Star in a Box

Exploring the lifecycle of stars

LCOGT.net

Guide to this presentation

White slides are section headings, and are hidden from the presentation. Show or hide the slides in each section as appropriate to the level required.

Rough guide to the levels:

- Beginner: KS3
- Intermediate: KS4 (GCSE)
- Advanced: KS5 (AS/A level)

Introduction

Basics of what a star is and how we observe them.

Level: Beginner +

What is a star?

- A cloud of gas, mainly hydrogen and helium
- The core is so hot and dense that nuclear fusion can occur.
- The fusion converts light elements into heavier ones

Every star is different

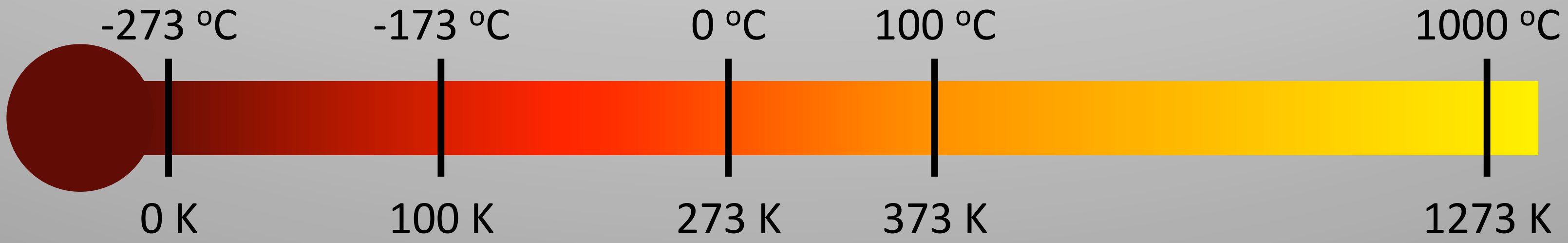
- All the stars in the night sky are different
- Brightness:
  - Tells us how luminous the star is, i.e. How much energy is being produced in the core
- Colour:
  - Tells us the surface temperature of the star

Units of luminosity

- We measure the luminosity of every day objects in Watts.
  - How bright is a light bulb?
- By comparison, the Sun outputs:
  - 380,000,000,000,000,000,000,000,000 Watts
  - (380 million million million million Watts!)
  - This is easier to right as 3.8 x 10^{26} Watts
- To make things easier we measure the brightness of stars relative to the Sun.

Units of temperature

- Temperature is measured in Kelvin
- The Kelvin temperature scale is the same as the Celsius scale, but starts from -273^{o}.
  - This temperature is known as “absolute zero”

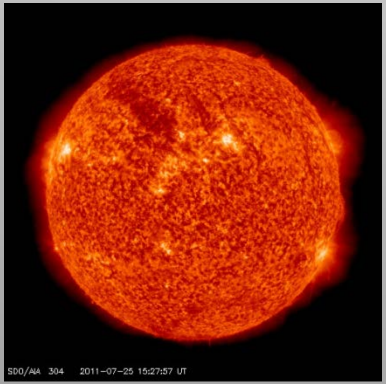


Kelvin = Celsius + 273

Measuring the temperature

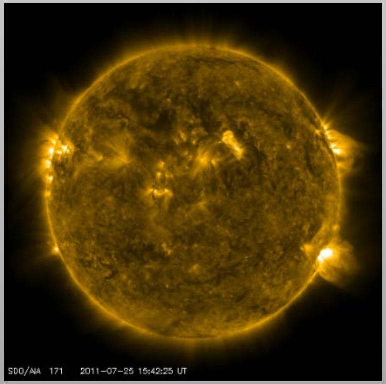
- The temperature of a star is indicated by its colour
- Blue stars are hot, and red stars are cold

