Index

The big picture

? Guiding question(s)

- How are elements created?
- What physical processes lead to the evolution of stars?
- Can observations of the present state of the universe predict the future outcome of the universe?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

The Earth is estimated to be 4.54 billion years old, and the Sun a little older at 4.60 billion years old. Before the Sun and the Earth existed, there was a nebula, which is an enormous gas cloud from which, under certain conditions, stars can form.

The nebula contained many elements – heavy elements such as uranium and silicon, which were created in dead stars long before, and light elements such as hydrogen, which may have been around unchanged since the beginning of time.

The same materials that formed the Sun and the planets are in you. You are a combination of different atoms, which join together to form molecules, which then work together to make your body function (**Figure 1**).

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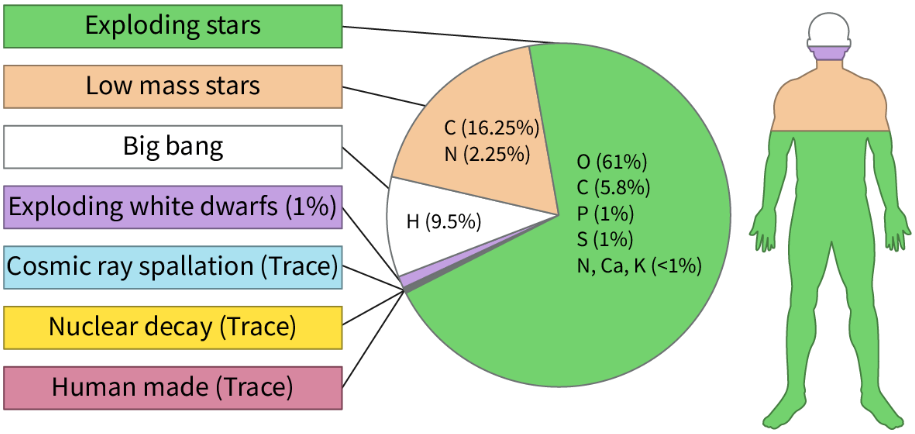

Figure 1. The human body is mostly made up of elements made in stars.

More information for figure 1

The image features a pie chart next to a simplified representation of a human figure. The pie chart displays the composition of the human body in terms of elements and their origins.

The chart is split into various sections: - Oxygen (O) constitutes 61% and is represented in green. - Carbon (C) makes up 5.8% and is also highlighted in a similar green shade but distinguished by the adjacent text box (16.25%). - Hydrogen (H) makes up 9.5%, shown in pale orange. - Nitrogen (N) is 2.25%, also in pale orange. - Phosphorus (P) constitutes 1%. - Sulfur (S) also makes up 1%. - Trace elements like Nitrogen (N), Calcium (Ca), and Potassium (K) are under 1% each.

Adjacent to the pie chart, there are labeled boxes indicating the origins of these elements: - "Exploding stars" which align with green regions. - "Low mass stars" correlate with orange shades. - "Big bang" connects to what is likely the origin of hydrogen. - "Exploding white dwarfs (1%)" are associated with minor purple segments. - "Cosmic ray spallation (Trace)", "Nuclear decay (Trace)", and "Human made (Trace)" indicate the sources of trace amounts, each corresponding to uniquely colored small sections in the chart.

[Generated by AI]

Some of these elements were created in the cores of stars as they burned throughout their lives. Most, however, were created in the final stage of a large star's life – a supernova explosion. Imagine all the energy used by humans in one year multiplied by a trillion trillion trillion trillion!

The Sun provides all the energy required for us to live, but how?

Student
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Overview
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Nature of Science

Aspect: Science as a shared endeavour

In 1923, Cecilia Payne left England for the United States. In England, women had little opportunity for advanced learning, and so she left for the Harvard College Observatory to pursue a graduate degree.

At the observatory was Annie Jump Cannon, in a team called the Harvard Computers. Despite losing her hearing as a young adult, Cannon was a brilliant scientist and simplified the classification system of stars to one based on spectral types, which is a measure of temperature.

When Payne joined the observatory, she analysed these spectral classes. At the time, the understanding about the Sun was that it was like a hot planet. Spectroscopy of the Sun had revealed that it held many of the same elements as Earth. Payne deduced the quantities in which these elements existed. The elements found on Earth were there in small quantities, but the vast majority of the Sun was only two elements — hydrogen and helium. This formed the basis of Payne's doctoral thesis, 'Stellar Atmospheres; A Contribution to the Observational Study of High Temperature in the Reversing Layers of Stars'.

The reaction to the thesis was disbelief, with the reviewer, Henry Norris Russell, not willing to accept the conclusions Payne drew as it disagreed with current understanding. Four years later, Russell did his own research and came to the same conclusions as Payne, thus affirming her work.

Payne went on to become the first female head of department at Harvard, and Cannon was the first woman to receive the Henry Draper Medal 'In recognition of her astronomical work, in particular for cataloging the spectra of stars' and the first woman to be elected as an officer of the American Astronomical Society.

Creativity, activity, service

Strand: Activity
Learning outcome: Demonstrate engagement with issues of global significance

It is important that there is discussion around how minority groups are treated in the sciences. With your physics class or local physics society, you could run an event highlighting the roles of women, people of colour and other marginalised people in the sciences. Think about giving credit to those who are under-represented in the sciences, and providing role models for young people who do not regularly see people who look like themselves in the media.

You could create a presentation on why this is an important topic, how it engages with issues of global significance, and what you hope to achieve during the event. You could present it to your school leadership when requesting permission to run the event.

Student
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Overview
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Prior learning

Before you study this subtopic make sure that you understand the following:

- Energy calculations (see subtopic E.4 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-46447/))
- Nuclear binding energy (see subtopic E.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44319/))
- Wien's displacement law, Stefan-Boltzmann law and black bodies (see subtopic B.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43777/))

E. Nuclear and quantum physics / E.5 Fusion and stars

Fusion in stars

E.5.1: Stability of stars E.5.2: Fusion E.5.3: Density and temperature conditions for fusion

Learning outcomes

By the end of this section you should be able to:

- Describe star stability in terms of the equilibrium between gravitational forces and radiation pressure.
- Describe fusion in stars and calculate the energy released by fusion.
- Explain the conditions required for fusion in stars.

Stars are essentially giant nuclear reactors, emitting billions of times more energy per second than anything we can produce on Earth. So if our Sun is an enormous ongoing explosion, how can it look (and be) so stable and constant?

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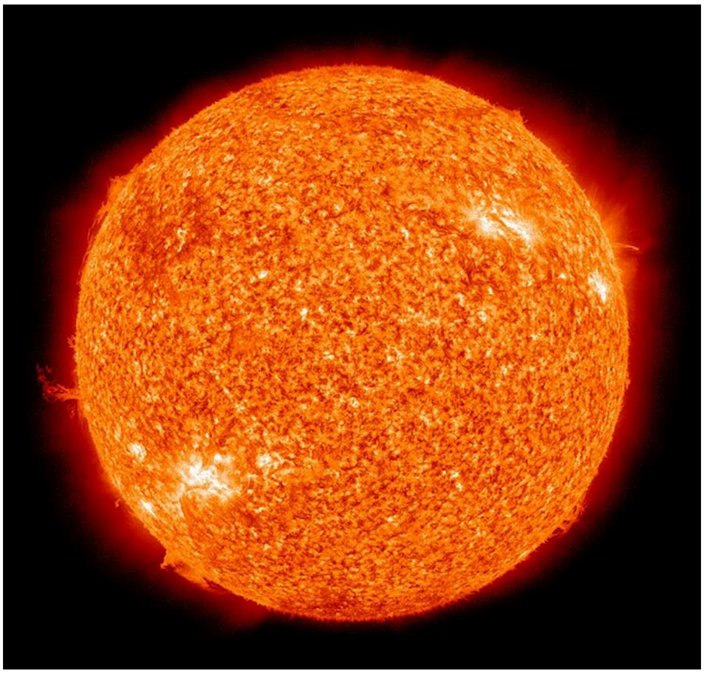

Figure 1. The Sun.

Source: The Sun (https://commons.wikimedia.org/wiki/File:The_Sun_by_the_Atmospheric_Imaging_Assembly_of_NASA%27s_Solar_Dynamics_C_20100819.jpg) by NASA/SDO (AIA) is in the public domain

Star stability

The Earth orbits the Sun because of the gravitational force of the Sun on the Earth. If the gravitational force of the Sun is so great, why does the Sun not collapse in on itself?

The Sun is not a solid but a plasma. If there is a resultant force acting on an object, then this results in an acceleration (subtopic A.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43136/)). The Sun does not have a force imbalance. If it did, then the Sun would contract over time as the gravitational force pulled the outer layers of plasma in. There must be another force counteracting the gravitational force.

This force is produced by nuclear fusion reactions in the core of the Sun. Nuclear fusion occurs when two or more atomic nuclei join together, creating a new larger nucleus and releasing energy. It is a similar process to nuclear fission (subtopic E.4 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-46447/)), where larger nuclei split into two smaller nuclei, which releases energy.

In the Sun, the main nuclear fusion processes taking place are between:

- hydrogen nuclei
- hydrogen and deuterium (a hydrogen isotope with one neutron)
- helium-3 and hydrogen.

Student view

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These reactions produce vast amounts of radiation. This radiation provides an outwards force that acts against the gravitational force (**Figure 2**). It is this equilibrium that keeps the Sun from collapsing in on itself.

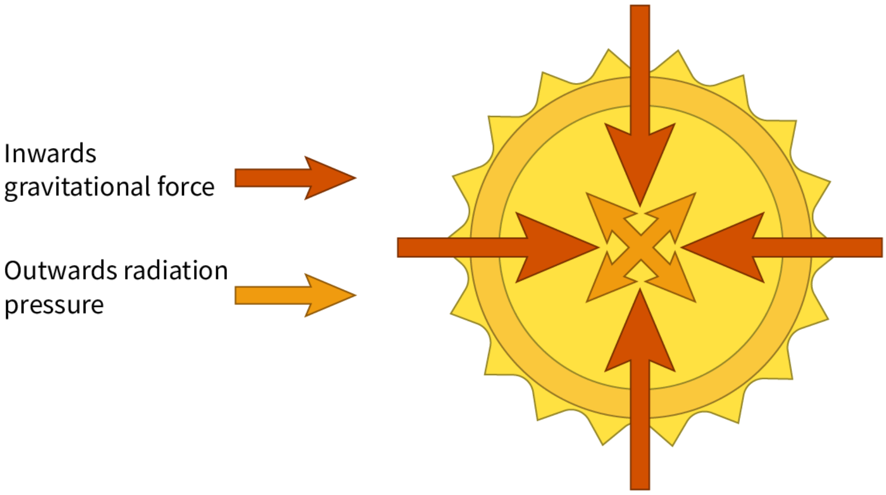

Figure 2. The balance between outwards radiation force and inwards gravitational force in a star.

More information for figure 2

This is a diagram illustrating the balance of forces within a star. The image depicts a stylized representation of a star with arrows indicating different forces. A large yellow circle represents the star, with an outward radiation pressure indicated by arrows pointing outward from the center. An inward gravitational force is depicted with arrows pointing towards the center of the star. The diagram is labeled with 'Inwards gravitational force' and 'Outwards radiation pressure', showing the balance between these forces that prevents the star from collapsing under its own gravity.

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The large mass of the Sun produces a very large gravitational force, which acts inwards to compress the star. This is balanced by many small forces produced in the core by nuclear fusion reactions. The sum of these nuclear forces is equal in magnitude to the gravitational force, producing equilibrium and preventing the collapse of the star.

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Making connections

Linking question: How does equilibrium within a star compare to stability within the nucleus of an atom?

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Fusion in stars

Figure 3 shows the basic process of fusion in stars, such as the Sun.

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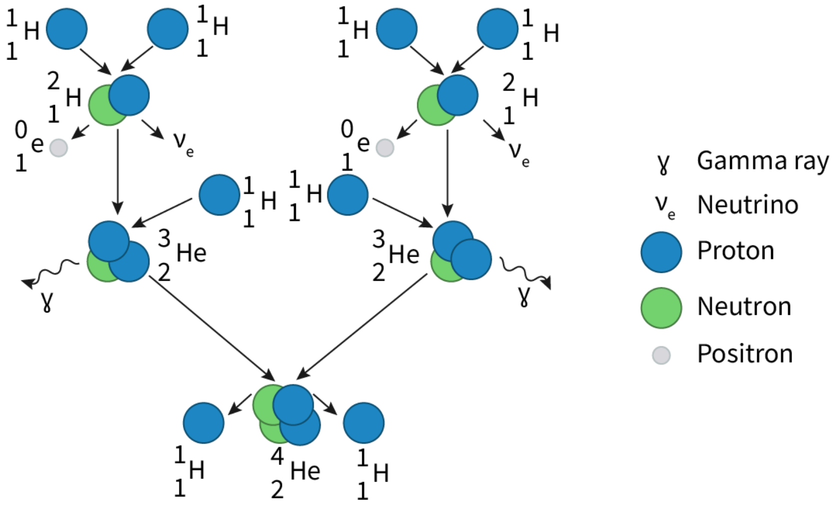

Figure 3. The process of fusion in stars.

More information for figure 3

The diagram illustrates the process of nuclear fusion in stars, highlighting the fusion of hydrogen into helium. It displays a series of chain reactions beginning with the fusion of two protons (hydrogen nuclei), resulting in the formation of deuterium with the release of a positron and neutrino. This is followed by further interactions involving gamma rays and the creation of helium-3. Finally, helium-3 nuclei collide to form helium-4, releasing two protons. The image uses symbols to depict particles: gamma rays (γ), neutrinos (ve), protons (blue), neutrons (green), and positrons (gray).

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Concept

Concepts that will help you in your understanding of this section can be found in subtopic E.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44319/):

- Mass defect is the difference in mass between the mass of a nucleus and the total mass of its nucleons.
- The energy released after a nuclear reaction is proportional to the mass defect.
- Nuclear binding energy is the amount of energy released when constructing a nucleus from its constituent nucleons, or the amount of energy required to break apart a nucleus into its constituent nucleons. Binding energy per nucleon is used as a measure of nucleus stability, where the higher the value, the more stable the nucleus.

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Overview (/study/app 423- cid- 762593/c

Energy released by fusion

The amount of energy released in nuclear fusion can be calculated by looking at the mass defect in the reaction. The products of fusion have a higher binding energy per nucleon than the reactants, meaning that, according to Einstein's equation $E = mc^2$, there should be a mass loss during the reaction, which is released as energy.

Figure 3 shows the p–p (proton–proton) chain, where four hydrogen nuclei are fused into a helium-4 nucleus.

The p–p chain is thought to be the dominant process in most stars. There are three stages to the process:

- Hydrogen and hydrogen fuse to make deuterium (^{2}H).
- Deuterium and hydrogen fuse to make helium-3 (^{3}He).
- Helium-3 fuses with another helium-3 to form helium-4 and two hydrogen atoms.

