# A2 Level Physics

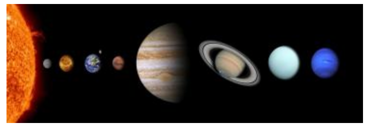
Chapter 16 – Astrophysics and Cosmology

16.1.1 Stars

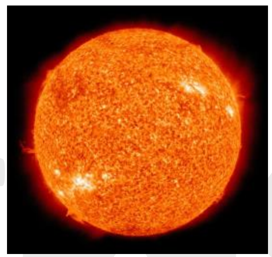
Notes

# The Universe

There are countless galaxies in the universe, each with many stars. It's also packed with interstellar dust and dark matter (neutrinos and black holes), and it's saturated with electromagnetic radiation, mostly in the microwave range.



- A **galaxy** is a cluster of billions of stars that rotate slowly around its centre of gravity. **Our galaxy is the Milky Way**.

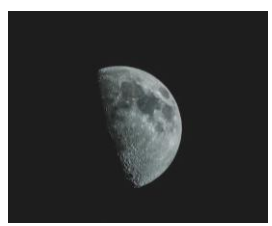


- Our **solar system** is found in the Milky Way. The Sun, planets, asteroids, satellites and comets are all part of the solar system.

- **Stars** are massive nuclear fusion reactors that constantly release large amounts of electromagnetic radiation. **The Sun is a star**.

- **Planets** are relatively cold objects moving in slight elliptical orbits. The **Earth is a planet**.

- **Moons** are natural satellites of planets.





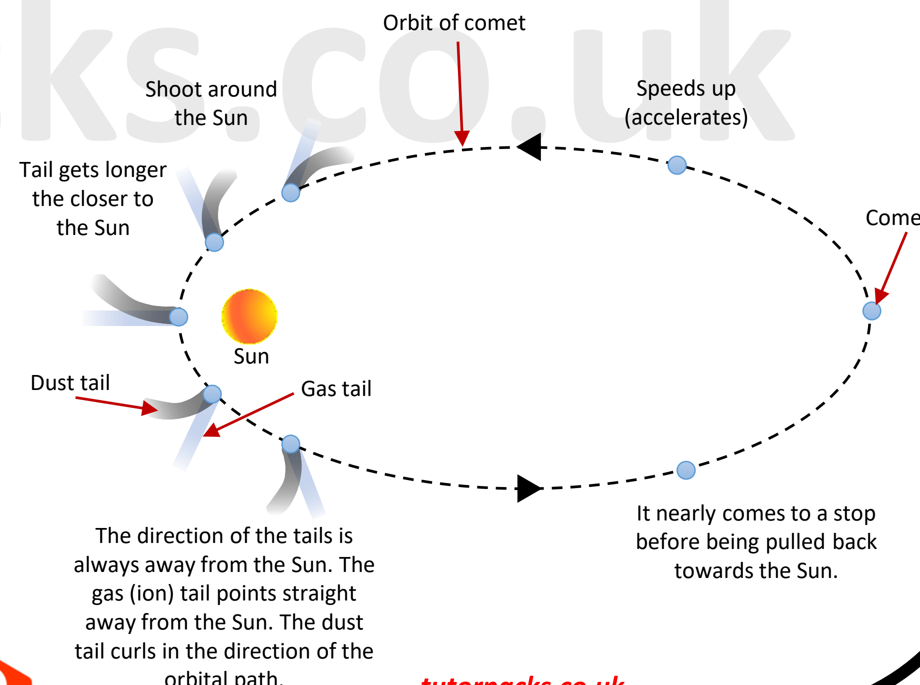
# The Universe

**Comets:**

Consist of ice, rock and a cloud of gas.

The comet's faint tail emerges only when it is close to the Sun, and it always points away from the Sun.

The solar wind, an emission of ions from the Sun's surface, causes the comet's gases to spread out, become ionised and therefore glow creating the tail.



# Formation of a Star

Stars, such as our Sun, go through several stages in their existence and move around the H-R diagram as they do so.

All stars are formed from a cloud of dust and gas (a nebula).

The cloud's denser clumps then contract (slowly) under the force of gravity, causing gravitational collapse and the dust cloud collapses.

Due to gravitational collapse, the temperature of the dust cloud rises. This is because as the density of gases in a nebula increases, the atoms within it are attracted to each other, losing potential energy and gaining kinetic energy.

When these clumps become dense enough, the cloud fragments produce a large core of material known as a protostar, which continues to gather material, increasing its mass, density, and temperature.

The temperature in the protostar's core eventually rises to $10^7\ K$. This indicates an increase in pressure, and hydrogen nuclei begin to fuse together to form helium nuclei under these conditions. This releases a large amount of energy, raising the temperature even higher.

