19 STARS

19.1 Objects in the Universe

Specification reference: 5.5.1

Learning outcomes

Demonstrate knowledge, understanding, and application of:

→ the terms planets, planetary satellites, comets, solar systems, galaxies, and the Universe

→ the formation of a star from interstellar dust and gas in terms of gravitational collapse, fusion of hydrogen into helium, radiation, and gas pressure.

▲ **Figure 1** *The Horsehead Nebula gets its name from one of the swirling clouds of dark dust and gases that resembles a horse's head*

Stellar nurseries

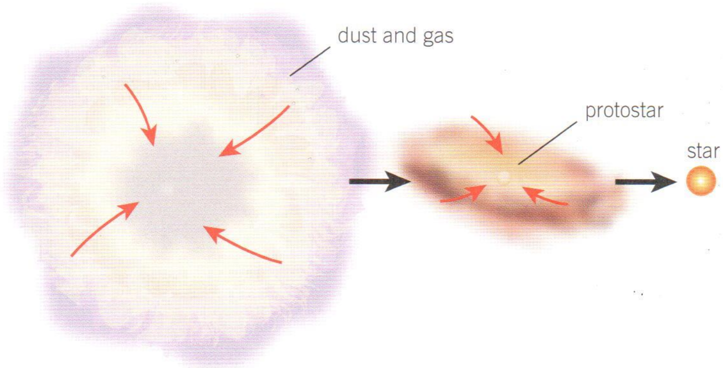
The **Universe** contains countless amazing objects, including the spectacular Horsehead Nebula in our own galaxy. **Nebulae** are gigantic clouds of dust and gas (mainly hydrogen), often many hundreds of times larger than our Solar System. The scale is difficult to comprehend.

Nebulae are often referred to as stellar nurseries, as they are the birthplace of all stars. Every star you see in the night sky is on its own journey from birth to eventual death. Our very own Sun was born in a nebula, and it too will eventually die.

Star birth

Nebulae are formed over millions of years as the tiny gravitational attraction between particles of dust and gas pulls the particles towards each other, eventually forming the vast clouds.

As the dust and gas get closer together this gravitational collapse accelerates. Due to tiny variations in the nebula, denser regions begin to form. These regions pull in more dust and gas, gaining mass and getting denser, and also getting hotter as gravitational energy is eventually transferred to thermal energy. In one part of the cloud a **protostar** forms – this is not yet a star but a very hot, very dense sphere of dust and gas.



▲ **Figure 2** *A single protostar forming a star from the gravitational collapse of an interstellar cloud of dust and gas*

For a protostar to become a star, **nuclear fusion** needs to start in its core. Many protostars never reach this stage. Fusion reactions produce energy in the form of kinetic energy. Extremely high pressures and temperatures inside the core are needed in order to overcome the electrostatic repulsion between hydrogen nuclei in order to fuse them together to form helium nuclei. In some cases, as more and more mass is added to the protostar, it grows so large and the core becomes so hot that the kinetic energy of the hydrogen nuclei is large enough to overcome the electrostatic repulsion. Hydrogen nuclei are forced together to make helium nuclei as nuclear fusion begins. A star is born.

Star life

Once a star is formed, it remains in a stable equilibrium with almost a constant size. Gravitational forces act to compress the star, but the **radiation pressure** from the photons emitted during fusion and the **gas pressure** from the nuclei in the core push outwards. The force from this radiation and gas pressure balances the force from the gravitational attraction and maintains equilibrium.

Stars in this stable phase of their lives are described as being on their **main sequence**. How long a star remains stable depends on the size and mass of its core. The cores of large, massive supergiant stars are much hotter than those of small stars, releasing more power and converting the available hydrogen into helium in a much shorter time. Really massive stars are only stable for a few million years, whereas smaller stars like our Sun are stable for tens of billions of years.

What happens when a star runs low on hydrogen fuel in its core is discussed in Topic 19.2, The life cycle of stars.

Beyond stars

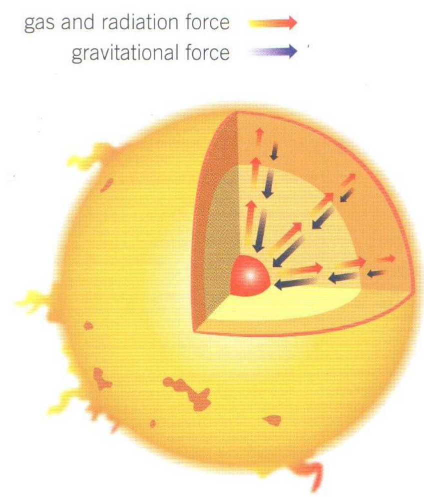
The Universe contains a variety of other objects beyond stars (Table 1).