This multi-step process can be summarised in one equation:

$$6\text{H} \rightarrow \text{He} + 2\text{H}$$

To determine the energy released, we need to know the mass of each nucleus in atomic mass units, u (subtopic E.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44319/)):

- mass of hydrogen = 1.007276 u
- mass of helium-4 = 4.001506 u

The atomic mass unit, u, is 1.661×10^{-27} kg or 931.5 MeV c^{-2}, where 931.5 MeV is the energy equivalent of 1u per c^2.

To find the mass deficit (how much mass is lost in the reaction), we subtract the mass of the the helium nuclei (product) from the four hydrogen nuclei (reactants):

$$\begin{aligned} 4\text{H} - \text{He} &= (4 \times 1.007276) - 4.001506 \\ &= 0.027598 \text{ u} \end{aligned}$$

Study skills

If you always do the subtraction as reactant mass − product mass, then you will get a **positive** value if the process can happen with no energy input, and a **negative** value if the process needs an energy input.

Student view

Overview
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423-
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Being consistent with how you solve problems in physics reduces the chance of making errors.

We can use Einstein's equation $E = mc^2$ to find the energy that the mass deficit corresponds to.

In joules:

$$\begin{aligned} m &= 0.027598 \text{ u} \\ &= 0.027598 \times 1.661 \times 10^{-27} \\ &= 4.5840278 \times 10^{-29} \text{ kg} \end{aligned}$$

$$\begin{aligned} E &= mc^2 \\ &= 4.5840278 \times 10^{-29} \times (3.00 \times 10^8)^2 \\ &= 4.1 \times 10^{-12} \text{ J} \end{aligned}$$

In MeV:

$$\begin{aligned} E &= m \times 931.5 \text{ (MeV c}^{-2}) \\ &= 0.027598 \times 931.5 \\ &= 25.7 \text{ MeV} \end{aligned}$$

An electronvolt, eV, is the amount of energy gained by an electron accelerated through a potential difference of 1 V (subtopic D.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44743/)), so:

$$\begin{aligned} 25.7 \text{ MeV} &= 25.7 \times 10^6 \text{ eV} \\ &= 25.7 \times 10^6 \text{ eV} \times 1.60 \times 10^{-19} \text{ C} \\ &= 4.1 \times 10^{-12} \text{ J} \end{aligned}$$

Conditions for fusion

Nuclear fusion in stars relies on the nuclei being very close to one another – approximately, the size of an atom, 1 fm (10^{-15} m). This is happening to charged hydrogen nuclei (lone protons), so according to Coulomb's law (subtopic D.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44743/)), the electromagnetic repulsion between these nuclei is:

$$\begin{aligned} F &= k\frac{q_1 q_2}{r^2} \\ &= 8.99 \times 10^9 \times \left[\frac{(1.60 \times 10^{-19} \times 1.60 \times 10^{-19})}{(1 \times 10^{-15})^2}\right] \\ &= 230.144 \text{ N} \end{aligned}$$

Student view

When calculating the acceleration, this force is experienced by each individual proton:

Overview
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$$
\begin{aligned}
a &= \frac{F}{m} \\
&= \frac{230.144}{1.661 \times 10^{-27}} \\
&= 1.39 \times 10^{29} \text{ m s}^{-2}
\end{aligned}
$$

To overcome this large outward acceleration there needs to be exceptionally extreme conditions for fusion to occur in stars:

- The nuclei need to have an incredibly high velocity, enough that their kinetic energy can supply the work needed to overcome the Coulomb repulsion between the nuclei.
- The nuclei must be very close to one another, meaning the core needs to be very dense.

Figure 4 shows why high temperature and high pressure are required for fusion to occur in stars.

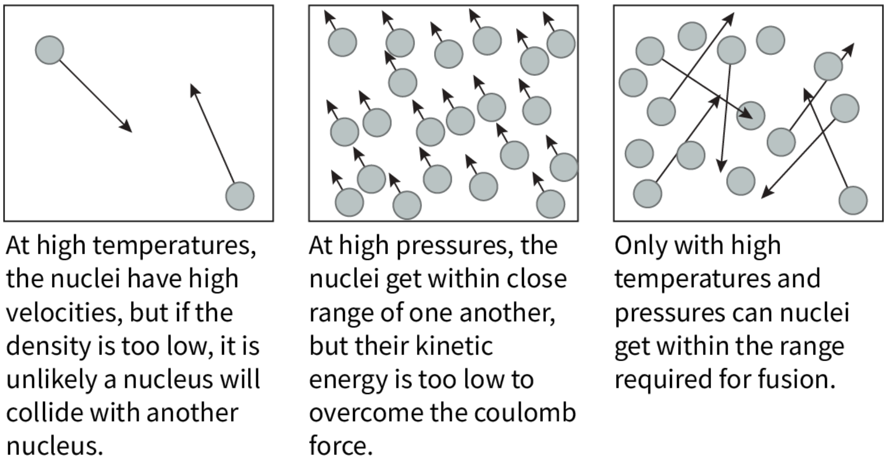

Figure 4. The conditions required for fusion in stars.

More information for figure 4

The image consists of three panels illustrating the conditions required for nuclear fusion in stars. Each panel contains diagrams with gray circles representing atomic nuclei and arrows indicating motion, accompanied by explanatory text.

1. The first panel shows two nuclei with a large distance between them and arrows indicating high velocity. The accompanying text states: "At high temperatures, the nuclei have high velocities, but if the density is too low, it is unlikely a nucleus will collide with another nucleus."
2. The second panel depicts several closely packed nuclei with short arrows pointing in various directions. The text reads: "At high pressures, the nuclei get within close range of one another, but their kinetic energy is too low to overcome the Coulomb force."
3. The third panel shows nuclei at varying distances and highlighted trajectories with arrows suggesting paths. The text explains: "Only with high temperatures and pressures can nuclei get within the range required for fusion."

These visuals demonstrate the need for both high temperatures and pressures for nuclei to overcome repulsive forces and effectively engage in nuclear fusion.

Student
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Without these conditions, nuclear fusion would happen too infrequently to produce the radiation energy needed to maintain equilibrium, and the star would collapse.

Nature of Science

Aspect: Hypotheses

Measurements of the Sun and models of its core suggest that the temperature of the Sun's core (1.5×10^7 K) is too low for nuclear fusion to occur while maintaining its observed size and energy output. While some nuclei do have enough energy to overcome the Coulomb force, most nuclei never get close enough to another nucleus for fusion to occur.

Physicists think that quantum tunnelling events happen with a low probability. In quantum tunnelling, two nuclei can momentarily be found much closer to each other, thus allowing the fusion reaction to occur.

Worked example 1

One fusion process in older stars is known as the triple-alpha process:

$$3\,{}^{4}_{2}\text{He} \rightarrow {}^{12}_{6}\text{C}$$

Determine the energy released from this process. Give your answer in MeV.

(Mass of a helium nucleus is 4.0015 u; mass of a carbon nucleus is 11.9967 u.)

Solution steps	Calculations
Step 1: Find the mass deficit between the reactants and the products.	$3\,{}^{4}_{2}\text{He} \rightarrow {}^{12}_{6}\text{C}$ mass of reactants: $3 \times 4.0015 = 12.0045\text{u}$ mass of products: $1 \times 11.9967 = 11.9967\text{ u}$ $12.0045\text{ u} - 11.9967\text{ u} = 0.0078\text{ u}$
Step 2: Write out the equation.	$E = mc^2$

Overview
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423-
cid-
762593/c

Solution steps	Calculations
Step 3: Substitute the values given.	$= 0.0078\,\text{u} \times 931.5\ \text{MeV c}^{-2}$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$7.2657\ \text{MeV}\ (5\ \text{s.f.})$

Work through the activity to check your understanding of equilibrium in a star.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 5—10 minutes
- **Activity type:** Individual activity

Stars are stable because they maintain an equilibrium between inward and outward forces. Identify one other system which exists in equilibrium in terms of forces. How are your examples similar and different to the Sun?

You could consider:

1. What forces are acting to keep the Sun in equilibrium?
2. What forces are acting to keep your object in equilibrium?
3. Where do those forces originate from and what type of force are they?

Struggling for ideas? Try these!

- Our atmosphere exists in equilibrium — why don't the air particles fall down to Earth, or float out into space?
- An inflated balloon is in equilibrium — what forces are acting?

5 section questions

Question 1

SL HL Difficulty:

Student
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Overview (/study/app/423-cid-762593/c

A star is stable when the inwards 1 gravitational ✓ force, caused by the huge mass of the star, and the outwards 2 radiation ✓ pressure, caused by nuclear fusion reactions in the core, are in 3 equilibrium ✓ .

Accepted answers and explanation

#1 gravitational

#2 radiation

#3 equilibrium

General explanation

A star is stable when the inwards gravitational force, caused by the huge mass of the star, and the outwards radiation pressure, caused by nuclear fusion reactions in the core, are in equilibrium. This equilibrium keeps the Sun from collapsing in on itself.

Question 2

SL HL Difficulty:

The main fusion process in the Sun fuses six 1 hydrogen ✓ nuclei into a 2 helium ✓ nucleus and two 3 protons ✓ . This process releases 4 energy ✓ .

Accepted answers and explanation

#1 hydrogen

#2 helium
He

#3 protons
hydrogen

#4 energy
radiation

General explanation

Nuclear fusion occurs within the core of the Sun as the large gravitational forces push the hydrogen nuclei close enough together with sufficient velocity for fusion to occur. Two hydrogen nuclei fuse to create deuterium, which fuses with a further hydrogen to create helium-3. In the final stage, two helium-3 nuclei fuse to create one helium-4 nucleus and two protons. Each stage releases large amounts of energy.

Student view

Question 3

SL HL Difficulty:

Overview
(/study/ap
423-
cid-
762593/c

In a very heavy star, a carbon nucleus and a hydrogen nucleus fuse to form nitrogen-13:

$$^{12}_{6}\mathrm{C} + \, ^{1}_{1}\mathrm{H} \rightarrow \, ^{13}_{7}\mathrm{N}$$

Determine the energy released in this process. Give your answer to three significant figures.

mass of carbon-12: 12.00000 u

mass of hydrogen: 1.00784 u

mass of nitrogen-13: 13.00574 u

The energy released is 1 1.96 ✓ MeV

Accepted answers and explanation

#1 1.96

General explanation

$$^{12}_{6}\mathrm{C} + \, ^{1}_{1}\mathrm{H} \rightarrow \, ^{13}_{7}\mathrm{N}$$

$$\text{mass of reactants: } 12.00000 + 1.00784 = 13.00784 \text{ u}$$

$$\text{mass of product: } 13.00574 \text{ u}$$

$$\begin{aligned}\text{mass deficit} &= 13.00784 - 13.00574 \\ &= 0.00210 \text{ u}\end{aligned}$$

$$E = mc^2$$

$$\begin{aligned}0.00210 \times 931.5 \ (\text{MeV c}^{-2}) &= 1.95615 \text{ MeV} \\ &= 1.96 \text{ MeV (3 s.f.)}\end{aligned}$$

Question 4

SL HL Difficulty:

Which of the following reactions are possible fusion reactions that release energy?

Reaction A: He-4 + 3H → Li-7

Reaction B: Fe-56 + He-4 → Ni-60

mass (He-4) = 4.002603 u
mass (H) = 1.00784 u
mass (Li-7) = 7.016004 u
mass (Fe-56) = 55.845 u
mass (Ni-60) = 59.93079 u

1 A only ✓

Student view

2 Neither A nor B

Overview
(/study/ap
423-
cid-
762593/c

3 B only

4 A and B

Explanation

For a nuclear fusion reaction to release energy, there must be a positive mass deficit between the reactants and the products. If the reactants are heavier than the products, energy is released.

Reaction A:
$[4.002603 + (3 \times 1.00784)] - 7.016004 = 0.010119$ u
This is a positive value, so the reaction is possible and releases energy.

Reaction B:
$(55.845 + 4.002603) - 59.93079 = -0.083187$ u
This is a negative value, so energy needs to be input in order for this reaction to be possible.

Question 5

SL HL Difficulty:

Star A fuses large nuclei such as carbon and oxygen. Star B fuses only hydrogen.

By considering the repulsive force between nuclei, deduce which row of the table gives the correct information about the relative temperature and pressure in each star's core.

	Star A	Star B
A	Relatively high temperature, relatively high pressure	Relatively low temperature, relatively low pressure
B	Relatively high temperature, relatively low pressure	Relatively low temperature, relatively high pressure
C	Relatively low temperature, relatively high pressure	Relatively high temperature, relatively low pressure
D	Relatively low temperature, relatively low pressure	Relatively high temperature, relatively high pressure

1 A ✓

2 B

3 C

4 D

Student
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Overview
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423-
cid-
762593/c

Explanation

In an old large star, the majority of fusion is between heavier nuclei such as carbon or oxygen. The Coulomb force between these nuclei is very large because the electrostatic repulsion from larger nuclei is greater. The nuclei need a much greater kinetic energy in order to overcome the Coulomb repulsion, which means that a much higher temperature and pressure is required in the core.

Small stars fusing lighter nuclei, such as hydrogen, do not need such a high temperature and pressure because the coulomb force between hydrogen nuclei is relatively small, meaning less kinetic energy is required.

E. Nuclear and quantum physics / E.5 Fusion and stars

The HR diagram

E.5.4: Stellar mass and star evolution E.5.5: Hertzsprung—Russell (HR) diagrams

Learning outcomes

By the end of this section you should be able to:

- Describe the main regions of the HR diagram.
- Recall the different properties of stars based on their region on the HR diagram.
- Outline the evolution of different types of stars.

Look into the night sky, even without a telescope, and you might see some slight differences in colour and some bigger differences in the brightness of stars. How can we classify them? How could we communicate these differences with someone a long distance away, or who is reading our notes a long time from now?

Student
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Overview
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cid-
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Figure 1. Night sky.

Source: Suchart Kuathan, Getty Images

International Mindedness

Scientific communication often needs to be interpreted by people in different countries and cultures to enable different societies to build on work that has gone before them. Classifications and common terminology are essential to ensure collective scientific progress.

Hertzsprung—Russell (HR) diagram

The stars we see in the sky vary very little in terms of how they look from Earth. Some are brighter and some are redder, but these differences are small to the naked eye. The actual physical differences between stars can be huge.

Categorising stars is useful, as it makes it easier to identify certain properties, or learn about a new star from a known property. The most common properties we use to measure stars are:

- **Luminosity, *L***: The total energy emitted per second from the surface of a body, measured in watts (W). It is usually given in terms of $L_{\odot}$, which is the luminosity of the Sun.
- **Radius, *r***: The average distance between the surface of a star and its centre, measured in metres (m). This is usually given in terms of $R_{\odot}$, which is the radius of the Sun. The radius can be used to find the surface area, A, of the star.
- **Temperature, *T***: The surface temperature of the star, measured in kelvin (K).
- **Mass, *m***: The mass of the star, measured in kilograms (kg). It is usually given in terms of $M_{\odot}$, which is the mass of the Sun.

Temperature and luminosity tell us a great deal about a star. They can give us an idea of the star's size, mass, distance from the Earth, what the star is made of, where the star is in its life cycle, and how we expect the star to end its life.