When the gravitational pressure equals the radiation pressure produced by photons released in fusion reactions, a stable-sized star is formed.

The star has now reached the main sequence and will remain there relatively unchanged, fusing hydrogen into helium.

Our Sun is a relatively small, stable main sequence star with a mass of $2 \times 10^{30}\ kg$.

Stars spend most of their lives as main-sequence star. The pressure produced in their core by hydrogen fusion balances the gravitational force that is attempting to compress them. This stage is called core hydrogen burning.



# Formation of a Star

The mass of the nebula from which the star forms determines the stars initial size/mass. This initial mass also determines the star's ultimate fate. Depending on the initial mass the star can go through one of the two processes and come to an end.

**For a star of mass equal to or smaller than the Sun**

The radiation pressure decreases when the fuel is used up. The increase in the gravitational pressure causes the outer layer's helium nuclei to fuse together. The increase in the power production from the helium shell causes the outer layer of the star to expand due to radiation pressure.

As the surface area increases, and the surface temperature decreases, the star evolves into a **Red Giant**.

The core continues to collapse. Helium starts to fuse when the temperature hits $10^8\ K$. This is known as helium flash and the outer layers surrounding the core are blown off in huge clouds of gas and dust known as planetary nebula.

The remaining core is a white dwarf. A white dwarf is very dense. There are no fusion reactions taking place inside, and it has a high surface temperature/low luminosity.

The white dwarfs collapse is prevented by Fermi pressure or electron degeneracy pressure.

Fermi pressure or electron degeneracy pressure prevents further gravitational collapse. The electrons are no longer free to move between energy levels when matter is compressed into a very small volume, such as the incredibly dense core of a collapsing star. When the star contracts, electrons in nearby atoms are forced into the lowest energy levels first. Once the lowest unoccupied energy levels are filled then the electrons occupy the higher and higher energy levels.

Since two or more electrons cannot occupy the same state in the same energy level at the same time, it is impossible to add another electron to a particular volume when all available energy levels are full. It is as if the electrons exert a repulsive outwards force. This is referred to as the Fermi pressure or electron degeneracy pressure.

The electron degeneracy pressure stops further gravitational collapse if a star is not too large, and a stable white dwarf is formed. Remember, only if the stellar remnant is less than a maximum mass known as the Chandrasekhar limit, is when the electron degeneracy pressure sufficient to keep the star from collapsing.

A Chandrasekhar Limit is roughly 1.4 times the mass of the Sun; any white dwarf with a mass less than this will remain a white dwarf forever, whereas a star with a mass more than this will end its life as a supernova.

As the star cools, it transforms into a lump of cold, incredibly dense matter. Then it's a black dwarf.

# Formation of a Star

**For a star of mass greater than the Sun**

When a star with a mass higher than the Sun approaches the end of its red giant phase, it continues to increase its surface area until it becomes a red supergiant.

The mass of a white dwarf formed when the core collapses is larger than 1.4 solar masses. The gravitational pressures are massive, significantly exceeding the Fermi pressure. The electrons within the core combine with protons to produce neutrons and neutrinos. The neutrinos escape, and the central core fills up with neutrons.

The outer shell that surrounds the neutron core collapses rapidly and collides with the solid neutron core. This causes a shock wave, which causes the star's surface layers to burst as a supernova.

Heavy elements like iron and oxygen are blasted into space by the supernova (all elements originate from supernova).

The remnant core of a star with a mass of 3–10 solar masses is a neutron star. For stars of about 3 solar masses, the neutrons core continues to collapse into a black hole.

A solar mass is the mass of the Sun used as a unit of mass. 1 solar mass is equal to $\approx 2.0 \times 10^{30}\ kg$.



# Formation of a Star

**Summary:**

- Star is formed from a cloud of gas and dust (a nebula).
- Gravitational collapse occurs and dust cloud collapses.
- Due to gravitational collapse, the temperature of the dust cloud rises. The KE of the atoms in the cloud increases, causing the cloud to heat up.
- Fusion occurs (when temperature is $\approx 10^7 K$).
- Protons/hydrogen nuclei combine to make helium nuclei and energy.
- Stable size star is produced when radiation pressure is equal to gravitational pressure.

