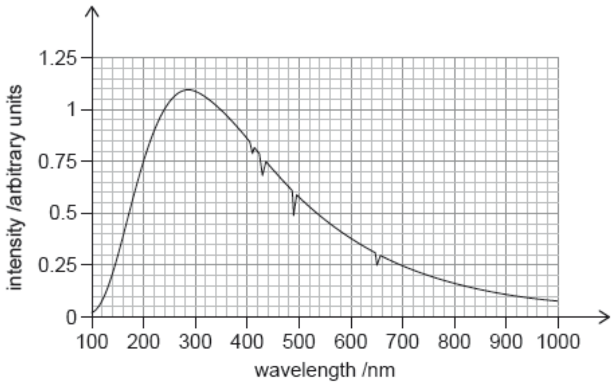
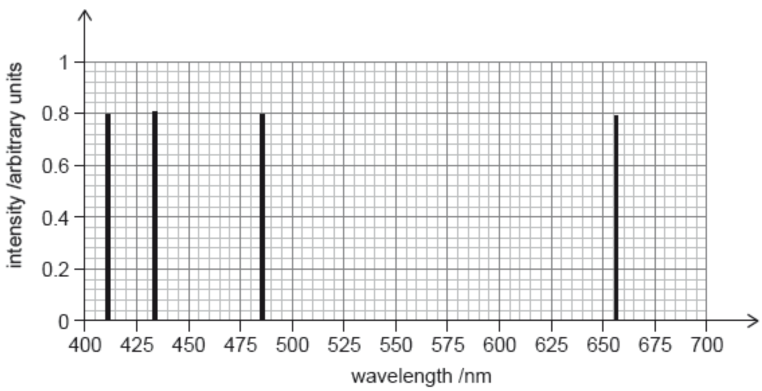
D.2D.3 *[207 marks]*

The graph shows the observed spectrum from star X.



The second graph shows the hydrogen emission spectrum in the visible range.



1a. Suggest, using the graphs, why star X is most likely to be a main sequence star. *[2 marks]*

Markscheme

the wavelengths of the dips correspond to the wavelength in the emission spectrum

the absorption lines in the spectrum of star X suggest it contains predominantly hydrogen

OR

main sequence stars are rich in hydrogen

[2 marks]

1b. Show that the temperature of star X is approximately 10 000 K. *[2 marks]*

Markscheme

peak wavelength: 290 ± 10 «nm»

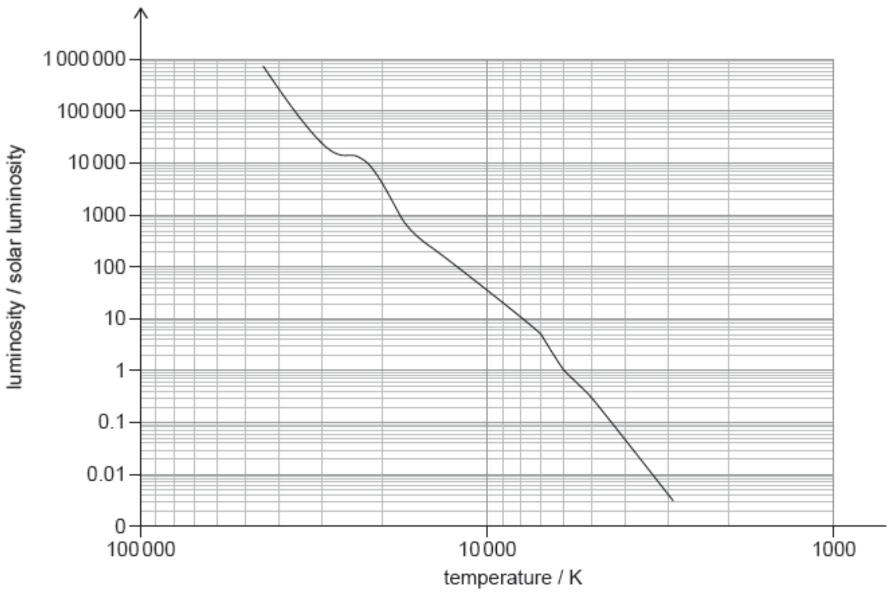
$T = \frac{2.9\times10^{-3}}{290\times10^{-9}}$ = «10 000 ± 400 K»

Substitution in equation must be seen.

Allow ECF from MP1.

***[2 marks]**[*

The following diagram shows the main sequence.



1c. Write down the luminosity of star X (L_X) in terms of the luminosity of the Sun (L_s). *[1 mark]*

Markscheme

35 ± 5 L_s

[1 mark]

1d. Determine the radius of star X (R_X) in terms of the radius of the Sun (R_s). *[3 marks]*

Markscheme

$\frac{L_X}{L_s} = \frac{R_X^2 \times T_X^4}{R_s^2 \times T_s^4}$

OR

$R_X = \sqrt{\frac{L_X T_s^4}{L_s T_X^4}} \times R_s$

$R_X = \sqrt{\frac{35 \times 6000^4}{10\,000^4}} \times R_s$ (mark for correct substitution)

$R_X = 2.1\,R_s$

Allow ECF from (b)(i).

Accept values in the range: 2.0 to 2.3R_s.

Allow TS in the range: 5500 K to 6500 K.

[3 marks]

1e. Estimate the mass of star X (M_X) in terms of the mass of the Sun (M_s). *[2 marks]*

Markscheme

$M_X = (35)^{\frac{1}{3.5}} M_s$

$M_X = 2.8\,M_s$

Allow ECF from (b)(i).

Do not accept $M_X = (35)^{\frac{1}{3.5}}$ for first marking point.

Accept values in the range: 2.6 to 2.9M_s.

[2 marks]

1f. Star X is likely to evolve into a stable white dwarf star. *[2 marks]*

Outline why the radius of a white dwarf star reaches a stable value.

Markscheme

the star «core» collapses until the «inward and outward» forces / pressures are balanced

the outward force / pressure is due to electron degeneracy pressure «not radiation pressure»

[2 marks]

The Hubble constant is accepted to be 70 km s^{-1} Mpc^{-1}. This value of the Hubble constant gives an age for the universe of 14.0 billion years.

The accepted value of the Hubble constant has changed over the past decades.

2a. Explain how international collaboration has helped to refine this value. *[1 mark]*

Markscheme

experiments and collecting data are extremely costly

data from many projects around the world can be collated

OWTTE

[1 mark]

The redshift of a galaxy is measured to be $z = 0.19$.

2b. Estimate, in Mpc, the distance between the galaxy and the Earth. *[2 marks]*

Markscheme

v = «zc = 0.19 × 3 × 10^{8} =» 5.7 × 10^{7} «ms^{-1}»

d = «$\frac{v}{H_0} = \frac{5.7\times10^4}{70}$» = 810Mpc ***OR*** 8.1× 10^{8} pc

Correct units must be present for MP2 to be awarded.

*Award **[2]** for BCA.*

[2 marks]

2c. Determine, in years, the approximate age of the universe at the instant when the detected light from the distant galaxy was emitted. *[3 marks]*

Markscheme

ALTERNATIVE 1

$\frac{R_{\text{now}}}{R_{\text{then}}}$ = 1 + z = 1.19

so (assuming constant expansion rate) $\frac{t_{\text{now}}}{t}$ = 1.19

t = $\frac{14}{1.19}$ = 11.7By = 12 «By (billion years)»

ALTERNATIVE 2

light has travelled a distance: (810 × 10^6 × 3.26 =) 2.6 × 10^9ly

so light was emitted: 2.6 billion years ago

so the universe was 11.4 billion years old

MP1 can be awarded if MP2 clearly seen.

Accept 2.5 × 10^{25} m for mp1.

MP1 can be awarded if MP2 clearly seen.