Red star



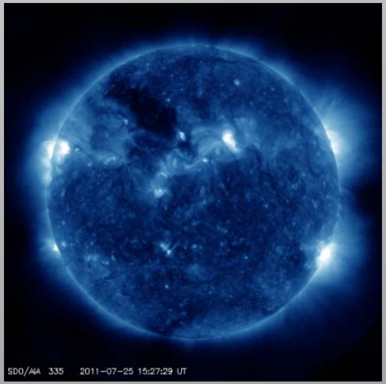
3,000 K

Yellow star



5,000 K

Blue star



10,000 K

Black Body Radiation

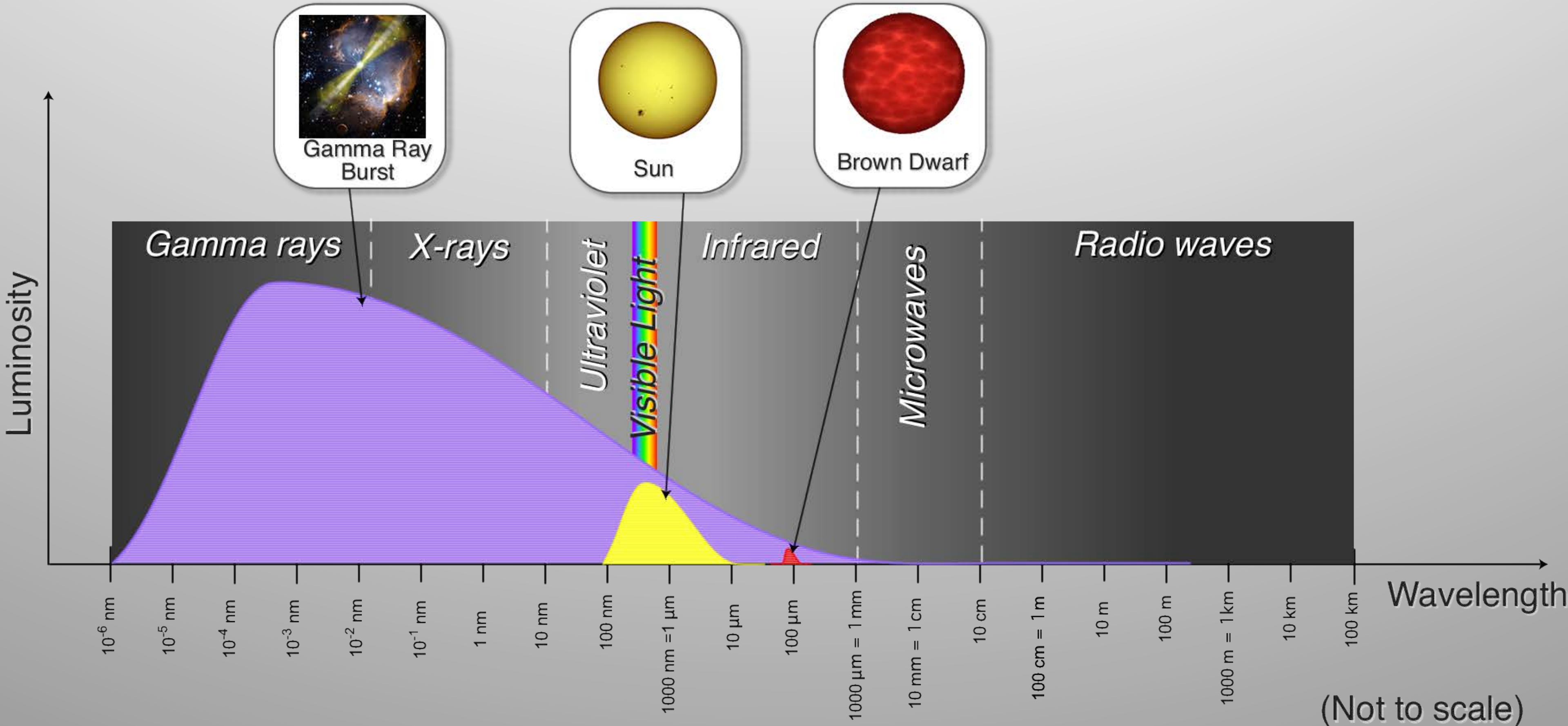
More detail about the colour and temperature of a star, using black body radiation.

Level: Advanced +

Black Body radiation

- A “black body” is a perfect emitter and absorber of light
- It emits light at a range of wavelengths which is dependent on its temperature

Blackbody Radiation



(Not to scale)

Wein’s Displacement Law

- The peak intensity of the light is related to the temperature:

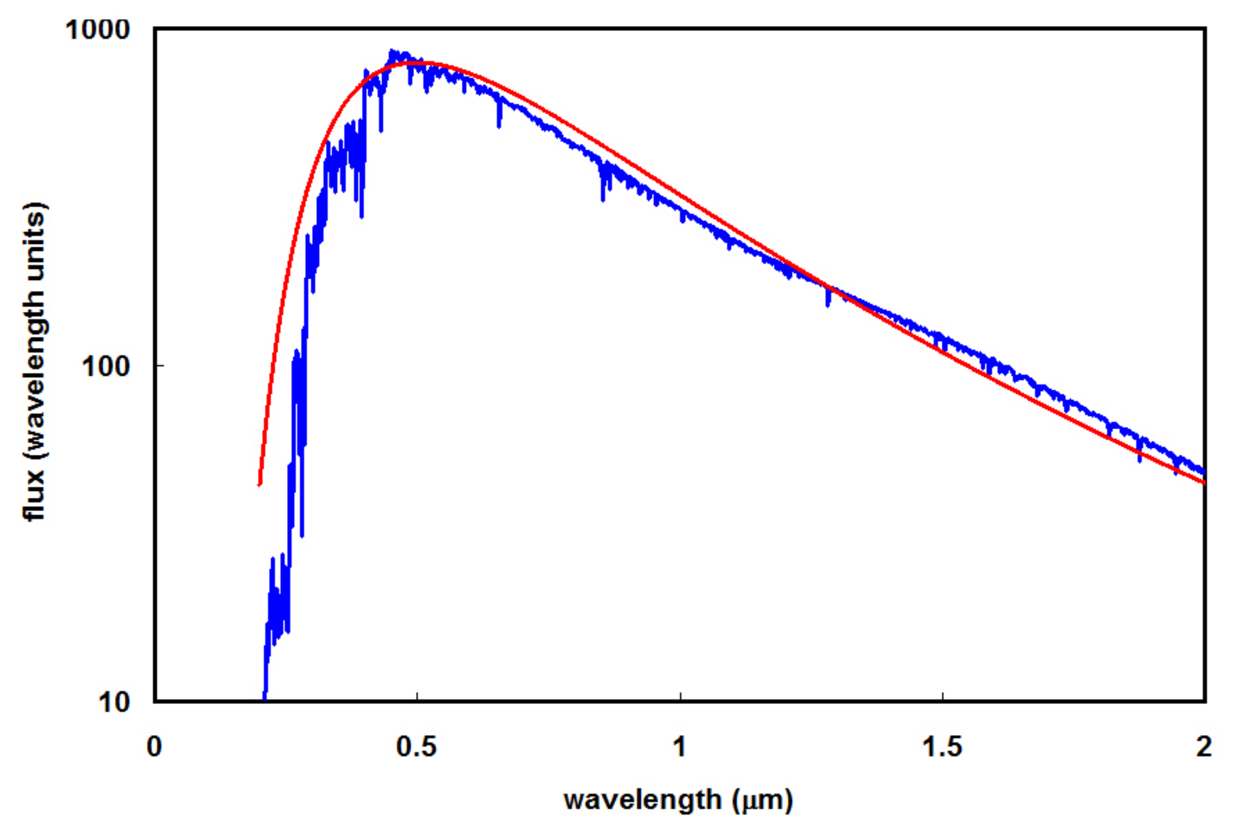
Temperature (K) = Wien’s constant (K.m) / peak wavelength (m)

$$T = \frac{b}{\lambda_{max}}$$

(b = 0.002898 m.K)

How hot is the Sun

- Here is a graph of the Sun’s energy output



How hot is the Sun?