Concept

Stars are perfect black body radiators. Two important concepts that will help you in your understanding of this can be found in subtopic B.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43777/):

Wien's displacement law, which relates the temperature of a black body radiator to the peak wavelength of light emitted by the body:

$$\lambda_{\max}T = 2.90\times10^{-3}\ \mathrm{mK}$$

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Overview
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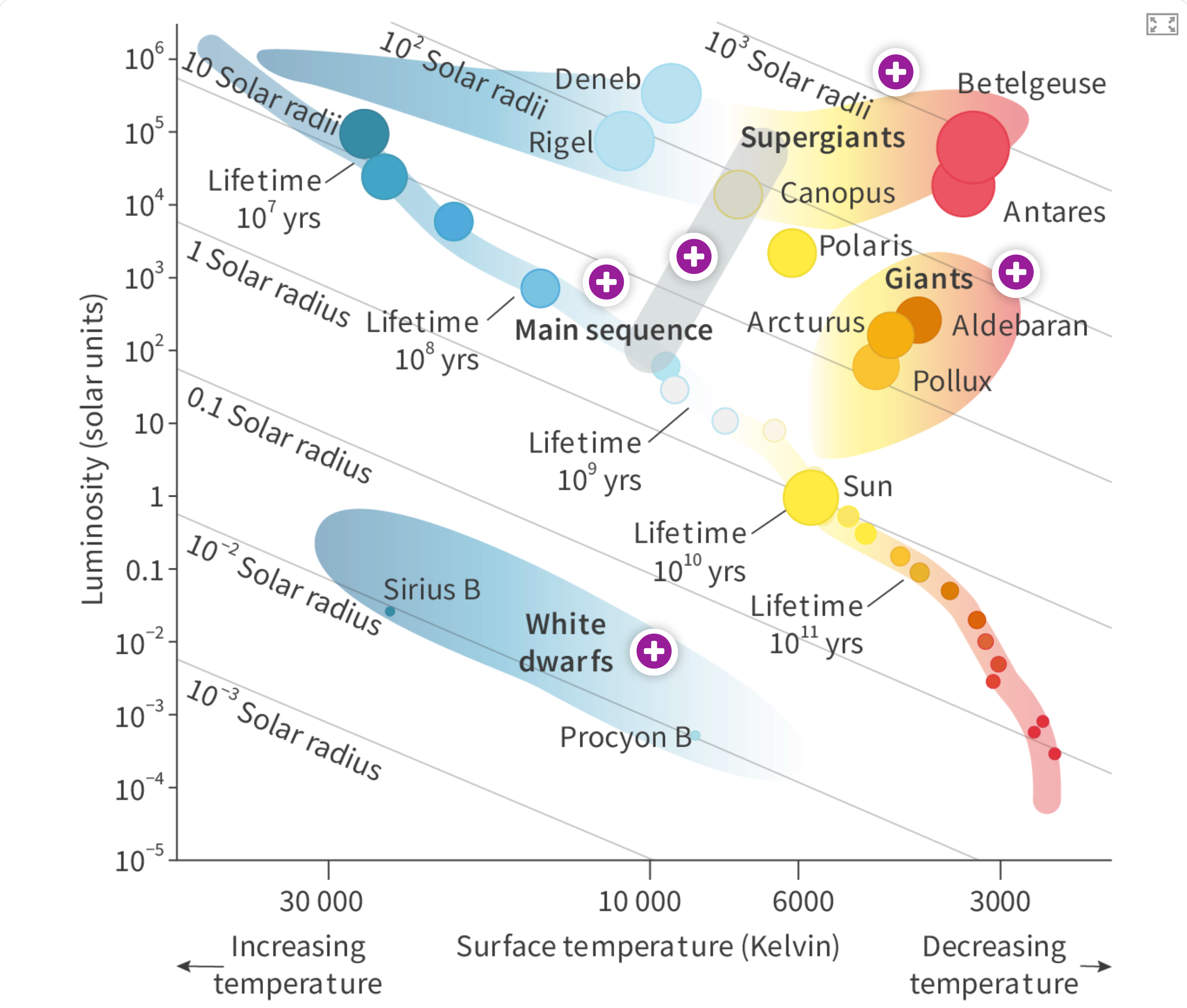
Stefan-Boltzmann law, which relates the power emitted by a black body radiator (luminosity) to the surface temperature of the body:

$$L = \sigma A T^4$$

By plotting a star graph, with temperature and luminosity as the axes, we can put stars into categories. This graph is known as a Hertzsprung–Russell (HR) diagram. **Interactive 1** is an HR diagram for our own galaxy. The regions shown are approximate. Click on the hotspots to see information about some of the regions of the HR diagram.



Interactive 1. The HR Diagram Categorises Stars Based on Their Temperature and Luminosity.

More information for interactive 1

This interactive visualizes a Hertzsprung—Russell (HR) diagram, which categorizes stars based on their temperature and luminosity. The diagram is filled with color-coded regions representing different types of stars and their properties. Plus-shaped circular hotspots are scattered across the diagram, allowing for deeper exploration of specific star categories and their characteristics when clicked.

Student
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Overview
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423-
cid-
762593/c

Hotspot 1: Supergiants

These old, supermassive stars are some of the biggest objects in the known Universe. YY Canis Majoris extends past the orbit of Jupiter. Supergiants mostly fuse materials larger than helium.

Hotspot 2: Instability Strip

Stars in this region tend to 'pulsate', varying in size and luminosity. Most stars that are more massive than the Sun spend some of their lifetime in this.

Hotspot 3: Main Sequence

The main sequence has a huge range of stars within it, and constitutes over 90% of the stars in the known Universe. They range from cool but tiny red dwarfs that live for up to a trillion years, to hot and massive hypergiants that burn so fast that they only last a few million years. Main sequence stars mainly fuse hydrogen in their core, and they exist in this region for the majority of their lives.

Hotspot 4: Giants

Giants have moved off the main sequence. As they stop fusing hydrogen in their core, the core of the star shrinks, causing the outer layers of the star to expand. This creates a much cooler but more massive outer layer.

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Hotspot 5: White Dwarfs

White dwarfs have lived their lives and died, usually as part of a smaller red giant star shedding its outer layers and leaving the white dwarf behind as the core, which is too small to fuse its remaining material. A white dwarf is likely how the Sun will end its life.

The HR diagram plots all known stars on a scale of temperature against luminosity:

- The x-axis is the temperature of the star. It is logarithmic and gets smaller from left to right, with the coldest stars being the red stars on the right and the hottest stars being blue or white stars on the left.
- The y-axis is the luminosity of the star. The luminosity is relative to the Sun and is logarithmic.
- The diagonal lines are the lines of constant radius and show the relative size of stars compared to the Sun.

The HR diagram shows that the most massive stars – giants and supergiants – are relatively ‘cool’ but extremely luminous. Their high luminosity comes from their size – they emit light over a large surface area.

Student
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Overview (/study/app/ 423- cid- 762593/c

Stars are not spread across the spectrum of temperatures and luminosities on the HR diagram. Instead, they are in regions where stars share similar properties, based on their luminosity and temperature. If we look for other stars around the same temperature and luminosity as the Sun, we would expect their other characteristics, such as composition or life cycle, to be very similar to the Sun's characteristics.

Table 1 shows the regions of the HR diagram.

Table 1. Regions of the HR diagram.

Name	Proportion of stars (approx.)	Ages	Colour	Radius
White dwarf	5%	Dead	White	Very small (less than 1.44 $M_\odot$)
Main sequence	90%	Young to billions of years old	Blue, white, yellow, orange, red	Very small to very large
Giant	<1%	Young to millions of years old	Red	Large
Supergiant	~0%	Young to a few million years old	Red	Very large

The stars in the regions in **Table 1** form the majority of the stars we see in the sky at night, with most being on the main sequence. The Sun is a main sequence star, and it is only about halfway through its lifetime, at around 5 billion years old.

Stars in the instability strip include cepheid variable stars, which change their brightness and radius over a fixed period of time. Variable stars are beyond the scope of IB physics.

Evolution of stars

By looking at the groupings of stars on the HR diagram and their compositions, we can get an understanding of the evolution of a star. **Figure 2** shows the evolution of stars of $1 M_\odot$ (Sun), $5 M_\odot$ and $10 M_\odot$.

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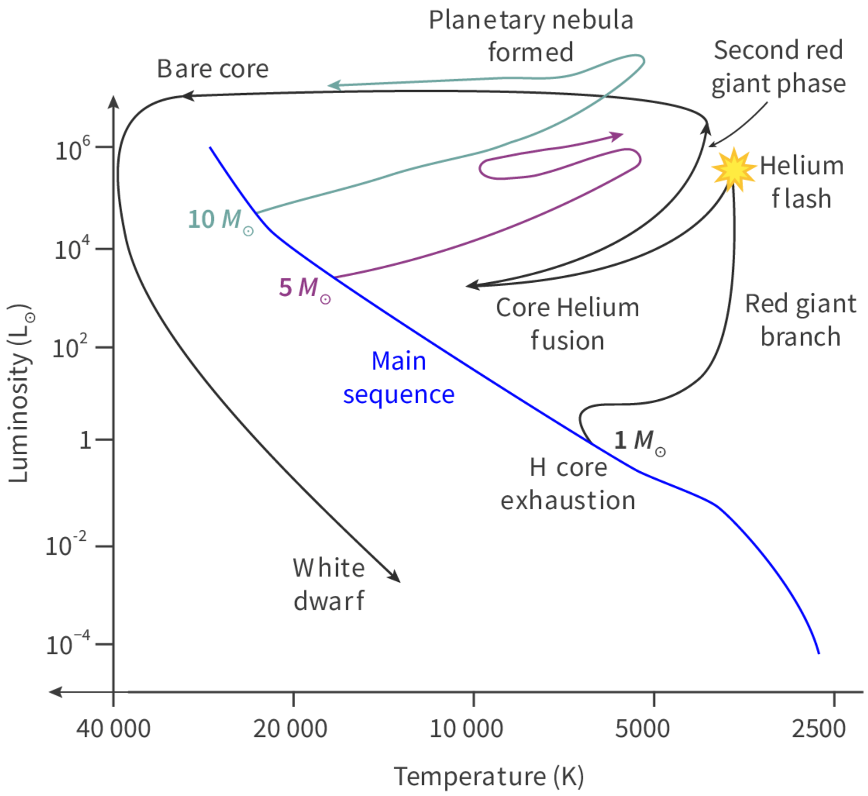

Figure 2. The evolution of a star depends on the mass it has while on the main sequence.

More information for figure 2

This is a Hertzsprung-Russell (HR) diagram illustrating the evolution of stars based on their mass: 1M ⊙ , 5M ⊙ , and 10M ⊙ . The X-axis represents temperature (in Kelvin) ranging from 40,000K to 2,500K, moving from left to right. The Y-axis shows luminosity (in solar units, L ⊙) on a logarithmic scale from 10^-4 to 10^6.

Three evolutionary tracks are depicted:

1. **Star with 1M ⊙ :** The path moves from the main sequence to a point labeled "H core exhaustion," then towards the "Red giant branch," and follows through "Helium flash" and "Second red giant phase," finally reaching "White dwarf."

2. **Star with 5M ⊙ :** This path moves off the main sequence, goes through "Core Helium fusion," and continues with looping paths.

3. **Star with 10M ⊙ :** It has a similar progression but diverges at higher luminosities, undergoing changes faster than its lower-mass counterparts.

The diagram helps visualize how more massive stars evolve differently compared to less massive ones, becoming brighter and larger before concluding as white dwarfs or different stellar remnants.

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In **Figure 2**, we can see that the expected evolution of a star depends on the mass of the star on the main sequence.

For the Sun, we would expect a red giant phase after most hydrogen has finished fusing, then a helium fusing phase, followed by the formation of a planetary nebula and a white dwarf at the end of the star's life.

The Sun will spend about 5 billion years on the main sequence before fusion ends and it becomes a white dwarf, but the lifetime of a massive star can be as short as a million years, and the least massive stars will stay on the main sequence for trillions of years. This may seem strange, since less massive stars have less fuel for fusion. However, the rate at which stars undergo fusion increases very rapidly with their mass, and this has a greater effect on lifetime.

Heavier stars often end as superdense heavy objects known as neutron stars (very heavy stars) or black holes (exceptionally heavy stars). **Figure 3** is a flow chart that shows the evolution of stars based on their mass.

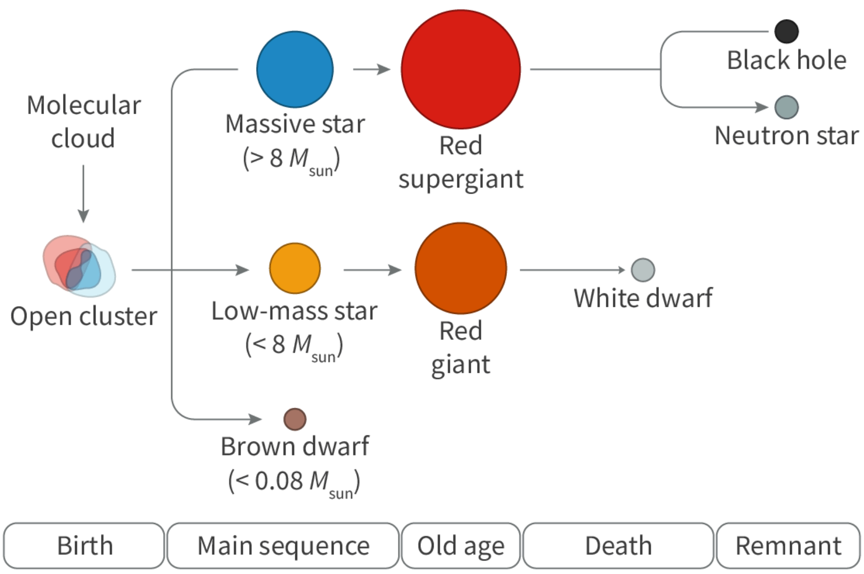

Figure 3. A flow chart showing the evolution of stars based on their mass.

More information for figure 3

This flowchart illustrates the evolution of stars according to their mass, beginning from a molecular cloud. The sequence starts with an open cluster formation, leading to three potential pathways depending on the mass: massive stars, low-mass stars, or brown dwarfs.

1. **Massive Stars (> 8 M☉):**
2. These stars develop into red supergiants.
3. Red supergiants can further evolve into either neutron stars or black holes.

4. **Low-Mass Stars (< 8 M☉):**

Student view

Overview
(/study/ap
423-
cid-
762593/c

5. These stars become red giants.
6. Eventually, red giants turn into white dwarfs.

7. **Brown Dwarfs (< 0.08 M ☉):**

8. This category does not go through significant evolutionary changes like the more massive counterparts.

The flowchart is organized into sections labeled at the bottom: Birth, Main sequence, Old age, Death, Remnant, corresponding to different life stages and outcomes of stellar evolution. Arrows indicate the process direction, showing which forms stars transition into at each stage.

