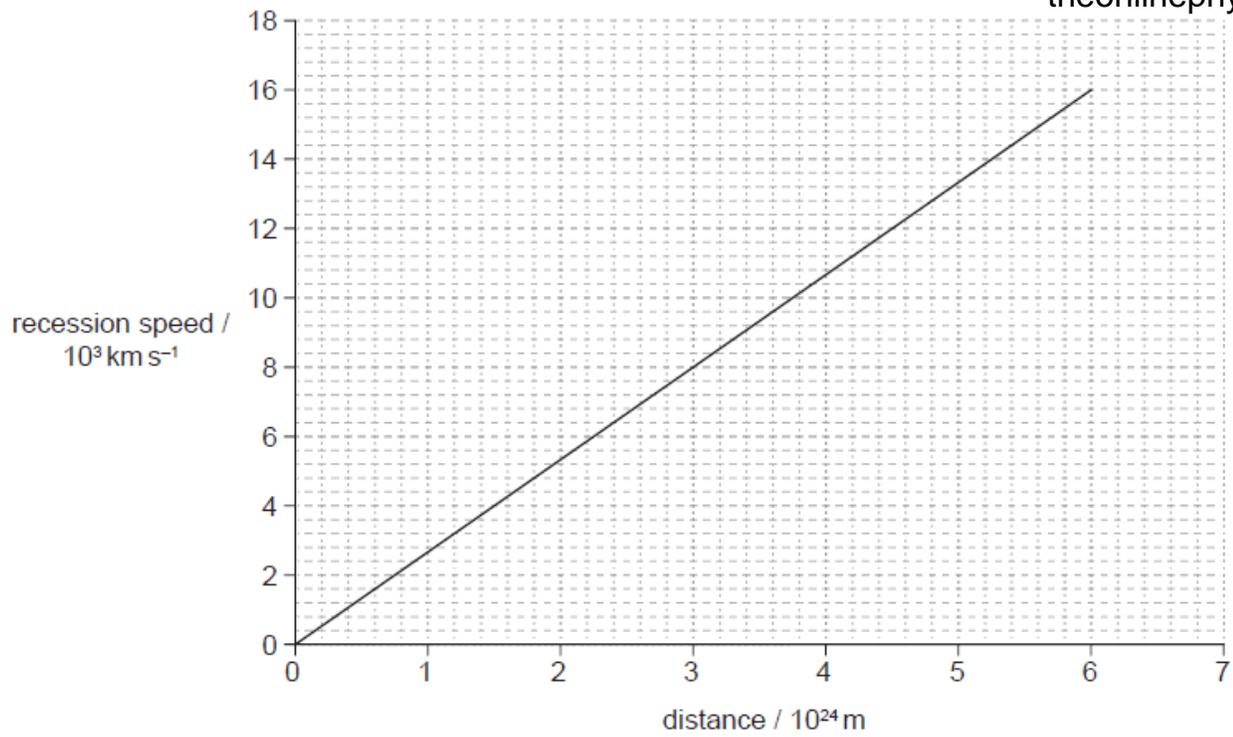
This question is about Hubble's law.

a. The light from distant galaxies is red-shifted. Explain how this red-shift arises.

[3]

b. The graph shows the variation of recession speed with distance from Earth for some galactic clusters.

[4]



