IB · HL · Physics

2 hours 13 questions

Structured Questions

Fusion & Stars

Fusion Reactions in Stars / Energy Released in Fusion Reactions / Star Formation / Life Cycle of a Star / The Hertzsprung–Russell (HR) Diagram / Emission & Absorption Spectra in Stars / Stellar Parallax / Determination of Stellar Radii

Easy (5 questions)	/53
Medium (4 questions)	/43
Hard (4 questions)	/52
Total Marks	**/148**

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Easy Questions

1 (a) The binding energy per nucleon of Helium−4 $\left({}^{4}_{2}\mathrm{He}\right)$ is 7.1 MeV.

Determine the energy required to completely separate the nucleons of the atom of helium. Give your answer in MeV.

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(2 marks)

(b) Match the processes with the correct definition by drawing a line:

Nuclear fusion	The splitting of a large atomic nucleus into smaller nuclei
Nuclear fission	The joining of two small nuclei to produce a larger nucleus

....

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(2 marks)

(c) Complete the following sentences:

Helium is formed inside main sequence stars due to the process of nuclear ....

For this process to occur, both nuclei must have high .... energy.

A high energy is required because the protons inside the nuclei are .... charged and a very high energy is needed to overcome the .... force of repulsion.

....

(4 marks)

(d) Main sequence stars can remain stable for millions of years due to the equilibrium of internal forces.

Explain how a main sequence star can remain in equilibrium.

(2 marks)

2 (a) The nuclear equation for the fusion of a proton ${}^{1}_{1}\text{p}$ and a deuterium nucleus ${}^{2}_{1}\text{H}$ to form a ${}^{3}_{2}\text{He}$ nucleus is shown below.

$$ {}^{1}_{1}\text{p} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + 5.49\ \text{MeV} $$

State the meaning of the value 5.49 MeV.

....

(1 mark)

(b) The masses of the proton and deuterium nuclei, in terms of atomic mass unit u, are shown in the table.

	nuclear mass
${}^{1}_{1}\text{p}$	1.007825u
${}^{2}_{1}\text{H}$	2.014102u

Use the information given in **(a)** and the table to calculate

(i) the mass defect of the fusion reaction, in terms of u

[2]

(ii) the mass of a ${}^{3}_{2}\text{He}$ nucleus, in terms of u.

[2]

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(4 marks)

(c) For a $^{3}_{2}He$ nucleus, calculate:

(i) the energy required to separate the nucleons, in MeV

[3]

(ii) the binding energy, in units of MeV per nucleon.

[1]

(4 marks)

(d) For the fusion of a proton and a deuterium nucleus to occur, they must get very close together.

To do this, they must overcome the electrostatic repulsion between them due to their positive charges.

State

(i) the conditions necessary to overcome the electrostatic repulsion between the nuclei

(ii) the name of the force which acts when the nuclei get close enough to fuse.

(3 marks)

3 (a) The Stefan-Boltzmann law states that the power output of a star depends on two factors.

Place a tick (✓) next to the **two** correct factors.

mass	
radius	
surface temperature	
core temperature	

(2 marks)

(b) Distances to nearby stars can be measured by using stellar parallax.

Modern techniques enable the measurement of parallax angles as small as 0.001 arcseconds.

(i) Outline how parallax angle is determined.

[2]

(ii) Calculate the maximum distance, in light years, that can be measured using this method.

[2]

(4 marks)

(c) For objects further from Earth, the distance can be determined if the luminosity of the object is known.

Explain how an object of known luminosity can be used to measure astronomical distances.

....

....

(2 marks)

(d) A distant galaxy is found to have a luminosity of 2.0×10^{36} W and an apparent brightness of 2.59×10^{-15} W m^{-2}.

Show that the distance between the galaxy and the Earth is about 800 million light years.

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....

(3 marks)

4 (a) Outline what is meant by

(i) the luminosity of a star

[1]

(ii) the apparent brightness of a star.

[1]

....

....

(2 marks)

(b) The Sun emits radiation with a peak emission occurring at a wavelength of 5.2×10^{-7} m.

Show that the Sun has a surface temperature of about 6000 K.

....

(1 mark)

(c) The average intensity of radiation received from the Sun at the surface of the Earth is 1370 W m^{-2}.

Show that the Sun's luminosity is about 4×10^{26} W.

Mean distance between the Sun and the Earth = 1.49×10^{11} m

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(2 marks)

(d) Use the Stefan-Boltzmann law to determine the radius of the Sun.