▼ Table 1

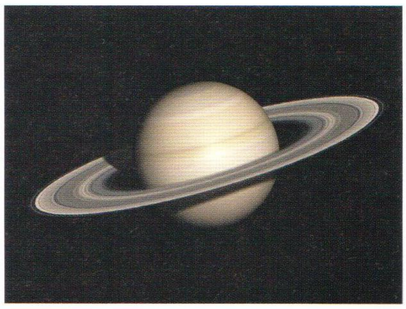
Objects within the Universe	Description
Planets	A planet (named from the ancient Greek 'wanderer') is an object in orbit around a star with three important characteristics: • it has a mass large enough for its own gravity to give it a round shape (unlike the irregular shape of asteroids) • it has no fusion reactions (unlike a star) • it has cleared its orbit of most other objects (asteroids, etc.).
Dwarf planets*	A dwarf planet, like Pluto, has one important difference from a planet. Dwarf planets have not cleared their orbit of other objects. In Pluto's case there are many other bodies of comparable size close to its orbit.
Asteroids*	Asteroids are objects too small and uneven to be planets, usually in near-circular orbits round the Sun and without the ice present in comets.
Planetary satellites	A planetary satellite is a body in orbit around a planet. This includes moons and man-made satellites.

Synoptic link

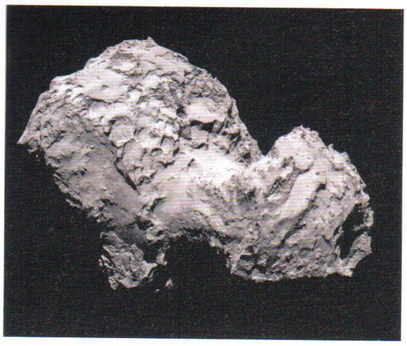
Nuclear fusion and the formation of new elements in stars is covered in detail in Topic 26.4, Nuclear fusion.



▲ **Figure 3** *The radiation and gas pressures in the core balance the pressure created by the gravitational attraction so that the shape of the star remains stable*



▲ **Figure 4** *Saturn is perhaps the most beautiful of all the planets orbiting the Sun, and has the largest number of planetary satellites and countless pieces of ice and rock that make up its rings*



▲ **Figure 5** *Comet Churyumov–Gerasimenko photographed by the Rosetta spacecraft. The space probe Philae landed on this comet in November 2014.*

▼ **Table 1** *(continued)*

Comets	Comets range from a few hundred metres to tens of kilometres across. They are small irregular bodies made up of ice, dust, and small pieces of rock. All comets orbit the Sun, many in highly eccentric elliptical orbits. As they approach the Sun, some comets develop spectacular tails.
Solar systems	Our Solar System contains the Sun and all objects that orbit it (planets, comets, etc.). It is one of many. In 2014 over 1100 other solar systems (sometimes called planetary systems) have been discovered.
Galaxies	A galaxy is a collection of stars, and interstellar dust and gas. On average a galaxy will contain 100 billion stars, a significant proportional of which have their own solar systems. Our galaxy is known as the Milky Way.

*Not examined in the A Level course

Defining what we mean by our Universe is a little more complex. Our Universe is quite literally everything! It is all electromagnetic radiation, energy and matter, all of space-time and everything that exists within it. This includes all the galaxies and all the contents of intergalactic space (including subatomic particles). This topic has given you some insight into the vastness of the Universe.

Summary questions

1 Sort the objects in Table 1 into a generalised list from smallest to largest. *(2 marks)*

2 Explain why nuclear fusion in the core of a star prevents further gravitational collapse. *(2 marks)*

3 Describe the similarities and differences between planets and comets. *(2 marks)*

4 Explain why larger stars tend to spend less time in their main-sequence phase. *(2 marks)*

5 The Sun has a radius of 7.0×10^5 km and an average density of 1410 kg m^{-3}. Calculate:

a the mass of the Sun;

b the ratio of the volume of Sun to the volume of the Earth ($m_{Earth} = 5.97 \times 10^{24}$ kg, $r_{Earth} = 6730$ km)

c the number of atoms within the Sun if the average spacing between each atom is around 10^{-10} m. *(5 marks)*

19.2 The life cycle of stars

Specification reference: 5.5.1

Birth, life, and death

Orion is one of the most instantly recognisable constellations. It is rather unusual, as it contains several bright stars in different stages of their life cycle. It even includes a nebula.

One of the brightest stars in Orion, Betelgeuse (top left), is a **red supergiant**. This huge star is in the last stages of its life and will soon 'explode' in an enormous **supernova** (in fact, it may have already happened, and the light from this blast could be on its 700-year journey towards us). Our Sun's ending will be far less spectacular than that of Betelgeuse. What happens to a star as it dies depends on the mass of the star.