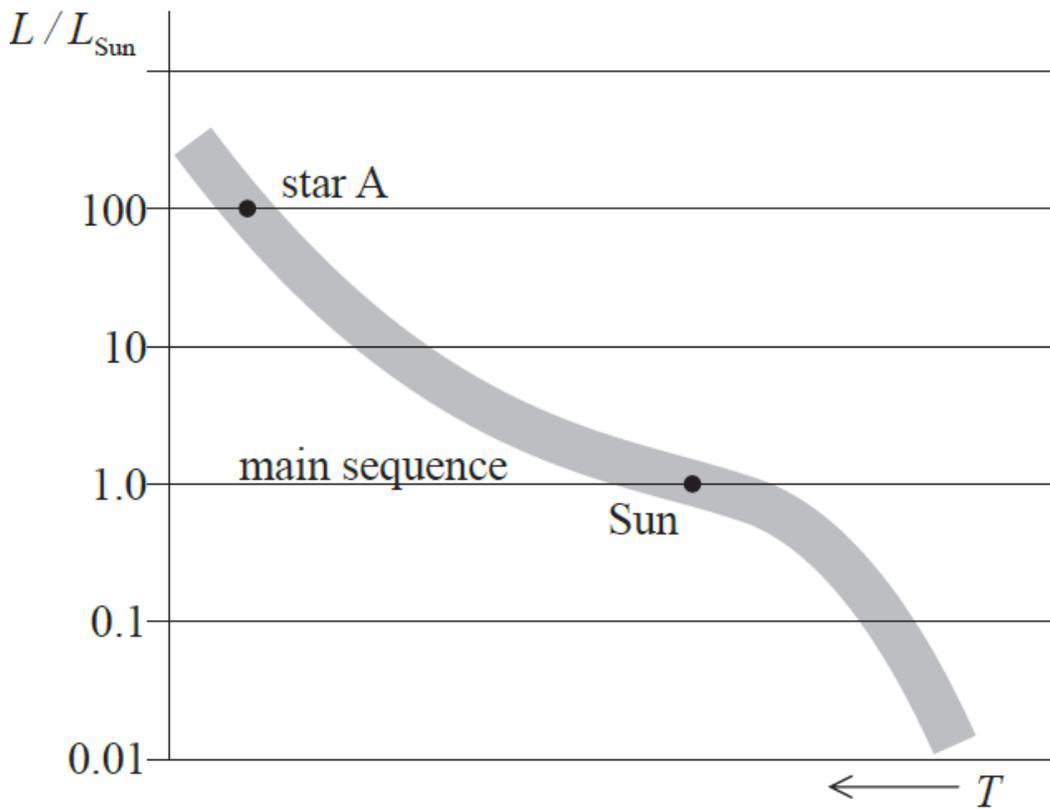
- Calculate, in  $\text{s}^{-1}$ , the Hubble constant.
- Estimate, in s, the age of the universe.
- State the assumption that you made in your estimate in (b)(ii).

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This question is about stellar evolution.

- The Hertzsprung–Russell (HR) diagram shows the Sun, a star A and the main sequence.

[2]



Using the mass–luminosity relation  $L \propto M^{3.5}$ , determine the ratio of the mass of star A to the mass of the Sun.

b. Star A will leave the main sequence and will evolve to become a neutron star. State the

[2]

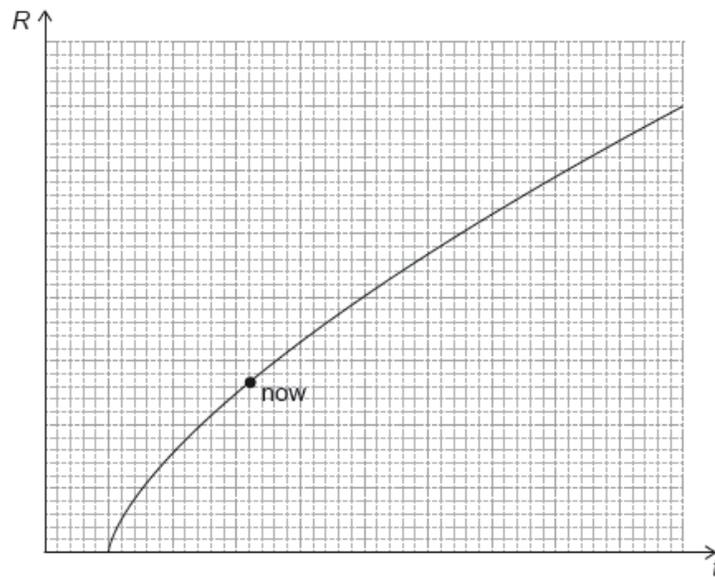
(i) change in star A that marks its departure from the main sequence.

(ii) range of mass of a neutron star.

Recent evidence from the Planck observatory suggests that the matter density of the universe is  $\rho_m = 0.32 \rho_c$ , where  $\rho_c \approx 10^{-26} \text{ kg m}^{-3}$  is the critical density.

a. The graph shows the variation with time  $t$  of the cosmic scale factor  $R$  in the flat model of the universe in which dark energy is ignored.

