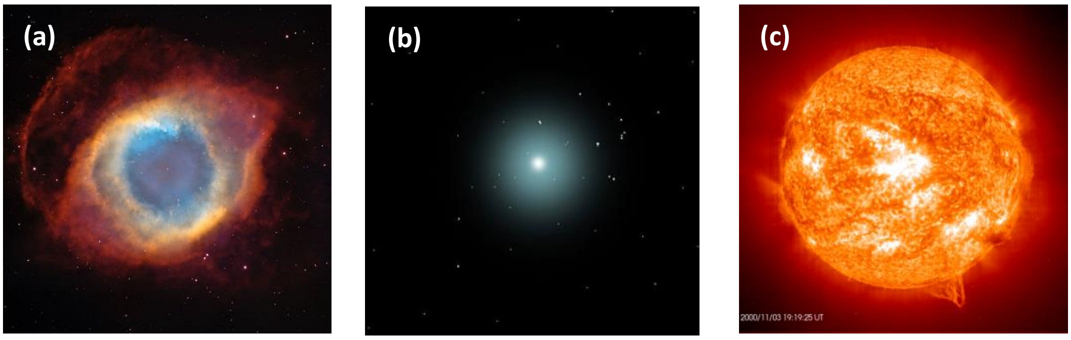
Stellar Lifecycles

Changes in the processes and properties of stars as they evolve over their lifetime

Humans go through various stages throughout their lifetime, beginning as babies, to toddlers, to children, to adolescents, to adults. Stars also go through different stages during their millions to billions of years of life. The Sun for instance, will not spend its entire life in the state we see it today. How a star evolves is highly dependent on the **mass** of the star.

Figure 1 – Guess the astronomical objects? Image Credits: (a) HST/Helix MAST (b) Sephirohg CC BY 3.0 (c) SOHO



Step 1: Take a look at Figures 1 (a), (b) and (c) and consider the following questions:

Do you know what these objects are?

What differences can you see between the objects?

Do you think the objects are all the same size and mass?

Do you think these observations were all made using the same type of telescope?

The objects displayed in Figure 1 represent some of the various stages of stellar lifecycles. Figure 1a is a **planetary nebula**, 1b shows a **white dwarf** and 1c is **the Sun** in its current main sequence stage of its lifecycle.

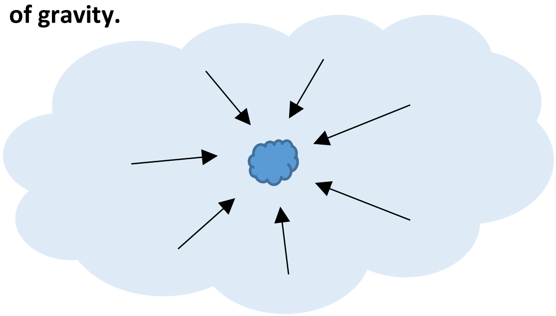
Let's take a closer look at these different stages and stellar lifecycle.

Star Formation

Many galaxies in the Universe contain regions of **gas and dust**. Where conditions are very **cold** (around 10-20 K), gas atoms are able to bind together to form molecules. We call these regions **molecular clouds.**

These molecular clouds are not uniform in density and regions of **higher density will clump together** due to gravity attracting the surrounding material into these regions as shown in Figure 2. As more and more material accumulates, the **mass, pressure** and **temperature** of the cloud **increases** and eventually the material collapses under its own gravity forming what we call a protostar. This process takes place over a period of around **10 million years.**

Figure 2 – Denser regions of a molecular cloud pulling in surrounding material under the force of gravity.



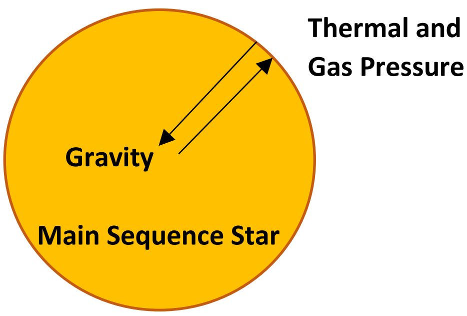
The pressure and temperature of the protostar continues to rise as it accumulates more and more of the surrounding gas and dust. The protostar becomes a star when the pressure is high enough to overcome **electrostatic repulsion,** (where particles of the same charge repel each other when they come close). When this happens, hydrogen nuclei are forced together and **nuclear fusion** of **hydrogen** can begin producing **helium nuclei** and **releasing energy**.