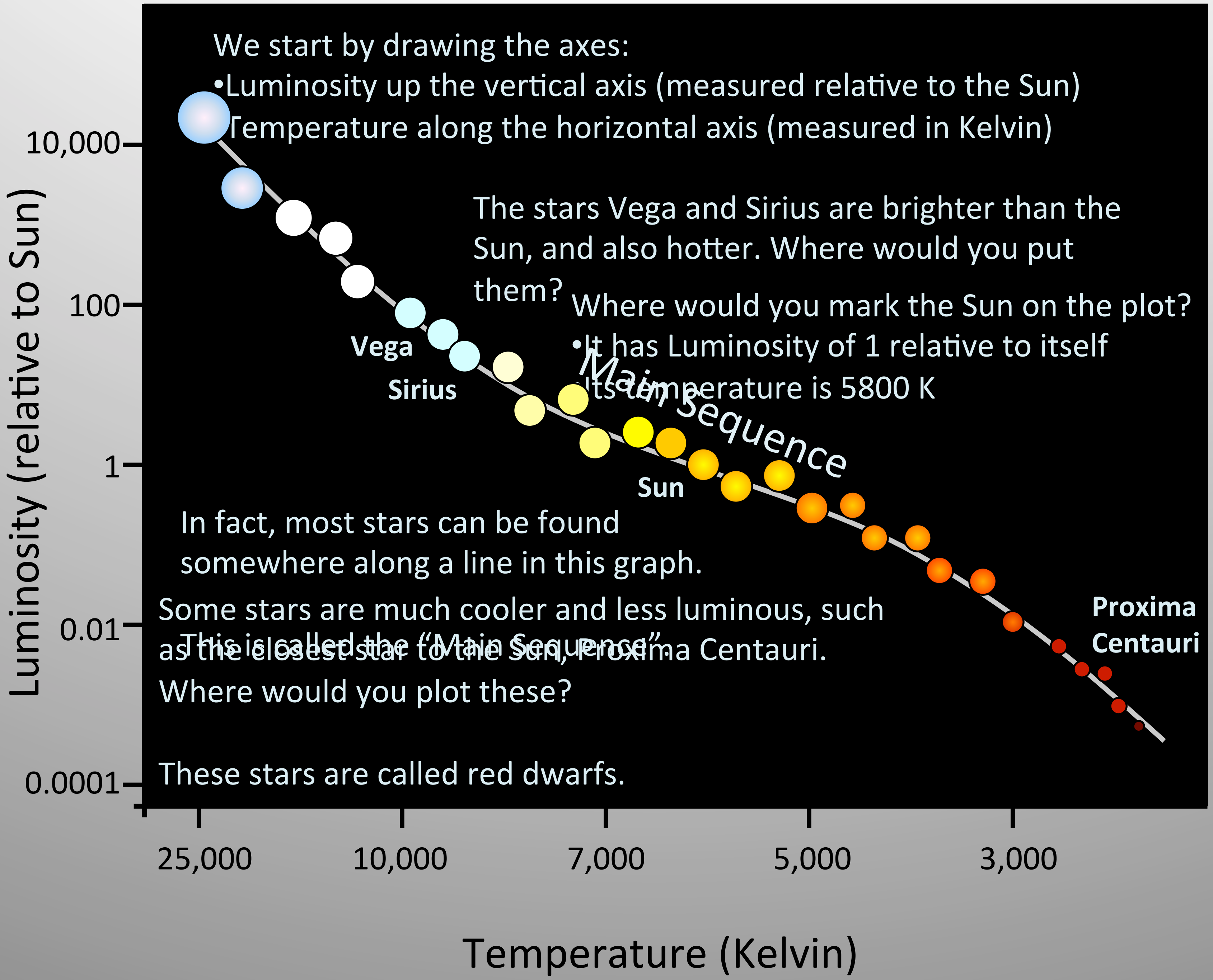
Hertzsprung-Russell Diagram

An introduction to the H-R diagram, on which various stars will be plotted – try to get the students to suggest where they might appear before they are plotted.

Level: Beginner +

The Hertzsprung Russell Diagram

- We can compare stars by showing a graph of their temperature and luminosity



We start by drawing the axes:

- Luminosity up the vertical axis (measured relative to the Sun)
- Temperature along the horizontal axis (measured in Kelvin)

The stars Vega and Sirius are brighter than the Sun, and also hotter. Where would you put them?

Where would you mark the Sun on the plot?