[1]



On the axes above draw a graph to show the variation of  $R$  with time, when dark energy is present.

b.i. The density of the observable matter in the universe is only  $0.05 \rho_c$ . Suggest how the remaining  $0.27 \rho_c$  is accounted for. [1]

b.ii. The density of dark energy is  $\rho_\Lambda c^2$  where  $\rho_\Lambda = \rho_c - \rho_m$ . Calculate the amount of dark energy in  $1 \text{ m}^3$  of space. [2]

a. Describe what is meant by dark matter. [2]

b. The distribution of mass in a spherical system is such that the density  $\rho$  varies with distance  $r$  from the centre as [1]

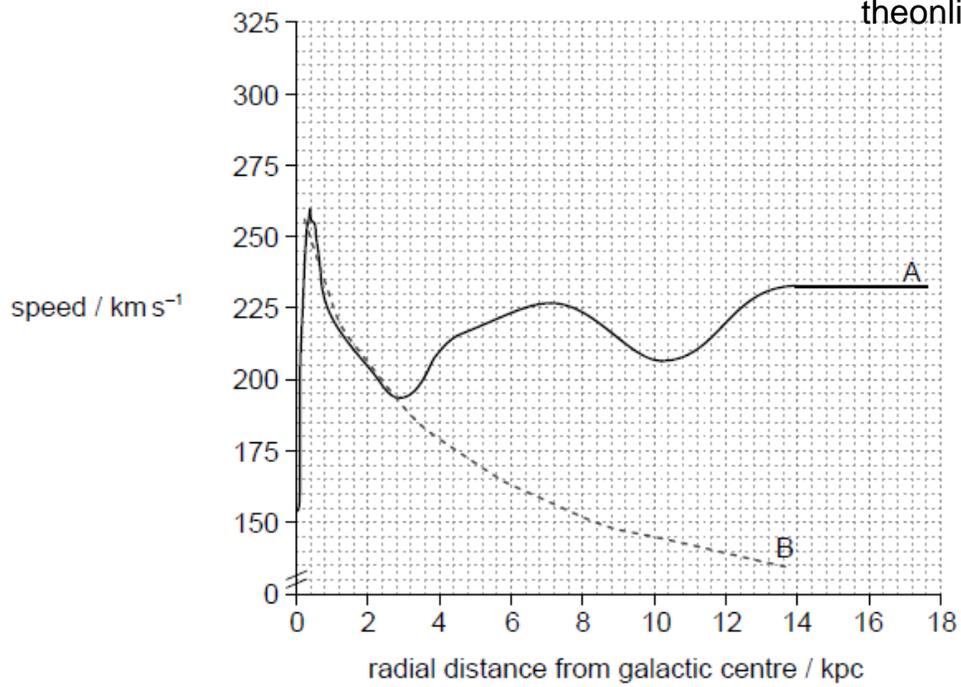
$$\rho = \frac{k}{r^2}$$

where  $k$  is a constant.

Show that the rotation curve of this system is described by

$$v = \text{constant.}$$

c. Curve A shows the actual rotation curve of a nearby galaxy. Curve B shows the predicted rotation curve based on the visible stars in the galaxy. [2]



Explain how curve A provides evidence for dark matter.