Note: For further details on nuclear fusion see the 'Nuclear Fusion in Stars' worksheet.

Main Sequence Stars

Once nuclear fusion is underway and the inward pull of gravity is balanced with the outward push of the star's internal pressure (Figure 3), the star is said to be in **hydrostatic equilibrium**. At this point, the star is stable and is on the **main sequence** stage of its stellar lifecycle.

Figure 3 – The balancing forces of gravity and radiation pressure in a main sequence star.



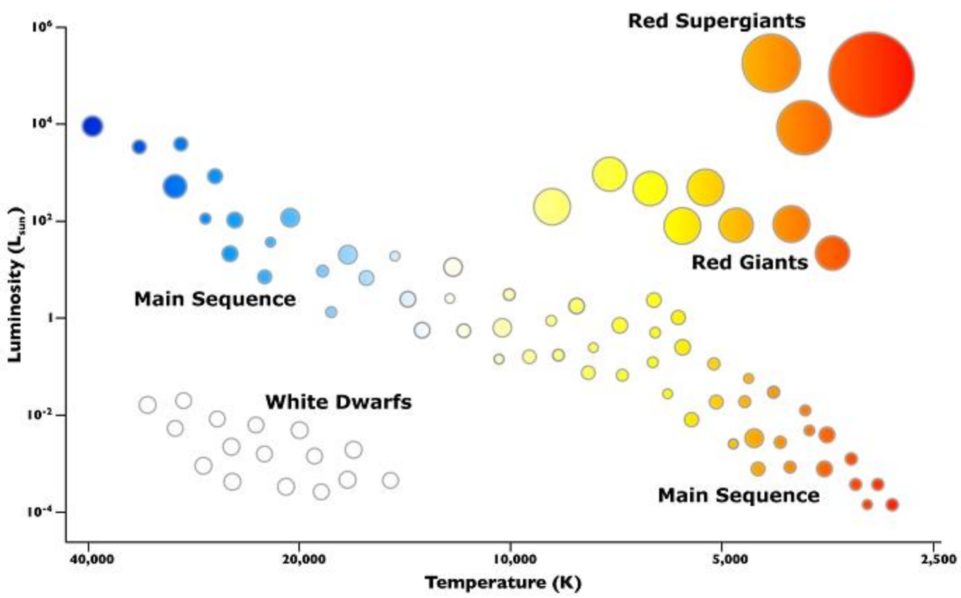
Nuclear fusion is a star's primary energy source which keeps the star alive. The majority of a star's lifetime is spent in the main sequence stage where it is powered by the energy produced in the fusion of **hydrogen** into **helium.** The Sun for example, will spend approximately **10 billion years** on the main sequence.

However, a star's supply of hydrogen is not infinite and it will eventually be exhausted. When this happens, the pressure in the star reduces and gravity becomes the dominant force. This causes the star to **compress** and therefore **rise in temperature**, creating an environment where nuclear fusion of **heavier elements** can occur. If the star is massive enough, heavier elements in the periodic table, up to iron can be produced, any elements heavier than iron are produced in supernova explosions.

As the star's temperature rises and nuclear fusion of heavier elements begins, the **star expands** and evolves into the next phase of its lifecycle. However, not all main sequence stars are identical and how they evolve after the main sequence stage will depend largely on the **mass** of the star.

The evolutionary stages of stars are presented on a **Hertzsprung-Russell (HR) diagram** as seen in Figure 4. HR diagrams plot **surface temperature** (x-axis) against **luminosity** or **magnitude** (y-axis). Stars are not located in the same region on the HR diagram for their entire lifetime, as they age and evolve they will move around the diagram according to the evolutionary processes they go through.

Figure 4 – The various stages of a star's lifecycle. Image Credit: Jon Yardley/Faulkes Telescope Project.



Red Giant Stars

After the main sequence stage, the Sun and other **low mass** stars (up to around 8 solar masses), become **red giants**. Stars of **higher mass**, evolve into **supergiants**.

So just how much do stars expand as they enter the red giant phase?

Let's take a look at the Sun. The Sun is currently a main sequence star with a radius of **6.96 x 10^5 km**. However, when it evolves into its red giant phase, its radius is expected to increase by a factor of approximately **256.**

1/. What will the Sun's *radius* be when it is a *red giant*?

