NATIONAL QUALIFICATIONS CURRICULUM SUPPORT

Physics

Stellar Physics

Support Material

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Background

Stellar physics is the study of stars throughout their birth, life cycle and death. It aims to understand the processes which determine a star's ultimate fate.

Figure 1 *An example of a spiral galaxy.*

Throughout the Universe there are estimated to be something like 100 billion (10^{11}) galaxies (Figure 1), each consisting of perhaps 10^{11} stars, meaning that there are in the order of 10^{22} stars in the observable Universe. Naked-eye observation from Earth reveals just a few thousand of these.

Our closest star is, of course, the Sun, approximately 150 million kilometres from Earth. After that the next closest is Alpha Centauri at 4.4 light years (42 trillion km). The most distant stars are beyond 13 billion light years (10^{23} km) away. This means that travelling at the speed of light of 3.0×10^8 m s^{-1}, light would take 13 billion years to arrive on Earth. As the Universe is believed to be 13.7 billion years old, some of this light set off soon after the Universe was created at the Big Bang.[1]

Astronomers classify stars according to their mass, luminosity and colour, and in this part of the course we will explore the processes, properties and life cycle of the major stellar classes. For example Figure 2 shows a solar flare, an example of a process occuring in stars, such as our Sun.

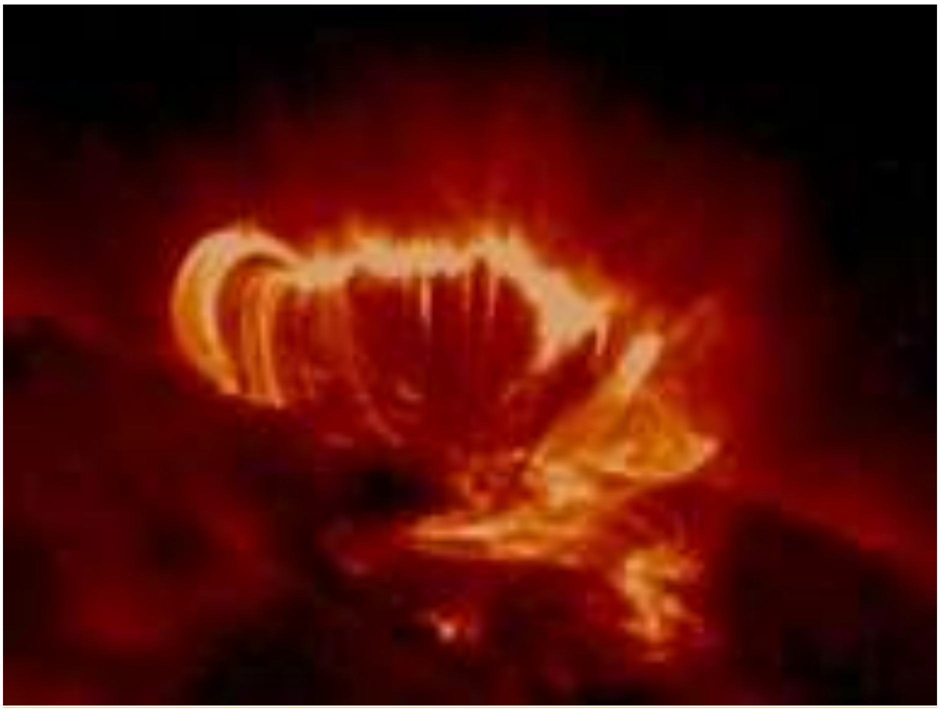

Figure 2 *Solar flare.*

[1] We cannot observe the Universe beyond approx. 13.7 billion light years as this would mean looking back beyond the time when the universe existed.

Properties of stars

Until the beginning of the 20th century, the process by which our Sun produced heat and light was not well understood. Early theories, developed before the size and distance of the Sun was known, involved chemical production, just like burning wood or coal.

However, by the mid-19th century, when the Sun's size and distance were more accurately estimated, it became clear that the Sun simply couldn't sustain its power output from any sort of chemical process, as all of its available fuel would have been used up in a few thousand years. The next suggestion was that heat was produced by the force of gravity producing extremely high pressures in the core of the Sun in much the same way that pressurising a gas at constant volume causes its temperature to rise. It was estimated that the Sun could produce heat and light for perhaps 25 million years if this were the source of the energy.

At around this time it became apparent from geological studies that the Earth (and therefore the Sun) were very much older than 25 million years so a new theory was required. This new theory emerged in the early years of the 20th century with Einstein's famous $E = mc^2$ equation establishing an equivalence between mass and energy. Here at last was a mechanism which could explain a large, sustained energy output by converting mass to energy.

We now know that an active star produces heat by the process of nuclear fusion. At each stage of a fusion reaction a small amount of mass is converted to energy. The process involves fusing two protons together to produce a deuterium nucleus, a positron, a neutrino and energy. The positron is annihilated by an electron, producing further energy in the form of gamma rays. The deuterium nucleus then combines with a further proton to produce a helium-3 nucleus, gamma rays and energy. Two helium-3 nuclei then combine to produce a single helium-4 nucleus, two protons and energy. The energy released is the *binding energy*, the energy that would be required to overcome the strong nuclear force and disassemble the nucleus again. The whole process is summarised in Figures 3 to 5.

Fusion in the Sun

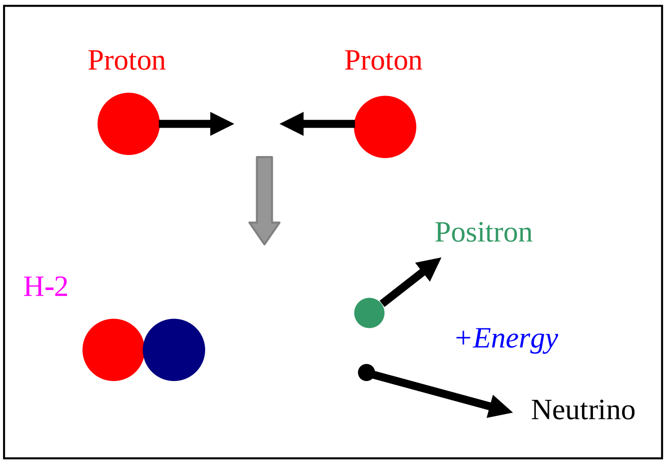

Figure 3 *Two protons fuse and one is converted to a neutron to form deuterium (H-2). Energy is released.*

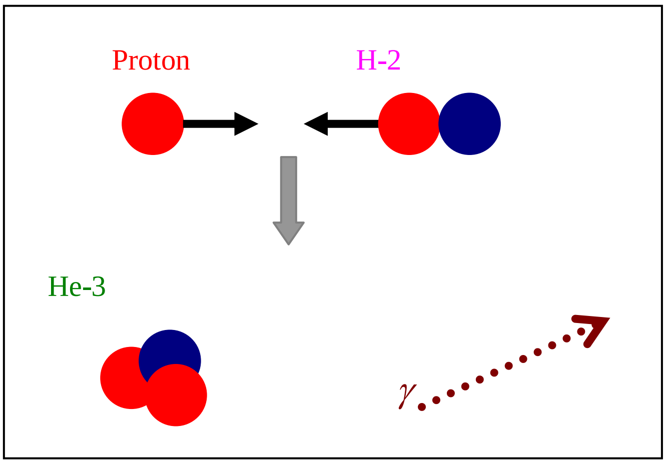

Figure 4 *The deuterium captures another proton to form helium-3 (He-3). Energy is released as gamma rays*

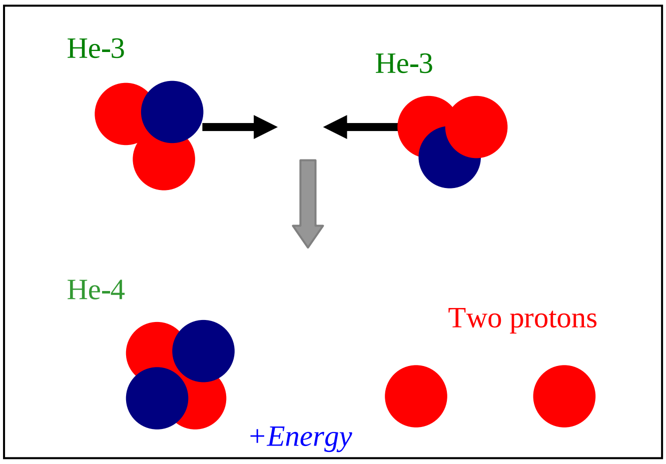

Figure 5 *Two helium-3 nuclei fuse, giving helium-4 (He-4) and freeing two protons.*

This whole sequence is known as the *proton–proton chain reaction* and may be summarised as:

$$4\,(^{1}H) \rightarrow {}^{4}He + 2\,e^{+} + 2 \text{ neutrinos} + \text{energy}$$

Two protons, being positively charged, will repel each other as they approach. Forcing two protons close enough together so that they will fuse can only occur at extremely high temperature and pressure, capable of overcoming the internuclei repulsive electrostatic forces. Conditions in the core of the Sun meet the requirements of nuclear fusion with a temperature of around 15 million kelvin and a pressure of 200 billion atmospheres.