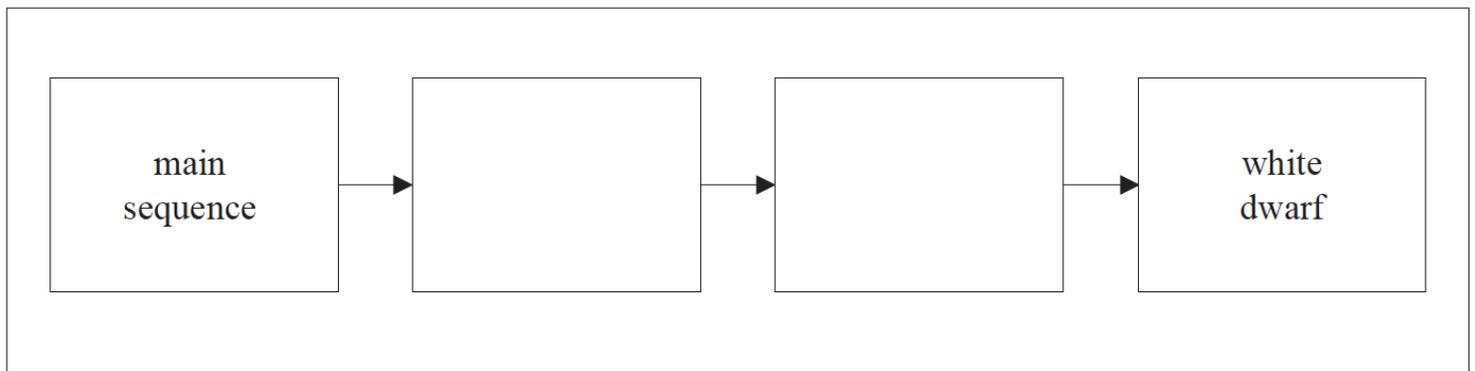
This question is about stellar evolution.

- a. A main sequence star has a mass of  $2.2M_{\odot}$  where  $M_{\odot} = 1$  solar mass. The lifetime of a star on the main sequence is proportional to  $\frac{M}{L}$  where [3]  
 $M$  is the mass and  $L$  is the luminosity of the star.

Using the mass–luminosity relation  $L \propto M^{3.5}$  show that the

- (i) luminosity of the star is  $16L_{\odot}$  where  $L_{\odot} = 1$  solar luminosity.
- (ii) lifetime of this star on the main sequence will be approximately  $\frac{1}{7}$  of the lifetime of the Sun.

- b. The star in (a) will evolve to become a white dwarf. The diagram represents the stages in the evolution of the star. [3]



- (i) On the diagram, label the **two** intermediate stages.
- (ii) State what may be deduced about the mass of this star when it is in the white dwarf stage.

This question is about stars in the constellation Canis Minor.

d. (ii) Gomeisa has a radius four times that of the Sun. Use the data in (c) to show that the ratio

[7]

$$\frac{\text{luminosity of Gomeisa}}{\text{luminosity of Sun}}$$

is about 200.