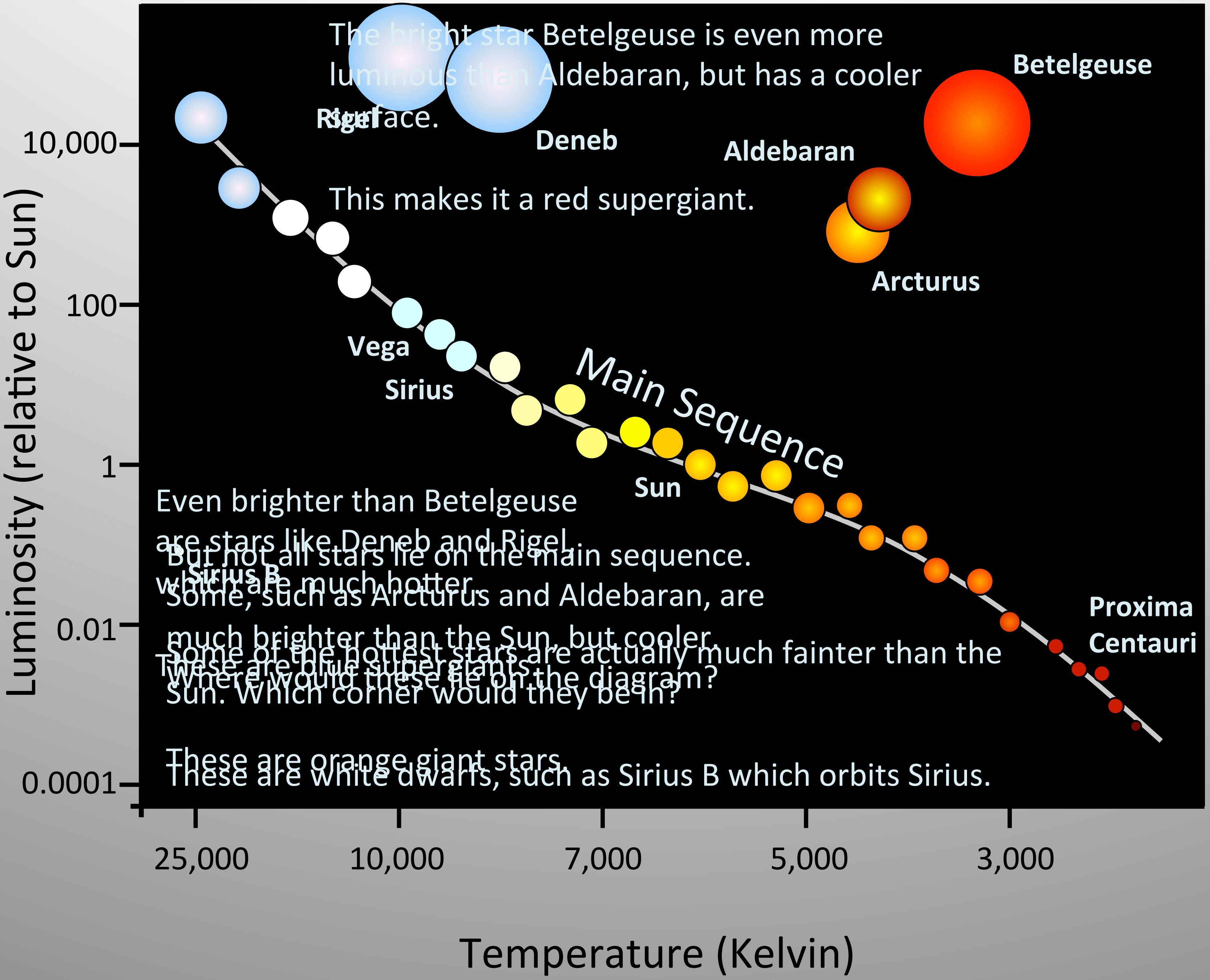
- It has Luminosity of 1 relative to itself
- Its temperature is 5800 K

In fact, most stars can be found somewhere along a line in this graph.

This is called the “Main Sequence”.

Some stars are much cooler and less luminous, such as the closest star to the Sun, Proxima Centauri. Where would you plot these?

These stars are called red dwarfs.



But not all stars lie on the main sequence. Some, such as Arcturus and Aldebaran, are much brighter than the Sun, but cooler. Where would these lie on the diagram?

These are orange giant stars.

The bright star Betelgeuse is even more luminous than Aldebaran, but has a cooler surface.

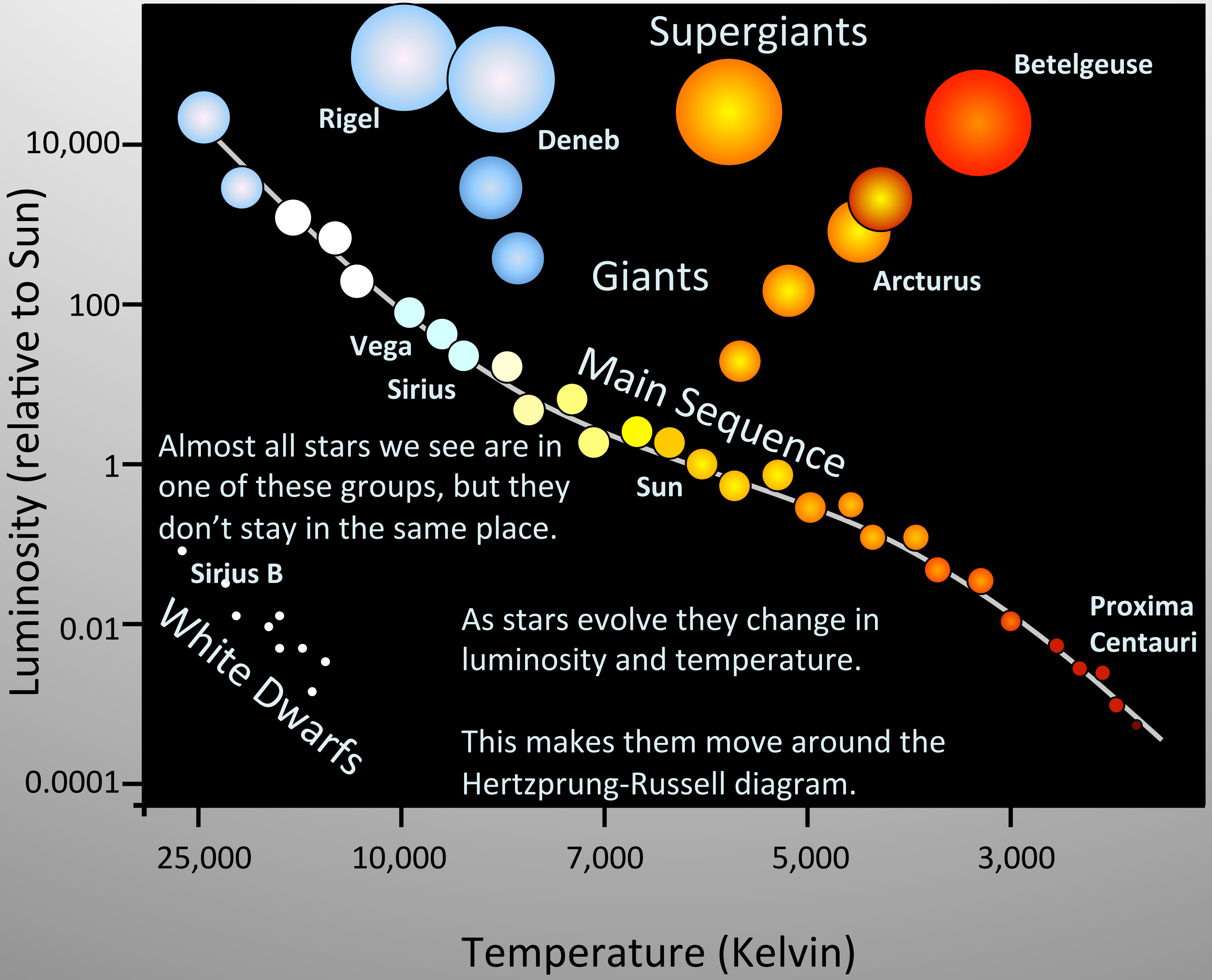
This makes it a red supergiant.