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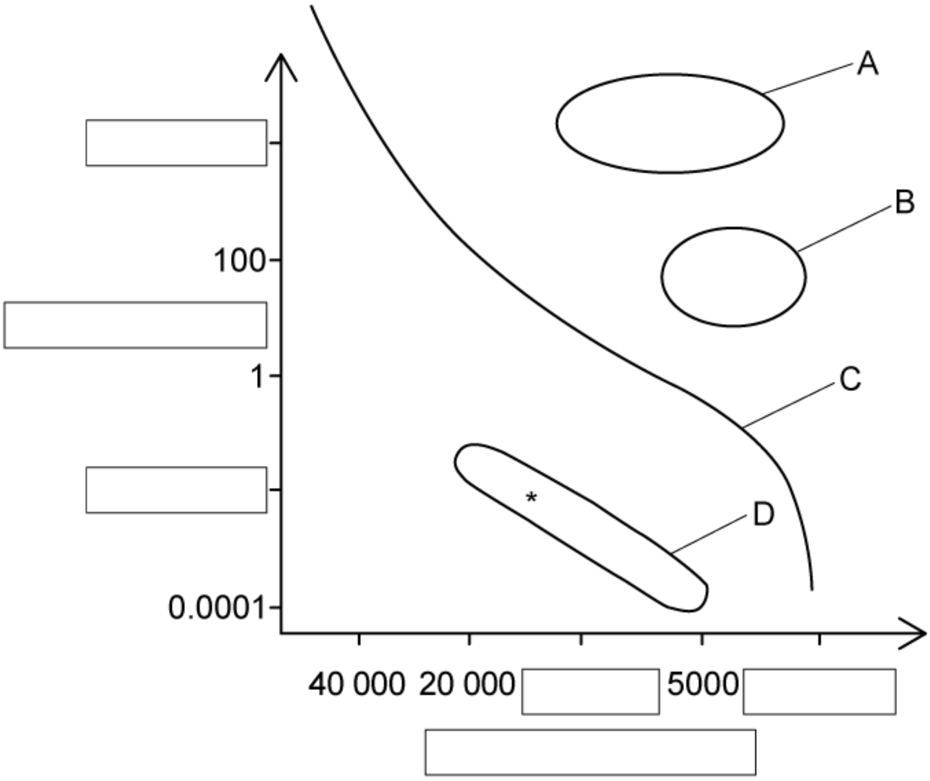
(3 marks)

5 (a) A sketch of a Hertzsprung-Russell (HR) diagram is shown below.



Label the axes, including appropriate units and complete the missing numbers on the scales.

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(4 marks)

(b) State and describe the type of stars shown by A, B, C and D.

....

....

(4 marks)

(c) Add the following to the HR diagram:

(i) a cross (X) to show the position of the Sun.

[1]

(ii) an arrow to show the direction that the star in region D labelled (*) would move over time.

[1]

(2 marks)

(d) On the HR diagram, draw a line to indicate the evolutionary path of the Sun from its present position to its final position.

(2 marks)

Medium Questions

1 (a) Under the right conditions, four hydrogen nuclei can fuse to make a helium nucleus in a process known as the proton–proton cycle.

Nuclei	Mass/ u
^{1}H	1.0078
^{4}He	4.0026

Show that 4×10^{-12} J of energy is released as a result of the fusion of four hydrogen nuclei.

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(4 marks)

(b) Fusion occurs naturally in the core of stars.

Explain why very high densities of matter and very high temperatures are needed to bring about and maintain nuclear fusion in stars.

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(2 marks)

(c) While on the main sequence, the Sun maintains a constant luminosity of 3.86×10^{26} W. It is predicted that the Sun will spend a total of 10^{10} years in this phase of its evolutionary cycle.

Show that the Sun will convert a total mass of 2×10^{29} kg of hydrogen into helium during its time on the main sequence.

(2 marks)

(d) One day, the Sun will leave the main sequence and move on to the next stage of its evolutionary cycle.

Discuss what will happen to the Sun.

In your answer, you should outline

- the conditions that will initiate this change
- the nuclear processes that will occur
- the physical changes that the Sun will undergo.

(3 marks)

2 (a) A star has a luminosity that is known to be 4.5×10^{27} W. A scientist observing this star measures the intensity of the light received on Earth from the star as 2.6 nW m^{-2}.

Determine the distance of the star from Earth.

....

....

(2 marks)

(b) The scientist observing the star finds that the wavelength for which the maximum rate of emission occurs from the star is 430 nm.