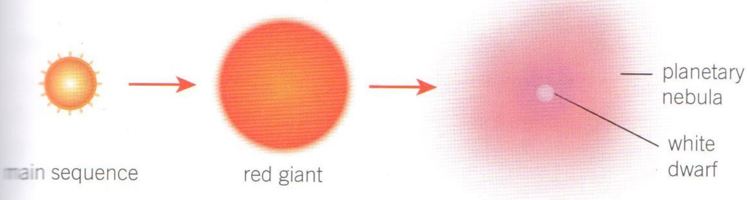
Stars with low mass

Since the core of stars with low mass is cooler than that of more massive stars, they remain on their main sequence for much longer. However, eventually, often after billions of years, they run low on hydrogen fuel in their core. At this stage, they begin to move off the main sequence into the next phase of their lives.

Red giants

Stars between 0.5 $M_\odot$ and 10 $M_\odot$ will evolve into **red giants**. At the start of the red giant phase, the reduction in energy released by fusion in the core means that the gravitational force is now greater than the reduced force from radiation and gas pressure. The core of the star therefore begins to collapse. As the core shrinks, the pressure increases enough to start fusion in a shell around the core.

Red giant stars have inert cores. Fusion no longer takes place, since very little hydrogen remains and the temperature is not high enough for the helium nuclei to overcome the electrostatic repulsion between them. However, fusion of hydrogen into helium continues in the shell around the core. This causes the periphery of the star to expand as layers slowly move away from the core. As these layers expand, they cool, giving the star its characteristic red colour. In about 4 billion years from now, when our Sun expands into a red giant, it will engulf Mercury and Venus, stopping just short of the Earth.



▲ **Figure 2** *The evolution of stars of lower mass, from main sequence to red giant and ending with white dwarf. The planetary nebula may collapse again to form another star, or even a solar system with its own planets (which explains its name).*

Learning outcomes

Demonstrate knowledge, understanding, and application of:

- → evolution of a low-mass star like our Sun into a red giant and white dwarf
- → planetary nebula
- → characteristics of a white dwarf; electron degeneracy pressure; Chandrasekhar limit
- → evolution of a massive star into a red supergiant and then either a neutron star or black hole; supernova
- → characteristics of neutron stars and black holes.

Study tip

Solar mass $M_\odot$ is the mass of the Sun, about 1.99×10^{30} kg.

▲ **Figure 1** *The constellation of Orion the hunter contains many bright stars, three of which form its famous belt, and a nebula, just below the belt*

White dwarfs, electron degeneracy pressure, and the Chandrasekhar limit

Eventually most of the layers of the red giant around the core drift off into space as a **planetary nebula**, leaving behind the hot core as a **white dwarf**. The white dwarf is very dense, often with a mass around that of our Sun, but with the volume of the Earth. No fusion reactions take place inside a white dwarf. It emits energy only because it leaks photons created in its earlier evolution. The surface temperature of a white dwarf can be as much as 30 000 K.

▲ **Figure 3** *Subrahmanyan Chandrasekhar calculated the Chandrasekhar limit whilst still at university, and was awarded the 1983 Nobel Prize for Physics for his later work on black holes*

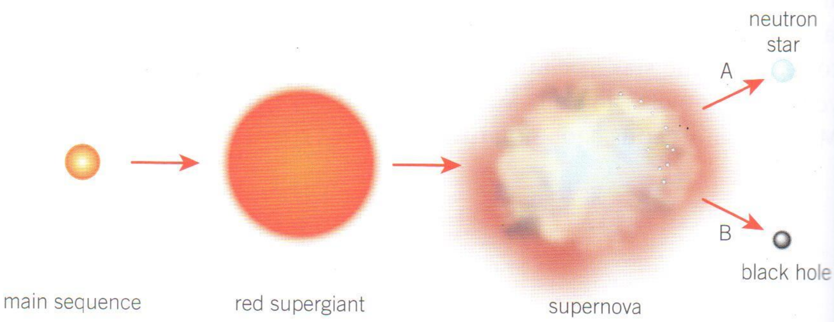
According to an important rule of quantum physics, the Pauli exclusion principle, two electrons cannot exist in the same energy state. When the core of a star begins to collapse under the force of gravity, the electrons are squeezed together, and this creates a pressure that prevents the core from further gravitational collapse. This pressure created by the electrons is known as **electron degeneracy pressure**.