Even brighter than Betelgeuse are stars like Deneb and Rigel, which are much hotter.

These are blue supergiants.

Some of the hottest stars are actually much fainter than the Sun. Which corner would they be in?

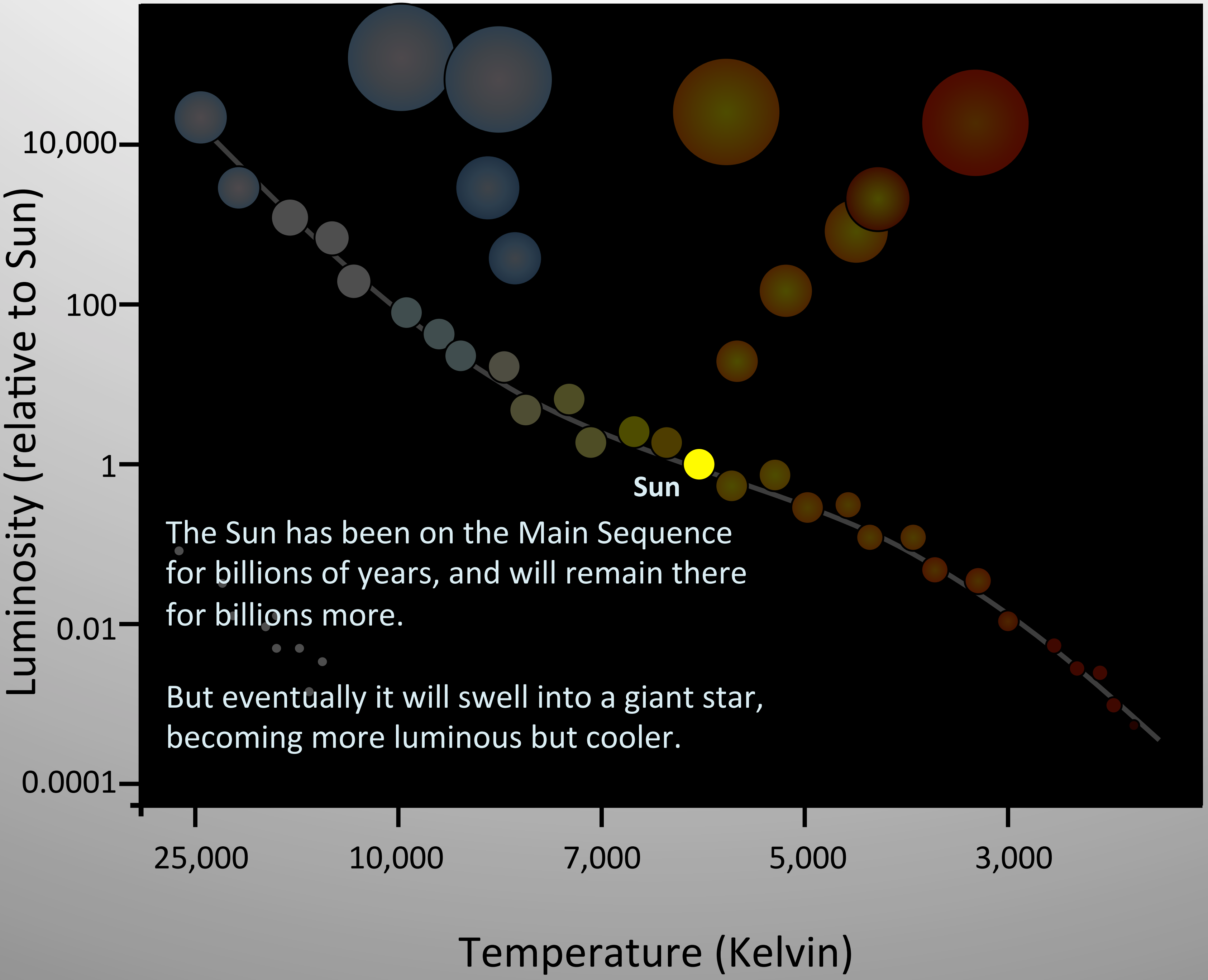
These are white dwarfs, such as Sirius B which orbits Sirius.



Almost all stars we see are in one of these groups, but they don’t stay in the same place.