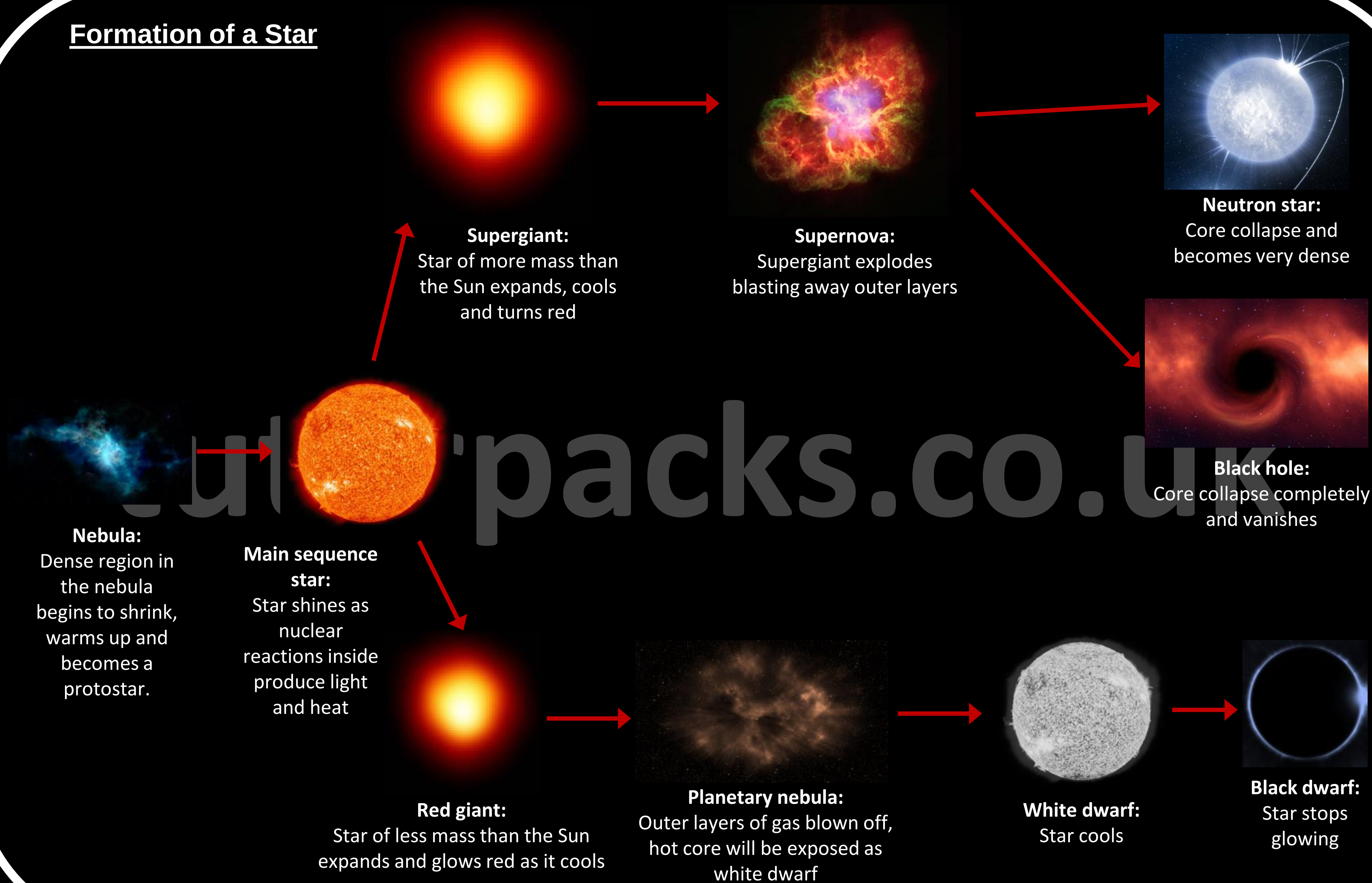
**Stars with a mass smaller than our Sun:**

- When the star's hydrogen runs out, the outer layer expands while the core shrinks.
- Red giant formed and eventually the core becomes a white dwarf.
- The white dwarf is extremely dense, has a high surface temperature, and has a low luminosity, with no fusion reactions.
- Fermi pressure prevents the white dwarf from collapsing.
- Although a red giant is colder than a white dwarf, it has a large surface area and hence emits a lot of energy. As a result, the star shines brightest when it is at its coldest.

**Stars with a mass greater than our Sun:**

- When hydrogen/helium runs out the outer layers of the star expands, forming a super red giant is formed.
- The core of the star collapse rapidly, and a supernova is formed.
- Depending on the initial mass of the star the remnant either a neutron star or a blackhole is formed.

# Formation of a Star



# Formation of a Star

## Neutron Stars

A neutron star is almost entirely made up of neutrons, which are packed as densely as the nucleons in an atom's nucleus.

Neutron stars are incredibly dense. They're very small and have a high rotational speed.