(i) Show that the surface temperature of the star is approximately 6700 K.

[2]

(ii) Hence, determine the radius of the star.

[2]

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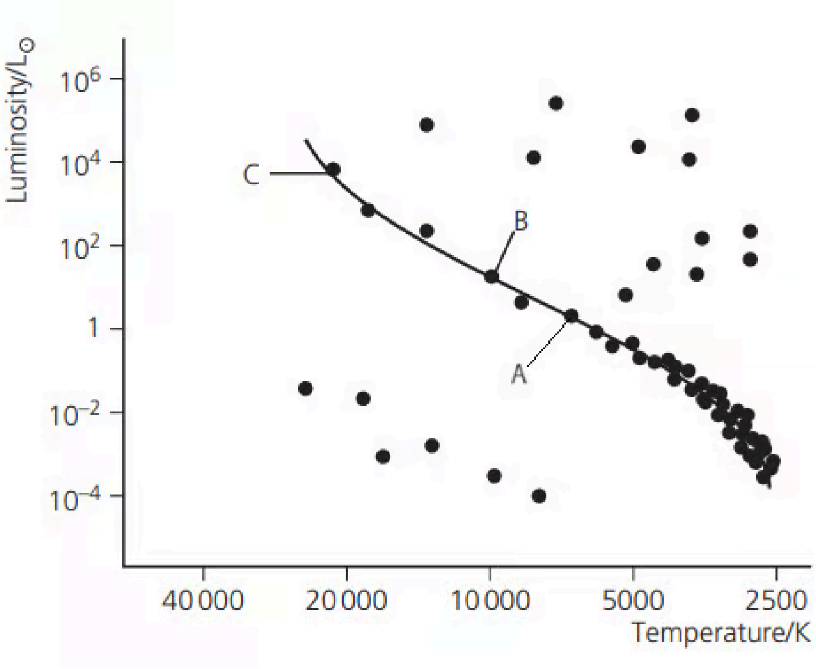
(4 marks)

(c) The Hertzsprung–Russell diagram shows three main sequence stars, A, B and C. Star A is the one described in (a) and (b).



Determine the ratio of the radius of star A to the radius of star B.

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(3 marks)

(d) Outline the final stages in the evolutionary cycle of star C.

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(4 marks)

3 (a) The table summarises some information about four stars in the constellation Cygnus.

Name	**Colour**	**Luminosity / L_{Sun}**
Aljanah	orange	62
Deneb	blue-white	196 000
Fawaris	blue	155
Sadr	yellow-white	33 000

State which star has

(i) the highest surface temperature [1]

(ii) the lowest surface temperature [1]

(iii) the largest radius. [1]

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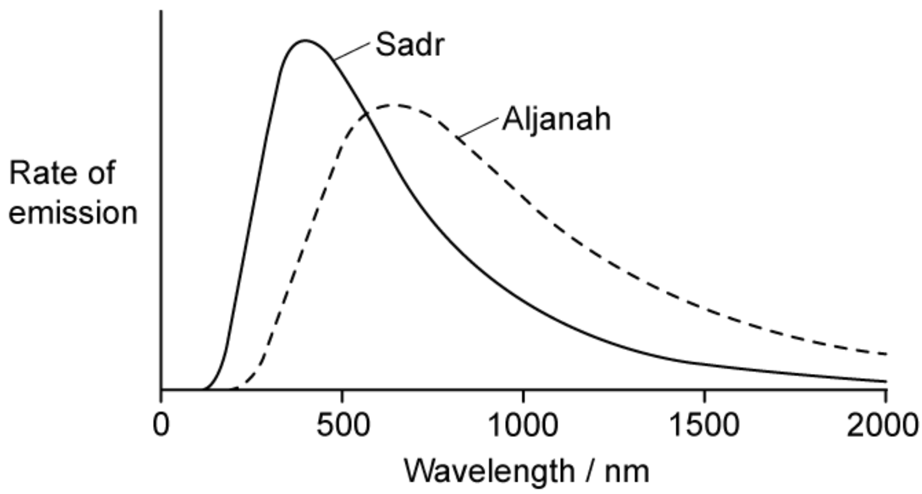
(3 marks)

(b) The graph shows the rate of emission from two of the stars, Sadr and Aljanah, plotted against wavelength.



Without calculation, explain how the curves can be used to determine the surface temperature of the stars.

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(2 marks)

(c) The surface temperatures of Aljanah and Sadr are known to be 4700 K and 7600 K respectively.