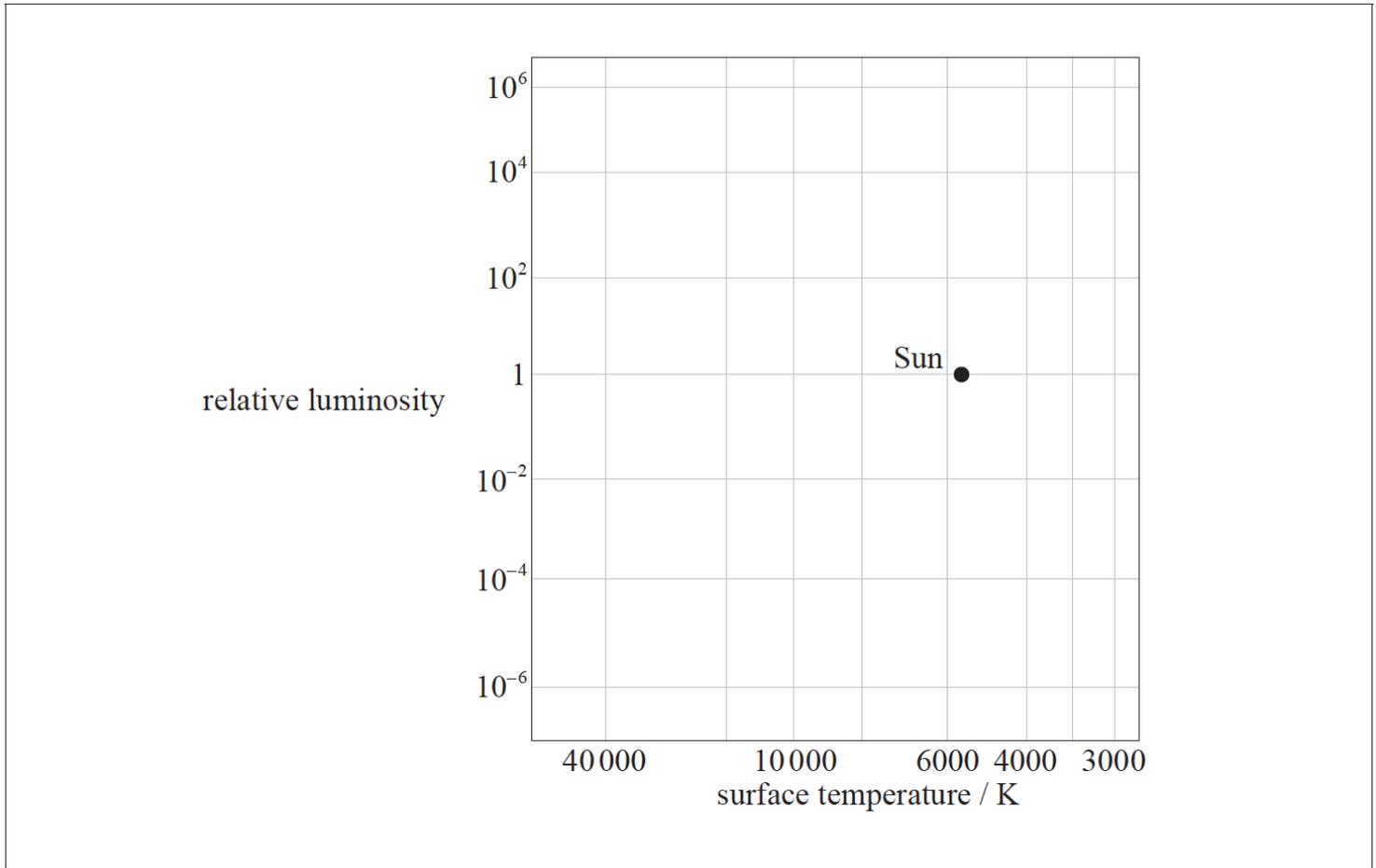
(iii) Assuming the value of  $n$  in the mass–luminosity equation to be 3.5, calculate

$$\frac{\text{mass of Gomeisa}}{\text{mass of Sun}}$$

(iv) Outline, with reference to the Chandrasekhar limit, the likely eventual fate of Gomeisa.

f.