One of the methods by which the proton–proton chain reaction could be confirmed to be the source of the Sun's energy was to predict the number of neutrinos that could be expected to arrive at the Earth if the reaction was proceeding at a rate which was consistent with the rate of energy production observed. Neutrinos are very difficult to detect as they rarely interact with other particles (in fact as you are reading this many billions are passing unhindered through your body each second), but because so many are produced by the Sun it is possible, with a sufficiently large detector, to measure these interactions.

The first solar neutrino detector consisted of an underground reservoir containing 400,000 litres of dry-cleaning fluid. Chlorine nuclei within this fluid occasionally interacted with neutrinos to produce argon, so the quantity of argon accumulated within the reservoir allowed the number of neutrinos arriving at the Earth's surface to be estimated.

Unfortunately, the quantity of neutrinos detected was only about one-third of the number that theory predicted, suggesting either that the proton–proton chain reaction was *not* the source of the Sun's energy or that the experiment was for some reason failing to detect two-thirds of the neutrinos. This problem remained unsolved for over 30 years and became known as the *solar neutrino problem*.

It was known that the proton–proton chain reaction produced only *electron neutrinos* but the existence of two other types, the *muon neutrino* and the *tau neutrino* was also known. (Muons and taus are more massive cousins of the electron.) Until recently neutrino detectors were only able to detect electron neutrinos, but with the introduction of a detector that could detect all three types it rapidly became apparent that the number arriving on Earth did, indeed, match the expected output from the proton–proton chain reaction, but that all three types were present. It is now believed that some of the electron neutrinos are converted to the other two types during their passage from the core to the surface of the Sun. Thus, after three decades of observations, it was possible to be confident that the models which predicted the source of the Sun's energy were correct.

Modern observations tell us that the Sun converts around 4 million tonnes of its mass to energy each second. Even at this prodigious rate its huge mass means its fuel will last for many billions of years to come.

Nuclear fusion is the focus of much applied research on Earth as a way of producing power, allowing our reliance on fossil fuels to be reduced. Progress has been slow because the engineering required to contain plasma at high temperatures and pressures is very challenging.

Additional Information

The nuclei in the Sun actually do not have quite enough energy to completely overcome the repulsive Coulomb forces and rely partly on a process called quantum tunnelling for fusion to occur. For this reason manmade fusion reactors must produce temperatures of the order of 10–100 times higher than those found in the Sun.

The ITER project (ITER, 2011) based in the south of France hopes by 2019 to produce the first reactor capable of giving out more power (500 MW) than it takes to contain the plasma (50 MW). Figure 6 shows one method of creating a fusion reaction on Earth, notice how different this is to that of our Sun.

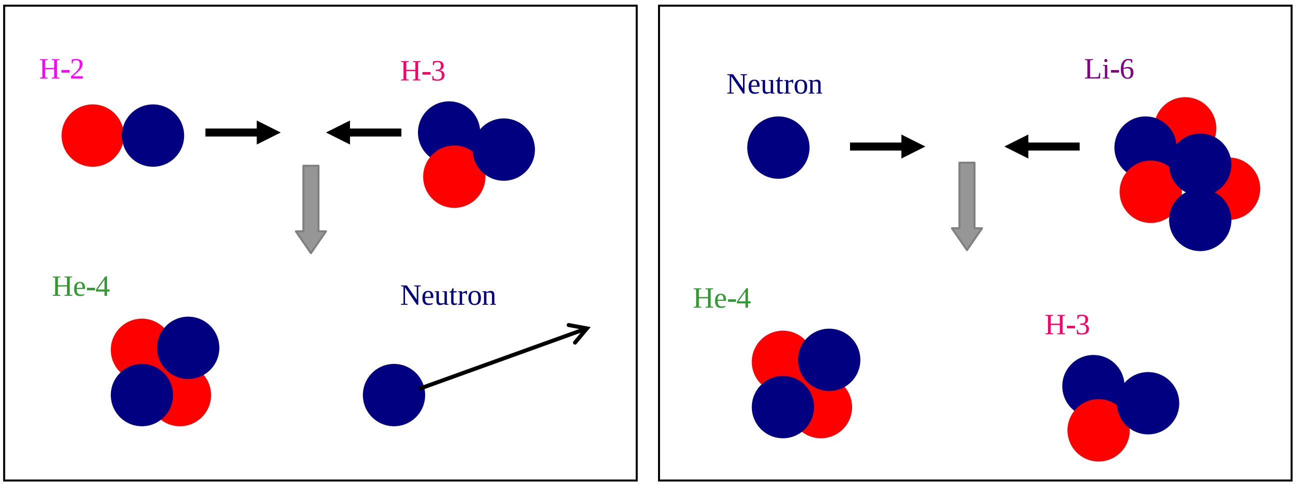

Figure 6 *A possible method of fusion used on Earth. Deuterium and tritium (H-3) are heated to a very high temperature. The neutrons released fuse with lithium (Li-6) around the hot gases, breeding more tritium. Most of the useful energy comes from the deuterium–tritium reaction.*

For life to have evolved on Earth, it is reasonable to suppose that the output of the Sun has been fairly stable for a long time. This stability can be attributed to *gravitational equilibrium*, where the inward force of gravity is repelled by the thermal pressure produced by the fusion reactions in the core. If for any reason the output from the fusion reaction were to decrease, then the outward thermal pressure would decrease, and hence the pressure due to gravity in the core would rise, leading to a rise in thermal output and thus restoring the equilibrium. A similar feedback would prevent thermal output from increasing. This is shown in Figure 7.