[Generated by AI]

Fusion in different stellar phases

A main sequence star fuses hydrogen into helium (see section E.5.1 (/study/app/physics/sid-423-cid-762593/book/fusion-in-stars-id-46455/)). When the concentration of remaining hydrogen becomes too low for this to continue, the star's outwards pressure falls and the star begins to collapse inwards under gravity. This makes the star's interior temperature increase, and processes occur that result in the concentration of remaining hydrogen into a layer deep within the star. Hydrogen fusion then restarts within this layer. The resulting temperature and pressure increase causes significant expansion of the star, and its outer temperature falls (and so it becomes redder). The fusion of helium then occurs. In relatively low-mass stars such as the Sun, this helium fusion begins suddenly in a process called the helium flash (see **Figure 2**).

When the star's supply of helium becomes depleted, this triggers a series of events that is similar to what happened when the hydrogen supply ran low, and the star enters a second red giant phase (see **Figure 2**) in which further fusion occurs. After this phase, a star of relatively low mass becomes a planetary nebula as it loses its outer layers, exposing a hot core called a white dwarf. No further nuclear fusion occurs.

A white dwarf continues to emit radiation for a long time as it slowly cools down. Note that the lifetime of a star usually means the time during which nuclear fusion occurs, so it does not include the white dwarf phase.

The most massive stars become red supergiants after their time on the main sequence. Red supergiants fuse helium and also heavier nuclei, forming nuclei of a variety of elements of which the heaviest is iron.

Student
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Overview
(/study/ap
423-
cid-
762593/c

Neutron stars and black holes

At the end of the red supergiant phase, the star undergoes an explosion called a supernova, throwing material out into space. During a supernova, nuclei of elements heavier than iron are formed. The leftover core of the star becomes a neutron star or, for the most massive stars, a black hole.

A neutron star consists of closely packed neutrons (formed from electrons and protons being forced together). This object resembles a giant nucleus (but without any protons) and no further fusion can occur. It is extremely dense: a cubic centimetre of neutron star material has a mass of around a billion tonnes.

A black hole is an object that is so dense that its gravitational field is extremely strong. Anything that comes too close to it – even light – cannot escape. A black hole itself cannot be seen because it does not emit radiation, but its effects on surrounding matter can be observed.

Work through the activity to check your understanding of the HR diagram.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 5 minutes
- **Activity type:** Individual activity

Drag and drop the labels onto the correct part of the HR diagram in **Interactive 2**. For the stars, use the data to deduce their location on the HR diagram.

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Interactive 2. Drag and drop the labels onto the correct parts of the HR diagram.

More information for interactive 2

This is a drag and drop activity that centers around the Hertzsprung-Russell (HR) diagram, a fundamental tool in astrophysics that plots stars based on their luminosity and temperature. The vertical axis represents luminosity in solar units, ranging from 10 power -5 to 10 power 6. In contrast, the horizontal axis indicates the temperature in Kelvin, spanning from 40,000 K to 3,000 K. Diagonal lines across the diagram mark curves of constant stellar radius, labeled “1 Solar radius.”

The background of the diagram is shaded with colored regions, each corresponding to different groups of stars. Blue and white regions on the top left represent high-temperature, high-luminosity stars, while yellow and red regions on the right represent cooler, larger stars. The lower left area features a smaller, light blue shaded zone, indicating low-luminosity, high-temperature stars.

On the left of the image, twelve draggable labels are listed and numbered. These labels are: 1. Giants, 2. Supergiants, 3. Main sequence, 4. White dwarfs, 5. 40000, 6. 3000, 7. Temperature (K), 8. Sun $1\ L_{\odot}$, $1 R_{\odot}$, 9. Betelgeuse 3500 K, $764\ R_{\odot}$, 10. Sirius B $0.056\ L_{\odot}$, $0.0084\ R_{\odot}$, 11. Pollux $33\ L_{\odot}$, 4865 K, and 12.

Overview
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423-
cid-
762593/c

Instability strip.

Gray boxes are scattered throughout the HR diagram to indicate where the user should drop the corresponding labels. The "Check" button at the bottom left allows users to verify if their selections are correct. The interactivity helps users explore star classification and understand the relationship between temperature, luminosity, and radius in stellar evolution.

Solution:
Here is the correct placement for each label in the HR diagram:

1. Giants — in the orange/red region to the upper right of the main sequence band, representing stars with moderate luminosity and low temperature.
2. Supergiants — in the large red region at the top left of the diagram, representing the most luminous and coolest stars.
3. Main sequence — diagonally from top left to bottom right across the diagram, cutting through the middle, showing stars like the Sun.
4. White dwarfs — in the lower right, where luminosity is low and temperature is high (hot but small stars).
5. 40 000 — at the far left end of the temperature axis, indicating the hottest stars.
6. 3000 — at the far right end of the temperature axis, indicating the coolest stars.
7. Temperature (K) — just above the temperature scale along the horizontal axis.
8. Sun $1\ L_{\odot}, 1 R_{\odot}$ — directly on the main sequence line near the middle, where the Sun lies (about 5800 K and 1 solar luminosity).
9. Betelgeuse 3500 K, $764\ R_{\odot}$ — in the supergiant region at the top right of the diagram.
10. Sirius B $0.056\ L_{\odot}, 0.0084\ R_{\odot}$ — in the white dwarf region in the lower left corner.
11. Pollux $33\ L_{\odot}$, 4865 K — in the giant region, just above the main sequence near the right center of the diagram.
12. Instability strip — in the vertical band that cuts through the upper part of the main sequence and into the giant region, slightly left of center.

5 section questions

Question 1

SL HL Difficulty:

Which property of a star does the *y*-axis on the HR diagram show?

Luminosity ✓

Accepted answers

Luminosity, luminosity, L

Explanation

The *y*-axis on the HR diagram shows the luminosity of a star.

Student
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Overview
(/study/ap
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Question 2

SL HL Difficulty:

The HR diagram is a way of classifying stars by their surface 1 temperature ✓ and 2 luminosity ✓ . The 3 main sequence ✓ is where the majority of the stars are. Red 4 giants ✓ have a very large radius and are formed from low mass stars in the dying stages of their lives. Red 5 supergiants ✓ have an exceptionally large radius and are formed from high mass stars in the dying stages of their lives. 6 White dwarfs ✓ are the remnants of stars too small to supernova. The 7 instability ✓ strip is a region of the HR diagram where variable, unstable stars exist, such as pulsars.

Accepted answers and explanation

#1 temperature
luminosity

#2 luminosity
temperature

#3 main sequence

#4 giants

#5 supergiants

#6 White dwarfs
white dwarves
white dwarfs

#7 instability

General explanation

The HR diagram is a way of classifying stars by their surface temperature and luminosity. The main sequence is where the majority of the stars are. Red giants have a very large radius and are formed from low mass stars in the dying stages of their lives. Red supergiants have an exceptionally large radius and are formed from high mass stars in the dying stages of their lives. White dwarfs are the remnants of stars too small to supernova. The instability strip is an area of the HR diagram where variable, unstable stars exist, such as pulsars.

Question 3

SL HL Difficulty:

A star has a luminosity of $1.2 \times 10^5\ L_\odot$ and a radius of $10.5\ R_\odot$. In which region of the HR diagram would you find it?

1 Main sequence ✓

2 Giants

Student view

Overview
(/study/ap
423-
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3 Supergiants

4 White dwarfs

Explanation

On the HR diagram in this section, move up the luminosity scale to just above 10^5, then move from left to right until you reach the line of constant radius just larger than the 10 solar radius line. The star is on the main sequence.

Question 4

SL HL Difficulty:

A star has a luminosity of 170 $L_\odot$ and a radius of 25.4 $R_\odot$. In what region of the HR diagram would you find it?

1 Giants ✓

2 Main sequence

3 Supergiants

4 White dwarfs

Explanation

On the HR diagram in this section, move up the luminosity scale to just above 10^2, then move from left to right until you reach the line of constant radius just larger than the 10 solar radius line. The star is a giant.

Question 5

SL HL Difficulty:

For a star three times the mass of the Sun, how would you expect the star to evolve?

1 Main sequence → red giant → white dwarf ✓

2 Main sequence → red supergiant → white dwarf

3 Red giant → red supergiant → white dwarf

4 Red giant → main sequence → white dwarf

Explanation

All stars start their lives on the main sequence. After this, most stars (up to around 8 solar masses) become red giants, after which they will become a red supergiant if their mass is at the upper end of this scale. Stars on the main sequence with a mass greater than 8 solar masses may go from main sequence to red supergiant. Stars with a mass less than about 8 solar masses will likely end as white dwarfs.

Student view

Star radius

E.5.7: Stellar radii

Learning outcomes

At the end of this section, you should be able to calculate the radius of a star from surface temperature and luminosity.

Imagine you are in a perfectly dark desert in the middle of the night. You can't see anything at all. Then, someone lights a candle a metre away from you, and someone lights a large fire a kilometre away from you. Which would look brighter? What about a star billions of kilometres away? What determines the brightness that we perceive?

Figure 1. A candle.

Source: Candle-earthquake by Bencmq at Chinese Wikipedia (https://commons.wikimedia.org/wiki/File:Candle-earthquake.jpg) is in the public domain

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Overview (/study/app/physics/sid-423-cid-762593/c

Radius of a star

The HR diagram is a graph of luminosity against temperature. We can use the HR diagram to determine the radius of a star.

The Stefan-Boltzmann equation is (see subtopic B.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43777/)):

$$L = \sigma A T^4$$

We treat stars as spherical objects, so the area through which this energy is emitted is given by the equation for the surface area of a sphere:

$$A = 4\pi r^2$$

Substituting this back into the Stefan-Boltzmann equation, we can write the ratio of luminosity and temperature (raised to the power four) as proportional to the star's radius squared:

$$L = \sigma 4\pi r^2 T^4$$

$$\frac{L}{T^4} \propto r^2$$

The gradient of the HR diagram gives us a way to measure the radius of a star. On the HR diagram, the gradient is shown as lines of constant radius.

Practical skills

Tool 3: Mathematics — Graphing

The lines of constant radius are plotted on a HR diagram, which means they have to follow logarithmic *x*- and *y*-axes.

Logarithmic scales are useful where the points plotted are from a very large, but not well distributed, range. For example, some stars on the HR diagram have temperatures of 50 000 K and above and luminosities 100 000 times brighter than the Sun, The majority of stars exist in the 2000—5000 K range, with luminosities less than the Sun. When plotted linearly, this leads to a graph that looks like the graph in **Figure 2**.

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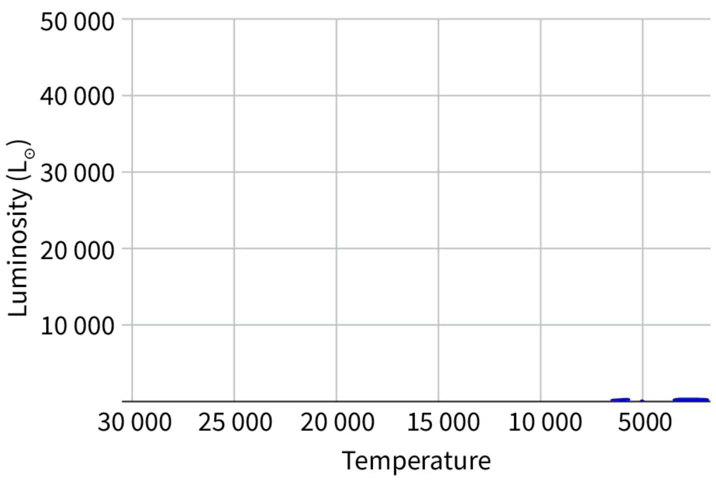

Figure 2. HR diagram with a non-logarithmic scale. 75% of stars in less than 1 solar mass range, 20% of stars in 1—10 solar mass range, and 5% of stars in more than 100 solar mass range.

More information for figure 2

The image is an HR (Hertzsprung-Russell) diagram plotting temperature on the X-axis against luminosity on the Y-axis. The X-axis, labeled "Temperature," ranges from 5,000 to 30,000 Kelvin, marked at 5,000, 10,000, 15,000, 20,000, 25,000, and 30,000 K. The Y-axis, labeled "Luminosity (L ☉)," ranges from 10,000 to 50,000, marked at intervals of 10,000 L ☉ . The graph primarily features data points clustered at the lower end of the temperature scale (near 5,000 K), with most of the graph being empty space. This indicates a concentration of stars with lower temperature and luminosity in the dataset.

The Even distribution across the axes leads to sparse placement of data points, making it difficult to read and interpret trends clearly, reflecting the text before and after the image which discusses the challenges presented by non-logarithmic scales.

[Generated by AI]

This graph is mostly empty space, and it is difficult to read and interpret. By applying a logarithmic scale on both the *x*- and *y*-axes, the data looks like the graph in **Figure 3**, which gives us a much better view of the data trends.

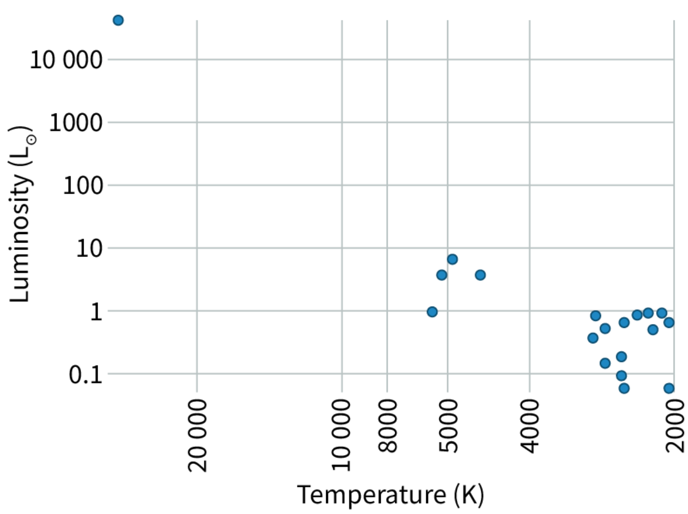

Figure 3. HR diagram with a logarithmic scale: 75% of stars in less than 1 solar mass range, 20% of stars in 1—10 solar mass range, and 5% of stars in more than 100 solar mass range.

More information for figure 3

The HR diagram uses a logarithmic scale on both the X-axis and Y-axis. The X-axis represents temperature in Kelvin, ranging from 20,000 K to 2,000 K, decreasing to the right. The Y-axis represents luminosity (L_ ⊙), ranging from 0.1 L_ ⊙ to 10,000 L_ ⊙ . Data points are scattered, with a concentration of points in the lower temperature and luminosity ranges, and a single point at high luminosity.

[Generated by AI]

As with the other scales on the HR diagram, the lines of constant radius are displayed logarithmically in terms of $R_\odot$ (radius of the Sun) (**Figure 4**).