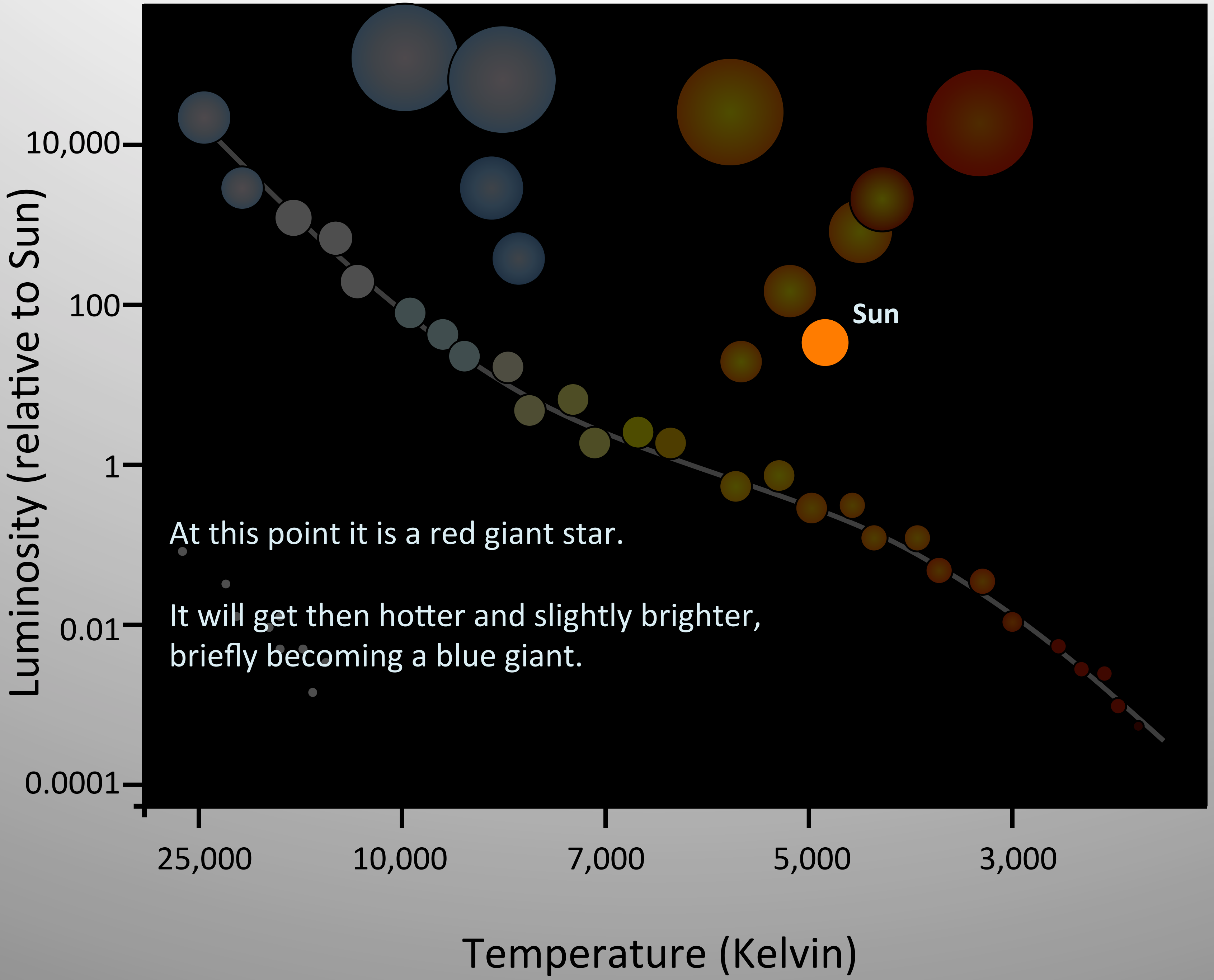
As stars evolve they change in luminosity and temperature.

This makes them move around the Hertzsprung-Russell diagram.



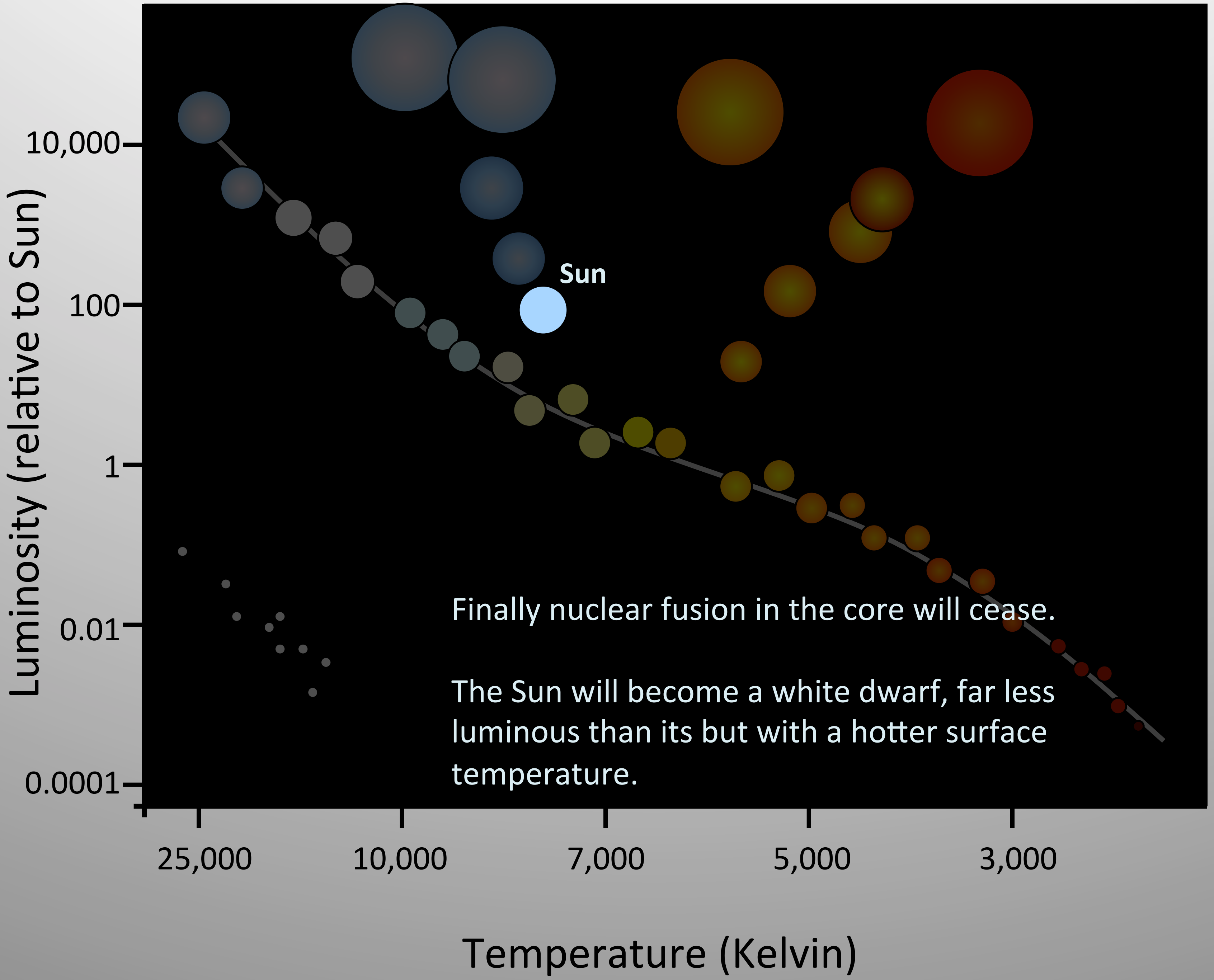
The Sun has been on the Main Sequence for billions of years, and will remain there for billions more.