As they rotate, they release two beams of radio waves. These rays occasionally sweep over the Earth and can be seen as radio pulses, similar to lighthouse flashes. These pulsing neutron stars are called pulsars.





# Formation of a Star

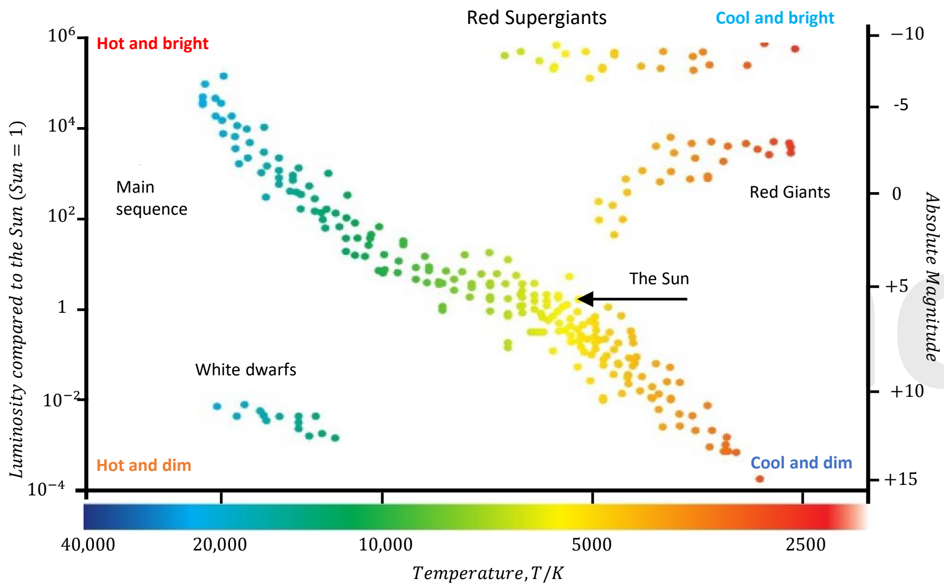
## Black Hole

Black holes are smaller than neutron stars, yet they can hold more matter. This means that their gravitational pull is enormous, so intense that even objects travelling at the speed of light are unable to escape.

Astronomers now believe that every galaxy has a supermassive black hole at its centre. They release tremendous radiation as they consume nearby stars, making galaxies' centres very bright.

# The Hertzsprung-Russell (H-R) Diagram

There is a general correlation between luminosity and star temperature, if you plot a graph of the two. However, keep in mind that the temperature measurement assumes the star behaves like a black body (an idealised physical body capable of absorbing all incident EM radiation regardless of frequency or angle of incidence and emitting all wavelengths of EM radiation). Also, the luminosity measurement is often inaccurate.




This diagram proved to be crucial in the study of star evolution. The main sequence is a diagonal line that runs across the H-R diagram and contains most of the stars we see. These are stable stars that will spend the most of their lives in this state. Their correlation represents the connection between the brightness and high temperature. It's worth noting that the plot is usually drawn with the hotter temps on the left.

# The Hertzsprung-Russell (H-R) Diagram

Other stages of a star's evolution can be seen in other parts of the diagram, although they have a much shorter lifespan than the stable period. As a result, certain areas of the H-R diagram have considerably fewer stars. For example, while blue supergiants burn for only a few million years, most of these have already done so, and we don't see many of them and so the H-R diagram's top left quadrant is lightly populated.

The three separate zones on the H-R diagram, where stars fall, correspond to three main types of stars:

- The long, diagonal band is called the main sequence. Main sequence stars are fusing hydrogen into helium and are in their long-lived stable phase. The Sun is a main sequence star.
- Stars that have a high luminosity and a relatively low surface temperature must have a huge surface area. These stars are known as red giants and are found on the H-R diagram's top-right corner. Red giants are stars that have evolved off the main sequence and are undergoing fusion processes other than hydrogen to helium.
- The Sun will become a red giant in billions of years. It will grow to around 20% the size of Earth's current orbit and shine 3000 times brighter than it does now.
- Stars that have a low luminosity, but a high temperature must be very small. These stars are known as White Dwarfs, and they are roughly the same size as the Earth. They are found in the H-R diagram's bottom left corner. White dwarfs are stars that have reached the end of their lives and are progressively cooling down since all of their fusion processes have ended.

**Tip: Make sure you know the axis scales by heart, as you may be required to draw an H-R diagram in your exam.**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Please see **’16.1.2 Stars worked examples’** pack for exam style questions.

For more revision notes, tutorials and worked examples please visit www.tutorpacks.co.uk.