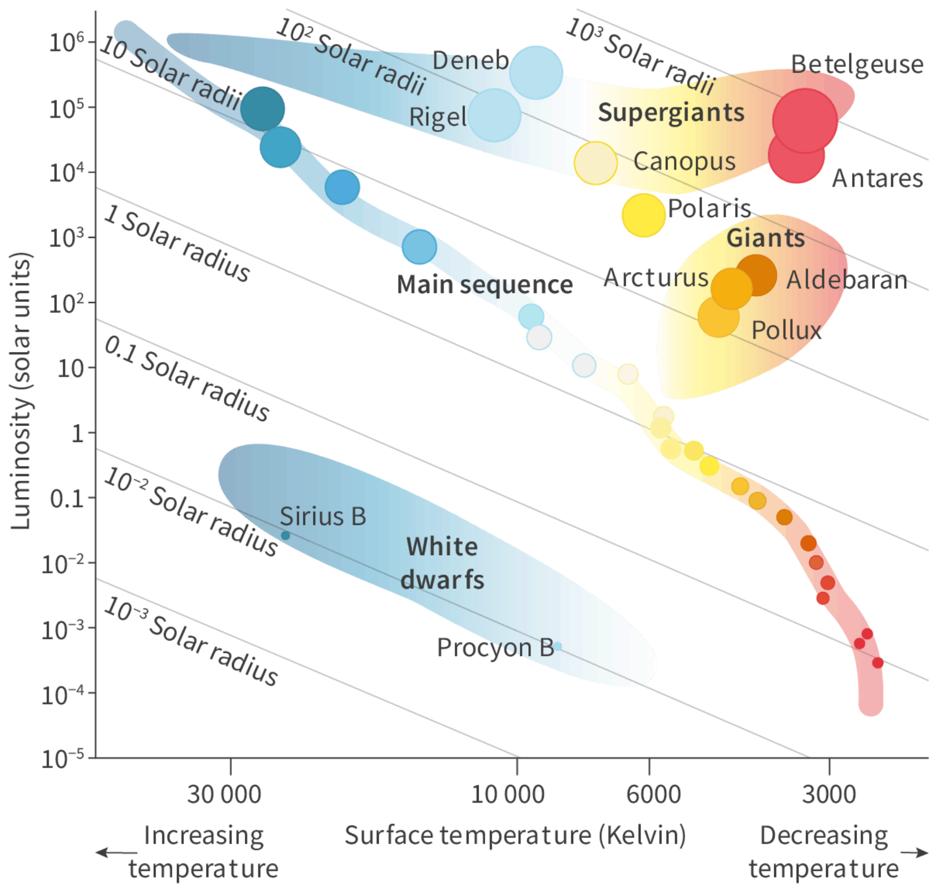

Figure 4. HR diagram showing lines of constant radius.

More information for figure 4

The image is a Hertzsprung-Russell (HR) diagram that plots stellar characteristics with lines of constant radius displayed logarithmically. The X-axis represents surface temperature measured in Kelvin, with scales increasing from left to right. The Y-axis shows luminosity in solar units, increasing from bottom to top. The diagram is populated with several notable stellar groupings: "Main Sequence," "Supergiants," "Giants," and "White Dwarfs." Specific stars like Deneb, Rigel, Betelgeuse, Antares, Polaris, and

Overview (/study/ap 423- cid- 762593/c

Sirius B are labeled. The lines of constant radius, in terms of solar radii (R ⊙), connect through these groups and are shown as diagonal lines spanning across the diagram. The colors range from blue at higher temperatures to red at lower temperatures, illustrating the temperature shifts across different types of stars.

[Generated by AI]

Study skills

Using the data in the HR diagram is not the only way to determine the radius of a star. There are other ways to collect the data needed to determine the radius of a star.

One way is to use Wien's displacement law (see subtopic B.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43777/)):

$$\lambda_{\text{max}} T = 2.90 \times 10^{-3}\ \text{mK}$$

This allows us to find the surface temperature of the star from its emission spectrum. We then use a known, measured or calculated luminosity to determine the radius using the Stefan—Boltzmann equation:

$$L = \sigma A T^4$$

Worked example 1

Given the following star data, calculate the radius of the star.

$L = 4.8\ L_\odot$

$1\ L_\odot = 3.828 \times 10^{26}$ W

The star’s emission spectrum is shown below.

Student view

Overview
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423-
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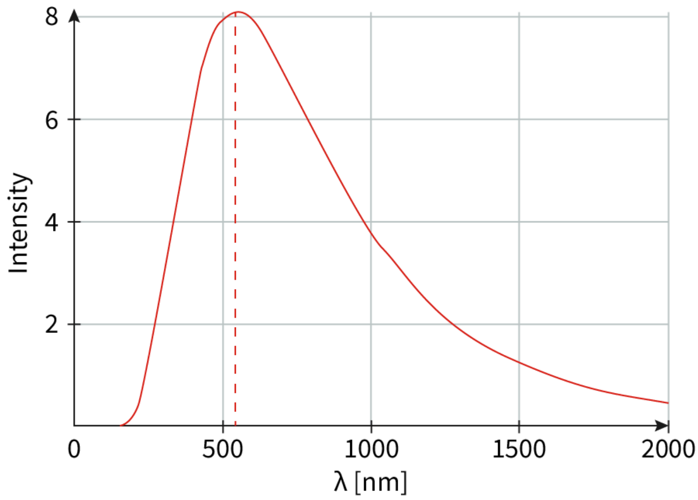

Figure 5. Emission spectrum.

More information for figure 5

This graph represents the emission spectrum of a star.

- The X-axis is labeled as "λ [nm]" and represents the wavelength in nanometers, ranging from 0 to 2000 nm.
- The Y-axis is labeled as "Intensity" and shows intensity units from 0 to 8.

The curve begins at the origin, rises steeply to a peak slightly below 500 nm, and then gradually declines as the wavelength increases, demonstrating the typical pattern of an emission spectrum. A vertical dashed line marks the peak near 500 nm, highlighting the point of maximum intensity.

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Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$L = 4.8 \times 3.828 \times 10^{26}$ $= 1.837 \times 10^{27}$ W
Step 2: Write out the Stefan-Boltzmann equation and the equation for area and rearrange to find r.	$L = \sigma A T^4$ and $A = 4\pi r^2$ $L = \sigma 4\pi r^2 T^4$ $r = \sqrt{\dfrac{L}{\sigma 4\pi T^4}}$

Student
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Overview
(/study/ap
423-
cid-
762593/c

Solution steps	Calculations
Step 3: Write out Wien's displacement law and rearrange to find T.	$\lambda_{\max}T = 2.90 \times 10^{-3}\,\mathrm{m\,K}$ $T = \dfrac{2.9 \times 10^{-3}}{\lambda_{\max}}$ From the graph, you can read the peak wavelength to be around 520 nm: $T = \dfrac{2.9 \times 10^{-3}}{520 \times 10^{-9}}$ $= 5580\ \mathrm{K}$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$r = \sqrt{\dfrac{L}{\sigma 4\pi T^4}}$ $= \sqrt{\dfrac{1.837 \times 10^{27}}{5.67 \times 10^{-8} \times 4 \times \pi \times 5580^4}}$ $= 1\,630\,758\,755\ \mathrm{m}$ $= 1\,600\,000\ \mathrm{km}\ (2\ \mathrm{s.f.})$

We can use the HR diagram to inform our calculations.

Worked example 2

Using the HR diagram and the data below, estimate the radius of the Sun.

Student
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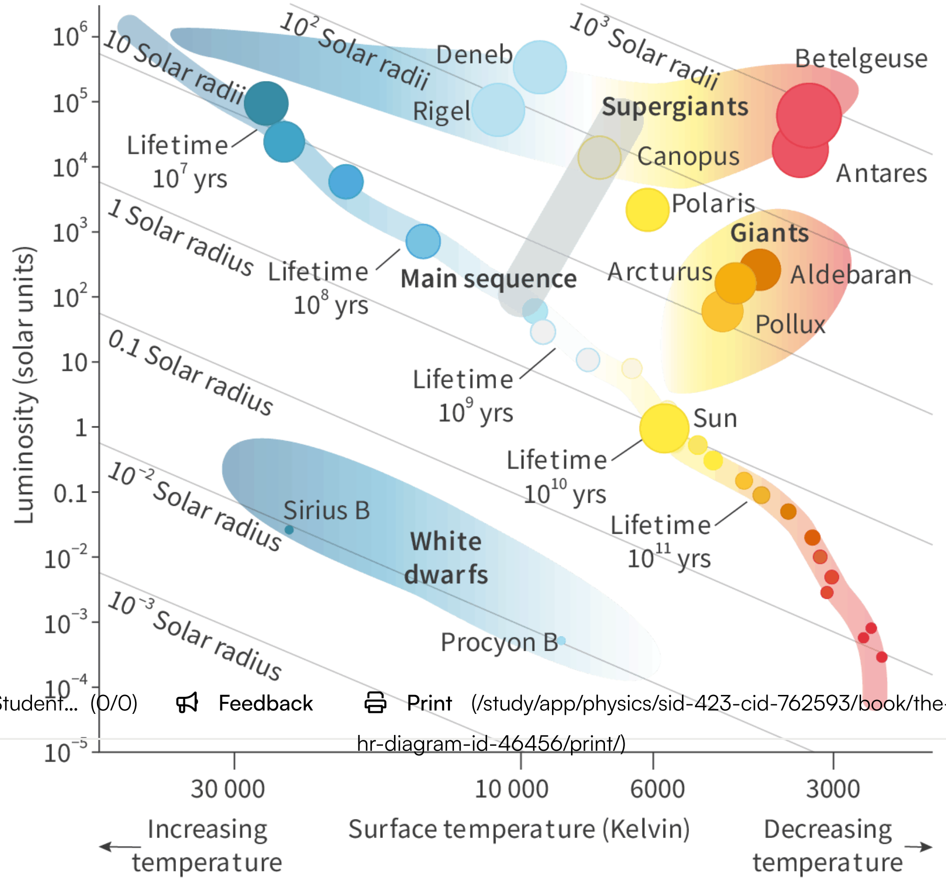

Figure 6. Use the diagram to estimate the radius of the Sun.

More information for figure 6

The image is a Hertzsprung-Russell diagram, a graphical tool used by astronomers to classify stars according to their luminosity, spectral type, color, temperature, and evolutionary stage. The diagram has two main axes: the vertical axis represents luminosity in solar units ranging from 10^-5 to 10^6, while the horizontal axis represents surface temperature in Kelvin, running from 30,000 K on the left to 3,000 K on the right. The temperature increases to the left and decreases to the right.

Several major sections and characteristics are present in the diagram:

1. **Main Sequence:** A diagonal band where stars like the Sun fall, spans from high temperature and high luminosity to low temperature and low luminosity.
2. **Supergiants and Giants:** Positioned toward the upper right, these stars are large and more luminous with lower temperatures.
3. **White Dwarfs:** Located below the main sequence, these stars are hot but have low luminosity and small radii.
4. **Sun's Position:** The Sun is situated on the main sequence with a specified lifetime of 10^10 years.
5. **Additional Labels:** Specific stars such as Deneb, Rigel, Betelgeuse, Antares, and Sirius B are labeled along with radius lines like 10^3 Solar radii and 10^-2 Solar radii, indicating their relative size.

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Overview
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$1\,L_\odot = 3.828 \times 10^{26}$ W

$$L = \sigma A T^4 \text{ and } A = 4\pi r^2$$

$$L = \sigma 4\pi r^2 T^4$$

$$r = \sqrt{\frac{L}{\sigma 4\pi T^4}}$$

Find the Sun on the HR diagram and read off an estimated temperature: about 5700–5900 K. Use the median: 5800 K.

$$\begin{aligned} r &= \sqrt{\frac{3.828 \times 10^{26}}{5.67 \times 10^{-8} \times 4 \times \pi \times 5800^4}} \\ &= 689\,022\,677 \text{ m} \\ &= 689\,000 \text{ km (3 s.f.)} \end{aligned}$$

The solar radius is about 695 700 km, so this is a close estimate.

Work through the activity to check your understanding of how to determine the radius of a star.

Activity

- **IB learner profile attribute:**
  - Thinker
  - Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20—30 minutes
- **Activity type:** Individual/group activity

Download the worksheet and complete the questions. You can check your answers at the end of the worksheet.

Worksheet (https://d3vrb2m3yrmyfi.cloudfront.net/media/edusys_2/content_uploads/Physics E.5.3 ACTIVITY Star radius.8ea1230ecb887003752e.pdf)

5 section questions

Student
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Overview
(/study/ap
423-
cid-
762593/c

Question 1

SL HL Difficulty:

Lines of 1 constant radius ✓ are used on an 2 HR ✓ diagram to show 3 stars ✓ of similar sizes. We can use 4 luminosity ✓ (in $L_\odot$) and 5 temperature ✓ (in kelvin) to find the radius of a star.

Accepted answers and explanation

#1 constant radius

#2 HR
Hertzsprung-Russell

#3 stars

#4 luminosity

#5 temperature
surface temperature

General explanation

The HR diagram is a graph of luminosity against surface temperature using logarithmic scales. Lines on the HR diagram show the relationship between the radius of stars on different parts of the graph and compare the size of stars to our Sun. If the luminosity and surface temperature of a star can be measured, then the radius of the star can be determined.

Question 2

SL HL Difficulty:

Which of the following stars are most likely to be approximately 100 $R_\odot$ in size? Use the HR diagram to help you.