But eventually it will swell into a giant star, becoming more luminous but cooler.



At this point it is a red giant star.

It will get then hotter and slightly brighter, briefly becoming a blue giant.



Finally nuclear fusion in the core will cease.

The Sun will become a white dwarf, far less luminous than its but with a hotter surface temperature.

Star in a Box

At this point, run star in a box to explore the Hertzsprung-Russell diagram for different mass stars.

Level: Beginner +

Nuclear fusion

The processes taking place in the centre of a star.

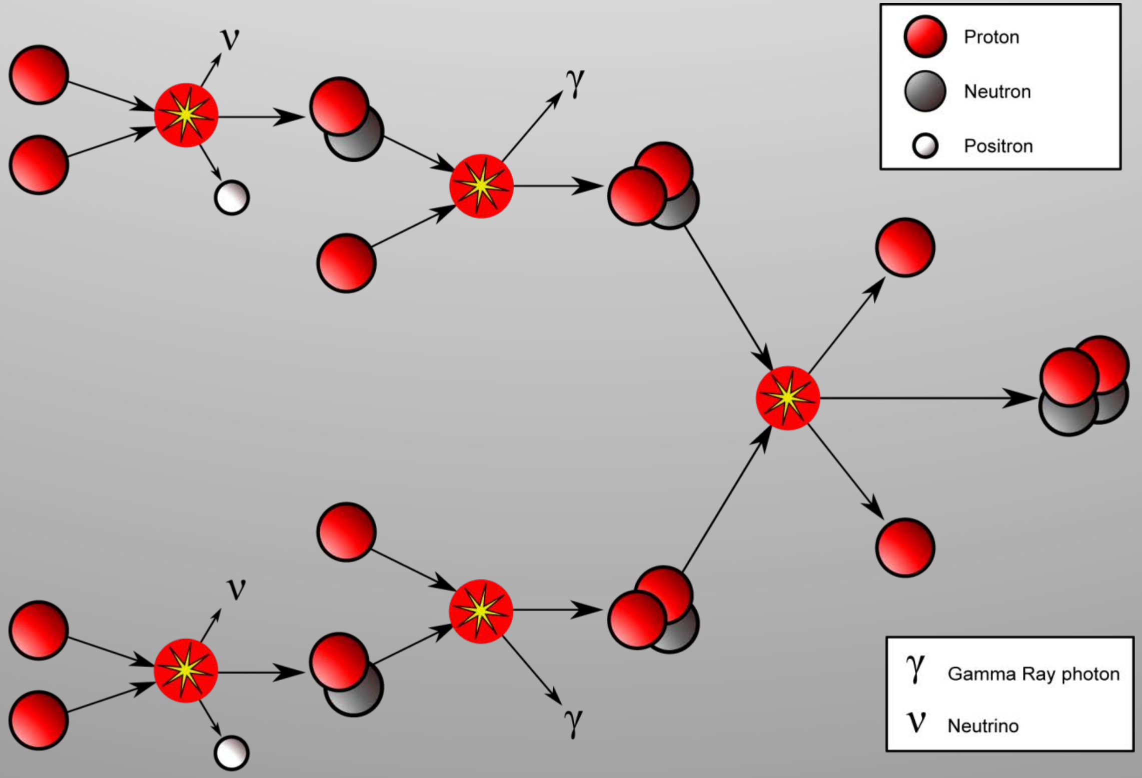
Level: Intermediate +

Nuclear fusion

- The luminosity of a star is powered by nuclear fusion taking place in the centre of the star
  - The temperature and density are sufficient to allow nuclear fusion to occur.
  - Stars are primarily composed of hydrogen, with small amounts of helium.
  - They are so hot that the electrons are stripped from the atomic nuclei.
  - This ionised gas is called a plasma.