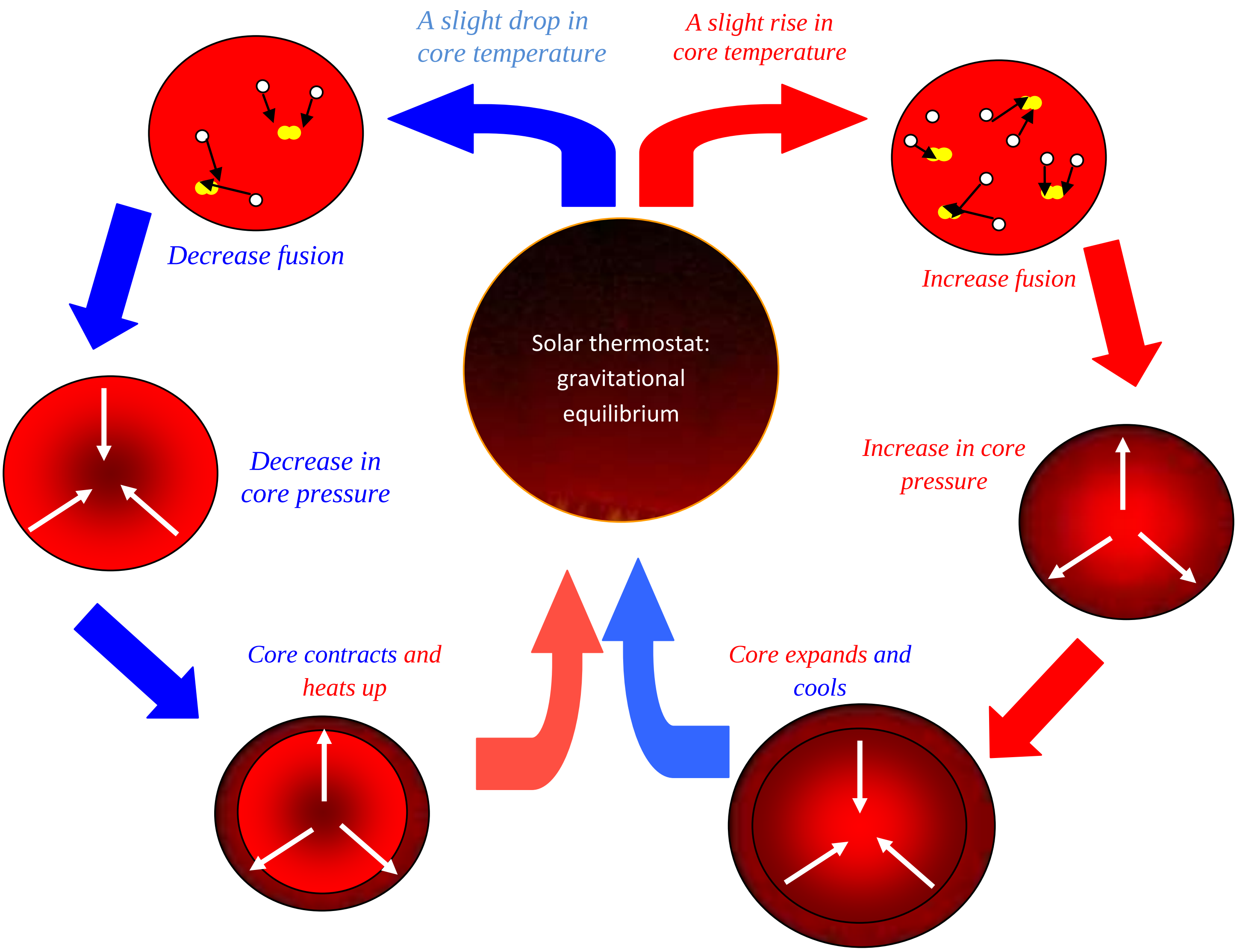

Figure 7 *The solar thermostate.*

The structure of the Sun

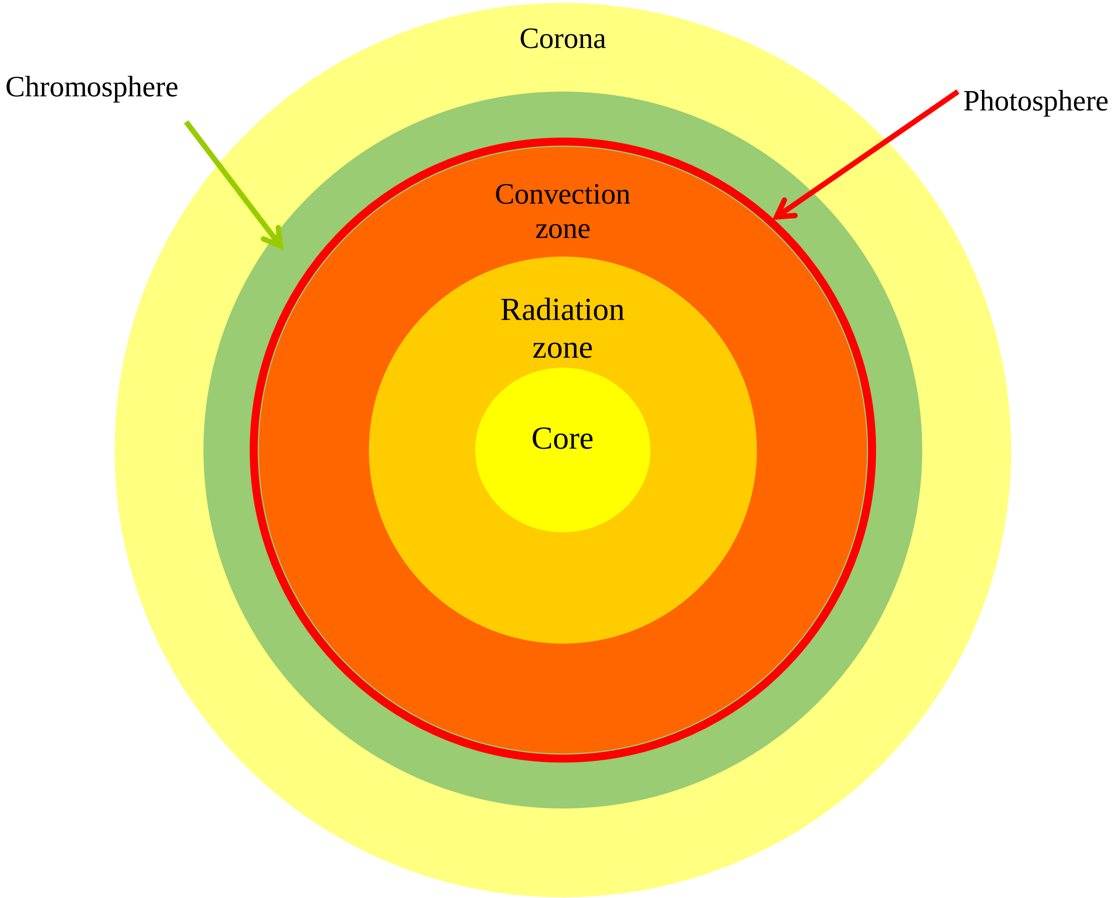

Figure 8 *The solar zones.*

Around 99% of the heat production from fusion takes place in the core (although even here this is at a surprisingly low rate per unit volume, around 300 W m^{-3}, which is considerably less than the heat produced by a human body. Stars have such a huge power output because of their enormous size).

Moving outwards from the core of the Sun (Figure 8) there is first the radiation zone, where heat transfers radiatively outwards, followed by the convection zone, where pressures are low enough to allow heat transfer by convection. The 'surface' of the Sun (ie the boundary between the plasma and gas) is the photosphere, above which is the 'atmosphere' consisting first of the chromosphere then the corona. The typical temperatures of each layer are given in Table 1.

Table 1 Temperature of solar regions

Region	Typical temperature (K)
Core	15×10^6
Radiation zone	10×10^6
Convection zone	10×10^6 to 6000
Photosphere	5800
Chromosphere	10000
Corona	1×10^6

Although the corona is at around one million kelvin, the surface temperature we perceive from Earth is that of the photosphere because this is a relatively dense region compared to the corona.

Since most of the energy is released in the core in the form of photons, these must radiate and convect outwards through the extremely dense inner layers of the Sun. This high density means that a photon takes hundreds of thousands of years to reach the surface of the Sun, then just a little over 8 minutes to reach the Earth.

So far we have considered data relating just to our Sun since that is the star about which we know the most. From here on we will consider stars in general.

Size of stars

There is a large variation amongst stars and each star is placed into a ‘spectral class’ (which we will look at later) partly depending on the star’s size. Our Sun, a main-sequence star (again we will deal with this later), has a radius, R_{Sun}, of approximately 696,000 km (109 times that of Earth) (Moore, 2002). White dwarfs (small, dense stars nearing the end of their lives) may have a radius of around $0.01R_{Sun}$, whilst at the other extreme supergiants may typically be $500R_{Sun}$.

Surface temperature

The surface temperature of a star is, in general, the temperature of the photosphere and depends on many factors, not least the amount of energy the star is producing and the radius of the star.

When viewing the night sky it is apparent that stars are not a uniform white colour. There are red stars, such as Betelgeuse in the Orion constellation, and blue ones, like Spica in Virgo. A dramatic contrast in star colours can be seen by observing the double star Albireo in Cygnus using a small telescope. Here the contrast between an orange and blue-green star is striking.

The reason why stars appear in a wide range of colours is directly related to their surface temperature. The hotter the star the more blue or white it appears. The surface temperature is shown to be directly linked to the irradiance (power per unit area). The energy radiated by the hot surface of a star can be calculated using a modified Stefan–Boltzman law (Monteith, 1973).

$P = \sigma T^4$

where P is the power per unit area (W m^{-2}), σ is the Stefan–Boltzman constant (5.67×10^{-8} W m^{-2} K^{-4}) and T *is* the absolute temperature (K).

For example, the power per unit area of our Sun would be calculated as follows:

$$\begin{aligned} P &= \sigma T^4 \\ &= 5.67 \times 10^{-8} \times (5800)^4 \\ &= 64 \times 10^6 \text{ W m}^{-2} \end{aligned}$$