Determine whether this graph is consistent with Wien's displacement law.

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(3 marks)

(d) Calculate the radius of Sadr in units of solar radius R_{Sun}.

Radius of the Sun, $R_{Sun} = 6.96 \times 10^8$ m
Luminosity of the Sun, $L_{Sun} = 3.83 \times 10^{26}$ W

....

....

(2 marks)

4 (a) State what is meant by the luminosity of a star.

....

(1 mark)

(b) In a comparison of two stars, A and B, the following data was collected

Surface temperature of star A = 25 000 K

Surface temperature of star B = 4300 K

The radius of star B was determined to be 1.1×10^5 times larger than the radius of star A.

Calculate the ratio

$$\frac{luminosity\ of\ star\ B}{luminosity\ of\ star\ A}$$

....

....

....

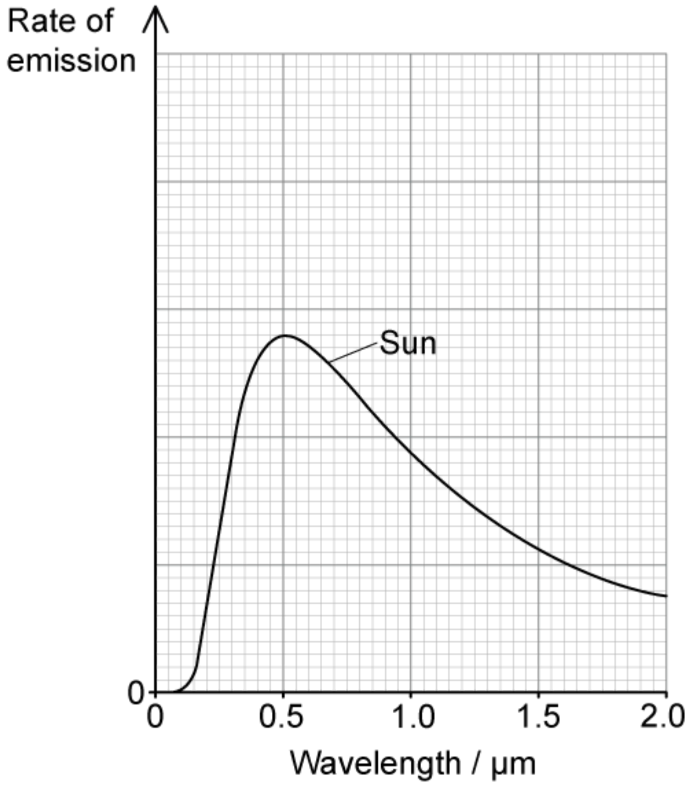
(3 marks)

(c) Determine the wavelengths of light for which the maximum rate of emission occurs from stars A and B.

....

(1 mark)

(d) The graph shows the variation of rate of emission against wavelength for the Sun.



On the graph, sketch the variation of rate of emission against wavelength for stars A and B.

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....

(4 marks)

Hard Questions

1 (a) In the research into nuclear fusion, one of the most promising reactions is between deuterium ${}^{2}_{1}H$ and tritium nuclei ${}^{3}_{1}H$ in a gaseous plasma.

Although deuterium can be extracted relatively easily from seawater, tritium is more difficult to produce. It can, however, be produced through the induced fission of lithium−6 ${}^{6}_{3}Li$ nuclei.

These reactions can be represented in the following nuclear equations:

$$ {}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + \text{energy} $$

$$ {}^{6}_{3}Li + X \rightarrow {}^{3}_{1}H + Y + \text{energy} $$

The masses of the nuclei involved are given in the following table:

Nucleus	Mass / u
neutron	1.008665
deuterium	2.014102
tritium	3.016049
helium−4	4.002604
lithium−6	6.015122

(i) Determine the nature of particles X and Y.

[1]

(ii) Calculate the energy released from the fission of 1.0 kg of lithium-6.

[2]

(iii) Calculate the energy released from the fusion of 1.0 kg of a 50:50 mixture of deuterium and tritium (D-T).

[2]

(5 marks)

(b) Calculate the mass of deuterium and lithium-6 required to produce a power output of 500 MW from a fusion plant for a year.

Assume an efficiency of one-third for the conversion of fusion energy into electrical energy.

(4 marks)

(c) Over the coming decades, nuclear fusion reactors are expected to become commercially viable for the first time. Meanwhile, nuclear fission reactors have been in operation for decades already.