But there is a limit. The electron degeneracy pressure is only sufficient to prevent gravitational collapse if the core has a mass less than $1.44 M_{\odot}$. This is called the **Chandrasekhar limit** – named after the astrophysicist Subrahmanyan Chandrasekhar (Figure 3), who improved the model used to describe the star when he was just 19 years old. This limit is the maximum mass of a stable white dwarf star. If the core is more massive than this, the star's life takes a more dramatic turn.

More massive stars

Stars with a mass greater than $10 M_{\odot}$ live very different lives. Since their mass is much greater, their cores are much hotter. They consume the hydrogen in their core in much less time, some in only a few million years.

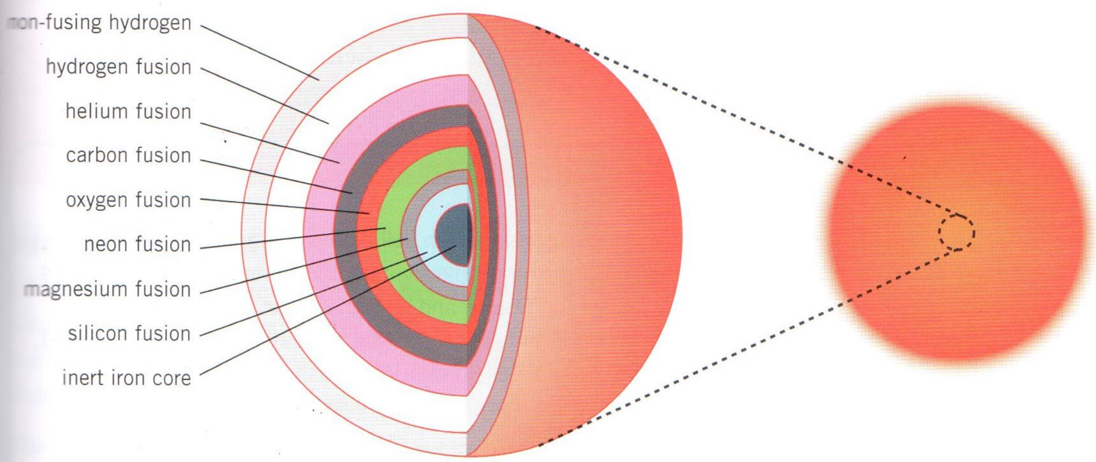
As with stars with smaller masses, when the hydrogen in the core runs low, the core begins to collapse under gravitational forces. However, as the cores of these more massive stars are much hotter, the helium nuclei formed from the fusion of hydrogen nuclei are moving fast enough to overcome electrostatic repulsion, so fusion of helium nuclei into heavier elements occurs.



▲ **Figure 4** *The evolution of more massive stars*

Red supergiants

These changes in the core cause the star to expand, forming a red supergiant (sometimes called super red giant). Inside, the temperatures and pressures are high enough to fuse even massive nuclei together, forming a series of shells inside the star (Figure 5).



▲ **Figure 5** *Inside a red supergiant the core is made of onion-like layers in which different elements are created by fusion, with heavier elements deeper in, up to the central core, made of stable iron nuclei that cannot fuse any further*

This process continues until the star develops an iron core. Iron nuclei cannot fuse, because such reactions cannot produce any energy. This makes the star very unstable and leads to the death of the star in a catastrophic implosion of the layers that bounce off the solid core, leading to a shockwave that ejects all the core material into space. This 'explosion' is called a (type II) supernova.

Synoptic link

You will learn about the importance of the fusion of lighter elements up to iron in Topic 26.2, Binding energy.

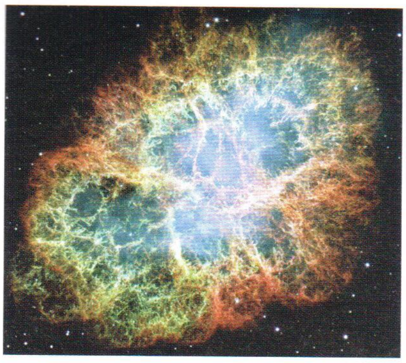
Supernova and beyond

For more massive stars, at a critical point (depending on the mass of the star) the nuclear fusion taking place in the core suddenly becomes unable to withstand the crushing gravitational forces. The star collapses in on itself, leading to a supernova. Afterwards, the remnant core is compressed into one of two objects:

- **Neutron star**: If the mass of the core is greater than Chandrasekhar limit, the gravitational collapse continues, forming a neutron star. These strange stars are almost entirely made up of neutrons and can be very small – just 10 km in diameter. They have a typical mass of $2M_{\odot}$ and densities similar to that of an atomic nucleus ($\sim 10^{17}\,kg\,m^{-3}$).
- **Black hole**: If the core has a mass greater than about $3M_{\odot}$, the gravitational collapse continues to compress the core. The result is a gravitational field so strong that in order to escape it an object would need an escape velocity greater than the speed of light. Nothing, not even photons, can escape a black hole. Black holes vary in mass. Super-massive black holes with masses of several million $M_{\odot}$ are thought to be at the centre of most galaxies.