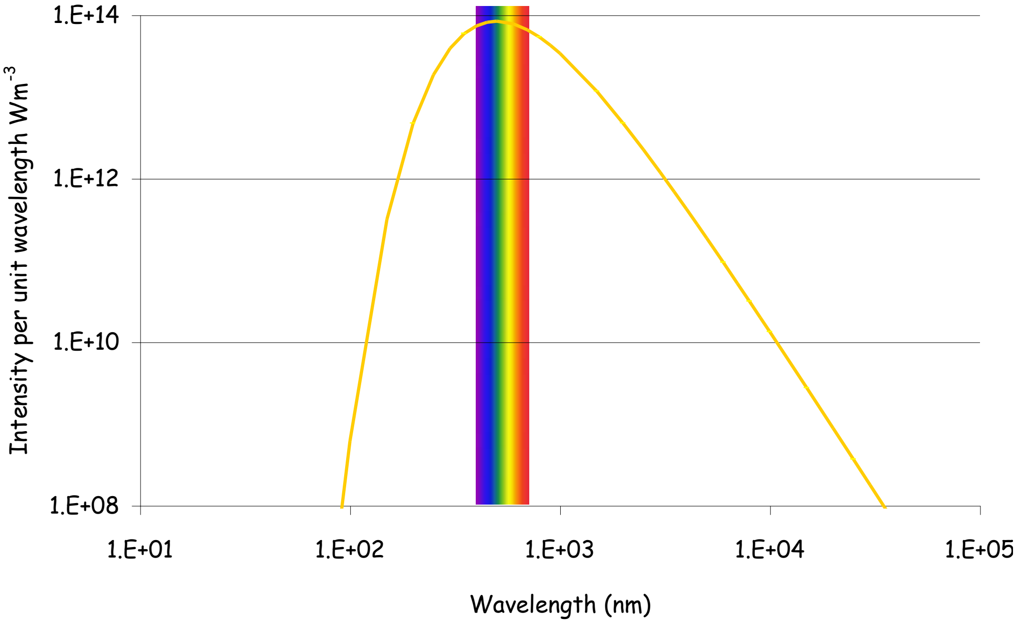

Figure 9 *Black-body radiation from the Sun*

As the power per unit area is proportional to T^4, this means that as temperature rises the quantity of radiation emitted per unit area increases very rapidly. However, radiation is not emitted at a single wavelength but over a characteristic waveband, as shown in Figure 9. This diagram is called a black-body radiation diagram. Black-body radiation is the heat radiation emitted by an ideal object and has a characteristic shape related to its temperature. Many astronomical objects radiate with a spectrum that closely approximates to a black body. Figure 9 shows this black-body pattern for our Sun, with a surface temperature of 5800 K. The visible part of the spectrum has been plotted to put the graph in context and to demonstrate the relatively small proportion of total energy emitted in the visible waveband.

Additional information

This curve is given by the Planck radiation law (Young & Freedman, 1996):

$$I(\lambda) = \frac{2\pi hc^2}{\lambda^5\left(e^{hc/\lambda kT} - 1\right)}$$

where $I(\lambda)$ is the radiation intensity per unit wavelength, h is Planck's constant, c is the speed of light and k is the Boltzman constant.

The maximum intensity in Figure 9 occurs at a wavelength of:

$$\lambda_{max} = \frac{2.9 \times 10^6}{T} \text{ (Wien's law)}$$

and gives a value of 500 nm for the light from our Sun, a value towards the middle of the visible spectrum (400–700 nm). Evolution has resulted in humans having eyesight most sensitive to light with the greatest energy per unit wavelength.

Maximum wavelength and Surface Temperature

If the emission spectra of stars of different temperatures are plotted (Figure 10) the emission curves show the same general shape but different values for their peak radiation. By measuring λ_{max} from a particular star we can therefore calculate its surface temperature. An alternative approach using just the visible part of the spectrum is to measure the ratio of red:violet intensity and use that to predict λ_{max} by applying the Planck radiation law.

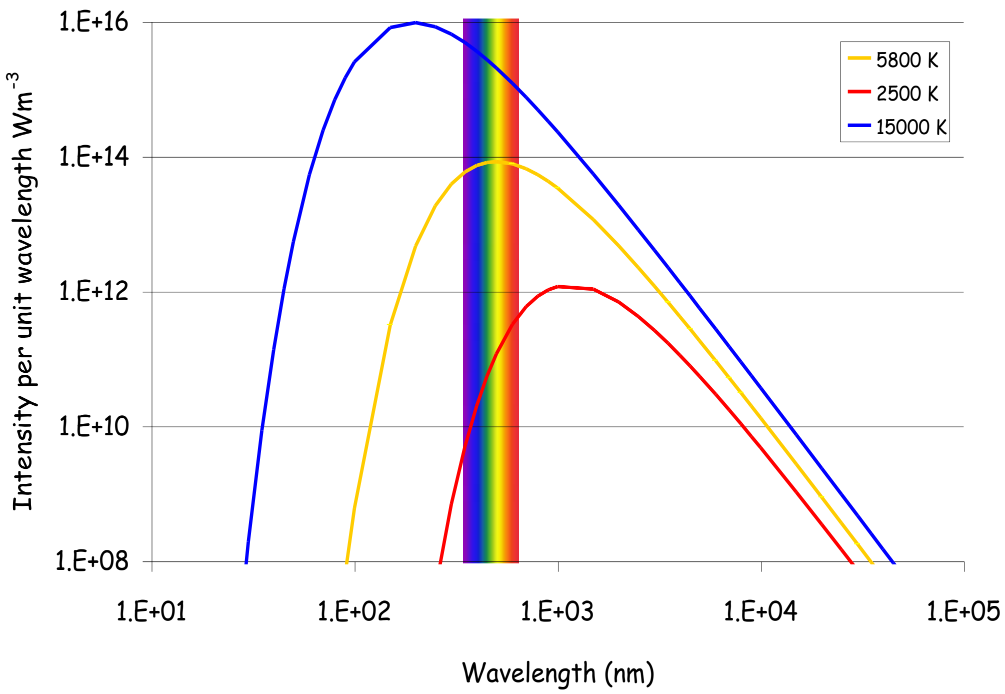

Figure 10 *Black-body radition from stars with 2500 K, 5800 K and 15,000 K surface temperatures.*

Mass

Our Sun has a mass, $M_{Sun,}$ of 1.989 × 10^{30} kg (Moore, 2002) or roughly 330,000 times that of the Earth. Other stars range in size from roughly $0.08M_{Sun}$ to $150M_{Sun}$. The most numerous stars are the smallest, with only a (relatively) few high mass stars in existence. No stars with masses outside this range have been found. Why should this be?

Stars with a mass greater than $150M_{Sun}$ produce so much energy that, in addition to the thermal pressure which normally opposes the inward gravitational pressure, an outward pressure caused by photons (and known as *radiation pressure*) overcomes the gravitational pressure and causes the extra mass to be driven off into space.

Stars with a mass less than $0.08M_{Sun}$ are unable to achieve a core temperature high enough to sustain fusion. This arises because of another outward pressure, called *degeneracy pressure*, which occurs in stars of this size. This pressure is explained in terms of quantum mechanics, which we don't propose to cover here, but the outcome is that this outward pressure prevents the star from collapsing and raises the core temperature and pressure enough to sustain nuclear fusion.

Small stars which fail to initiate fusion become *brown dwarfs*, slowly dissipate their stored thermal energy and cool down. To give an idea of scale, a star with a mass of $0.08M_{Sun}$ is approximately 80 times the mass of Jupiter, so brown dwarfs occupy a middle ground between the largest planets and the smallest stars.

Luminosity

The luminosity of a star is a measure of the total power the star emits. It is calculated by multiplying the power per unit area, P, by the surface area of the star, thus:

$$L = P \times 4\pi r^2$$

where L is the luminosity of the star (W), P is the power per unit area (W m^{-2}) and r is the radius of the star (m).

For example, we can calculate the luminosity of the Sun:

$$\begin{aligned} L_{Sun} &= P \times 4\pi r^2 \\ &= 64 \times 10^6 \times 4\pi \times (6.96 \times 10^8)^2 \\ &= 3.9 \times 10^{26} \text{ W} \end{aligned}$$

The Sun has a luminosity, L_{Sun} of 3.9×10^{26} W, and the range of stellar luminosities found throughout the universe is from around $10^{-3} L_{Sun}$ to $10^5 L_{Sun}$.

Because the range of luminosities covers eight to nine orders of magnitude, the luminosity can also be described using the *absolute magnitude* scale. The concept of using a range of magnitudes to measure the brightness of stars was introduced by the Greek astronomer Hipparchus, in the second century BC. His scale had the brightest stars as magnitude 1 whilst the faintest visible to the naked eye were magnitude 6.

Additional information

The modern definition of luminosity uses the same principle, but describes what the visual magnitude of a particular star would be when viewed from a distance of 10 parsecs (a parsec is 3.26 light years). The definition of luminosity has changed slightly over the years, but the modern scale can be obtained using:

$$L = 10^{\frac{4.83-M}{2.5}} L_0$$

where L_0 is the luminosity of our Sun, M is the absolute magnitude of the star and L the luminosity of the star (Wolfram Alpha, 2011).

The form of this equation makes it easy to see that the scale is not linear. In fact, a difference of 5 in magnitude corresponds to a 100-fold difference in luminosity. It is also apparent from the equation that as the magnitude increases, the luminosity decreases. In fact, the most luminous stars have *negative* magnitudes, eg Sirius has an absolute magnitude –3.6 and our Sun +4.83.

Apparent brightness

When viewed from Earth, the brightness of stars does not necessarily reflect their absolute magnitude, it is quite possible that a high-luminosity star a long way from Earth could appear to be less bright than a low-luminosity star nearby. The brightness of any star when viewed from Earth is its *apparent brightness* and is a measure of the radiation flux density (W m^{-2}) at the surface of an imaginary sphere with a radius equal to the star–Earth distance.