Student view

Overview
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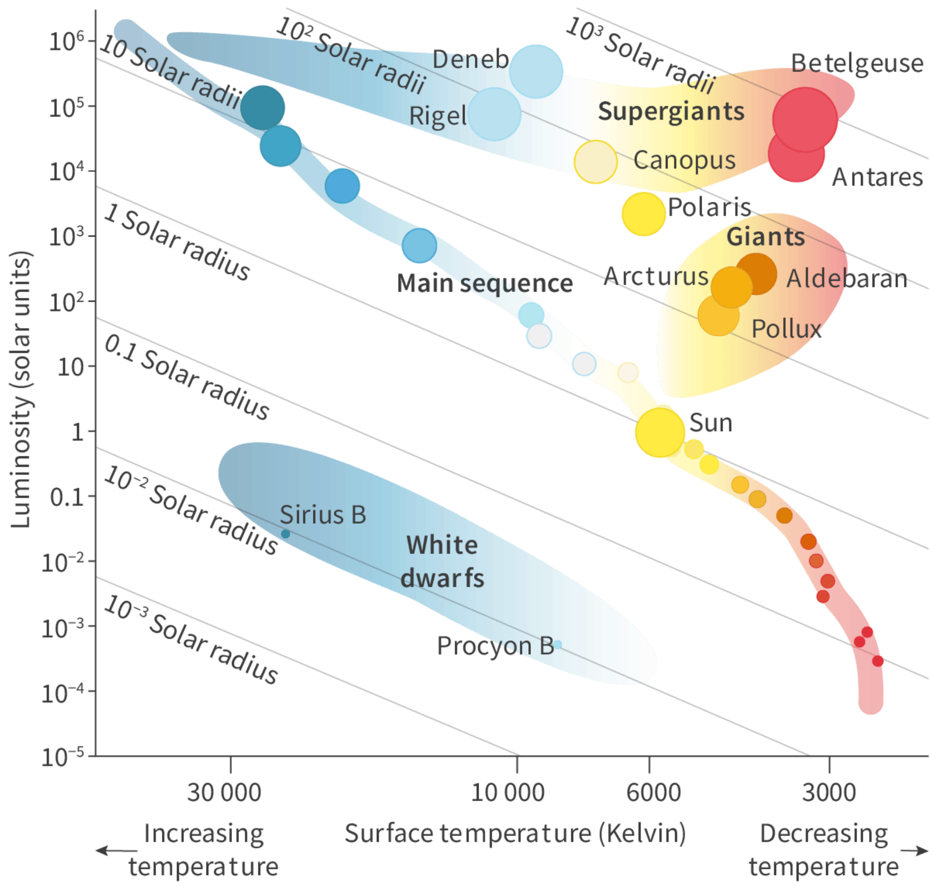

More information

1 15 000 L⊙ and 6400 K surface temperature ✓

2 60 000 L⊙ and 3200 K surface temperature

3 1 L⊙ and 5500 K surface temperature

4 100 L⊙ and 8000 K surface temperature

Explanation

Roughly plot the four stars on an HR diagram:

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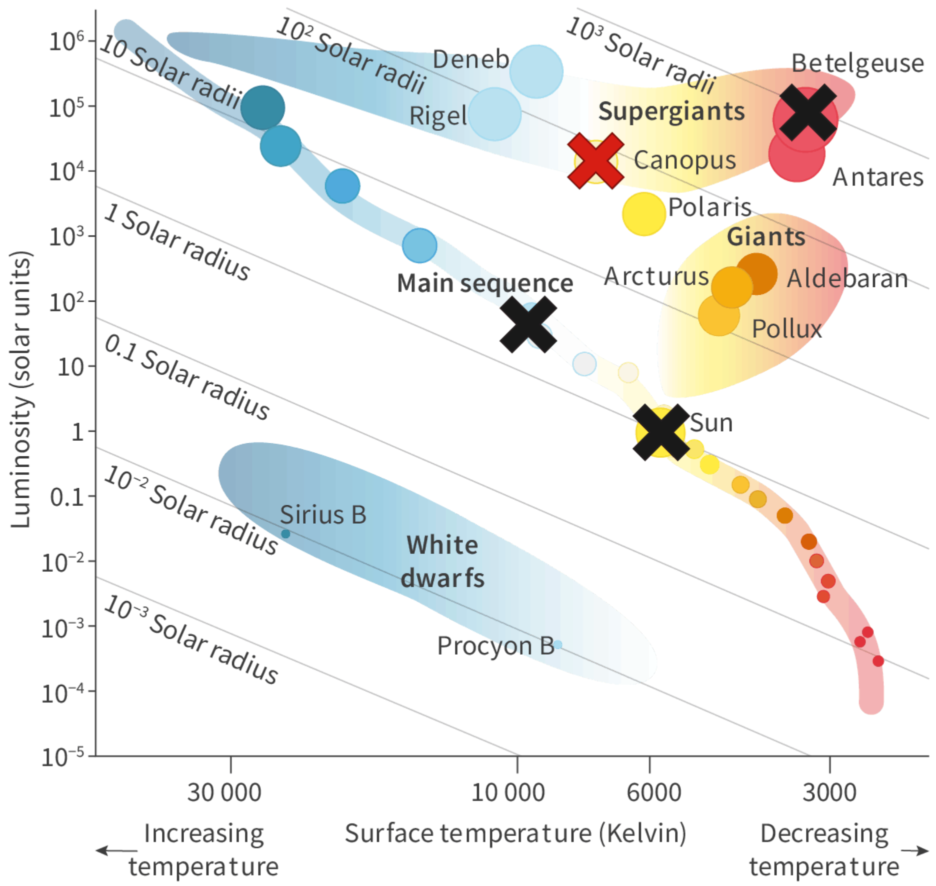

More information

The red cross is the one that sits most closely to the 10^2, or 100 solar radius line of constant radius. This is the '15 000 $L_\odot$ and 6400 K surface temperature' option.

Question 3

SL HL Difficulty:

A red supergiant of temperature 3000 K is on the 10^3 line of constant radius.

$$L_\odot = 3.86 \times 10^{26}\text{ W}$$

$$R_\odot = 696\,340\text{ km}$$

The luminosity of the star is 1 0.0725 ✓ $L_\odot$

Give your answer to three significant figures.

Accepted answers and explanation

#1 0.0725

General explanation

$$L = 3.86\times10^{26}\text{ W}$$

Student view

Overview (/study/app/ 423- cid- 762593/c

$$R = 696\,340 \text{ km}$$
$$= 696\,340\,000 \text{ m}$$

$$r = 696\,340\,000 \text{ m}$$

$$T = 3000 \text{ K}$$

$$L = \sigma A T^4$$

$$L = \sigma 4\pi r^2 T^4$$
$$= 5.67\times10^{-8}\times4\times\pi\times(696\,340\,000)^2\times3000^4$$
$$= 2.79847\times10^{25} \text{ W}$$

$$\frac{L}{L_\odot} = \frac{2.79847\times10^{25}}{3.86\times10^{26}}$$
$$= 0.072499\ L_\odot$$
$$= 0.0725\ L_\odot \text{ (3 s.f.)}$$

Question 4

SL HL Difficulty:

A star similar to the Sun has the following luminosity and temperature:

$L_\odot$ = 3.86 × 10^{26} W

$T_\odot$ = 5772 K

Determine the radius of the star. Give your answer to three significant figures.

The radius of the star is 1 699000 ✓ km

Accepted answers and explanation

#1 699000

699 000

699,000

General explanation

$$L = 3.86 \times 10^{26} \text{ W}$$

$$T = 5772 \text{ K}$$

$L = \sigma A T^4$ and $A = 4\pi r^2$

$$L = \sigma 4\pi r^2 T^4$$

$$r = \sqrt{\frac{L}{\sigma 4\pi T^4}}$$
$$= \sqrt{\frac{3.86 \times 10^{26}}{5.67 \times 10^{-8} \times 4\pi \times 5772^4}}$$
$$= 698\,625\,681 \text{ m}$$
$$= 699\,000 \text{ km (3 s.f.)}$$

Student view

Question 5

SL HL Difficulty:

Overview
(/study/ap
423-
cid-
762593/c

What is the approximate radius in $R_\odot$ of a star with a luminosity of 10 $L_\odot$ and a temperature of 1000 K?

Use the following data to help you:

$L_\odot$ = 3.86×10^{26} W

$R_\odot$ = 695 700 km

1 10^2 ✓

2 10^1

3 10^3

4 10^4

Explanation

$L_\odot = 3.86 \times 10^{26}$ W

$$R_\odot = 695\,700 \text{ km}$$
$$= 695\,700\,000 \text{ m}$$

$L = \sigma A T^4$ and $A = 4\pi r^2$

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/star-radius-id-46457/print/) Assign

$$L = \sigma 4\pi r^2 T^4$$

$$r = \sqrt{\frac{L}{\sigma 4\pi T^4}}$$

Use the powers of ten to solve this:

$$r \approx \sqrt{\frac{10 \times 10^{26}}{10^{-8} \times 10^1 \times 1000^4}}$$
$$\approx \sqrt{\frac{10^{27}}{10^5}}$$
$$\approx \sqrt{10^{22}}$$
$$\approx 10^{11}$$

The radius of the star is of the order 10^{11} m and the radius of the Sun is approximately 10^9 m.

E. Nuclear and quantum physics / E.5 Fusion and stars

Measuring distances in space

Student view

E.5.6: Stellar parallax and distance determination

Overview
(/study/ap
423-
cid-
762593/c

Learning outcomes

By the end of this section you should be able to:

- Explain the measuring system of parsecs, and convert between parsecs (pc), light years (ly) and astronomical units (AU).
- Describe the method of stellar parallax and its advantages and disadvantages.

How far away is your computer screen from you right now? How far away is your school? How far away is the North Pole? You might have used different units for each of these distances, because they are so different in magnitude. In space, distances are much, much bigger, and measuring them in kilometres would give enormous numbers. To fully understand these distances we need a different set of measurement tools.

Figure 1. The North Pole.

Distances in space

In astrophysics, many of the values scientists deal with are extremely large or small relative to humans:

- It is estimated that there are more than 1000 times more stars in the Universe than grains of sand on the Earth.
- The energy released in a single fusion reaction would only be enough to power a light bulb for about a thousand billionth of a second.

Student view

Overview (/study/app/physics/sid-423-cid-762593/c

When measuring the angles of stars relative to Earth, we get comparatively small values. So, instead of degrees (°), we use a unit called the arcsecond.

Figure 2 shows how a degree is related to an arcminute, and how an arcminute is related to an arcsecond.

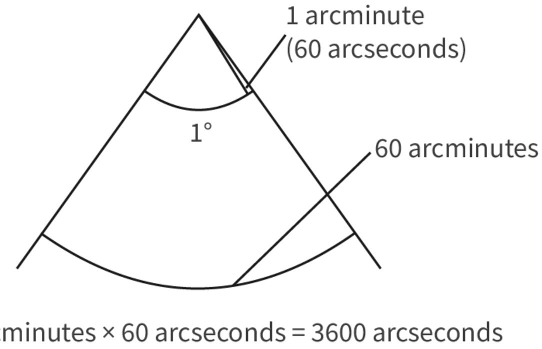

Figure 2. How the degree, arcminute and arcsecond are related.

More information for figure 2

The diagram illustrates how angles are divided into smaller units of measurement. It shows a circular sector, with the center angle labeled as 1 degree (1°). One arcminute, which is 1/60 of a degree, is represented as a smaller segment along the same arc. There is a note indicating that 1 arcminute equals 60 arcseconds. Additionally, the broader arc shows that 1 degree is equivalent to 60 arcminutes or 3600 arcseconds in total. These relationships are essential for understanding the finer divisions of angles used in various applications, such as astronomy.

[Generated by AI]

One arcminute is $\frac{1}{60}$ of a degree, and one arcsecond is $\frac{1}{60}$ of an arcminute. Thus, one arcsecond is $\frac{1}{(60\times60)} = \frac{1}{3600}$ of a degree, or 0.0002778°.

By measuring angles in arcseconds, they are easier to use when calculating stellar distances, which involves measuring relatively small angles.

Exercise 1

Click a question to answer

Student view

Overview
(/study/ap
423-
cid-
762593/c

Stellar parallax

In order to find the distances to other stars in our galaxy, we use a technique that humans use to estimate the distance to things – parallax.

Concept

Place your finger away from your head against a stationary background that is relatively far away (if your finger is half a metre from your face, the background should be at least 3 or 4 metres away). Now close one eye. Alternate which eye is open.

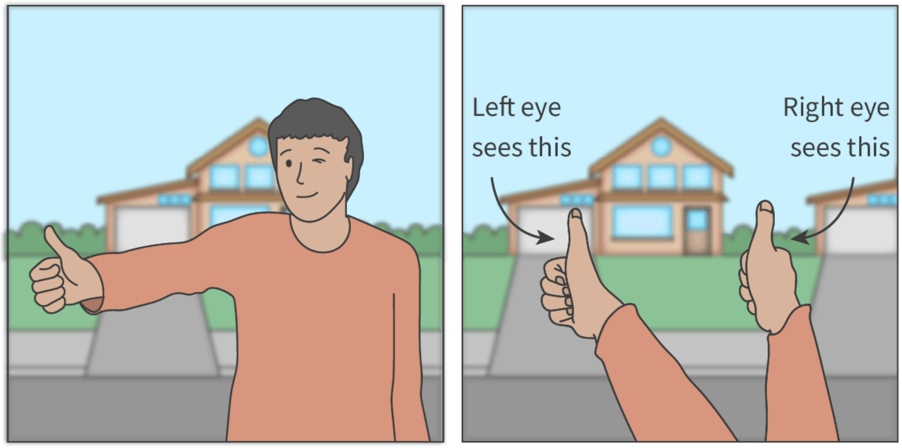

Figure 3. Different viewpoints give different views.

What do you observe when you switch your open eye? Your finger appears to move against the stationary background. This is the parallax effect. Because your eyes are in different places in your head, you actually see two different images. Your brain puts them together to form a 3D representation of the world, but what we actually see is 2D.

In our brains, we use parallax to merge the images from both of our eyes (which see individually in 2D) and give us a 3D representation of the world. This depth allows us to make estimates (based upon known values of things, such as how tall a person is) of how far away things are. If a person appears small, they are likely far away.

We can use the idea of parallax to find the distance to other stars in our galaxy in the same way. **Figure 4** shows stellar parallax. The two boxes show the view of the stars from Earth in January and July. Notice that the position of the nearby star changes relative to the more distant stars. The parallax angle is labelled p.

Student
view

Overview (/study/app 423-cid-762593/c

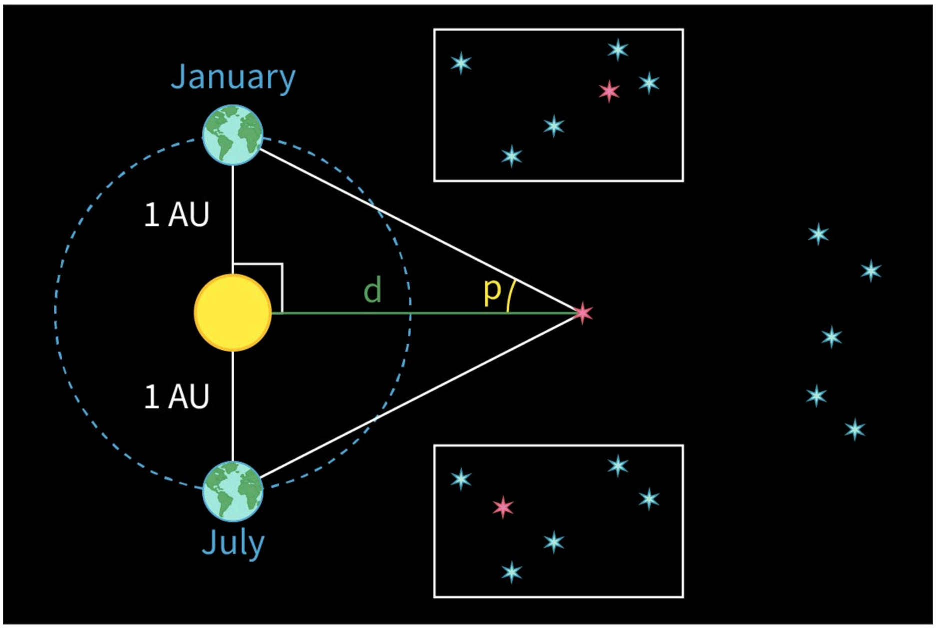

Figure 4. Stellar parallax.

More information for figure 4

The image is a diagram illustrating the concept of stellar parallax. It shows the Earth in two different positions along its orbit around the Sun, labeled as January and July. The orbit is represented by a dashed circular path with the Sun at its center. Each position is marked with Earth icons and labeled with '1 AU', indicating the average distance between the Earth and the Sun.