(i) Explain, with reference to the operating conditions of both types of reactor, why this discrepancy exists.

[4]

(ii) The average energy released per fission of a uranium-235 nucleus is about 200 MeV.

Compare the energy generated from the fusion of 1 kg of D-T and the fission of 1 kg of uranium-235.

[2]

(6 marks)

(d) The aim of current fusion research programs is to achieve fusion 'ignition', which occurs when enough fusion reactions take place for the process to become self-sustaining.

(i) Suggest how D-T fusion could be thought to be self-sustaining once 'ignition' is achieved.

[2]

(ii) Discuss **two** problems associated with sustaining D-T fusion reaction for the production of energy on a commercial scale.

[2]

(4 marks)

2 (a) Plasma is superheated matter. It is so hot that the electrons are stripped from their atoms, forming an ionised gas.

The Sun is made up of gas and plasma and can be thought of as a giant fusion reactor. At its core where fusion takes place, the plasma is (mainly) protons with a temperature of about 1.5×10^6 K.

Near the Sun's surface, however, protons have a mean kinetic energy of 0.75 eV, which is too low for fusion to take place.

Calculate the temperature of the Sun near its surface. Outline any assumptions you make.

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(3 marks)

(b) By considering the distance of closest approach between two protons, explain why fusion does not occur near the Sun’s surface.

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(4 marks)

(c) The energy produced by the Sun comes from a cycle of hydrogen fusion, during which the net effect is the fusion of 3 protons into a helium nucleus. One of the steps in the cycle is:

$$^{1}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + \text{energy}$$

The amount of energy radiated away in this step is 5.49 MeV.

The following data are available:

- Mass of $^{2}_{1}\mathrm{H}$ nucleus = 2.01355 u
- Mass of proton = 1.00728 u

(i) Calculate the mass of the helium nucleus, $^{3}_{2}\mathrm{He}$ in standard units

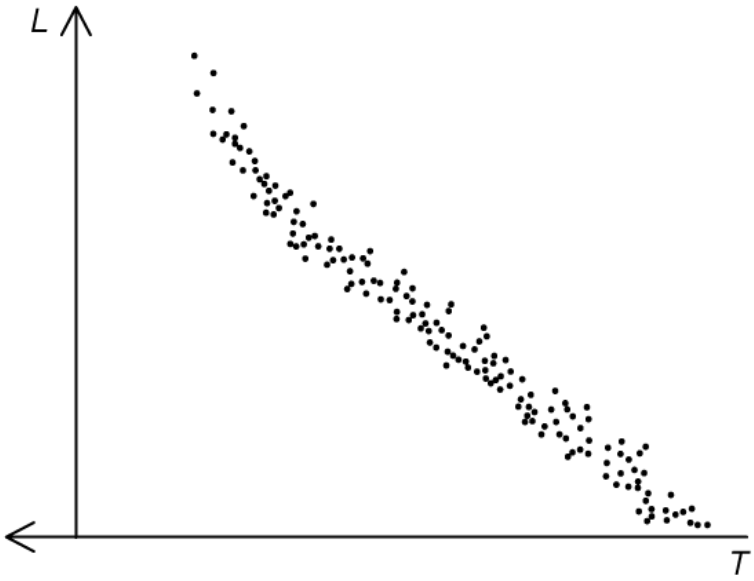
[2]

(ii) Outline the nature of the energy released.

[1]

(3 marks)

3 (a) A Hertzsprung-Russell (HR) diagram shows how the luminosity L depends on the surface temperature T for a cluster of stars.



(i) Suggest whether this cluster of stars is in the early or late stages of evolution. Explain your answer.

[2]

(ii) Explain why the most massive stars in the cluster have the greatest luminosities.

[3]

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(5 marks)

(b) Massive stars in the later stages of their evolutionary cycle have a layered structure with different chemical elements in different layers.

Discuss the structure of these stars by referring to the nuclear reactions taking place.

....

(2 marks)

(c) One of the stars in the cluster is the variable star Alpha Cephei. It is known to be at a distance of 4.6×10^{17} m from the Earth.