$6.96\ x\ 10^5\ km\ x\ 256 = 1.78\ x\ 10^8\ km$

2/. Using the information in Table 1, which planets in the Solar System would be engulfed by the Sun when it expands into a red giant?

Table 1 – Location of Planetary Orbits in the Solar System	
Planet	**Average Distance from Sun**
Mercury	5.79×10^7 km
Venus	1.08×10^8 km
Earth	1.50×10^8 km
Mars	2.28×10^8 km
Jupiter	7.78×10^8 km
Saturn	1.42×10^9 km
Uranus	2.87×10^9 km
Neptune	4.50×10^9 km

From Table 1 and the value of 1.78×10^8 km students calculated in Question 1, they should realise that this will engulf Mercury, Venus and Earth.

Step 4: How many Earths would you be able to fit inside the Sun when it reaches its red giant size?

Radius of Earth = 6,731 km

Students should recognise to calculate the volume of the Sun using their answer from Step 2 and the Earth radius provided to calculate the Earth's volume using the equation:

$$v = \frac{4}{3}\pi r^3$$

Where:

v = volume (km^3)
r = radius (km)

Volume of Sun:

$$\frac{4}{3} x\ \pi\ x\ (1.78\ x\ 10^8\ km)^3 = 2.36\ x\ 10^{25}\ km^3$$

Volume of Earth:

$$\frac{4}{3} x\ \pi\ x\ (6{,}731\ km)^3 = 1.28\ x\ 10^{12}\ km^3$$

Therefore:

$$\frac{2.36\ x\ 10^{25}\ km^3}{1.28\ x\ 10^{12}\ km^3} = 1.84\ x\ 10^{13}\ Earths$$

Planetary Nebulae, White Dwarfs and Black Dwarfs

Once red giants have exhausted all of their fuel for nuclear fusion they expel the majority of their outer layers into their surrounding space, This is known as a **planetary nebula** (Figure 1a). What remains of the star's core is around a thousand times smaller than the Sun's current size and is called a **white dwarf** (Figure 1b).

White dwarfs have masses similar to the Sun, but in size (radii) they are comparable to the Earth.

Using an equation you are familiar with, what does this information tell us about the density of white dwarfs?

Students should recall the equation for density:

$$density\ (kg\ m^{-3}) = \frac{mass\ (kg)}{volume\ (m^3)}$$

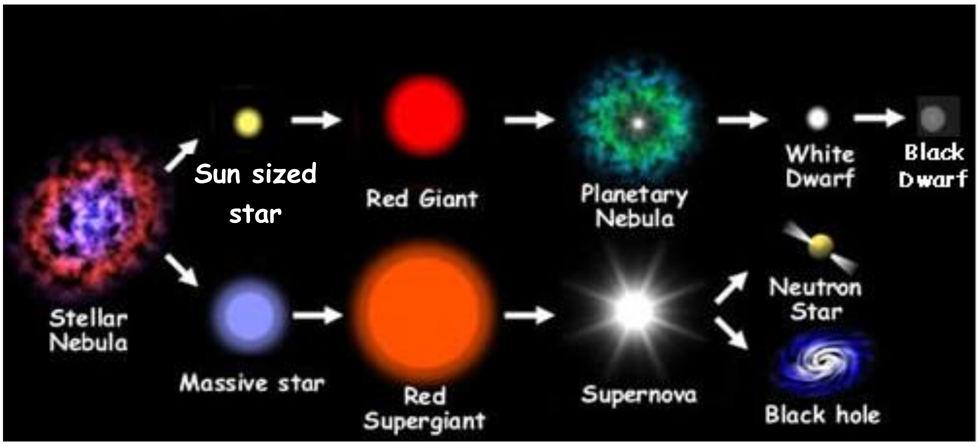
Therefore objects with a large mass and small volume will have high densities.

You will see that this makes white dwarfs very dense objects. White dwarfs gradually fade over time; as their energy and light decreases they become **black dwarfs**. This is a very slow process and happens over an extensive period of time, greater than the age of the whole Universe!

Supernovae and Black Holes

Alternative to the evolution of red giant stars, red supergiants expel their material in a much more explosive way in what is called a **supernova**. After this explosion either a **black hole**, a **neutron star**, or nothing at all is left behind. This is illustrated in Figure 5.

Figure 5 – The different evolutionary paths for stars. Image Credit: NASA



To check your understanding of stellar lifecycles and the HR diagram, see **Quick Quiz 1.**