[3 marks]

3a. Main sequence stars are in equilibrium under the action of forces. Outline how this equilibrium is achieved. *[2 marks]*

Markscheme

photon/fusion/radiation force/pressure balances gravitational force/pressure

gives both directions correctly (outwards radiation, inwards gravity)

OWTTE

[2 marks]

3b. A main sequence star P, is 1.3 times the mass of the Sun. Calculate the luminosity of P relative to the Sun. *[1 mark]*

Markscheme

«$L \propto M^{35}$ for main sequence»

luminosity of P = 2.5 «luminosity of the Sun»

[1 mark]

The following data apply to the star Gacrux.

$$\begin{aligned} &\text{Radius} &&= 58.5 \times 10^9 \text{ m} \\ &\text{Temperature} &&= 3600 \text{ K} \\ &\text{Distance} &&= 88 \text{ ly} \end{aligned}$$

3c. The luminosity of the Sun $L_{\odot}$ is 3.85×10^{26} W. Determine the luminosity of Gacrux relative to the Sun. *[3 marks]*

Markscheme

$L_{Gacrux} = 5.67 \times 10^{-8} \times 4\pi \times (58.5 \times 10^9)^2 \times 3600^4$

$L_{Gacrux} = 4.1 \times 10^{-29}$ «W»

$\frac{L_{Gacrux}}{L_{\odot}}$ «= $\frac{4.1 \times 10^{29}}{3.85 \times 10^{26}}$» = 1.1×10^3

[3 marks]

3d. The distance to Gacrux can be determined using stellar parallax. Outline why this method is not suitable for all stars. *[1 mark]*

Markscheme

if the star is too far then the parallax angle is too small to be measured

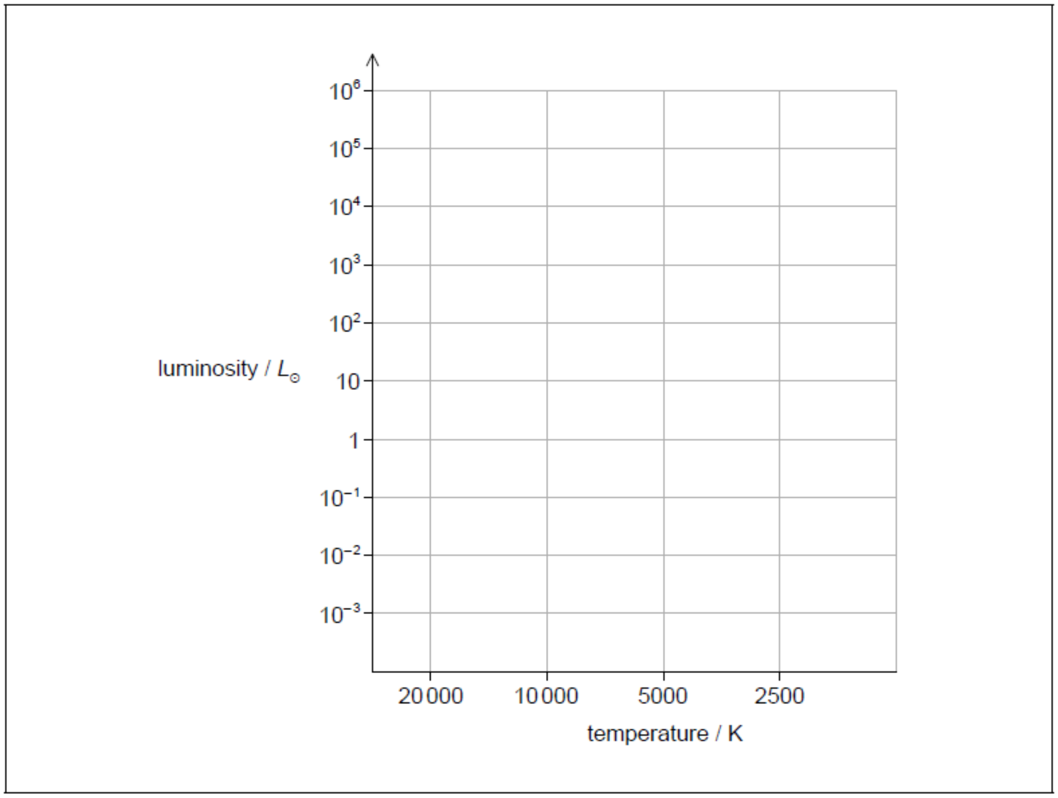
OR

stellar parallax is limited to closer stars

OWTTE

[1 mark]

A Hertzsprung–Russell (HR) diagram is shown.



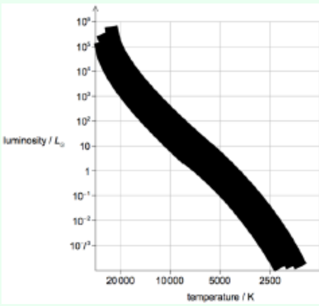
On the HR diagram,

3e. draw the main sequence. *[1 mark]*

Markscheme

line or area roughly inside shape shown – judge by eye

Accept straight line or straight area at roughly 45°



[1 mark]

3f. plot the position, using the letter P, of the main sequence star P you calculated in (b). *[1 mark]*

Markscheme

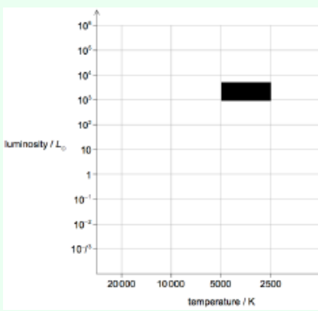
P between $1L_{\odot}$ and $10^1L_{\odot}$ on main sequence drawn

[1 mark]

3g. plot the position, using the letter G, of Gacrux. *[1 mark]*

Markscheme

at $10^3L_{\odot}$, further to right than 5000 K and to the left of 2500 K (see shaded region)



[1 mark]

3h. Discuss, with reference to its change in mass, the evolution of star P from the main sequence until its final stable phase. *[3 marks]*

Markscheme

ALTERNATIVE 1

Main sequence to red giant

planetary nebula with mass reduction/loss

OR

planetary nebula with mention of remnant mass

white dwarf

ALTERNATIVE 2

Main sequence to red supergiant region

Supernova with mass reduction/loss

OR

Supernova with mention of remnant mass

neutron star

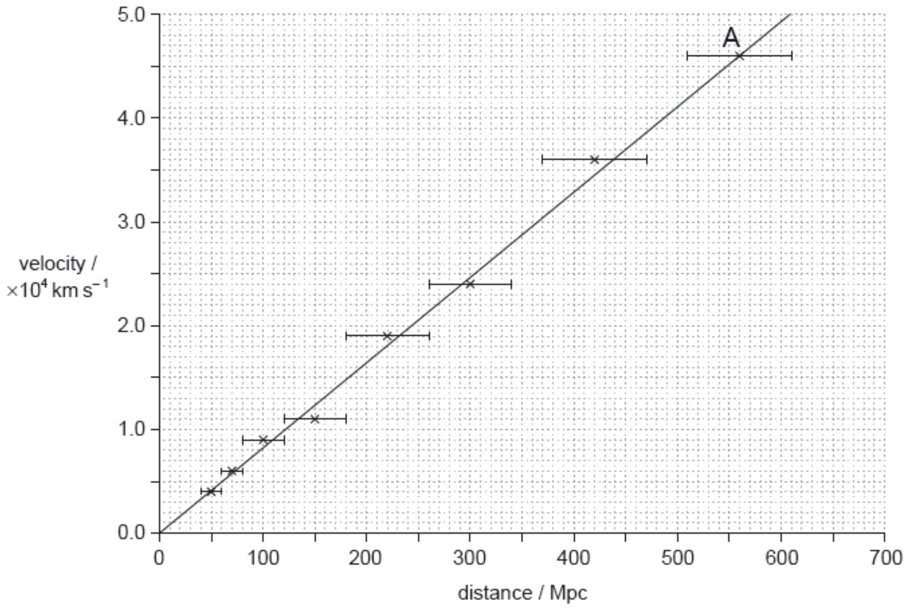
OR

Black hole

OWTTE for both alternatives

[3 marks]

Data from distant galaxies are shown on the graph.



4a. Estimate, using the data, the age of the universe. Give your answer in seconds. *[3 marks]*

Markscheme

use of gradient or any coordinate pair to find H_0 «= $\frac{v}{d}$» or $\frac{1}{H_0}$ «= $\frac{d}{v}$»

convert Mpc to m and km to m «for example $\frac{82\times10^3}{10^6\times3.26\times9.46\times10^{15}}$»

age of universe «= $\frac{1}{H_0}$» = 3.8×10^{17} «s»

Allow final answers between

3.7×10^{17} and 3.9×10^{17} «s» or 4×10^{17} «s»

[3 marks]

4b. Identify the assumption that you made in your answer to (a). *[1 mark]*

Markscheme

non-accelerated/uniform rate of expansion

OR

H_0 constant over time

OWTTE

[1 mark]

4c. On the graph, one galaxy is labelled A. Determine the size of the universe, relative to its present size, when light from the galaxy labelled A was emitted. *[3 marks]*

Markscheme

z « = $\frac{v}{c}$» = $\frac{4.6\times10^4\times10^3}{3.00\times10^8}$ = 0.15

$\frac{R}{R_0}$ = «z + 1» = 1.15

$\frac{R_0}{R}$ = « $\frac{1}{1.15}$ =» 0.87

OR

87% of the present size

[3 marks]

Sirius is a binary star. It is composed of two stars, Sirius A and Sirius B. Sirius A is a main sequence star.

5a. State what is meant by a binary star. *[1 mark]*

Markscheme

two stars orbiting a common centre «of mass»

Do not accept "stars which orbit each other"

5b. The peak spectral line of Sirius B has a measured wavelength of 115 nm. Show that the surface temperature of Sirius B is about 25 000 K. *[1 mark]*

Markscheme

«λ x T = 2.9 x 10^{-3}»

$T = \frac{2.9\times10^{-3}}{115\times10^{-9}}$ = 25217 «K»

5c. The mass of Sirius B is about the same mass as the Sun. The luminosity of Sirius B is 2.5 % of the luminosity of the Sun. Show, with a calculation, that Sirius B is **not** a main sequence star. *[2 marks]*

Markscheme

use of the mass-luminosity relationship ***or*** $\left(\frac{M_{\text{Sirius}}}{M_{\text{Sun}}}\right)^{3.5}$ = 1

if Sirius B is on the main sequence then $\left(\frac{L_{\text{Sirius B}}}{L_{\text{Sun}}}\right)$ = 1 «which it is not»

Conclusion is given, justification must be stated

Allow reverse argument beginning with luminosity

The Sun's surface temperature is about 5800 K.