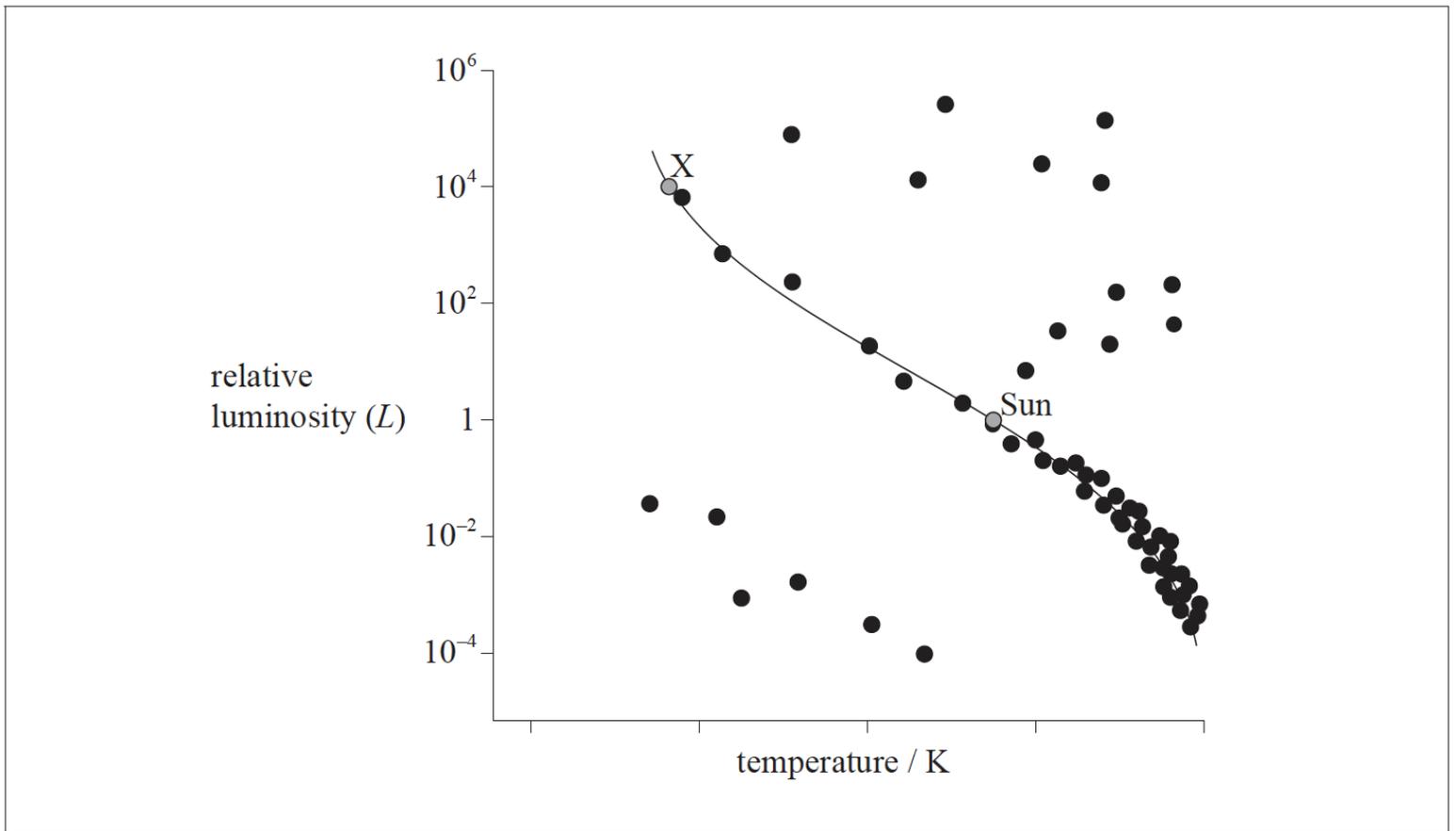
[1]



On the HR diagram above, sketch the likely evolutionary path of Luyten's star.

This question is about stellar evolution.

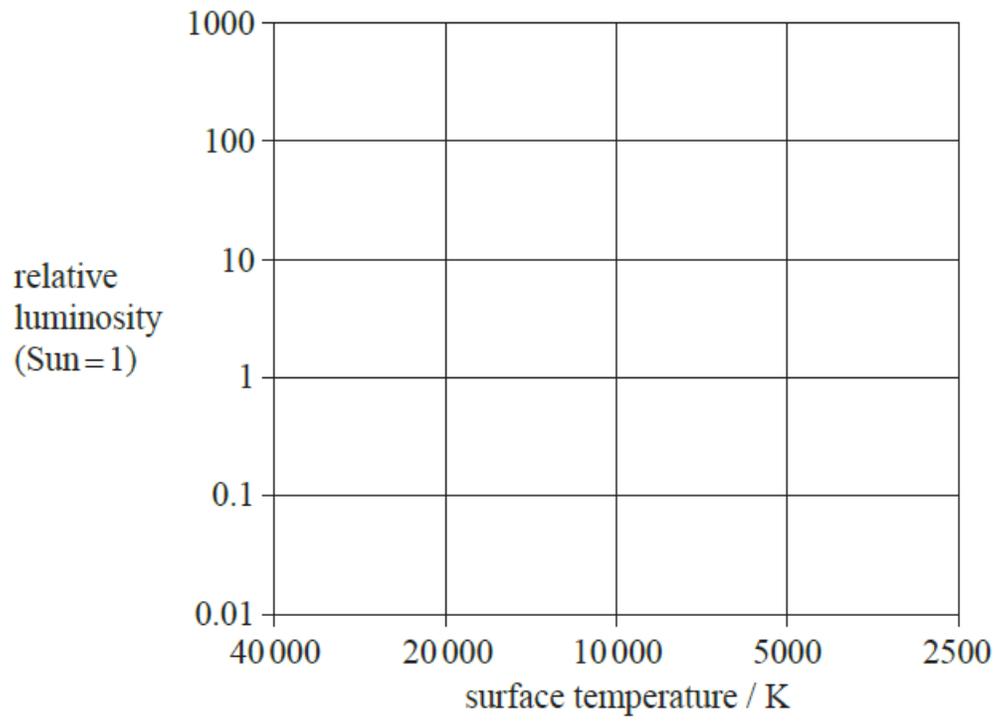
In the HR diagram below, the Sun and another main sequence star, X, have been marked.