Supernovae are rare — the last recorded in our galaxy was back in 1604. But they are so luminous that we can see them in even the most distant of galaxies. Their output power is so great that sometimes they are brighter than the rest of their galaxy, radiating more energy in a few thousandths of a second than our Sun will in its entire lifetime.

Supernovae create all the heavy elements. Everything above iron in the Periodic Table was created in a supernova, and such events help



▲ **Figure 6** *The neutron star at the centre of the Crab Nebula sends out regular pulses, proving that the nebula must result from a historical supernova*

Summary questions

1 Explain why heavier elements are not formed in the core of a red giant star. *(2 marks)*

2 Describe the process of the creation of heavier elements (nucleosynthesis) and how these elements come to be found distributed throughout the Universe. *(4 marks)*

3 Calculate the minimum and maximum values of the mass of a star that will form a red giant. *(2 marks)*

4 A neutron star has a density of 1.0×10^{17} kg m^{-3}. Calculate: **a** the mass of a 1.0 cm^3 piece of the star; **b** the volume of the star that would have the same mass as the Earth (5.97×10^{24} kg). *(4 marks)*

5 The red supergiant Betelgeuse is estimated to have a mass of between 8 and $20M_{\odot}$ and a radius of between 950 and 1200 times the radius of our Sun. Use this information to determine the minimum and maximum values for the gravitational field strength on the surface of the star and its escape velocity. *(6 marks)*

to distribute these heavier elements throughout the Universe. It is amazing to think that the copper in our wiring and the gold in our jewellery was once created by a star that went supernova.

LGM-1

In 1967 British astrophysicists Jocelyn Bell Burnell and Antony Hewish discovered a regularly repeating radio signal. It had a precise period of 1.337 s. Its regular nature made Bell Burnell and Hewish wonder whether the signal might come from an intelligent extraterrestrial civilization. They called it LGM-1, for 'Little Green Men'. Neither Bell Burnell nor Hewish really thought it was an alien signal, but nothing like this had been previously recorded in nature.

The signal turned out to be radio waves emitted from a rapidly spinning neutron star (dubbed a pulsar). As the star spins, the beam of radio waves sweeps across the Earth like the beam from a lighthouse. Many more pulsars have been discovered since, providing direct evidence for the existence of neutron stars left over after supernovae.

1 Explain why the Chandrasekhar limit must be exceeded in order for the core to form a neutron star.
2 The pulses received from LGM-1 came from a pulsar 2.18×10^{19} m from the Earth. Calculate the time taken for a pulse to travel from the star to Earth.
3 LGM-1 is estimated to have a radius 1.4 million times smaller than our Sun (solar radius 6.96×10^{8} m). Assuming LGM-1 has a density similar to that of a typical neutron star, calculate its mass.

The Schwarzschild radius

The Schwarzschild radius r_S of an object is the radius of an imaginary sphere sized so that, if all the mass of the object is compressed into the sphere, the escape velocity for the object would be greater than the speed of light. The radius of a black hole must be smaller than its Schwarzschild radius, so not even light can escape from its surface.

In 1916 the German astronomer Karl Schwarzschild used Einstein's theory of general relativity to calculate that for any object r_S is given by

$$r_S = \frac{2GM}{c^2}$$

where M is the mass of the object, c is the speed of light through a vacuum, and G is the gravitational constant.

1 Calculate the Schwarzschild radius for:
   a the Earth (mass 5.97×10^{24} kg);
   b the Sun (mass 1.99×10^{30} kg);
   c an average human being.
2 Use the ideas of escape velocity (Topic 18.7, Gravitational potential energy) and kinetic and potential energy to derive the expression above for r_S.

19.3 The Hertzsprung–Russell diagram

Specification reference: 5.5.1

Nine million Suns

R136a1 is a star in the Tarantula Nebula. At 265 times the mass of our Sun it is the most massive star discovered to date. It is also the most luminous star currently known, with a **luminosity** 8 700 000 times that of our Sun.

There is an enormous variety of stars in our galaxy, with dramatic variations in mass, brightness, diameter, luminosity, surface temperature, and colour. Astrophysicists use many methods of classification to understand the variation. One of the most useful is the **Hertzsprung–Russell diagram**.

Learning outcomes

Demonstrate knowledge, understanding, and application of:

→ Hertzsprung–Russell (HR) diagram as luminosity–temperature plot

→ main sequence; red giants; red supergiants; white dwarfs.