5d. Determine the radius of Sirius B in terms of the radius of the Sun. *[2 marks]*

Markscheme

$\left(\frac{L_{\text{Sirius B}}}{L_{\text{Sun}}}\right)$ = 0.025

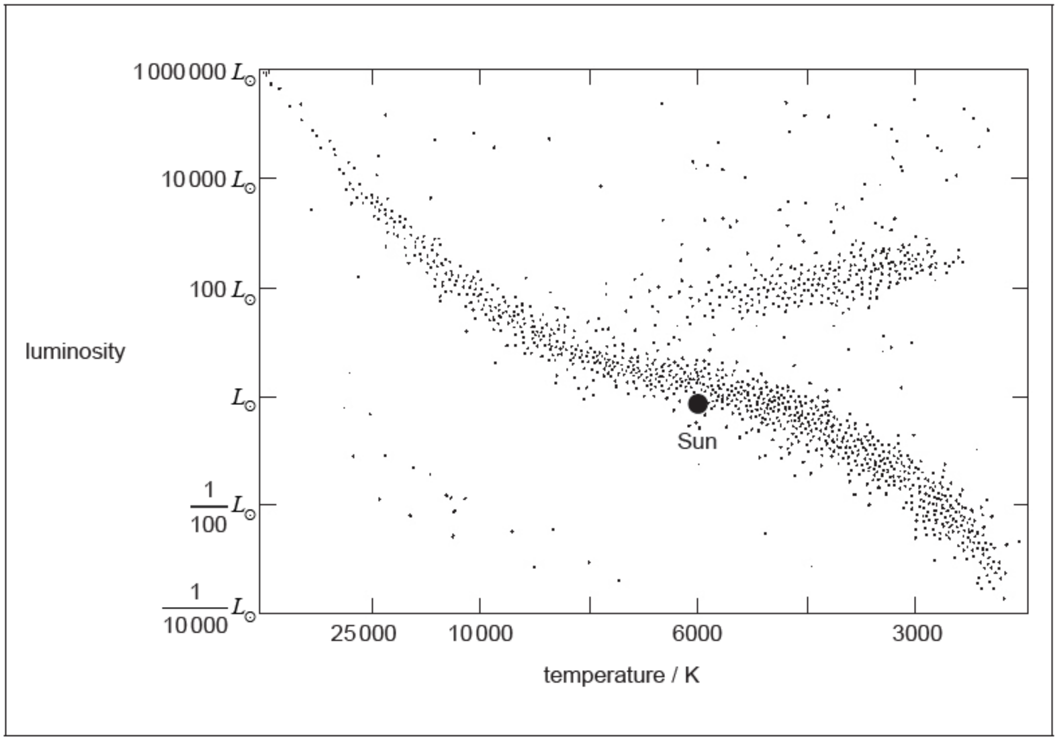
r_{Sirius} = «$\sqrt{0.025\times\left(\frac{5800}{25000}\right)^4}$ =» 0.0085 r_{Sun}

5e. Identify the star type of Sirius B. *[1 mark]*

Markscheme

white dwarf

The image shows a Hertzsprung–Russell (HR) diagram.



The mass of Sirius A is twice the mass of the Sun. Using the Hertzsprung–Russell (HR) diagram,

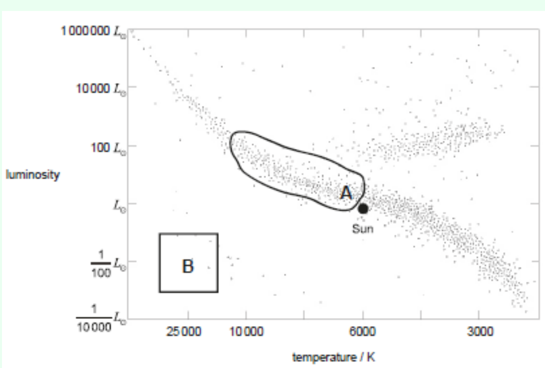
5f. draw the approximate positions of Sirius A, labelled A and Sirius B, labelled B. *[1 mark]*

Markscheme

Sirius A on the main sequence above and to the left of the Sun ***AND*** Sirius B on white dwarf area as shown

Both positions must be labelled

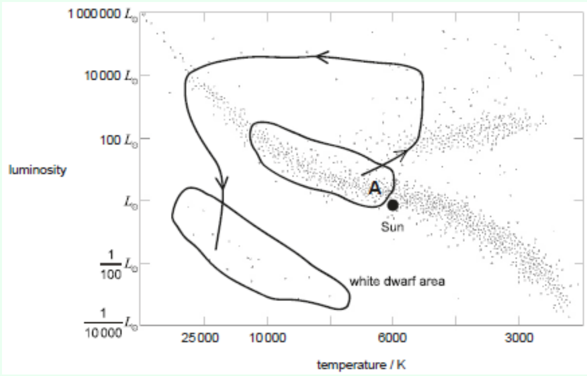
Allow the position anywhere within the limits shown.



5g. sketch the expected evolutionary path for Sirius A. *[1 mark]*

Markscheme

arrow goes up and right and then loops to white dwarf area



The collision of two galaxies is being studied. The wavelength of a particular spectral line from the galaxy measured from Earth is 116.04 nm. The spectral line when measured from a source on Earth is 115.00 nm.

6a. Outline **one** reason for the difference in wavelength. *[1 mark]*

Markscheme

galaxies are moving away

OR

space «between galaxies» is expanding

Do not accept just red-shift

6b. Determine the velocity of the galaxy relative to Earth. *[2 marks]*

Markscheme

«$\frac{\Delta\lambda}{\lambda}=$» $\frac{1.04}{115}=\frac{v}{c}$

0.009*c*

Accept 2.7×10^{6} *«m* s^{-1}*»*

Award ***[0]*** *if 116 is used for* λ

7a. State **two** characteristics of the cosmic microwave background (CMB) radiation. *[2 marks]*

Markscheme

black body radiation / 3 K

highly isotropic / uniform throughout
OR
filling the universe

Do not accept: CMB provides evidence for the Big Bang model.

[2 marks]

7b. The present temperature of the CMB is 2.8 K. Calculate the peak wavelength of the CMB. *[1 mark]*

Markscheme

«$\lambda = \frac{2.9\times10^{-3}}{2.8}$» ≈ 1.0 «mm»

[1 mark]

7c. Describe how the CMB provides evidence for the Hot Big Bang model of the universe. *[2 marks]*

Markscheme

the universe is **expanding** and so the wavelength of the CMB in the past was much smaller

indicating a very high temperature at the beginning

[2 marks]

A spectral line in the light received from a distant galaxy shows a redshift of z = 0.16.

7d. Determine the distance to this galaxy using a value for the Hubble constant of H_0 = 68 km s^{-1} Mpc^{-1}. *[2 marks]*

Markscheme

«$z = \frac{v}{c} \Rightarrow$» $v = 0.16 \times 3 \times 10^5$ «$= 0.48 \times 10^5$ km s^{-1}»

«$d = \frac{v}{H_0} \Rightarrow v = \frac{0.48\times10^5}{68} = 706$» ≈ 710 «Mpc»

*Award **[1 max]** for POT error.*

[2 marks]

7e. Estimate the size of the Universe relative to its present size when the light was emitted by the galaxy in (c). *[2 marks]*

Markscheme

$z = \frac{R}{R_0} - 1 \Rightarrow \frac{R}{R_0} = 1.16$

$\frac{R_0}{R} = 0.86$

[2 marks]

Theta 1 Orionis is a main sequence star. The following data for Theta 1 Orionis are available.

Luminosity	$L = 4 \times 10^5 L_\odot$
Radius	$R = 13R_\odot$
Apparent brightness	$b = 4 \times 10^{-11} b_\odot$

where $L_\odot$, $R_\odot$ and $b_\odot$ are the luminosity, radius and apparent brightness of the Sun.

8a. State what is meant by a main sequence star. *[1 mark]*

Markscheme

stars fusing hydrogen «into helium»

[1 mark]

8b. Show that the mass of Theta 1 Orionis is about 40 solar masses. *[1 mark]*

Markscheme

$M = M_\odot (4 \times 10^5)^{\frac{1}{3.5}} = 39.86 M_\odot$

«$M \approx 40 M_\odot$»

Accept reverse working.

[1 mark]

8c. The surface temperature of the Sun is about 6000 K. Estimate the surface temperature of Theta 1 Orionis. *[2 marks]*

Markscheme

$4 \times 10^5 = 13^2 \times \frac{T^4}{6000^4}$

$T \approx 42\,000$ «K»

Accept use of substituted values into $L = \sigma 4$ $\pi R^2 T^4$.