- a. (i) On the diagram above, draw a line to show the evolutionary path of the Sun from its present position on the main sequence to the final stage [3]  
in its evolution.
- (ii) Explain, by reference to the Chandrasekhar limit, why the final stage in the evolution of the Sun is the one you indicated in (a)(i).
- b. (i) Show that the mass of star X is approximately 14 solar masses. (Assume that  $n=3.5$  in the mass–luminosity relation.) [3]
- (ii) State the likely final stage of star X.

This question is about the properties of a star.

- b. (i) The radius of star X is  $4.5 R_{\odot}$  where  $R_{\odot}$  is the radius of the Sun. The surface temperature of the Sun is  $5.7 \times 10^3 \text{K}$ . [6]
- Determine the ratio  $\frac{\text{luminosity of star X}}{\text{luminosity of the Sun}}$ .
- (ii) Calculate, assuming that the power in the mass–luminosity relationship is 3.5, the ratio  $\frac{\text{mass of star X}}{\text{mass of Sun}}$ .
- c. On the Hertzsprung–Russell diagram, label [2]
- (i) the position of star X with the letter X.
- (ii) the position of the Sun with the letter S.

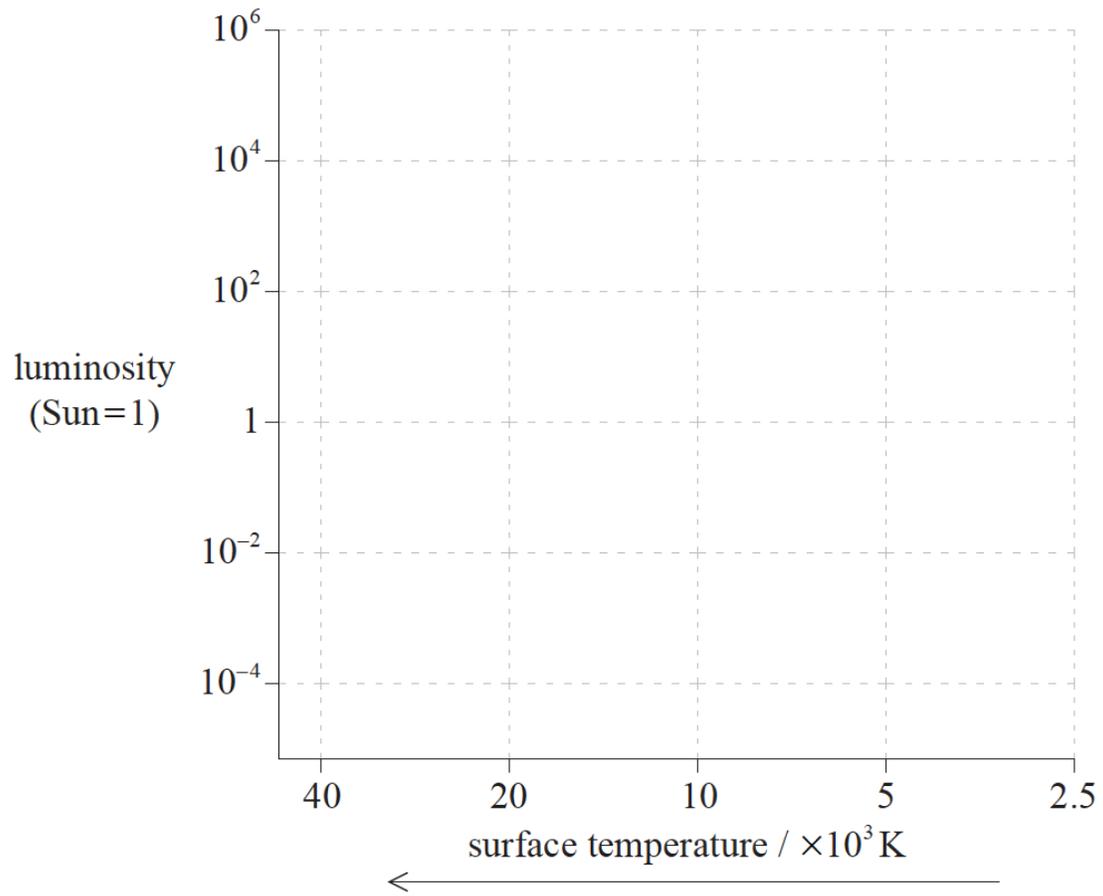


d. Explain, with reference to the Chandrasekhar limit, whether or not star X will become a white dwarf.

[2]

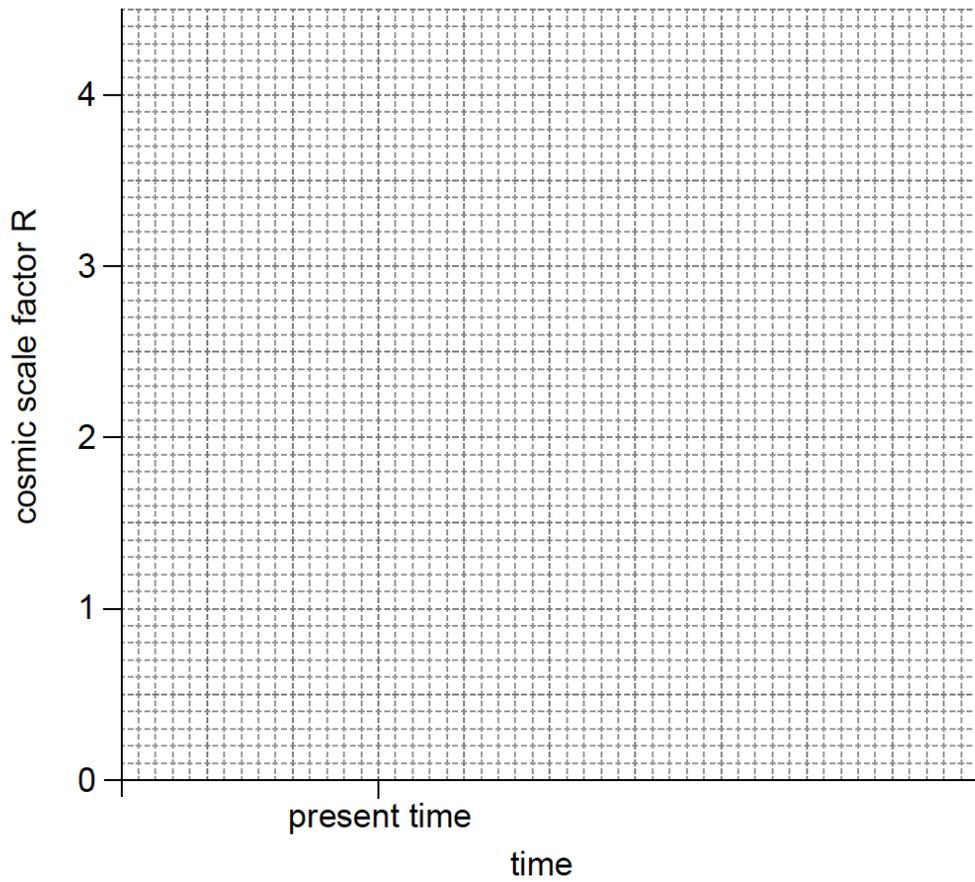
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This question is about stellar distances and stellar properties.



On the HR diagram on page 2, draw the evolutionary path of Barnard's star after it leaves the main sequence.

The Hot Big Bang model suggests several outcomes for the universe. There is now evidence that dark energy and dark matter exist.



a. On the axes, sketch a graph of the variation of cosmic scale factor with time for

[3]

(i) a closed universe without dark energy. Label this curve C.

(ii) an accelerating universe with dark energy. Label this curve A.

b. Explain **one** experimental observation that supports the presence of dark **matter**.

[2]