The radiation flux density is calculated using the inverse square law such that

$$\text{apparent brightness} = \frac{L}{4\pi d^2}$$

where *d* is the distance from the star to our observation point (usually Earth). To apply this to our Sun gives

$$\text{apparent brightness} = \frac{3.839 \times 10^{26}}{4\pi\left(150. \times 10^{9}\right)^{2}} = 1360 \text{ W m}^{-2}$$

and is the value of the *solar constant* at the top of Earth's atmosphere. In the UK, measurements of solar radiation at the Earth's surface give a value around 1000 W m^{-2} at midday in midsummer – the difference in values being caused by geometry, atmospheric absorption and scattering.

Just as luminosity has acquired the absolute magnitude scale to make it easier to compare, apparent brightness may also be described by the *apparent magnitude* scale. This uses the apparent brightness of the star Vega in the constellation Lyra to define an apparent magnitude of 0. Prior to this Polaris was used to define an apparent magnitude of 2, but was subsequently found to be a variable star (ie its luminosity is not constant, varying between magnitudes 2.1 and 2.2 every 4 days) and so the definition was dropped in favour of Vega. Just as in the case of absolute magnitude a difference of 5 in apparent magnitude corresponds to a 100-fold difference in apparent brightness.

From this it will be clear that when a star is described as having a particular magnitude it is important to clarify whether this is an apparent or absolute magnitude. For example, Sirius has an absolute magnitude of –3.6 but an apparent magnitude of –1.44. As a guide, the faintest stars detectable by naked eye on a clear night are of around apparent magnitude 5, although the threshold will vary from person to person. The Moon has an apparent magnitude of –10.6 and the Sun is –26.72.

Detecting astronomical objects

When recording images of distant stellar objects in order to measure their apparent brightness, people used to use film cameras (indeed some still do). These worked by photons of light reacting with chemically treated rolls of plastic film. Nowadays, digital cameras produce images using a charge-coupled device (CCD) chip positioned directly behind the camera lens (where the film used to be located in a film camera).

A CCD is a doped semiconductor chip based on silicon, containing millions of light-sensitive squares or pixels. A single pixel in a CCD is approximately 10 μm in diameter. When a photon of light falls within the area defined by one of the pixels it is converted into one (or more) electrons and the number of electrons collected will be directly proportional to the intensity of the radiation at each pixel. The CCD measures how much light is arriving at each pixel and converts this information into a number, stored in the memory inside the camera. Each number describes, in terms of brightness and colour, one pixel in the image.

Not all of the photons falling on one pixel will be converted into an electrical impulse. The number of photons detected is known as the quantum efficiency (QE) and is wavelength dependent. For example, the QE of the human eye is approximately 20%, photographic film has a QE of around 10%, and the best CCDs can achieve a QE of over 90% at some wavelengths.

Some CCDs detect over a very short waveband to produce several black and white images that are then coloured during image processing. This is how the Hubble Telescope and the Faulkes' Telescopes produce their images. Certainly some of the Hubble images give details that would never be observed by the human eye.

CCDs have several advantages over film: a high quantum efficiency, a broad range of wavelengths detectable and the ability to view bright as well as dim images. CCDs have an advantage over the eye in that their response is generally linear, ie if the QE is 100% efficient 100 photons would generate 100 electrons. The human eye does not observe linearly over a large range of intensities and has a logarithmic response. This makes the eye poor at astrophotometry (the determination of the brightness of stars).

Another of the major advantages of using CCDs in imaging stellar objects is the ability to use software to 'stack' images. Several images of the same object can be taken and easily superimposed to produce depth and detail that would not be observed from a single image.

Requirements when using CCDs include ensuring the detector is properly calibrated and that the absorption of light by the atmosphere is taken into account if CCDs are being used to measure apparent brightness. One disadvantage relative to film is that the sensors tend to be physically small and hence can only image small areas of the sky at one time, although this limitation can be overcome by using mosaics of sensors.

Stellar classification

Initial attempts to classify stars in the mid-19th century were based on colour and spectral absorption lines. The most commonly used scheme was that devised by Angelo Secchi. It is summarised in Table 2 (Moore, 2002).

Table 2 Secchi stellar classification

Classification type	Colour	Absorption lines	Examples
I	Blue-white.	Strong hydrogen	Sirius, Vega
II	Yellow, orange.	Dense metallic species.	Sun, Arcturus, Capella
III	Orange-red	Titanium oxide	Betelgeuse, Antares
IV	Deep red	Carbon	
V		Strong emission lines	

In the late 19th century a different approach was based on looking at hydrogen absorption line spectra and classifying them alphabetically from A to Q with Class A having the strongest absorption lines. However, it was eventually realised that such a system was slightly flawed and a clearer sequence studying absorption lines of many chemical species was established. This retained the lettering classification but moved some classes around and removed some altogether. Eventually the classification became the one used today (Table 3, Bennett *et al.*, 2008) and is a result of correcting previous errors or omissions in the classification.

Table 3 Modern stellar classification

Spectral type	**Temperature (K)**	**Examples**	**Colour**
O	> 30,000	Orion's Belt stars	Blue
B	30,000–10,000	Rigel	Blue-white
A	10,000–7,500	Sirius	White
F	7,500–6000	Polaris	Yellow-white
G	6000–5000	Sun	Yellow
K	5000–3500	Arcturus	Orange
M	<3500	Proxima Centauri, Betelgeuse	Red

The order of the spectral classes has been remembered by generations of astronomy students using the mnemonic 'Oh, Be A Fine Girl/Guy, Kiss Me'.

This work was carried out at the Harvard Observatory by (mostly female) 'computers'. These individuals had educated themselves in physics and astronomy, but the social pressures of the time meant they could not become undergraduates or have a formal position at the Observatory so this was the only type of work they could do within this field. Eventually, one of their number, Annie Jump Cannon, who led the work described above, was recognised with an honorary degree from Oxford University almost 20 years after the scheme was adopted.

The spectral types listed in Table 3 cover quite large temperature ranges, so within each type a numbering system is used, eg A0, A1, A2 etc up to A9, with each number representing one tenth of the difference between class A and class F. The smaller the number the hotter the star will be. The Sun is a star of spectral type G2 with a surface temperature of 5800 K.

Solar activity and sunspots

Although stellar activity is discussed here in the context of our Sun, similar processes are likely to be at work in all such stars. We saw in the first section that the interior of the Sun has distinct zones or regions, and that the zone closest to the surface is the convective zone, where heat is transferred towards the surface by convection of the plasma. Photographs of the Sun clearly show these areas of convection (Figures 11 and 12), with the bright areas being regions where hotter plasma is welling up from below and dark regions those where cooler plasma is sinking.

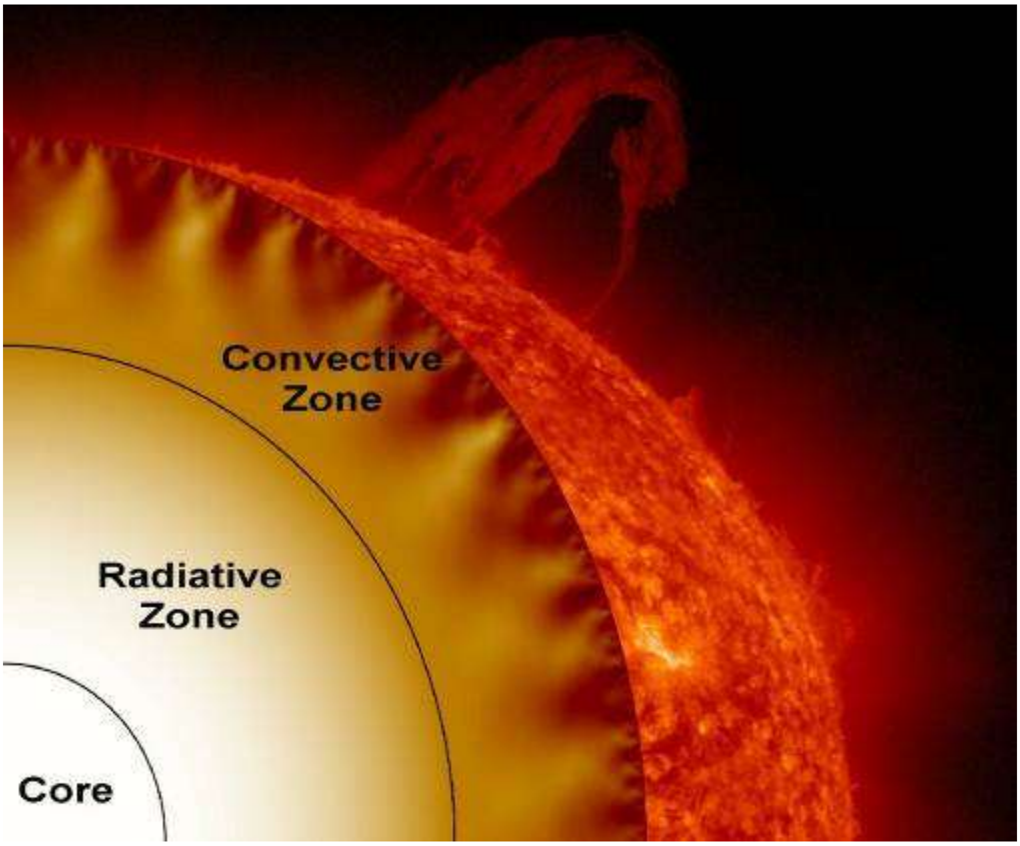

Figure 11 *The effects of convection seen at the surfaceof the Sun.*
http://solarscience.msfc.nasa.gov/images/cutaway.jpg.