Award ***[2]*** *for a bald correct answer.*

[2 marks]

8d. Determine the distance of Theta 1 Orionis in AU. *[2 marks]*

Markscheme

$4 \times 10^{-11} = 4 \times 10^5 \times \frac{1\text{AU}^2}{d^2}$

$d = 1 \times 10^8$ «AU»

Accept use of correct values into $b = \frac{L}{4\pi d^2}$.

[2 marks]

8e. Discuss how Theta 1 Orionis does not collapse under its own weight. *[2 marks]*

Markscheme

the gravitation «pressure» is balanced by radiation «pressure»

that is created by the production of energy due to fusion in the core / OWTTE

Award ***[1 max]*** *if pressure and force is inappropriately mixed in the answer.*

Award ***[1 max]*** *for unexplained "hydrostatic equilibrium is reached".*

[2 marks]

8f. The Sun and Theta 1 Orionis will eventually leave the main sequence. Compare and contrast the different stages in the evolution of the two stars. *[3 marks]*

Markscheme

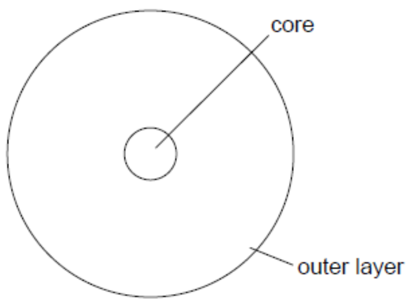
the Sun will evolve to become a red giant whereas Theta 1 Orionis will become a red super giant

the Sun will explode as a planetary nebula whereas Theta 1 Orionis will explode as a supernova

the Sun will end up as a white dwarf whereas Theta 1 Orionis as a neutron star/black hole

[3 marks]

The diagram shows the structure of a typical main sequence star.



9a. State the most abundant element in the core and the most abundant element in the outer layer. *[2 marks]*

core: . . . .

outer layer: . . . .

Markscheme

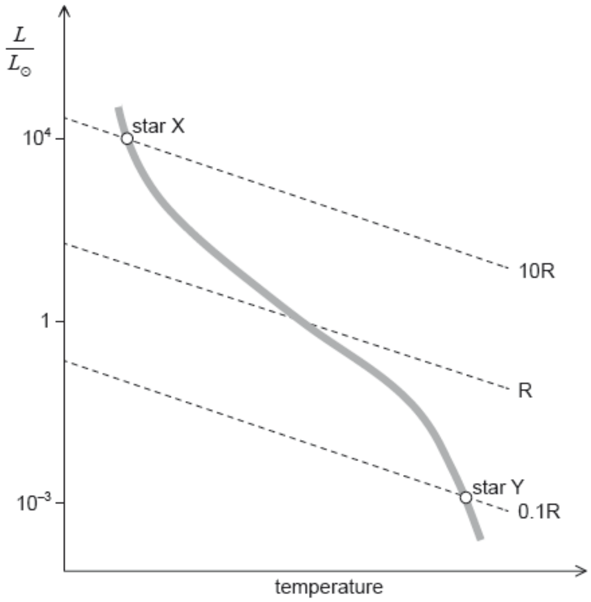
core: helium

outer layer: hydrogen

Accept no other elements.

[2 marks]

9b. The Hertzsprung–Russell (HR) diagram shows two main sequence stars X and Y and includes lines of constant radius. *R* is the radius of the Sun. *[3 marks]*



Using the mass–luminosity relation and information from the graph, determine the ratio $\frac{\text{density of star X}}{\text{density of star Y}}$.

Markscheme

ratio of masses is $\left(\frac{10^4}{10^{-3}}\right)^{\frac{1}{3.5}} = 10^2$

ratio of volumes is $\left(\frac{10}{10^{-1}}\right)^3 = 10^6$

so ratio of densities is $\frac{10^2}{10^6} = 10^{-4}$

Allow ECF for MP3 from earlier MPs

[3 marks]

Star X is likely to evolve into a neutron star.

9c. On the HR diagram in (b), draw a line to indicate the evolutionary path of star X. *[1 mark]*

Markscheme

line to the right of X, possibly undulating, very roughly horizontal

Ignore any paths beyond this as the star disappears from diagram.

[1 mark]

9d. Outline why the neutron star that is left after the supernova stage does not collapse under the action of gravitation. *[1 mark]*

Markscheme

gravitation is balanced by a pressure/force due to neutrons/neutron degeneracy/pauli exclusion principle

Do not accept electron degeneracy.

[1 mark]

9e. The radius of a typical neutron star is 20 km and its surface temperature is 10^{6} K. Determine the luminosity of this neutron star. *[2 marks]*

Markscheme

$L = \sigma AT^4 = 5.67 \times 10^{-8} \times 4\pi \times (2.0 \times 10^4)^2 \times (10^6)^4$

$L = 3 \times 10^{26}$ «W»
OR
$L = 2.85 \times 10^{26}$ «W»

*Allow ECF for **[1 max]** if*
πr^2 used (gives 7×10^{26} «W »)

Allow ECF for a POT error in MP1.

[2 marks]

9f. Determine the region of the electromagnetic spectrum in which the neutron star in (c)(iii) emits most of its energy. *[2 marks]*

Markscheme

$\lambda = \frac{2.9 \times 10^{-3}}{10^6} = 2.9 \times 10^{-9}$ «m»

this is an X-ray wavelength

[2 marks]

10a. Describe what is meant by the Big Bang model of the universe. *[2 marks]*

Markscheme

theory in which all space/time/energy/matter were created at a point/singularity

at enormous temperature

with the volume of the universe increasing ever since ***or*** the universe expanding

OWTTE

[2 marks]

10b. State **two** features of the cosmic microwave background (CMB) radiation which are consistent with the Big Bang model. *[2 marks]*

Markscheme

CMB has a black-body spectrum

wavelength stretched by expansion

is highly isotropic/homogenous

but has minor anisotropies predicted by BB model

T «= 2.7 K» is close to predicted value

For MP4 and MP5 idea of "prediction" is needed

[2 marks]

A particular emission line in a distant galaxy shows a redshift $z = 0.084$.

The Hubble constant is $H_0 = 68$ km s^{-1} Mpc^{-1}.

10c. Determine the distance to the galaxy in Mpc. *[2 marks]*

Markscheme

$\frac{v}{c} = z \Rightarrow v = 0.084 \times 3 \times 10^5 = 2.52 \times 10^4$ «km s^{-1}»

$d = \frac{v}{H_0} = \frac{2.52 \times 10^4}{68} = 370.6 \approx 370$ «Mpc»

Allow ECF from MP1 to MP2.

[2 marks]

10d. Describe how type Ia supernovae could be used to measure the distance to this galaxy. *[3 marks]*

Markscheme

type Ia have a known luminosity/are standard candles

measure apparent brightness

determine distance from $d = \sqrt{\frac{L}{4\pi b}}$

Must refer to type Ia. Do not accept other methods (parallax, Cepheids)

[3 marks]

Alpha Centauri A and B is a binary star system in the main sequence.

	Alpha Centauri A	Alpha Centauri B
Luminosity	$1.5L_{\odot}$	$0.5L_{\odot}$
Surface temperature / K	5800	5300

11a. State what is meant by a binary star system. *[1 mark]*

Markscheme

two stars orbiting about a common centre «of mass/gravity»
Do not accept two stars orbiting each other.

11b. (i) Calculate $\frac{b_A}{b_B} = \frac{\text{apparent brightness of Alpha Centauri A}}{\text{apparent brightness of Alpha Centauri B}}$. *[4 marks]*

(ii) The luminosity of the Sun is 3.8 × 10^{26} W. Calculate the radius of Alpha Centauri A.