The Hertzsprung–Russell diagram

The Hertzsprung–Russell (HR) diagram is a graph of stars in our galaxy showing the relationship between their luminosity on the *y*-axis and their average surface temperature on the *x*-axis. The temperature axis is a bit odd, with temperature increasing from right to left.

The luminosity of any star is the total radiant power output of the star. The luminosity of a star is related to its brightness – in general the greater the luminosity the brighter the star (more on luminosity in Topic 19.7, Stellar luminosity). Our Sun has a luminosity of 3.85×10^{26} W — it emits an incredible 385 000 000 000 000 000 000 000 000 J per second. In the HR diagram, luminosity is often plotted in units relative to the Sun, where $1L_{\odot} = 3.85 \times 10^{26}$ W. Both luminosity and surface temperature of stars can vary widely – luminosity from less than $0.0001L_{\odot}$ to over $1\,000\,000L_{\odot}$, and surface temperature from 3000 K to 40 000 K. As a result, both scales in the HR diagram are normally logarithmic plots.

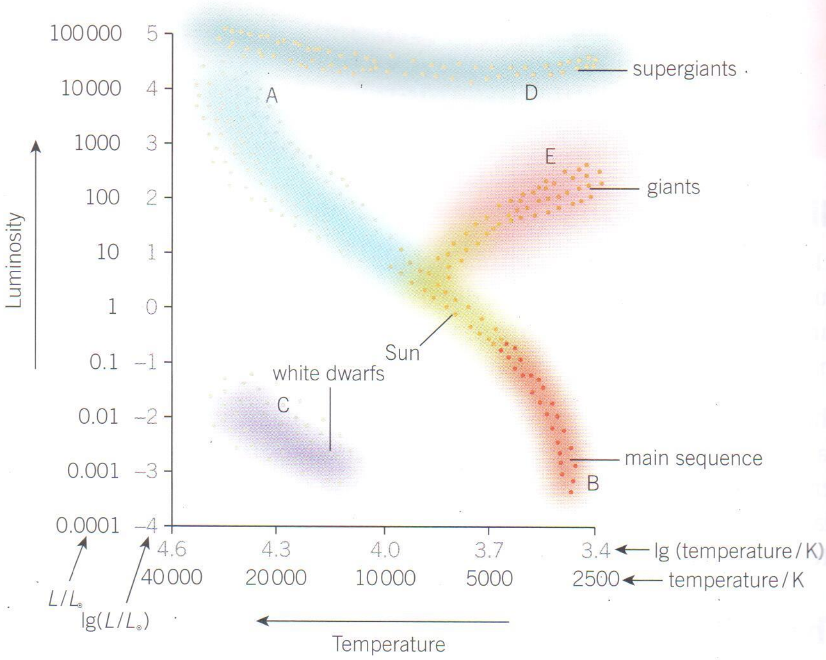
▲ **Figure 1** *The Tarantula Nebula is huge – 9.5×10^{18} m across – and contains millions of stars at different phases of their life cycle*

When stars are plotted on the HR diagram a pattern appears. The hottest, most luminous stars are in the top left at A, with the coolest, least luminous stars at B. Most stars on their main sequence form part of a curved line from A to B. Our Sun has a surface temperature of around 6000 K, and so sits near the middle of this line.

Very hot, dim stars like white dwarfs appear along a different line at C. Their surface temperatures can be many times greater than our Sun's. However, they are much smaller and less luminous.

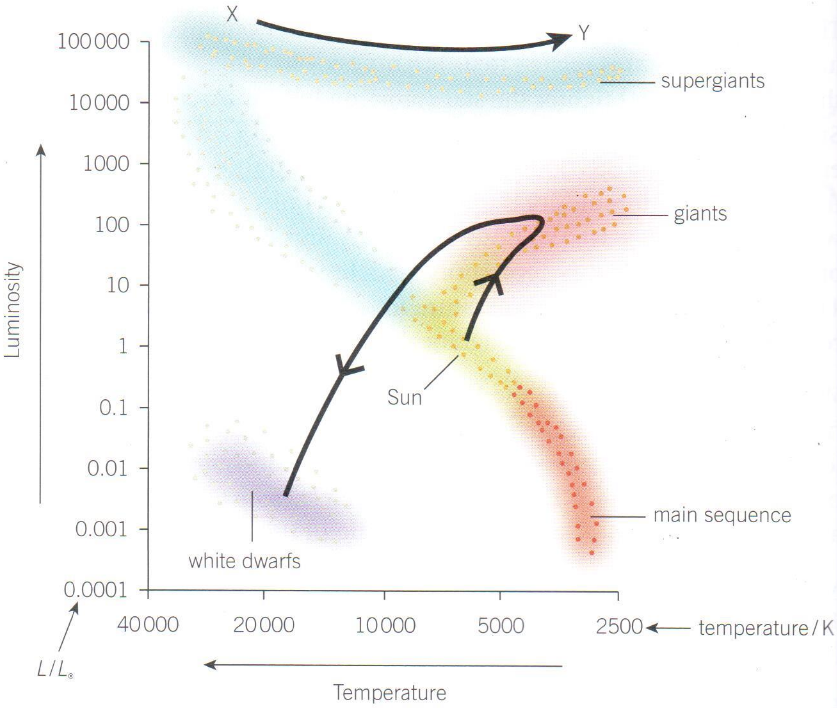
Red supergiants are very luminous because of their enormous size, but they have a relatively low surface temperature. They are found around D. Smaller red giants are found in a line splitting from the main sequence at E.