Two triangular lines extend from the Earth's positions, converging at a point labeled 'p', which represents the parallax angle. The base of this triangle shows the distance 'd' to a nearby star, indicated with a red star icon, while more distant stars are shown as smaller blue stars in the background.

The upper and lower boxes magnify the view of stars as seen from Earth in January and July, demonstrating the shift in position of the nearby red star against the stationary distant stars. This shift is the basis for measuring parallax and determining the star's distance from Earth.

[Generated by AI]

When measuring the parallax angle, we use the relative motion of the star against a fixed background of distant stars. As the distant stars appear stationary, the relative motion of the observed star tells us how far away it is from the Earth. One astronomical unit (AU) is the average distance between the Earth and the Sun.

In **Figure 4**, we look at the observed star in January, and again six months later in July. During this time, the observed star has moved against the background of distant stationary stars. By taking two observations, and by knowing the distance between the Earth and the Sun (1 AU), we can get an

Student view

Overview
(/study/ap
423-
cid-
762593/c

estimate for the parallax angle between the observed star and the Earth. As shown in **Figure 4**, the parallax angle is the angle of the right-angled triangle formed by the relationship between the Sun, Earth and observed star.

Once we have this angle, we can convert it to arcseconds, then use the equation for distance shown in **Table 1**.

Table 1. Equation for distance.

Equation	Symbols	Units
$d\,(\text{parsec}) = \dfrac{1}{p\ \ (\text{arcsecond})}$	d = distance to the celestial body from the Earth	parsecs (pc)
	p = parallax angle measured from the Earth	arcseconds

The unit for distance is the parsec (pc), which is defined as the distance a celestial body is from the Earth when the parallax angle is equal to one arcsecond. One parsec is equal to about 3.26 light years (ly):

- Light year (ly): The distance light travels during one year in a vacuum.
- Astronomical unit (AU): The average distance between the Earth and the Sun.

We usually calculate distances in parsecs using angles, but refer to distances using light years.

Study skills

$1 \text{ parsec (pc)} = 3.26 \text{ ly}$

$1 \text{ light year (ly)} = 9.46 \times 10^{15} \text{ m}$

$1 \text{ astronomical unit (AU)} = 1.50 \times 10^{11} \text{ m}$

You need to know how to convert parsecs into metres. For example:

$$\text{angle} = 0.005 \text{ arcseconds}$$

$$\begin{aligned} d\,(\text{parsec}) &= \frac{1}{p\ \ (\text{arcsecond})} \\ &= \frac{1}{0.005} \\ &= 200 \text{ pc} \end{aligned}$$

$$\begin{aligned} d\ (\text{m}) &= 200 \times 3.26 \times 9.46 \times 10^{15} \\ &= 6.17 \times 10^{18} \text{ m (3 s.f.)} \end{aligned}$$

Student
view

Overview
(/study/ap
423-
cid-
762593/c

Worked example 1

The distance to Betelgeuse from the Earth is 624 light years. Determine the parallax angle that Betelgeuse makes with the Earth.

$$d = 624 \text{ ly}$$

$$1 \text{ parsec} = 3.26 \text{ ly}$$

$$\frac{624}{3.26} = 191.41 \text{ parsecs}$$

$$d\,(\text{parsec}) = \frac{1}{p\,(\text{arcsecond})}$$

$$\begin{aligned} p\,(\text{arcsecond}) &= \frac{1}{d\,(\text{parsec})} \\ &= \frac{1}{191.41} \\ &= 0.0052243 \text{ arcseconds} \\ &= 0.00522 \text{ arcseconds } (3 \text{ s.f.}) \end{aligned}$$

Worked example 2

The apparent brightness of Sirius A is 1.16×10^{-7} W m^{-2} and its parallax angle is 0.379 arcseconds.

Its radiation spectrum peaks at a wavelength of 2.92×10^{-7} m. Determine the radius of Sirius A.

Solution steps	**Calculations**
Step 1: Convert the parallax angle to a distance in parsecs. Give the answer to an appropriate number of significant figures to avoid rounding errors in the final answer, which will be written to 3 significant figures.	$\begin{aligned} d(\text{parsec}) &= \frac{1}{p(\text{arcsecond})} \\ &= \frac{1}{0.379} \\ &= 2.6385 \text{ pc } (5 \text{ s.f.}) \end{aligned}$

Student
view

Overview (/study/app/physics/sid-423-cid-762593/c

Solution steps	Calculations
Step 2: Convert parsecs to metres using the unit conversions in the DP physics data booklet.	$1 \text{ light year (ly)} = 9.46\times10^{15} \text{ m}$ $1 \text{ parsec (pc)} = 3.26 \text{ ly}$ $d = 2.639\times3.26\times9.46\times10^{15} \text{ m}$ $= 8.1370\times10^{16} \text{ m (5 s.f.)}$
Step 3: Calculate the luminosity using the equation that relates it to apparent brightness (see section B.1.5 (/study/app/physics/sid-423-cid-762593/book/black-body-emission-id-43785/)).	$L = 4\pi d^2 b$ $= 4\pi\times(8.1370\times10^{16})^2\times1.16\times10^{-7}$ $= 9.6515\times10^{27} \text{ W (5 s.f.)}$
Step 4: Use Wien's law (see section B.1.5 (/study/app/physics/sid-423-cid-762593/book/black-body-emission-id-43785/)) to find the surface temperature of Sirius A.	$\lambda_{\text{max}}T = 2.9\times10^{-3} \text{ m K}$ $T = \frac{2.9\times10^{-3}}{2.92\times10^{-7}}$ $= 9931.5 \text{ K (5 s.f.)}$
Step 5: Use the Stefan-Boltzmann law (see section B.1.5 (/study/app/physics/sid-423-cid-762593/book/black-body-emission-id-43785/)) to find the surface area of Sirius A.	$L = \sigma A T^4$ $A = \frac{L}{\sigma T^4}$ $= \frac{9.6515\times10^{27}}{5.67\times10^{-8}\times9931.5^4}$ $= 1.7497\times10^{19} \text{ m}^2 \text{ (5 s.f.)}$
Step 6: Use the equation relating the surface area of a sphere to its radius. Give your answer to 3 significant figures.	$A = 4\pi r^2$ $r = \sqrt{\frac{A}{4\pi}}$ $= \sqrt{\frac{1.7497\times10^{19}}{4\pi}}$ $= 1.18\times10^9 \text{ m (3 s.f.)}$

Advantages and disadvantages of stellar parallax

Table 2 shows some advantages and disadvantages of using stellar parallax to determine distance.

Table 2. Advantages and disadvantages of stellar parallax.

Student view

Overview
(/study/ap
423-
cid-
762593/c

Advantage	Disadvantage
Very easy method of calculating distance to stars	When angle is smaller (object is further away), accuracy of calculated value is lower Does not work at large ranges (currently a 10 000 pc maximum)
Can be very accurate when using a satellite, and for close objects	Due to atmospheric distortions, not a good method of calculation from the Earth for stars further away than about 100 pc

The European Space Agency's Gaia mission, whose aim is to build a 3D map of our galaxy, has a parallax limit of about 10 microarcseconds for very bright stars, giving a maximum measurable distance of about 10 000 pc from Earth. All of the stars that we can measure using parallax are in our own galaxy.

Theory of Knowledge

Measuring the distances to faraway objects is very difficult. Over time, measured distances to celestial objects have changed. For example, the parallax angle to Betelgeuse over the past seven years has changed from 5.07 ± 0.16 milliarcseconds to 4.24 ± 0.07 milliarcseconds. Is this change because of uncertainty in the measurement, an increase in measurement accuracy, or because the distance of the star from the Earth is changing?

We may deduce from the change and our understanding of physics that it is moving away from us, but how can we know for sure? To what extent can the measurements and tools of physics achieve certainty?

Figure 5. Betelgeuse.
Source: Digitized Sky (https://commons.wikimedia.org/wiki/File:Digitized_Sky_Survey_Image_of_Betelgeuse.jpg) by

Student
view

Overview (/study/ap 423- cid- 762593/c

Work through the activity to check your understanding of stellar parallax.

Activity

- **IB learner profile attribute:** Inquirer, Communicator, Reflective
- **Approaches to learning:**
  - Thinking skills — Applying key ideas and facts in new contexts
  - Social skills — Working collaboratively to achieve a common goal
- **Time required to complete activity:** 20—30 mins
- **Activity type:** Pairs or group of three

Download the worksheet and complete the tasks. You are going to make an instrument called an astrolabe to practise parallax measurement. Finding the value of any measurement accurately in arcseconds will probably be beyond the scope of the equipment you have available, but this should give you an idea of how parallax works in practice.

Worksheet (https://d3vrb2m3yrmyfi.cloudfront.net/media/edusys_2/content_uploads/Physics E5.4 Measuring parallax angles.2acfaf462501ee84fd42.pdf)

5 section questions

Question 1

SL HL Difficulty:

A 1 parsec ✓ is the distance to an object with a measured parallax angle of 1 arcsecond.

A 2 light year ✓ is the distance that light travels in a vacuum in one year.

An 3 astronomical ... ✓ is the average distance between the Earth and the Sun.

Accepted answers and explanation

#1 parsec

pc

#2 light year

ly

Student view

Overview (/study/app/423-cid-762593/c

#3 astronomical unit

AU

General explanation

A parsec is the distance to an object with a measured parallax angle of 1 arcsecond.

A light year is the distance that light travels in a vacuum in one year.

An astronomical unit is the average distance between the Earth and the Sun.

Question 2

SL HL Difficulty:

Vega is 26.08 light years from the Earth. Determine the parallax angle Vega makes with respect to the Earth. Give your answer to three significant figures.

The parallax angle is 1 0.125 ✓ arcseconds.

Accepted answers and explanation

#1 0.125

.125

0,125

,125

General explanation

$$1 \text{ parsec} = 3.26 \text{ light years}$$

$$\frac{26.08}{3.26} = 8 \text{ parsecs (1 s.f.)}$$

$$d\ (\text{parsec}) = \frac{1}{p\ (\text{arcsecond})}$$

$$\begin{aligned} p\ (\text{arcsecond}) &= \frac{1}{d\ (\text{parsec})} \\ &= \frac{1}{8} \\ &= 0.125 \text{ arcseconds (3 s.f.)} \end{aligned}$$

Question 3

SL HL Difficulty:

A star is measured to have a parallax angle of 0.05 arcseconds with respect to the Earth. What will be the distance to a star with a parallax angle of $\frac{1}{4}$ this size?

The distance to the star will be 1 80 ✓ pc.

Student view

Accepted answers and explanation

Overview
(/study/ap
423-
cid-
762593/c

#1 80

General explanation

Star with known distance:

$$d = \frac{1}{p} = \frac{1}{0.05} = 20 \text{ pc}$$

Star with $\frac{1}{4}$ the parallax angle:

$$d = \frac{1}{\frac{1}{4}p} = 4 \times \frac{1}{p} = 4 \times \frac{1}{0.05} = 80 \text{ pc}$$

Question 4

SL HL Difficulty:

Stellar 1 parallax ✓ is a method of determining how far away stars are from the Earth. We observe a star from 2 two ✓ different positions. On Earth, these readings are taken 3 six ✓ months apart for the best parallax effect. By observing the motion of the star relative to a fixed background, we can determine the 4 parallax angle ✓ in arcseconds, which we can use to find the 5 distance ✓ in parsecs.

Accepted answers and explanation

#1 parallax

#2 two
2

#3 six
6

#4 parallax angle

#5 distance

General explanation

Stellar parallax is a method of calculating the distance to faraway stars using the relative motion of the star against a fixed background of distant stars. On Earth this is done by observing the position of a star at two different times, typically six months apart. The calculated parallax angle can then be used to determine the distance from Earth.

Student view

Overview
(/study/ap
423-
cid-
762593/c

Question 5

SL HL Difficulty:

An angle of 0.00045 arcseconds is measured to a distant star using the stellar parallax method. Determine the distance to the star. Give your answer to an appropriate number of significant figures.

The distance to the star is 1 14000 ✓ light years.

Accepted answers and explanation

#1 14000

14,000

14 000

General explanation

First, find the appropriate angle to use. As the angle given is found using stellar parallax, we must divide by two to get the angle needed. This is because the parallax angle (given) is formed between the moving object 1/2 an orbit apart, whereas we need the angle from the mid point of this orbit.

$$\frac{0.00045}{2} = 0.000225 \text{ arcseconds}$$

$$\begin{aligned} d\ (\text{parsec}) &= \frac{1}{p\ (\text{arcsecond})} \\ &= \frac{1}{0.000225} \\ &= 4444.4 \text{ pc} \end{aligned}$$

$$1 \text{ pc} = 3.26 \text{ ly}$$

$$\begin{aligned} 4444.4 \times 3.26 &= 14\,488.7 \text{ ly} \\ &= 14\,000 \text{ ly (2 s.f.)} \end{aligned}$$

E. Nuclear and quantum physics / E.5 Fusion and stars

Summary and key terms

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/summary-and-key-terms-id-46459/print/) Assign

- For a stable star, the inwards gravitational force is in equilibrium with the outwards radiation force.
- The radiation pressure is caused by nuclear fusion in stars, which releases energy.
- Fusion in stars requires very high temperatures and pressures.
- The HR diagram is a graph of luminosity against temperature for stars, with four main regions: white dwarfs, main sequence, giants and supergiants. The stars in each region have similar properties.
- The evolution of a star depends on its mass on the main sequence compared to the solar mass.

Student view

Overview
(/study/ap
423-
cid-
762593/c

- The HR diagram shows lines of constant radius. The radius of a star can also be determined from its surface temperature and luminosity.
- Distances in space are measured using special units: parsec (pc), light year (ly) and astronomical unit (AU).
- Stellar parallax is an important method of determining the distance to stars within about 10 000 pc of the Earth.

Student
view

Key terms

Interactive 1. Review the Key Terms: Fusion and Stars

Checklist

What you should know

After studying this subtopic, you should be able to:

- Describe star stability in terms of the equilibrium between gravitational forces and radiation pressure.
- Describe fusion in stars and calculate the energy released by fusion.
- Explain the conditions required for fusion in stars.
- Describe the main regions of the HR diagram.
- Recall the different properties of stars based on their region on the HR diagram.
- Outline the evolution of different types of stars.
- Calculate the radius of a star from surface temperature and luminosity.
- Explain the measuring system of parsecs, and convert between parsecs (pc), light years (ly) and astronomical units (AU).
- Describe the method of stellar parallax and its advantages and disadvantages.

Investigation

- **IB learner profile attribute:** Risk-taker
- **Approaches to learning:** Thinking skills – Applying key ideas and facts in new contexts
- **Time required to complete activity:** 1.5 hours
- **Activity type:** Pair activity

Overview (/study/ap 423-cid-762593/c

Your task

The Harvard Computers were a team of women who classified stars based on their spectral classes. Using these measurements, they could determine the stars' temperatures and compositions. Astronomers used the spectral diagrams to determine the stars' luminosities and create the HR diagram.