Markscheme

i
stars are roughly at the same distance from Earth
OR
d is constant for binaries

$$\frac{L_A}{L_B} = \frac{1.5}{0.5} = 3.0$$

Award **[2]** for a bald correct answer.

ii

$$r = \sqrt{\frac{1.5 \times 3.8 \times 10^{26}}{5.67 \times 10^{-8} \times 4\pi \times 5800^4}}$$

= 8.4 × 10^8 «m»

*Award **[2]** for a bald correct answer.*

11c. Show, without calculation, that the radius of Alpha Centauri B is smaller than the radius of Alpha Centauri A. *[2 marks]*

Markscheme

«A=$\frac{L}{\sigma T^4}$» B and A have similar temperatures

so areas are in ratio of luminosities

«so B radius is less than A»

11d. Alpha Centauri A is in equilibrium at constant radius. Explain how this equilibrium is maintained. *[3 marks]*

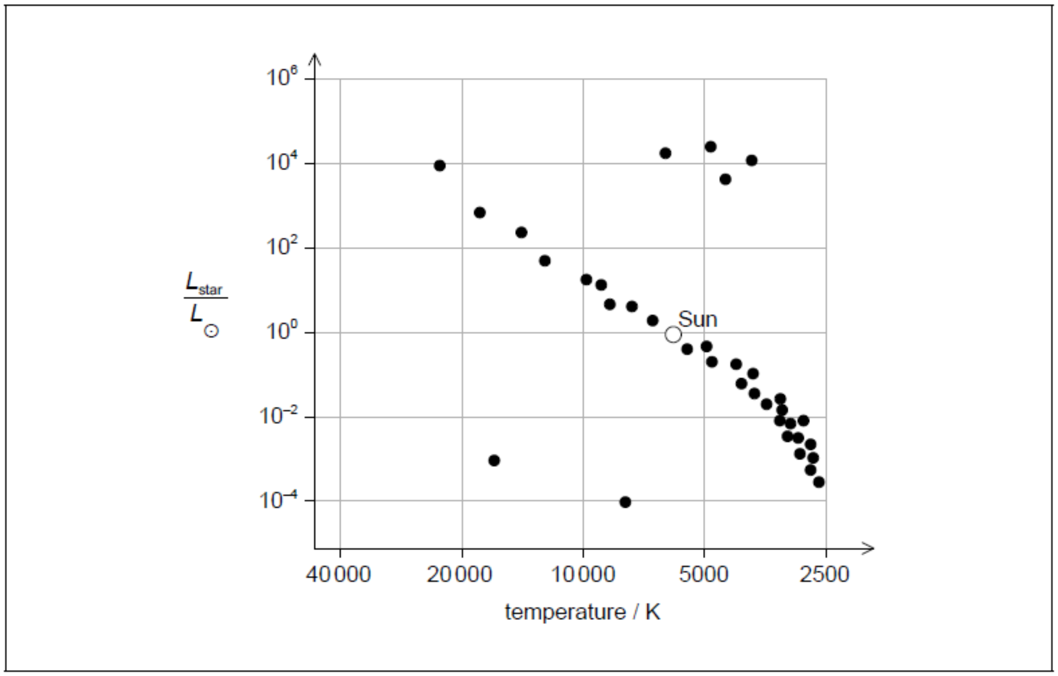
Markscheme

radiation pressure/force outwards

gravitational pressure/force inwards

forces/pressures balance

11e. A standard Hertzsprung–Russell (HR) diagram is shown. *[2 marks]*

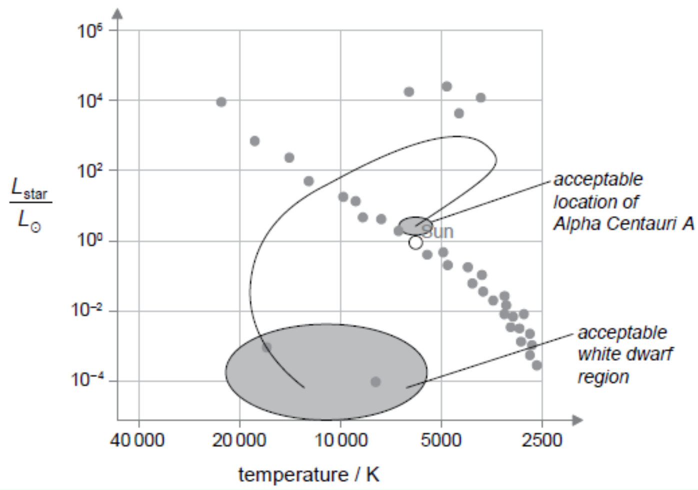


Using the HR diagram, draw the present position of Alpha Centauri A and its expected evolutionary path.

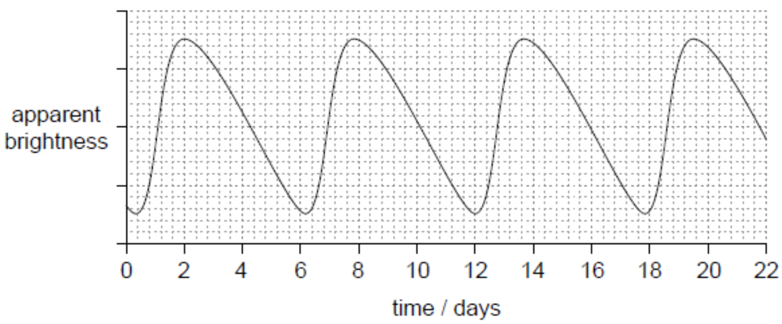
Markscheme

Alpha Centauri A within allowable region

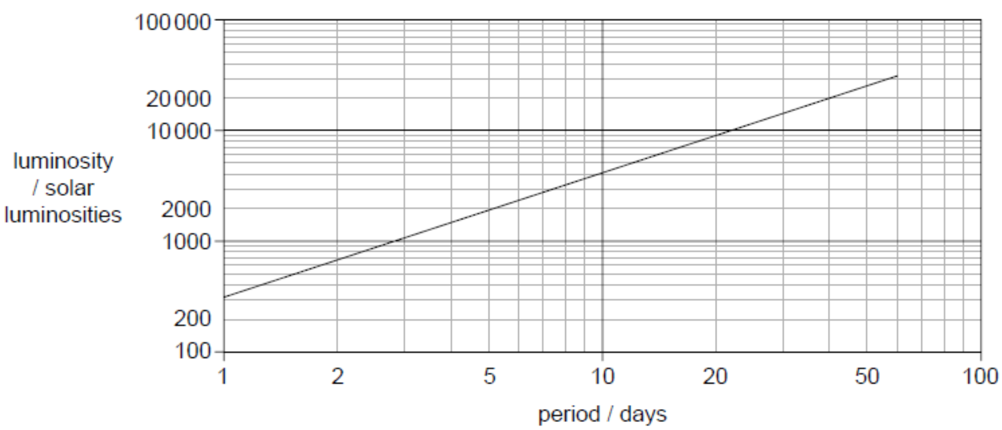
some indication of star moving right and up then left and down ending in white dwarf region as indicated



The first graph shows the variation of apparent brightness of a Cepheid star with time.



The second graph shows the average luminosity with period for Cepheid stars.



12a. Determine the distance from Earth to the Cepheid star in parsecs. The luminosity of the Sun is 3.8×10^{26} W. The average apparent brightness of the Cepheid star is 1.1×10^{-9} W m^{-2}. *[3 marks]*

Markscheme

from first graph period=5.7 «days» ±0.3 «days»

from second graph $\frac{L}{L_{\text{SUN}}} = 2300$ «± 200»

d = «$\sqrt{\frac{2500 \times 3.8 \times 10^{26}}{4\pi \times 1.1 \times 10^{-9}}} = 8.3 \times 10^{18} \text{m}$» =250 «pc»

Accept answer from interval 240 to 270 pc If unit omitted, assume pc.
Watch for ECF from mp1

12b. Explain why Cephids are used as standard candles. *[2 marks]*

Markscheme

Cepheids have a definite/known «average» luminosity

which is determined from «measurement of» period
OR
determined from period-luminosity graph

Cepheids can be used to estimate the distance of galaxies

Do not accept brightness for luminosity.

The peak wavelength of the cosmic microwave background (CMB) radiation spectrum corresponds to a temperature of 2.76 K.

13a. Identify **two** other characteristics of the CMB radiation that are predicted from the Hot Big Bang theory. *[2 marks]*

Markscheme

isotropic/appears the same from every viewing angle

homogenous/same throughout the universe

black-body radiation

13b. A spectral line in the hydrogen spectrum measured in the laboratory today has a wavelength of 21cm. Since the emission of the CMB radiation, the cosmic scale factor has changed by a factor of 1100. Determine the wavelength of the 21cm spectral line in the CMB radiation when it is observed today. *[1 mark]*

Markscheme

23 100 «cm»
OR
231 «m»

Aldebaran is a red giant star with a peak wavelength of 740 nm and a mass of 1.7 solar masses.

14a. Show that the surface temperature of Aldebaran is about 4000 K. *[2 marks]*

Markscheme

$T = \frac{2.9\times10^{-3}}{740\times10^{-9}}$
3900 K
Answer must be to at least 2SF.

14b. The radius of Aldebaran is 3.1×10^{10} m. Determine the luminosity of Aldebaran. *[2 marks]*

Markscheme

$L=5.67\times10^{-8}\times4\pi\times(3.1\times10^{10})^2\times4000^4$

$=1.8\times10^{29}$W

Accept use of 3900^4 to give 1.6×10^{29}W.

14c. Outline how the light from Aldebaran gives evidence of its composition. *[2 marks]*

Markscheme

absorption lines in spectra

are specific to particular elements

Accept "emission lines in spectra".

14d. Identify the element that is fusing in Aldebaran's core at this stage in its evolution. *[1 mark]*

Markscheme

helium

14e. Predict the likely future evolution of Aldebaran. *[3 marks]*

Markscheme

helium flash
expansion of outer shell ***OR*** surface temperature increase
planetary nebula phase
only the core remains
if below $1.4M_S$/Chandrasekhar limit then white dwarf

15a. Light reaching Earth from quasar 3C273 has z=0.16. *[4 marks]*

(i) Outline what is meant by z.