Life cycle of stars from the HR diagram



▶ **Figure 2** *The Hertzsprung–Russell diagram shows the positions of stars at various stages of their life cycle as a plot of luminosity against surface temperature (note the unusual axes)*

The HR diagram is often used to show stellar evolution.



▲ **Figure 3** *Stellar evolution shown on a Hertzsprung–Russell diagram*

- Lower mass stars like our Sun evolve into red giants, moving away from the main sequence. They then gradually lose their cooler outer layers, and slowly move across the diagram, crossing the main sequence line to end up as white dwarfs.
- Higher mass stars start at X, before rapidly consuming their fuel and swelling into red supergiants at Y before they go supernova.

Summary questions

1. Sketch a Hertzsprung–Russell (HR) diagram and identify the positions of main-sequence stars, white dwarfs, and red giants. *(5 marks)*
2. Explain why when a main sequence star becomes a red giant it moves towards the upper right of an HR diagram. *(2 marks)*
3. Suggest where a black hole might appear on an HR diagram. *(2 marks)*
4. Calculate the maximum luminosity in W of the white dwarfs shown in Figure 2. *(2 marks)*
5. Use the HR diagram to determine the ratio of the temperature of the hottest stars to our Sun. *(2 marks)*

19.4 Energy levels in atoms

Specification reference: 5.5.2

Illuminating

From their first demonstration at the Paris Motor Show in 1910, neon tubes revolutionised lighting. Unlike the filament lamps of the day, neon and other tubes could produce signs in different colours, and they were much more efficient, not getting nearly as hot.

There is no hot filament inside the glass tube of a neon light, only neon or another gas at low pressure. When a large enough p.d. is applied across the tube, the gas glows, giving off a characteristic colour depending on the gas. The gas emits light because of the behaviour of electrons within its atoms.

Learning outcomes

Demonstrate knowledge, understanding, and application of:

→ energy levels of electrons in isolated gas atoms

→ the idea that energy levels have negative values

→ emission spectral lines from hot gases in terms of transition of electrons between discrete energy levels and emission of photons

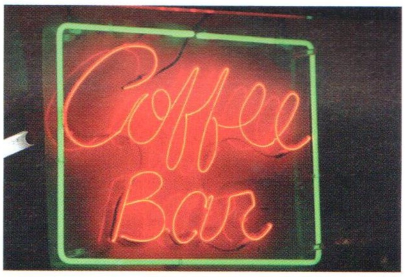
→ the equations $hf = \Delta E$ and $\frac{hc}{\lambda} = \Delta E$.

Energy levels in gas atoms

When electrons are bound to their atoms in a gas they can only exist in one of a discrete set of energies, referred to as the **energy levels** (or energy states) of an electron. This seemed a very odd idea when physicists discovered it a hundred years ago.

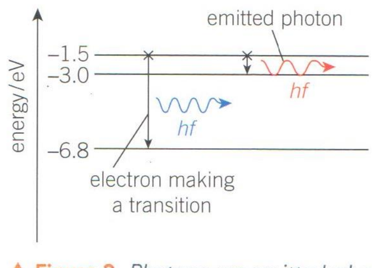
- An electron cannot have a quantity of energy between two levels.
- The energy levels are negative because external energy is required to remove an electron from the atom. The negative values also indicate that the electrons are trapped within the atom or bound to the positive nuclei.
- An electron with zero energy is free from the atom.
- The energy level with the most negative value is known as the ground level or the **ground state**.

When an electron moves from a lower to a higher energy level within an atom in a gas, the atom is said to be **excited**. Raising an electron into higher energy levels requires external energy, for example, supplied by an electric field (as in the neon tube), through heating, or when photons of specific energy (and therefore frequency) are absorbed by the atoms (more on this in Topic 19.5, Spectra).