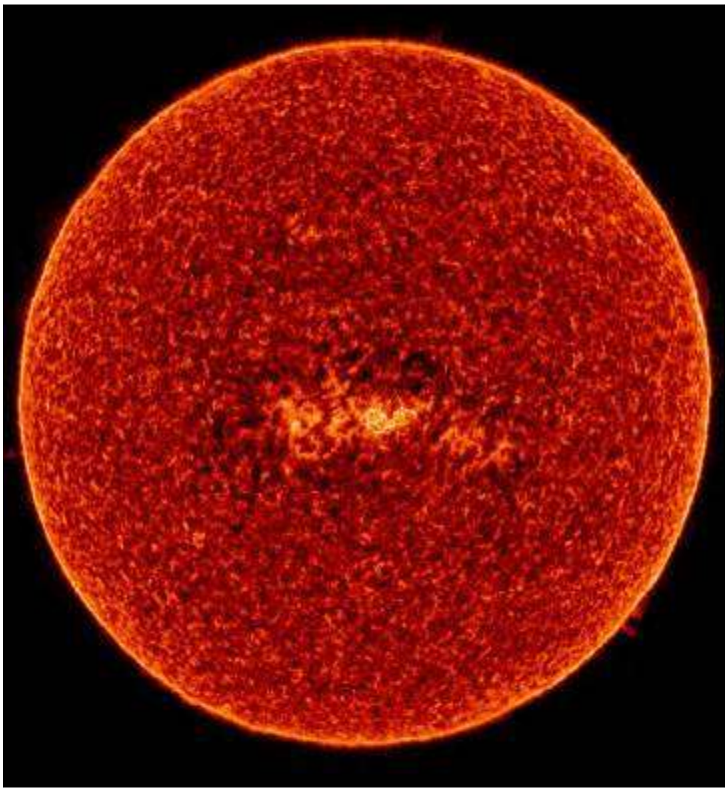

Figure 12 *Convection currents observed at the solar surface.*
http://solarscience.msfc.nasa.gov/images/sumer_S_VI.jpg.

From time to time, larger dark areas appear, ranging in size from 1000 km to 100,000 km in diameter (with the Earth for comparison being approximately 13,000 km in diameter). These *sunspots*, which usually occur in pairs, are thought to arise when strong magnetic field lines emerge from the surface of the Sun, curve out into space and then go back into the Sun. Sometimes loops of plasma can become established in this field and give rise to a *solar prominence*. These strong magnetic fields reduce the convective flow of plasma from below and therefore reduce the surface temperature within the sunspot to around 4000 K. Sunspots may last for anything from a few hours to a few months depending on the stability of the magnetic fields.

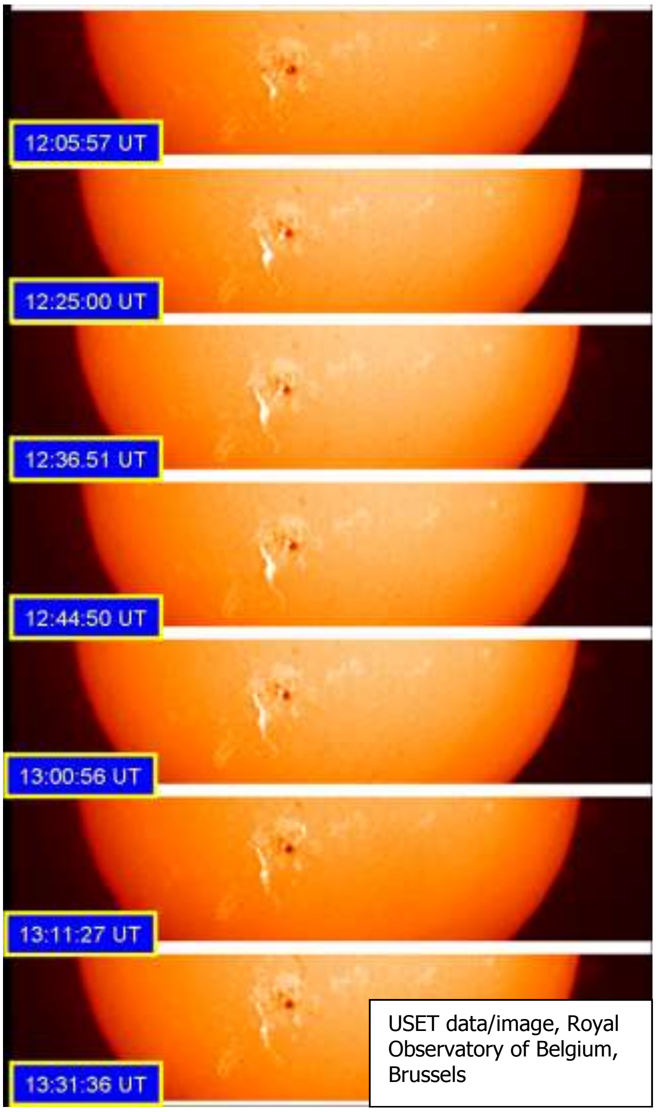

Figure 13 *Time sequence of a solar flare.*

The regions surrounding sunspots are associated with several aspects of solar 'weather'. The first of these is the *solar flare*. The mechanism is believed to be associated with sudden breakdowns of twisted magnetic fields that occur in the vicinity of sunspots. Solar flares last from a few minutes to a few hours and release large quantities of radiation, predominantly X-rays (although radiation is emitted across the entire spectrum), and a stream of fast-moving charged particles. Figure 13 shows a time-sequence of a flare taken in August 2002 showing the movement of the flare away from the region of a sunspot.

For reasons which are not yet fully understood, the total number of sunspots present follow a cyclical pattern known as the sunspot cycle. Since sunspots have been observed for several centuries it is possible to trace this cycle back for an extended period and this confirms that sunspot numbers peak (at solar maximum) and trough (at solar minimum) approximately every 11 years but that the total number of sunspots at each peak varies considerably (Figure 14; SIDC, 2011).

The historic data also show that total sunspot number is quite variable from cycle to cycle and that this cyclical behaviour was suspended between about 1645 and 1715. This period is known as the Maunder Minimum and coincided with the onset of the Little Ice Age, although the extent to which the latter was brought on by the former is uncertain. In fact, although the changes in X-ray and ultraviolet emissions are quite pronounced throughout the sunspot cycle, the total energy output of the Sun changes very little. Research into the effects of solar 'weather' on Earth's climate and weather is still at a relatively early stage.

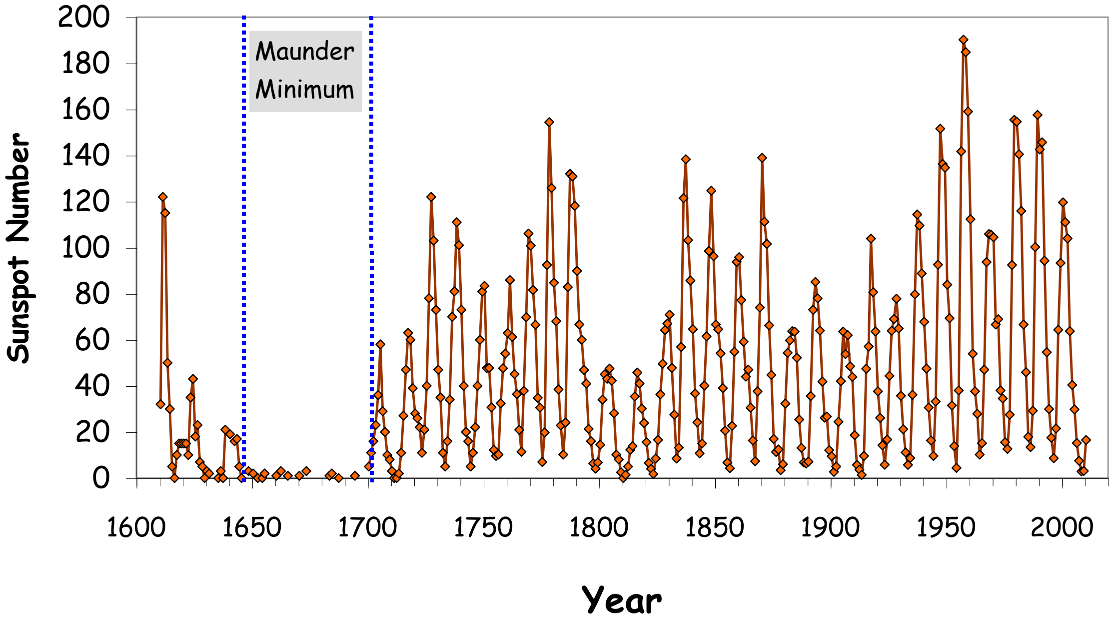

Figure 14 *Historic data for sunspots numbers. Data coutesy of SIDC (2011).*

Interestingly, the Sun's magnetic field reverses completely at each solar maximum so that it takes 22 years for the magnetic field to go from one state to another then back to the original state. This is known as the solar cycle. Earlier we saw that the temperatures of the Sun's chromosphere and corona are much higher than that of the photosphere, although the surface temperature that we observe from Earth is that of the photosphere. This arises because the densities of the chromosphere and corona are very small. The reasons for the occurrence of these high temperatures are imperfectly understood, but it is thought that they are produced by energy transferred via the movement of loops of magnetic field lines which are, in turn, caused by strong currents within the convection zone.