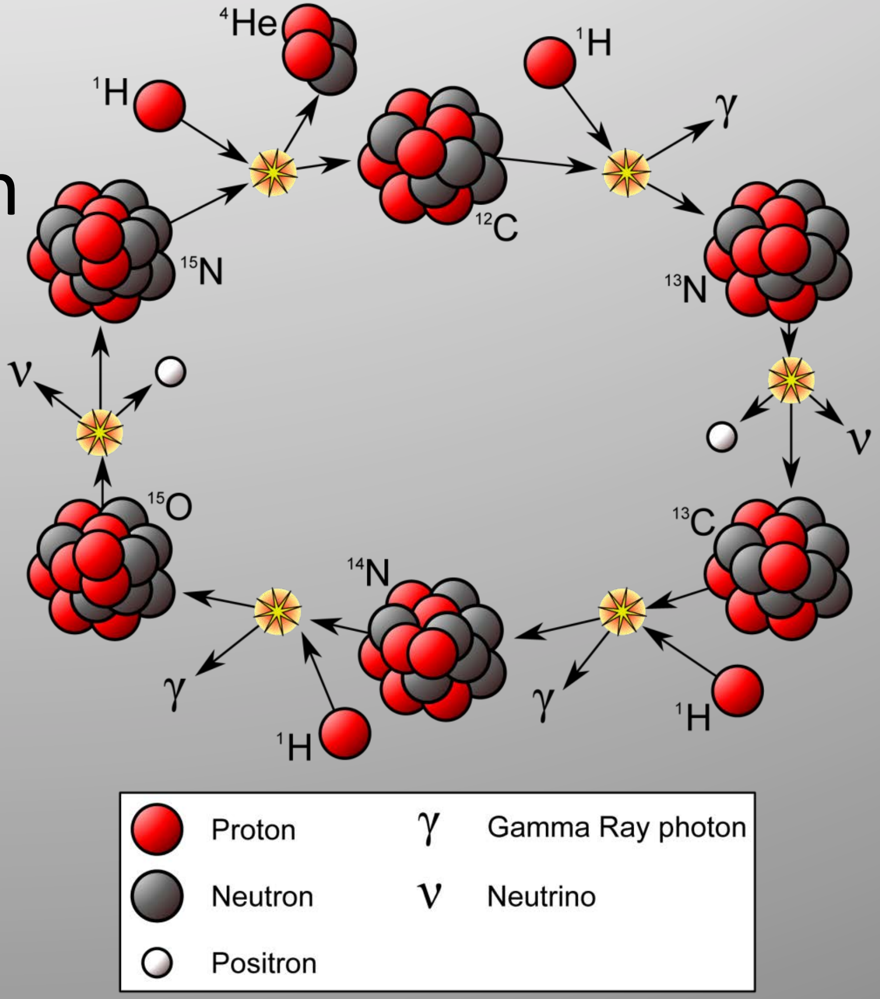
The proton-proton chain

- At temperatures above 4 million Kelvin hydrogen nuclei fuse into helium



The CNO cycle

- At temperatures above 17million Kelvin the star can use carbon, nitrogen and oxygen to help convert hydrogen into helium.

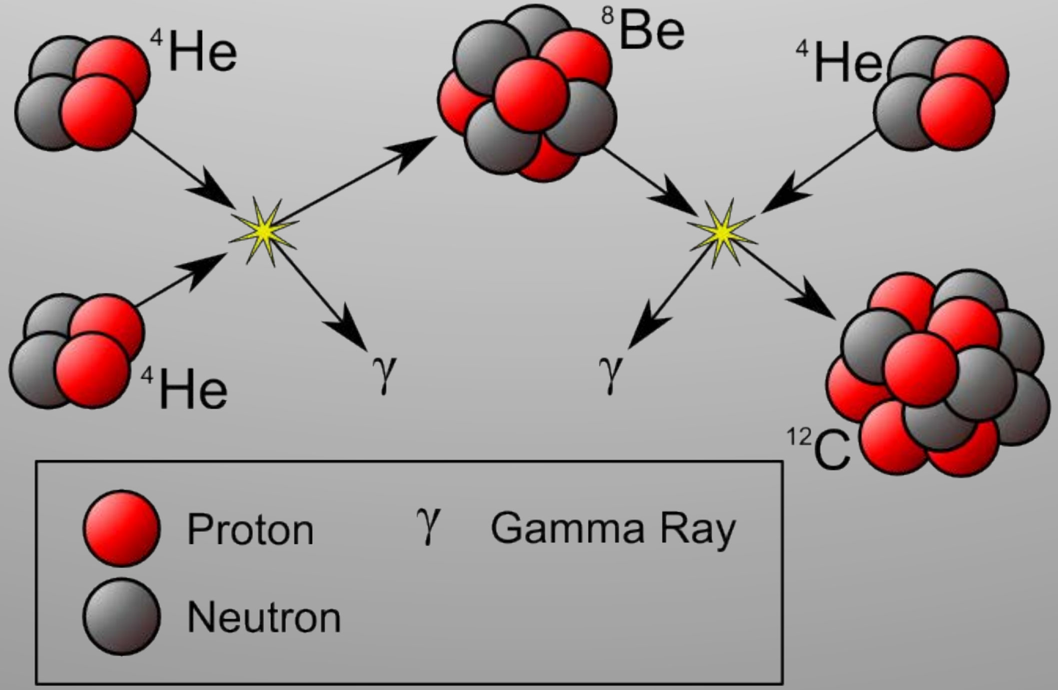


Running out of hydrogen

- The star is kept in a delicate balance between gravity trying to collapse it and radiation pushing it outwards.
- As the hydrogen runs out, the energy released from fusion decreases and the gravity causes the star to collapse.
- If the star is massive enough the core temperature increases until helium fusion starts.

Helium burning

- At temperatures above 100 million Kelvin helium can be fused to produce carbon. This reaction is called the “Triple Alpha process”



Heavier elements

- Helium is fused with carbon to make heavier elements:
  - oxygen, neon, magnesium, silicon, sulphur, argon, calcium, titanium, chromium and iron
- It's impossible to make elements heavier than through nuclear fusion without putting in more energy.

Running out of helium

- Eventually the helium is exhausted, and the star collapses again.
- If it is massive enough, then the temperature increases enough to allow carbon fusion.
- The cycle repeats, fusing heavier elements each time, until the core temperature cannot rise any higher.
- At this point, the star dies.

Burning heavier elements

- Heavier elements undergo fusion at even higher core temperatures
  - Carbon: 500 million Kelvin
  - Neon: 1.2 billion Kelvin
  - Oxygen: 1.5 billion Kelvin
  - Silicon: 3 billion Kelvin

Efficiency of fusion

Level: Advanced

Hydrogen fusion

- The proton-proton chain turns six hydrogen nuclei into one helium nucleus, two protons, and two positrons (anti-electrons)
- The energy released per reaction is tiny, and is measured in “Mega electron Volts”, or MeV.
  - 1 MeV = 1.6 x 10^{-13} Joules
- Each proton-proton chain reaction releases 26.73 MeV

Atomic masses

- The mass of the output is less than the mass of the input, so at every reaction the star loses mass.
- Just like the energies, the masses involved are tiny, measured in “atomic mass units” or u.
  - 1 u = 1.661×10^{-27} kg

Mass loss

- Mass of a proton (p): 1.007276 u
- Mass of a positron (e^+): 0.000549 u
- Mass of a helium nucleus (He): 4.001505 u

- How much mass is lost in every reaction?

- 0.026501 u = 4.4018×10^{-29} kg

Helium burning

- Helium fusion releases 7.275 MeV per reaction
- Carbon-12 has a mass of exactly 12 u. How much mass is lost in the Triple alpha reaction?

- 0.004515 u = 7.499415 x 10^{-30} kg