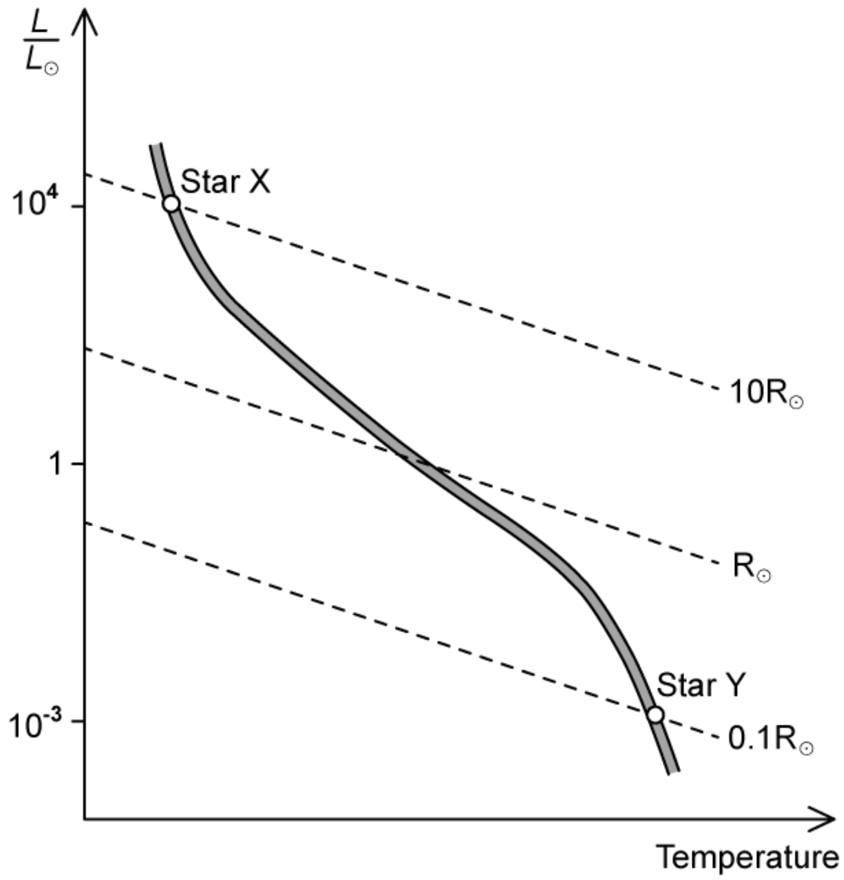
Using measurements of parallax angle, astronomers can determine distances to all stars with a parallax angle larger than 2.4×10^{-7} rad.

Deduce whether the distance to Alpha Cephei could be determined from parallax measurements.

(3 marks)

4 (a) The H-R diagram shows the logarithmic relationship between luminosity $\frac{L}{L_\odot}$ and temperature $\frac{T}{T_\odot}$ for a sample of stars, where $L_\odot$ and $T_\odot$ represent the luminosity and temperature of the Sun respectively.

Two stars, X and Y, are shown with their corresponding radii, in terms of the radius of the Sun $R_\odot$.



Deduce the colours of star X and star Y using the H-R diagram and the information in the table below.

star colour	surface temperature / $T_\odot$
blue	> 5.5
blue-white	1.7 – 5.5
white	1.3 – 1.7
yellow-white	1.0 – 1.3
yellow	0.8 – 1.0
orange	0.6 – 0.8
red	< 0.6

(4 marks)

(b) The relationship between the mass *M* and luminosity *L* of the stars shown on the H-R diagram is given by

$$L \propto M^{3.5}$$

Using this mass-luminosity relation and the H-R diagram, determine the ratio

$$\frac{\text{density of star } X}{\text{density of star } Y}$$

(3 marks)

(c) In 2017, an ultra-cool star named Trappist-1 was discovered in our galaxy. It was found to have at least five of its own orbiting planets.

Astronomers have studied it extensively to determine if there is a possibility of finding life on some of the planets orbiting Trappist-1.

Some of the data associated with Trappist-1 is shown in the table.

	Trappist-1	**Sun**
Luminosity $L / L_{\odot}$	5.26×10^{-4}	1
Surface temperature $T / T_{\odot}$	0.4	1
Radius of star / $R_{\odot}$	R	1
Distance between Earth and Sun / m	–	1.5×10^{11}
Distance between planets and Trappist-1 / m	1.6×10^{9} to 9.0×10^{9}	–

The temperature *T,* in K, of a planet, its distance *d* from the star and the luminosity *L* of the star are related by the expression

$$\frac{T^4 d^2}{L} = 419 \times 10^3$$

(i) Show that Trappist-1 is smaller than the Sun.

[2]

(ii) The average temperature of the Earth is about 290 K.

Using data from the table, comment on the possibility of life existing on some of the planets orbiting Trappist-1.

[4]

(6 marks)