The high temperatures of the chromosphere and corona cause them to emit X-ray radiation. X-ray images of the Sun reveal that the hottest areas of the corona are related to areas with sunspots and that the polar regions of the Sun have relatively cool areas of corona. These areas are known as coronal holes and are characterised by having magnetic field lines that do not loop back into the photosphere, but trail out into space, allowing streams of charged particles to escape along them. This stream of particles travels outwards from the Sun at around 500 $km\,s^{-1}$ and is known as the solar wind.

Coronal mass ejections (CMEs) are a more violent form of solar flare or storm. Massive quantities (far in excess of the quantity associated with the solar wind) of charged particles are ejected from the Sun. These pulses of particles have very strong magnetic fields, which can, if they happen to be ejected in the direction of Earth, cause geomagnetic storms.

During a geomagnetic storm, the effects on Earth are potentially serious. Bright auroras (northern and southern lights) may be observed but the main problem is that the strong magnetic fields cause currents to be induced in conductors. Thus electrical and electronic devices may malfunction or cease to work entirely, affecting communications and power distribution. If a CME is observed to be heading towards Earth, then we have some warning of the event as it takes around 3 days for the CME to reach us. CMEs are potentially dangerous to those aboard the International Space Station.

In recent years there have been several CME warnings, the most serious outcomes being: (i) in late 2003 a series of CMEs close together destroyed a satellite, disrupted others and caused problems with aircraft navigation systems; (ii) in 1989 parts of the Canadian power distribution grid failed for 9 hours and communications were lost with over 2000 military satellites. The total cost of this latter event was estimated to be around $100 million, emphasising how damaging a CME can be. Our almost total reliance on electronic and electrical devices nowadays mean that any threat of a CME hitting Earth must be taken seriously. A sufficiently large event could induce currents large enough to melt the cores of large numbers of national power grid transformers, causing serious disruption and potentially taking a long time to repair.

Stellar evolution

We have now explored the structure of stars and explained how they produce energy. In this section we are going to look back to the beginning of a star's life and explore the processes it goes through as it ages.

Star formation

Stars are formed in what are often called interstellar nurseries. These are volumes of space containing (relatively) high densities of molecules, although it should be emphasised that the densities are of the order of 300 million molecules per cubic metre. This may sound like a large number but must be considered against the density of air at sea level on Earth, which is of the order of 25×10^{24} molecules per cubic metre.

Viewed from Earth these molecular clouds appear as areas in the sky which block the light from stars beyond them and are called nebulae (although it should be noted that not all objects classed as nebulae are star-forming). One of the best known groups of nebulae are found in the constellation of Orion lying below the belt and forming the sword. They are easily observed with binoculars or a small telescope. Although appearing greenish to the naked eye, the nebulae are in fact a reddish-orange colour. This apparent contradiction arises because the human eye is more sensitive to light in the middle of the visible spectrum. Closer to Orion's belt is the famous Horsehead Nebula (Figure 15), in which a cloud of dark dust lies in front of a faint nebula.

The molecular clouds are formed mostly from hydrogen, with lesser quantities of other molecules such as carbon monoxide, ammonia, water and ethanol. In addition, small quantities of dust are commonly found, consisting of carbon, iron, oxygen and silicon. It should be noted that the first stars formed after the Big Bang arose from clouds containing only hydrogen and helium, and the other elements arose as a result of nuclear fusion in these first stars.

Figure 15 *The Horsehead Nebula. Bright stars can be seen shining through the dust clouds.*

Areas of space away from molecular clouds and stars are called the interstellar medium and contain low densities of molecules and dust. In these areas gravitational attraction between molecules is relatively weak because the molecules are widely spaced apart and this attraction is not enough to overcome the thermal pressure that arises as gravity brings the molecules closer together. Star formation is therefore not possible in the interstellar medium. However, in molecular clouds the molecules are close enough together that, given suitable circumstances, gravitational attraction overcomes the thermal pressure and progressively the molecules compress into a core. The process steadily heats the core until it reaches a temperature where nuclear fusion can be sustained, at which point a star has been formed. The processes which govern energy production and transfer within the star are covered in the section on the properties of stars.

Stellar nucleosynthesis

The process of stellar nucleosynthesis was first postulated by the British astronomer, Fred Hoyle, in the late 1940s when he was trying to understand how elements heavier then hydrogen and helium could have arisen in the Universe (Singh, 2004). The production of these heavier elements by nuclear fusion in a star of mass $25M_{\text{Sun}}$ is summarised in Table 4, which shows that progressively higher temperatures and densities are required to produce the heavier elements.

Table 4 Summary of nucleosynthesis occurring in a star of mass $25M_{Sun}$. (Singh, 2004)

Stage	**Temperature (K)**	**Density ($g\ cm^{-3}$)**	**Duration**
Hydrogen → helium	4×10^7	5	10^7 years
Helium → carbon	2×10^8	7×10^2	10^6 years
Carbon → neon + magnesium	6×10^8	2×10^5	600 years
Neon → oxygen + magnesium	1.2×10^9	5×10^5	1 year
Oxygen → sulfur + silicon	1.5×10^9	1×10^7	6 months
Silicon → iron	2.7×10^9	3×10^7	1 day

Hoyle's work was interesting not just for what he discovered, but also for the way in which he achieved it. All the reactions in Table 4 were explainable with the exception of the helium to carbon step, where the pathway required an intermediate reaction product that had never been observed and was not believed to exist. Hoyle adopted what is known as the *anthropic principle,* reasoning that since he was partly made of carbon-12 and lived in the universe he was investigating, then such a pathway must exist otherwise he could not exist. He predicted the energy level of this intermediate product and then pressed Willy Fowler (an American astrophysicist) to search for this specific product. It was discovered within a few days and thus confirmed the process by which nucleosynthesis occurs.

Thus, all the elements present in our Universe have been created by nucleosynthesis in many generations of stars, either due to the reactions described above or by the formation of heavier elements during a supernova explosion. Everything around us is made of stellar material, including ourselves. As Simon Singh states:

Romantics might like to think of themselves as being composed of stardust. Cynics might prefer to think of themselves as nuclear waste.
(Singh, 2004).

Hertzsprung–Russell diagrams

The characteristics, lifetime and ultimate fate of a particular star depend solely on its mass, which in turn is constrained by the quantity of material available during the star's formation.

We have seen in an earlier section that stellar masses are confined to a range $0.08M_{\text{Sun}}$ to $150M_{\text{Sun}}$ because outwith this range gravitational equilibrium is not possible. We will shortly discuss the evolution of low-mass and high-mass stars. However, to understand the processes of evolution it is necessary to understand how mass influences the basic characteristics of a star.

In the early 20th century, a Danish astronomer, Ejnar Hertzsprung, was exploring how a star's spectrum might be related to its apparent magnitude. The graphs he produced of apparent magnitude versus spectral class showed distinct patterns and clusters of stars. Working independently, Henry Norris Russell in the USA did a similar thing using absolute magnitude and found the same features as Hertzsprung.

Plots of luminosity versus temperature are now known as Hertzsprung–Russell diagrams (H–R diagrams; Figure 16) and understanding one is vital to explaining the lifetimes of various types of star. Note that both axes are logarithmic and that the *x*-axis is reversed so that the hottest stars are at the left-hand side of the diagram.

As we saw earlier, the spectral type sequence for classifying stars is O, B, A, F, G, K, M.