▲ **Figure 1** *Neon signs are common in many cities, although LED displays are now replacing them*

Figure 2 shows some electron energy levels within an atom. Each energy level has a specific negative value; in this example −6.8 eV, −3.0 eV, and −1.5 eV. An electron in the −3.0 eV energy level requires at least 3.0 eV to escape from the atom.



▲ **Figure 2** *Photons are emitted when electrons make transitions from higher to lower energy levels*

When an electron moves from a higher energy level to a lower one, it loses energy. Energy is conserved, so as the electron makes a transition between the levels, a photon is emitted from the atom. This transition between energy levels is sometimes called de-excitation.

In order for an electron to make a transition from −3.0 eV to −6.8 eV it must lose 3.8 eV. It emits this in the form of a photon with a specific energy of 3.8 eV. The energy of the photon $hf = 3.8$ eV. In general, the

Synoptic link

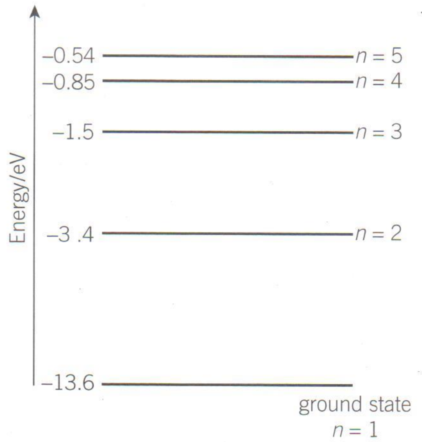
You met photons in Topic 13.1, The photon model, and learned more about energy in discrete quantities in a different context in Topic 13.2, The photoelectric effect.

energy of any particular photon emitted in an electron transition from a higher to a lower energy level is given by

$$\Delta E = hf \qquad \text{and} \qquad \Delta E = \frac{hc}{\lambda}$$

where f is the frequency of the photon and ΔE is the difference in energy between the two energy levels.

Each element has its own unique set of energy levels, like fingerprints, so the energy levels of electrons in helium are different from those in hydrogen. Figure 3 shows the lowest five energy levels for hydrogen.



▲ **Figure 3** *The five lowest energy levels for electrons in hydrogen atoms, labelled with the principal quantum number, n*

Worked example: Emitting photons

Use the information in Figure 2 to determine the frequency of the two photons emitted.

Step 1: Calculate the change in energy in J for each electron as it drops from the higher energy level to the lower one.

First photon: $\Delta E = 6.8 - 1.5 = 5.3\,\text{eV} = 5.3 \times 1.60 \times 10^{-19}\,\text{J} = 8.5 \times 10^{-19}\,\text{J}$

Second photon: $\Delta E = 3.0 - 1.5 = 1.5\,\text{eV} = 1.5 \times 1.60 \times 10^{-19}\,\text{J} = 2.4 \times 10^{-19}\,\text{J}$

Step 2: Use the appropriate relationship to determine the frequency of the emitted photon.

$\Delta E = hf$ therefore $f = \frac{\Delta E}{h}$

First photon: $f = \frac{\Delta E}{h} = \frac{8.5 \times 10^{-19}}{6.63 \times 10^{-34}} = 1.3 \times 10^{15}\,\text{Hz}$ (2 s.f.)

Second photon: $f = \frac{\Delta E}{h} = \frac{2.4 \times 10^{-19}}{6.63 \times 10^{-34}} = 3.6 \times 10^{14}\,\text{Hz}$ (2 s.f.)

The first photon has higher frequency because the difference between the energy levels is greater ($f \propto \Delta E$).

Summary questions

1. An atom emits a photon of frequency 4.5×10^{15} Hz. Calculate the difference in energy between the two energy levels in the gas atom. *(2 marks)*
2. Explain why the wavelength of the emitted photon is shorter when an electron in an atom moves into the ground state from $n = 3$ than when it drops to the ground state from $n = 2$. *(3 marks)*
3. An electron moves from an energy level of −4.0 eV to −6.7 eV. Calculate the wavelength of the photon it emits and state in which part of the electromagnetic spectrum this photon belongs. *(4 marks)*
4. Use the energy levels for hydrogen in Figure 3 to calculate the possible frequencies of the photons emitted when an electron moves into $n = 1$, $n = 2$, and $n = 3$ from a higher energy level (nine possible photons in total). *(9 marks)*
5. A laser emits photons when electrons make transitions between energy levels. If a laser has a power output of 1.0 mW and emits 3.48×10^{15} photons per second, all of the same frequency, calculate the difference between the energy levels in eV. *(3 marks)*