(ii) Calculate the ratio of the size of the universe when the light was emitted by the quasar to the present size of the universe.

(iii) Calculate the distance of 3C273 from Earth using $H_0 = 68 \text{kms}^{-1}\text{Mpc}^{-1}$.

Markscheme

(i) $z = \frac{\Delta\lambda}{\lambda_o}$ where Δλ is the redshift of a wavelength and λ_0 is the wavelength measured at rest on Earth ***OR*** it is a measure of cosmological redshift

Do not allow just "redshift".

(ii) $\ll z = \frac{R}{R_o} - 1, \frac{R}{R_o} = \frac{1}{z+1} \gg \text{so} \frac{R}{R_o} = \ll \frac{1}{1.16} \gg = 0.86$
Do not accept answer 1.16.

(iii) $v = zc = 0.16 \times 3 \times 10^8 = 4.8 \times 10^4 \text{kms}^{-1}$
$d = \frac{v}{H_o} = \frac{4.8 \times 10^4}{68} = 706\text{Mpc}$ ***OR*** 2.2×10^{25}m

15b. Explain how cosmic microwave background (CMB) radiation provides support for the Hot Big Bang model. *[2 marks]*

Markscheme

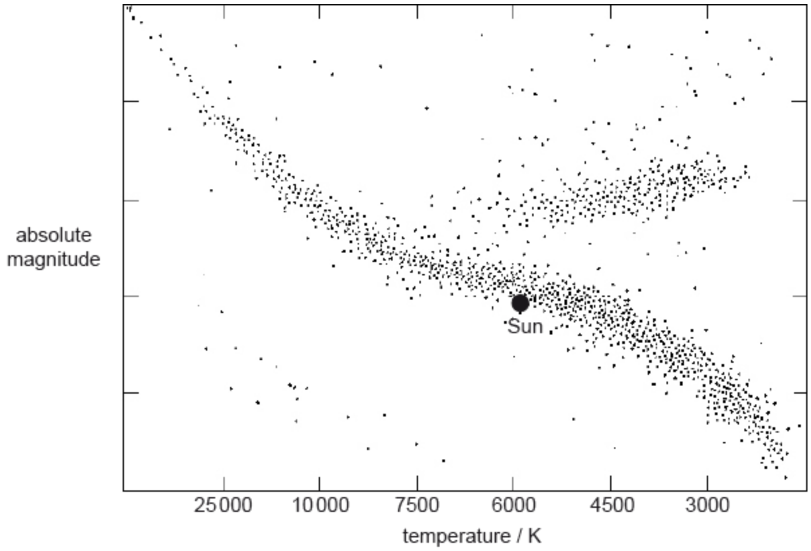
as the universe expanded it cooled/wavelength increased

the temperature dropped to the present approximate 3K ***OR*** wavelength stretched to the present approximate 1mm

Value is required for MP2.

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

A Hertzsprung–Russell (HR) diagram is shown.



16a. The following data are given for the Sun and a star Vega. *[3 marks]*

Luminosity of the Sun $= 3.85 \times 10^{26}\ \text{W}$

Luminosity of Vega $= 1.54 \times 10^{28}\ \text{W}$

Surface temperature of the Sun $= 5800\ \text{K}$

Surface temperature of Vega $= 9600\ \text{K}$

Determine, using the data, the radius of Vega in terms of solar radii.

Markscheme

$$\frac{L_{\text{V}}}{L_{\text{S}}} = \left(\frac{\sigma A_{\text{V}}[T_{\text{V}}]^4}{\sigma A_{\text{S}}[T_{\text{S}}]^4} =\right) \frac{\sigma [r_{\text{V}}]^2 [T_{\text{V}}]^4}{\sigma [r_{\text{S}}]^2 [T_{\text{S}}]^4};$$

$$\frac{1.54\times10^{28}}{3.85\times10^{26}} = \frac{[r_{\text{V}}]^2}{[r_S]^2} \times \frac{9600^4}{5800^4};$$

$$r_{\text{V}} = \left(\sqrt{\frac{1.54\times10^{28}}{3.85\times10^{26}} \times \frac{5800^4}{9600^4}} r_S =\right)\ 2.3\ r_{\text{S}};$$

Do not award third marking point if radius of the Sun is lost.

16b. Outline how observers on Earth can determine experimentally the temperature of a distant star. *[3 marks]*

Markscheme

obtain the spectrum of the star;

measure the position of the wavelength corresponding to maximum intensity;

use Wien's law (to determine temperature); } *(allow quotation of Wien's equation if symbols defined)*

*Award **[3 max]** for referring to identification of temperature via different ionizations of different elements.*

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

One of Newton's assumptions was that the universe is static. The peak intensity of the cosmic microwave background (CMB) radiation has a wavelength of 1.06 mm.

17a. Show that this corresponds to a temperature around 3 K. *[2 marks]*

Markscheme

$T = \frac{2.90 \times 10^{-3}}{\lambda_{\max}} = \frac{2.90 \times 10^{-3}}{1.06 \times 10^{-3}}$;

$= 2.7 \text{ K}$;

Must show 2 sig figs or more, as 3 K is given.

17b. Suggest how the discovery of the CMB in the microwave region contradicts Newton's assumption of the static universe. *[2 marks]*

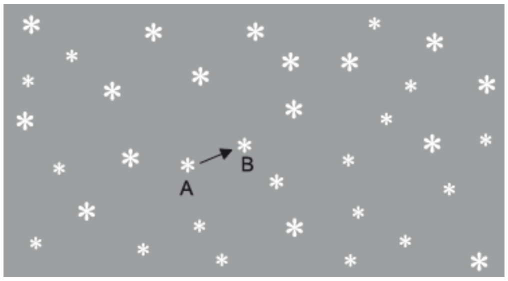
Markscheme

current low temperature observed is a result of expansion;

(expansion) has caused cooling from high temperatures;

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.



18. Discuss whether Hubble's Law can be used to determine reliably the distance from Earth to this star. *[2 marks]*

Markscheme

this star is less than 1000 pc away/in our galaxy;

Hubble's law is for galaxies (not local stars) / red-shift will be too small to measure / uncertainty in Hubble constant high for such measurement;

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 $69.3\ \text{km}\,\text{s}^{-1}\text{Mpc}^{-1}$,

19a. calculate the distance of this galaxy from Earth. *[2 marks]*

Markscheme

$$\left(\frac{\Delta\lambda}{\lambda} = \frac{v}{c} \Rightarrow\right)\ v = \left(\frac{3.00\times10^{8}\times74}{656} =\right)\ 3.38\times10^{7}\ (\text{ms}^{-1});$$

$$d = \frac{v}{H_0} = \frac{3.38\times10^{4}}{69.3} = 488\ \text{Mpc};$$

19b. discuss why different measurements of the Hubble constant do not agree with each other. *[1 mark]*

Markscheme

measurements from distant galaxies have large uncertainties;

This question is about a particular star called Barnard's star.

The peak wavelength in the spectrum of Barnard's star is 940 nm. The following data are available.

$$\frac{\text{apparent brightness of Barnard's star}}{\text{apparent brightness of the Sun}} = 2.5 \times 10^{-14}$$

$$\frac{\text{luminosity of Barnard's star}}{\text{luminosity of the Sun}} = 3.8 \times 10^{-3}$$

20a. (i) Show that the surface temperature of Barnard's star is about 3000 K. *[4 marks]*

(ii) Suggest why Barnard's star is not likely to be either a white dwarf or a red giant.

Markscheme

(i) $T = \frac{0.0029}{\lambda}$;
3080/3090 (K); *(more than 1 SD must be shown)*

(ii) temperature too low for white dwarf;
not luminous enough for red giant;

20b. (i) Determine, in astronomical units (AU), the distance between Earth and Barnard's star. *[8 marks]*

(ii) Calculate the parallax angle for Barnard's star as observed from Earth.

(iii) Outline how the parallax angle is measured.