Making connections

We can determine the temperature of a black body radiator using Wien's displacement law (see subtopic B.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43777/)):

$$\lambda_{\text{max}} T = 2.90 \times 10^{-3}\,\text{mK}$$

Stars are perfect black body radiators, which are objects that emit and absorb all forms of electromagnetic radiation. By analysing the black body emissions of stars, we can learn about their temperatures.

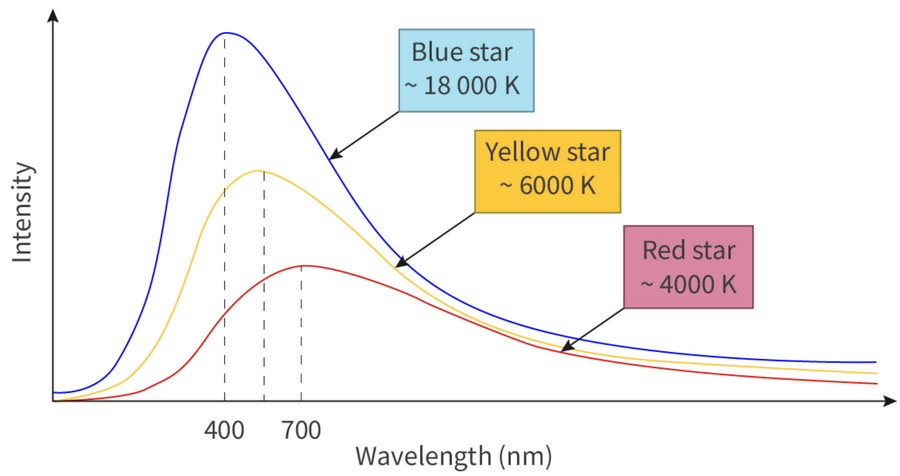

Figure 1. Black body spectral diagram.

More information for figure 1

The graph displays the intensity of light emitted by stars of different temperatures versus the wavelength. The X-axis represents wavelength in nanometers (nm), ranging from approximately 100 to 1000 nm. The Y-axis represents the intensity of light, although it has no specific scale or units given.

Three curves, color-coded and labeled, represent different star temperatures:

1. The blue curve peaks around 18,000 Kelvin and shows the highest intensity at shorter wavelengths, indicating blue stars which have shorter wavelengths.
2. The yellow curve represents a medium intensity that peaks around 6000 Kelvin.
3. The red curve peaks at a lower intensity around 4000 Kelvin, indicating red stars with longer wavelengths.

There are vertical dashed lines highlighting significant wavelengths along the X-axis, although these are not labeled with specific values.

Student view

Overview (/study/ap 423- cid- 762593/c

Overall, the diagram illustrates that stars with higher temperatures peak at shorter wavelengths with higher intensity, while stars with lower temperatures emit lower intensity at longer wavelengths, aligned with Wien's displacement law.

[Generated by AI]

Black body emission spectra of different stars show a peak wavelength that corresponds to the colour. Using Wien's displacement law, we can determine the temperature of the star. Blue stars have short wavelengths and high temperatures, and red stars have low temperatures and long wavelengths.

1. Copy and complete **Table 1**, filling in the missing values for each of the four stars.

Note that:

$L_\odot = 3.86 \times 10^{26}$ W
$R_\odot = 696\,000\,000$ m
1 pc = 3.26 light years
1 ly = 9.46×10^{15} m
1 AU = 1.50×10^{11} m

Table 1. Properties of some stars.

Star name	Mass ($M_\odot$)	Radius ($R_\odot$)	Temperature (K)	Luminosity ($L_\odot$)	Parallax angle (arcseconds)	Distance (pc)
Spica	11.43			2254	1.306×10^{-2}	
Sirius	2.06	1.71	10 000			2.637
Sun	1.00	1		1	N/A	
Antares	12.00			2754		169.49

2. **Figure 2** shows a black body spectral diagram for the stars.

Student view

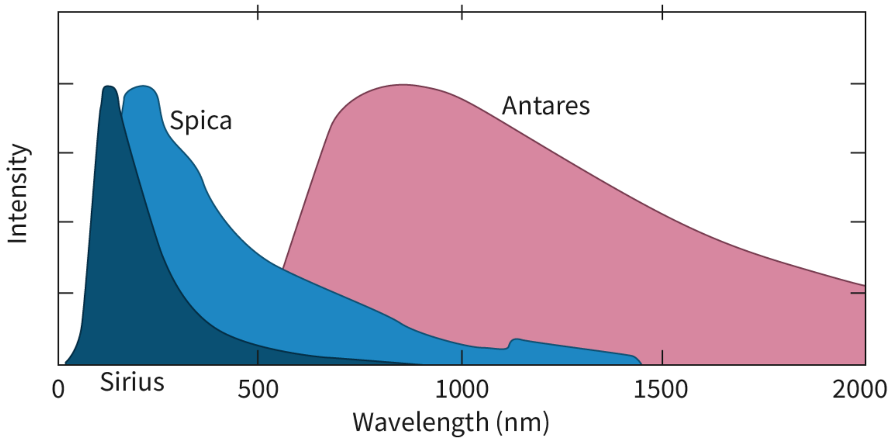

Figure 2. The black body radiation emitted by the stars, as measured from the Earth.

More information for figure 2

The graph is a black body spectral diagram illustrating the radiation emitted by stars Sirius, Spica, and Antares as measured from Earth. The X-axis represents the wavelength in nanometers (nm) ranging from 0 to 2000 nm. The Y-axis shows intensity.

- Sirius is depicted with a dark blue curve, showing a sharp peak at a lower wavelength indicating high intensity at short wavelengths.
- Spica has a light blue curve with a peak around 500 nm, indicating it emits primarily in the visible light range.
- Antares is represented with a pink curve that peaks at a longer wavelength and shows a broader distribution, indicating it emits more in the infrared spectrum.

The graph highlights the differences in emission spectra between these stars, showcasing Sirius' higher intensity at shorter wavelengths compared to Antares' longer wavelengths.

[Generated by AI]

3. Using the data from **Table 1** and **Figure 1**, plot the four stars, approximate 1 $R_\odot$ and 10 $R_\odot$ lines of constant radius, and each star's expected evolution onto a blank HR diagram (**Figure 3**). There is a downloadable version of this diagram below.

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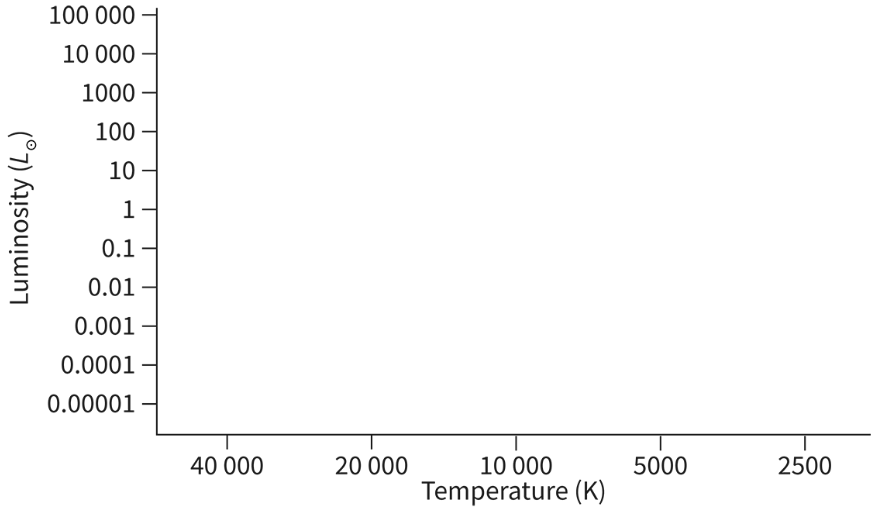

Figure 3. Axes of HR diagram.

More information for figure 3

The image shows a Hertzsprung-Russell (HR) diagram, which is a type of graph used in astronomy to plot stars according to their luminosity (intrinsic brightness) and temperature (or sometimes color or spectral type).

The X-axis represents the temperature of the stars, usually in decreasing order from left to right, labeled with values like '30,000 K', '10,000 K', etc. Alternatively, it can represent spectral type, from O to M.

The Y-axis represents the luminosity of the stars expressed in solar units, with values ranging from '0.0001 L ⊙ ' to '100,000 L ⊙ '.

Several features are depicted on the graph, including the main sequence where most stars lie, and lines of constant radius marked as 1 solar radius (1R ⊙) and 10 solar radii (10R ⊙). Furthermore, the positions of four stars are plotted based on their luminosity and temperature. These features help illustrate the evolutionary paths and characteristics of different stars across the HR diagram.

[Generated by AI]

HR diagram (https://d3vrb2m3yrmyfi.cloudfront.net/media/edusys_2/content_uploads/IB Physics E.5.7 HR diagram.c11f13b34f3e99daa54c.pdf)

From the stars' positions on the HR diagram, name the region each star is in. Suggest and explain the type of fuel likely being burned in the core of the star.

Comment on the relative size of the core between Antares and Sirius as a percentage of the total star size.

1. Adding missing values.

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Overview
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423-
cid-
762593/c

Solution to Table 1. Properties of some stars.

Star name	Mass ($M_\odot$)	Radius ($R_\odot$)	Temperature (K)	Luminosity ($L_\odot$)	Parallax angle (arcseconds)	Distance (pc)
Spica	11.43	**7.54**	**14 500**	2254	1.306×10^{-2}	**76.57**
Sirius	2.06	1.71	10 000	**26**	**0.3792**	2.637
Sun	1.00	1	**5780**	1	N/A	$\mathbf{4.86 \times 10^{-6}}$
Antares	12.00	**898.82**	**3200**	2754	**0.0059**	169.49

Missing temperatures. Spica and Antares: Use the graph in **Figure 1** to estimate the peak wavelength of each star, then use Wien's displacement law to determine the temperature:

$$\lambda_{\max} T = 2.90 \times 10^{-3}\,\mathrm{mK}$$

Sun: Rearrange the Stefan–Boltzmann equation to find the temperature:

$$L = \sigma 4\pi r^2 T^4$$

$$T = \sqrt[4]{\frac{L}{4\pi\sigma r^2}}$$

Missing luminosity. Use the Stefan–Boltzmann to determine the luminosity:

$$L = \sigma 4\pi r^2 T^4$$

The calculated value will be in watts, and the answer is required in terms of $L_\odot$ so you need to divide by $L_\odot$.

Missing radii. Rearrange the Stefan–Boltzmann equation to find the radius:

$$L = \sigma 4\pi r^2 T^4$$

$$r = \sqrt{\frac{L}{\sigma 4\pi T^4}}$$

The calculated value will be in metres, and the answer is required in terms of $R_\odot$ so you need to divide by $R_\odot$.

Student
view

Converting between arcseconds and parsecs. To convert between arcseconds and parsecs, use the following equation and rearrange as required:

Overview (/study/ap 423- cid- 762593/c

$$d\ (\text{parsec}) = \frac{1}{p\ (\text{arcsecond})}$$

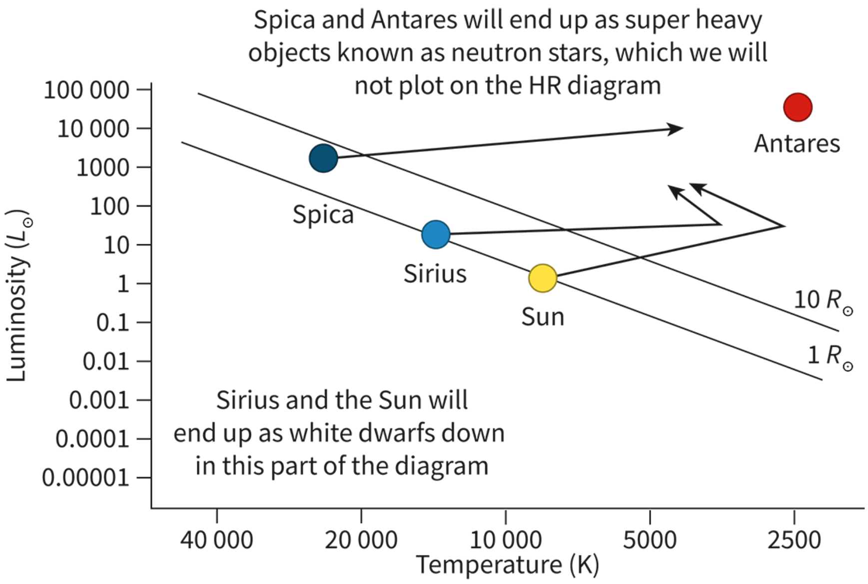
Finding the distance from the Earth to the Sun. Divide 1 AU by the distance of 1 parsec to find the distance between the Sun and the Earth in parsecs.

2. Plotting the stars on the HR diagram.

For the lower mass stars, Sirius (approximately 1.5 $M_\odot$) and the Sun, we expect them to be on the main sequence, then move into red giants, where they will remain until becoming white dwarfs at the end of their lives.

For the higher mass stars, Spica and Antares, which are over 10 $M_\odot$, we expect them to move from the main sequence quickly (due to their high luminosity) and become red supergiants in the later part of their lives. Antares has already moved into the red supergiant phase. This is because it is very large and very cool, but luminous. It is already at the end of its life.

The lines of constant radius can be estimates. Lines of constant radius are parallel to each other and diagonal on the HR diagram. Draw the 1 $R_\odot$ line through the two smaller stars, which are around 1, and the 10 $R_\odot$ line will be higher and parallel to this, just above Spica, which has a radius of about 7 $R_\odot$.



3. Region and type of fuel.

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Overview
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Table 2. Region and type of fuel.

Star name	Region	Fuel	Explanation
Spica	Main sequence	Hydrogen	These stars are in the main sequence. This means they are primarily fusing hydrogen in their cores. As Spica is very massive, it may be fusing some helium, but it is primarily fusing hydrogen.
Sirius	Main sequence	Hydrogen	
Sun	Main sequence	Hydrogen	
Antares	Red supergiant	Carbon, oxygen and heavier elements	As this star is a very large giant star, it has likely fused all its hydrogen and helium and is fusing larger elements. Huge stars can fuse elements all the way up to iron, after which the binding energy per nucleon reduces and energy is required for fusion to take place.

4. Relative size of core between Antares and Sirius.

In the core of Antares, heavier elements are fusing. This means the core has to be extra hot and extra dense to compensate for the increased coulomb forces between the particles. The core in Sirius is fusing hydrogen, a much lighter element with much smaller Coulomb forces. Temperature and pressure do not have to be quite as high for hydrogen nuclei to fuse. The core of Antares is likely to be much smaller proportion of Antares than the core of Sirius is of Sirius.

E. Nuclear and quantum physics / E.5 Fusion and stars

Reflection

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/reflection-id-47890/print/) Assign

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

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Overview
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Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44745/).

- How are elements created?
- What physical processes lead to the evolution of stars?
- Can observations of the present state of the universe predict the future outcome of the universe?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

⚠ Once you submit your response, you won't be able to edit it.

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Submit

Rate subtopic E.5 Fusion and stars

Help us improve the content and user experience.

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