Markscheme

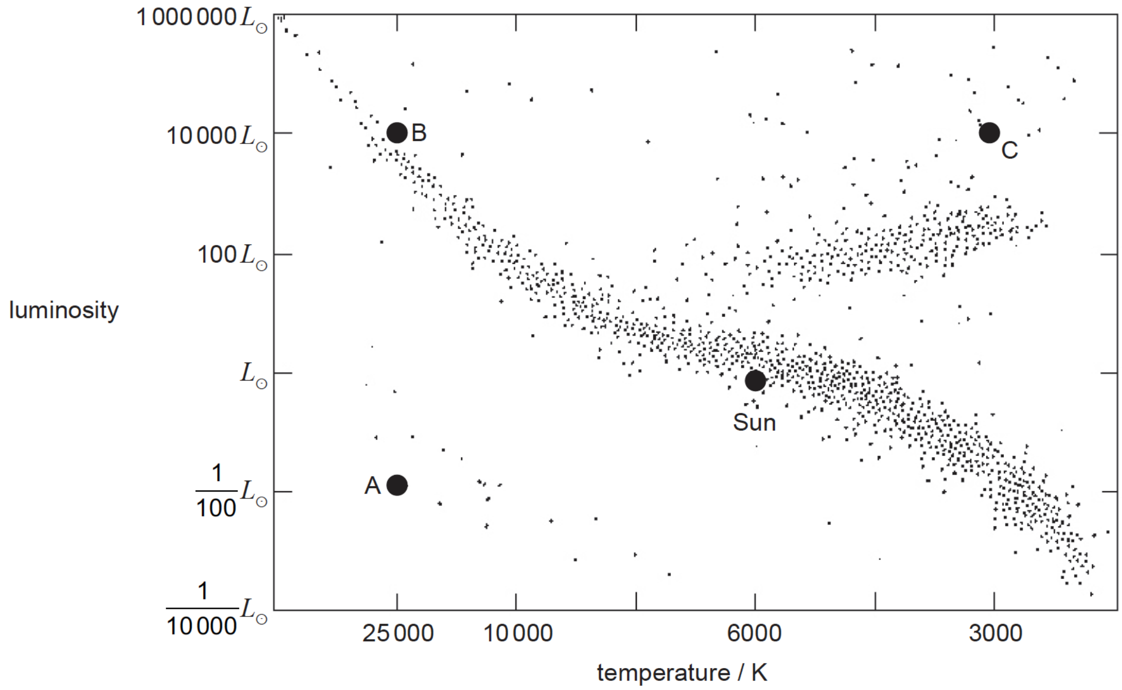
(i) $L = 4\pi d^2 b$;
$\frac{d_B}{d_S}\left(= \sqrt{\frac{L_B}{L_S}\frac{b_S}{b_B}}\right) = \sqrt{\frac{3.8\times10^{-3}}{2.5\times10^{-14}}}$;
3.9×10^5 AU;

(ii) conversion of AU to 1.89 pc;
0.53 (arc-seconds);

(iii) measure position of star;
with respect to fixed background;
with six months between readings;
parallax angle is half the total angle / *OWTTE*;
May be shown in a diagram.

This question is about stars.

The Hertzsprung–Russell (HR) diagram shows the position of the Sun and three stars labelled A, B and C.



21a. State the star type for A, B and C. *[3 marks]*

Markscheme

A: white dwarf;

B: main sequence / blue giant / blue supergiant;

C: red giant / red supergiant;

21b. The apparent brightness of C is 3.8×10^{-10} Wm^{-2}. The luminosity of the Sun is 3.9×10^{26} W. *[4 marks]*

(i) State what is meant by apparent brightness and luminosity.

Apparent brightness:
Luminosity:

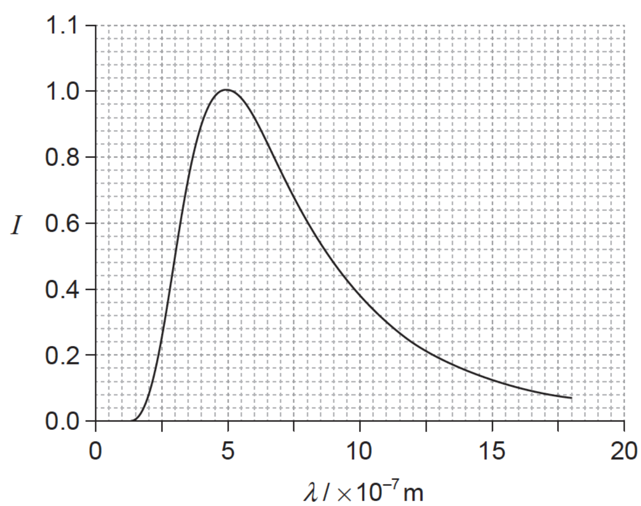
(ii) Determine the distance of C from Earth.

Markscheme

(i) *apparent brightness:* (total) power received per unit area/per m ^{2}} *(accept luminosity for power)*
luminosity: (total) power radiated;
Accept energy per second instead of power.

(ii) $d = \sqrt{\frac{L}{4\pi b}} \left(= \sqrt{\frac{10^4 \times 3.9 \times 10^{26}}{4\pi \times 3.8 \times 10^{-10}}} \right)$; *(mark is for rearrangement)*
d=2.9 × 1019 (m);
*Award **[1]** for 2.9×1017 (misses factor of 10000).*
*Award **[2]** for a bald correct answer.*

21c. The graph shows the variation with wavelength λ of the intensity *I* of the radiation emitted by 1.0m^2 of the surface of the Sun. The curve of the graph has been adjusted so that the maximum intensity is 1. *[2 marks]*



On the grid, draw a corresponding graph for star C. Your curve should have a maximum intensity of 1.

Markscheme

same shape as curve in graph and displaced to right;
peak at 10 ± 2 × 10-7 m with intensity ≤1;

This question is about the expanding universe.

Since 1929 it has been thought that the universe is expanding.

22a. State what is meant by the expansion of the universe. *[1 mark]*

Markscheme

(distant) galaxies are all moving away from each other/Earth;
the distance between galaxies is increasing;
the volume/diameter/radius/scale factor of the universe is increasing;
space itself is stretching with time;
Do not accept answers such as "everything is moving away from everything else" as this is clearly not true.

22b. Red-shift of light from distant galaxies provides evidence for an expanding universe. *[4 marks]*

(i) State **one** other piece of evidence in support of an expanding universe.

(ii) Explain how your answer in (b)(i) is evidence for the Big Bang model of the universe.

Markscheme

(i) cosmic microwave background/CMB/CBR;
helium/hydrogen ratio/abundance;
darkness of night sky (Olbers' paradox);
Do not accept answers that refer to Hubble's law/red-shift of galaxies.

(ii) CMB was a prediction of the Big Bang model;
radiation present in the early universe was at a high temperature/short wavelength;
as the universe expanded it cooled/wavelength increased;
so the radiation present today is in the microwave region / has temperature of 2.7 K;

or

the early universe contained high energy neutrons/protons;
as the universe expanded and cooled (to 109 K) nucleosynthesis could start, producing helium;
as the temperature dropped further, nucleosynthesis stopped leaving an excess of protons/hydrogen;
the current abundance of hydrogen and helium is consistent with the predictions of the Big Bang/expansion;

or

Olbers' paradox asks "why is the night sky dark?";
this cannot be explained if universe is infinite and static / *OWTTE*;
in an expanding universe some light is red-shifted out of visible range;
in a Big Bang universe some light from distant galaxies has not reached us yet;

This question is about the mass–luminosity relation.

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

23a. Identify whether star X is on the main sequence. Assume that $n = 3.5$ in the mass–luminosity relation. *[2 marks]*

Markscheme

luminosity=303.5×148 000 (times the luminosity of the Sun) ***or***
mass=(1.5×105)3.5=30 (times the mass of the Sun);
(this is close to the quoted luminosity/mass and) so X must be on the main sequence;

23b. (i) State the evolution of star X. *[3 marks]*

(ii) Explain the eventual fate of star X.

Markscheme

(i) red (super)giant goes supernova with core remaining;

(ii) Oppenheimer–Volkoff/mass of remnant will determine final fate;
(to give) neutron star/black hole;

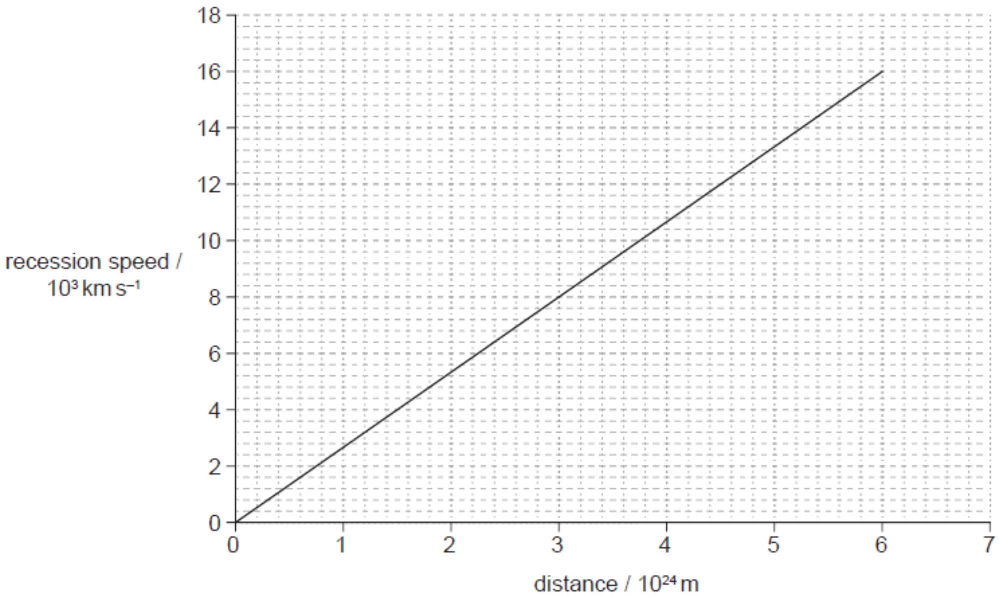
This question is about Hubble’s law.

24a. The light from distant galaxies is red-shifted. Explain how this red-shift arises. *[3 marks]*

Markscheme

(fabric of the) universe is expanding;
so the wavelength of the light increases;
during the time it has traveled from emitter to detector;

24b. The graph shows the variation of recession speed with distance from Earth for some galactic clusters. *[4 marks]*



(i) Calculate, in s^{-1}, the Hubble constant..

(ii) Estimate, in s, the age of the universe.

(iii) State the assumption that you made in your estimate in (b)(ii).

Markscheme

(i) correct substitution into $H_0 = \frac{v}{d}$;
2.7×10-18 (s-1);

(ii) $\frac{1}{2.7\times10^{-18}} = 3.8 \times 10^{17}$ (s)/3.7×1017;
Allow ECF from (b)(i).

(iii) universe has always had a constant rate of expansion;

This question is about stellar evolution.

25a. 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 marks]*

Markscheme

$\frac{L}{L_\odot} = 2^n$ with *n* between 3 and 4;
so $8L_\odot < L < 16L_\odot$;
*Award **[2]** for a bald correct answer.*

25b. The star in (a) will eventually leave the main sequence. *[3 marks]*

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.

Markscheme

(i) the core/remnant mass must be less than the Chandrasekhar limit/1.4 solar masses;
} *(must see core or remnant or similar term)*

(ii) residual/thermal/internal energy of the star / *OWTTE;*
Do not allow fusion.

(iii) C/O/Ne/Mg; (*accept no others*)

25c. Explain why a white dwarf maintains a constant radius. *[2 marks]*

Markscheme

gravitational attraction/pressure is balanced by;
electron (degeneracy) pressure/repulsion / pressure/force due to Pauli exclusion principle;
Award the first marking point independently of the second.

This question is about Hubble's law.

26a. A galaxy a distance *d* away emits light of wavelength λ. Show that the shift in wavelength $\Delta\lambda$, as measured on Earth, is given by *[1 mark]*

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

where H_0 is the Hubble constant.

Markscheme

combining $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$ and $v = H_0 d$;
Answer given, check working.

26b. 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 km $s^{-1}Mpc^{-1}$. *[1 mark]*

Markscheme

$d = \frac{c\Delta\lambda}{\lambda H_0} = \left(\frac{3\times10^5\times35}{620\times68}\right)$;
(mark is for rearrangement)
d=250(Mpc) ***or*** 7.7×1024 (m);
Allow only first marking point if incorrect value for λ is used.
*Award **[2]** for a bald correct answer.*

This question is about cosmology.

Newton assumed that the universe was infinite, uniform and static. The Big Bang model suggests space and time originated at one point around 14 billion years ago. At this time the temperature was very high.

27. In 1965, Penzias and Wilson discovered cosmic radiation with a wavelength that corresponded to a temperature of around 3 K. Outline how cosmic radiation in the microwave region is consistent with the Big Bang model. *[2 marks]*

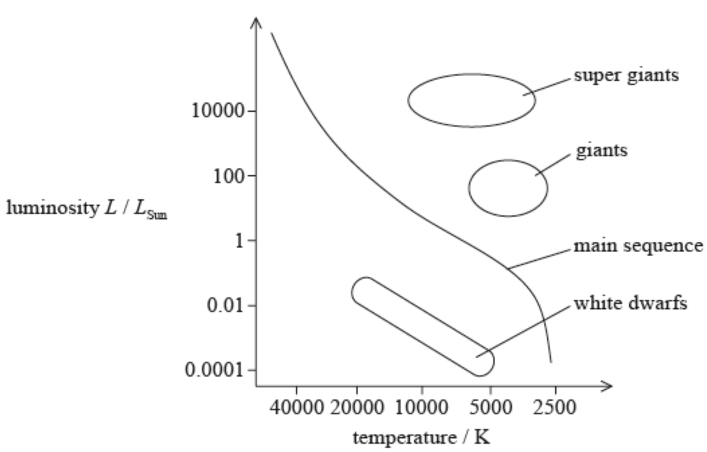
Markscheme

the temperature has cooled considerably since the Big Bang / the Big Bang model predicted cooling and the present temperature;

this cooling was caused by the expansion of the universe/the stretching of spacetime;

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.



28a. 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 marks]*

Markscheme

$\frac{L}{L_{\odot}} = \left(\left[\frac{m}{m_{\odot}}\right]^{3.5} =\right)\left[\frac{18m_{\odot}}{m_{\odot}}\right]^{3.5}$;

$L = 25000\ L_{\odot}$;

Answer must include $L_{\odot}$ in correct place.

28b. 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 marks]*

Markscheme

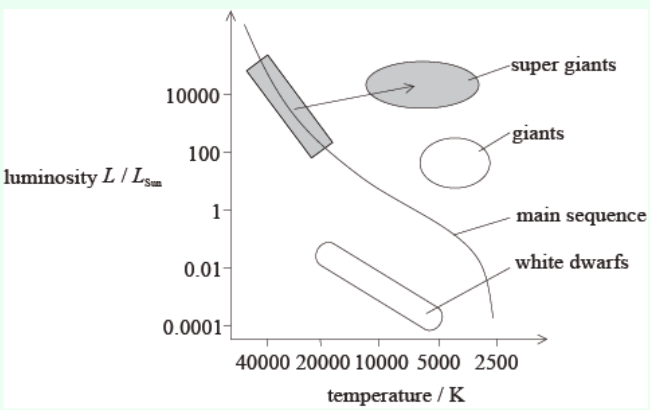
Phi-1 Orionis has a larger mass so it has a larger gravitational pressure;

to remain in equilibrium it requires (an equal) radiation pressure which is provided by burning (hydrogen) at a faster rate;

28c. Using the HR diagram on page 6, draw the evolutionary path of Phi-1 Orionis as it leaves the main sequence. *[1 mark]*

Markscheme

line drawn starting from the top-left of the main sequence towards (red) super giants;
} *(allow anywhere within the grey shaded regions)*



28d. Outline, with reference to the Oppenheimer–Volkoff limit, the fate of Phi-1 Orionis. *[1 mark]*

Markscheme

(mass of star is more than 15 solar masses so can be predicted, that) after supernova explosion it will be more than 3 solar masses/Oppenheimer-Volkoff limit and become a black hole;

or

if the mass after supernova explosion will be less than then Oppenheimer-Volkoff limit, it will become a neutron star;

This question is about the Hubble constant.

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

29a. Estimate, in seconds, the age of the universe. *[2 marks]*

Markscheme

$T = \frac{1}{H}\ \left(= \frac{1}{70\ \mathrm{km\,s^{-1}Mpc^{-1}}}\right)$;

$T = \left(\frac{1}{70\,000\ \mathrm{s}^{-1}} \times 10^6 \times 9.46 \times 10^{15} \times 3.26 =\right)\ 4.4 \times 10^{17}\ \mathrm{s}$;

29b. 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 shows that the same line has a wavelength of 725.6 nm. Determine the recessional velocity of the distant galaxy. *[2 marks]*

Markscheme

$\left(\frac{\Delta\lambda}{\lambda} = \frac{v}{c}\right)$

$\frac{\Delta\lambda}{\lambda} = \frac{725.6-656.3}{656} = 0.106$;

$v = \left(\frac{\Delta\lambda}{\lambda} \times c = 0.106 \times 3 \times 10^8 =\right)\ 3.17 \times 10^7\ \mathrm{m\,s^{-1}}$;

This question is about stellar evolution.

30a. 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 marks]*

Markscheme

from the mass–luminosity relation, Achernar has a higher luminosity; { *(reference to mass–luminosity is essential)*

so it is above/to the left of the Sun on the main sequence / temperature increases with luminosity in the main sequence;

Ignore irrelevant statements that $L = \sigma A T^4$.

Allow second marking point even if only mass is discussed.

30b. Outline why Achernar will spend less time on the main sequence than the Sun. *[2 marks]*

Markscheme

Achernar has greater luminosity/temperature and so fuses hydrogen at a (disproportionately) higher rate than the Sun / *OWTTE*;

so it will run out of hydrogen/move to red giant region in less time than the Sun / *OWTTE*;

Achernar may evolve to become a neutron star.

30c. (i) State the condition relating to mass that must be satisfied for Achernar to become a neutron star. *[3 marks]*

(ii) Some neutron stars rotate about their axes and have strong magnetic fields. State how these stars may be detected.

Markscheme

(i) the remnant mass/the mass of its core/the mass after the supernova stage; { *(do not allow "mass" bald)*

must be between the Chandrasekhar and Oppenheimer limits / $1.4M_{\square} < M_{\text{core}} < 3M_{\square}$; { *(allow answer in words or numerical values)*

Allow 2.5 $M_{\square}$ *to 3* $M_{\square}$ *as O–V limit.*

(ii) detection of EM radiation from pulsars/stars that pulsate / stars whose intensity varies rapidly / *OWTTE*;

Accept answers that refer to any regions of the electromagnetic spectrum.