A mnemonics to aid in remembering the order of stellar class are:

Oh, Be A Friendly Girl/Guy, Kiss Me!
or
Oh Be A Fantastic Goalie Kick Magnificently

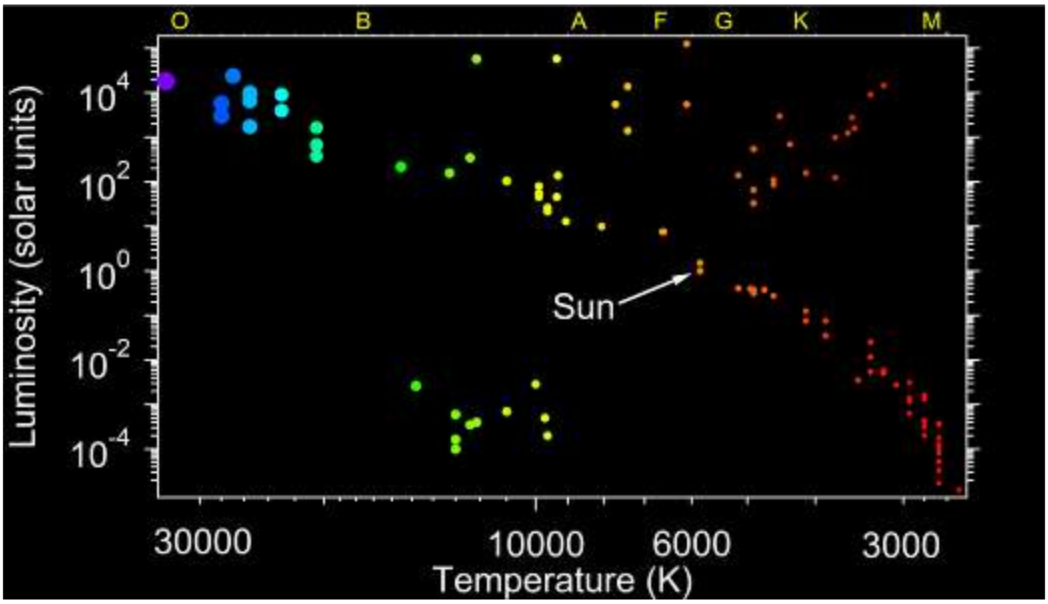

Figure 16 *The basic Hertzsprung–Russell diagram.*

There are four main groups of stars to highlight, each group containing stars at different stages of their life cycle: main sequence, giants, supergiants and white dwarfs (Figure 17).

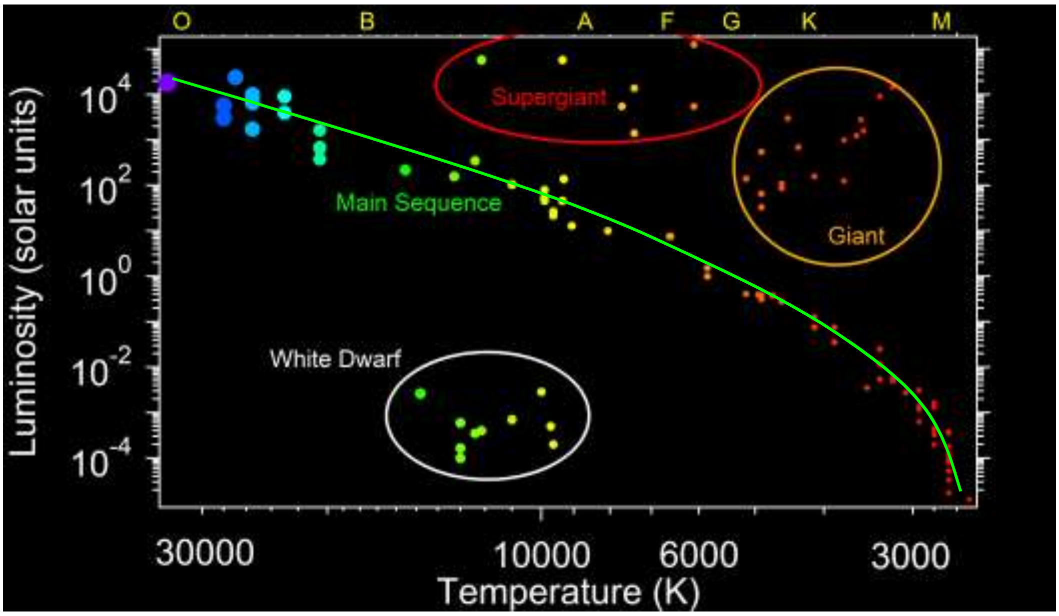

Figure 17 *The principal star groups.*

Main sequence

Once a star has formed and established hydrogen fusion it will occupy a position somewhere along the main sequence, a band of stars lying from the upper left to the lower right of the H–R diagram. The position within the main sequence is determined by the mass of the star, with the most massive at the upper left and the least massive at the lower right.

The mass of the star also directly influences its surface temperature. High-mass stars have a large gravitational pressure and correspondingly high core temperatures and pressures. This leads to high-mass stars having high surface temperatures in the region of 25000 K, whilst low mass stars may have surface temperatures as low as 2000 K. As described earlier, this leads to cool, low-mass stars having a red colouration whilst massive stars appear blue-white.

A further consequence of the very high temperatures and pressures in massive stars is that, despite having much larger reserves of hydrogen than smaller stars, they consume their hydrogen supply at such a rate that they are (relatively speaking) very short lived. Those at the upper left of the diagram have lifetimes of the order of several million years, whilst the smallest, coolest, stars have lifetimes in excess of 300 billion years, or more than 20 times longer than the universe has so far existed for. Our own Sun was formed around 4.5 billion years ago and will have a main sequence lifetime of 10 billion years, so it is roughly halfway through its main sequence phase.

Low-mass stars

Subgiants and giants

Towards the end of the life of a low-mass star (such as our Sun), it begins to run out of the hydrogen fuelling the fusion reaction. This causes the stellar pressure to decrease, which in turn causes the gravitational pressure to compress the core, leading to a higher temperature. At this higher temperature helium nuclei begin to fuse to form carbon. The star’s luminosity increases but because the star also expands in volume the surface temperature is lower than would be expected if it were still on the main sequence. The star expands and the surface temperature cools, passing through the subgiant region and eventually becoming a red giant. An easily observed example of such a giant star (actually an orange giant) is Aldebaran, the bull’s eye in the constellation of Taurus. When this happens to our Sun it will expand past the current radius of the Earth’s orbit. The radius of Earth’s orbit will by this stage have increased due to loss of solar mass, although tidal interactions with the Sun will tend to counteract this effect, leaving the likelhood that Earth will be engulfed by the Sun somewhat uncertain. Long before this point, however, the oceans will have evaporated due to the Sun's increasing luminosity, making continued human life on Earth unlikely.

Depending on the mass of the original star, once the helium is exhausted a further contraction raises the core temperature again, carbon atoms begin to fuse to produce neon and magnesium, and the star expands further.

This process of core compression followed by star expansion occurs for each of the fusion stages in Table 4, but low to medium mass stars are not able to produce elements heavier than carbon and oxygen.

White dwarfs

As a red giant continues to expand it eventually reaches a size where the outer layers of the star can no longer be retained by gravitational attraction and the star enters the final phase of its lifetime. In terms of the H–R diagram the star moves left and downwards out of the giant region, and the outer layers steadily disperse as a planetary nebula (Figure 18), leaving behind the stellar core. Since fusion no longer occurs in this dead core it steadily cools, moving down the H–R diagram until it becomes an inert white dwarf consisting mostly of carbon and oxygen. The term 'planetary nebula' is used for historical reasons and does not imply planet formation.

The death of a Sun-like star, from the point at which the hydrogen runs out until it becomes a white dwarf, is of the order of one billion years, compared with a 10 billion year main-sequence lifetime.

High-mass stars

Supergiants

The evolution of a high-mass star is similar to that of a low-mass star in the early stages, when hydrogen is fused to form helium. However, as the hydrogen runs out and helium fusion begins, the process of expansion is much greater than for a low-mass star and the star becomes a supergiant. In addition, the high mass means that fusion proceeds through all the stages listed in Table 4.

Figure 18 *The glowing eye of planetary nebula NGC6751.*

Neutron stars, black holes and supernovae

No fusion pathways possible within a star are capable of producing elements more massive than iron (although some stars produce heavier elements via a neutron capture process called the S process) so ultimately the star accumulates iron in its core. This process proceeds up to the point where the mass and density of the core are so large that gravitational forces cause the core to rapidly collapse in on itself. The immense pressure overcomes the electron degeneracy pressure, protons and electrons combine to form neutrons and the core collapses to diameter of perhaps a few kilometres, becoming a neutron star. Neutron stars are incredibly dense, the density varying with depth from the surface, but on average being such that a single teaspoon of the material would have a mass comparable with that of the entire human population. Surace gravity is of the order of 10^{11} times greater than that on Earth, meaning that an object released from a height of 1 m would impact the surface at over 1,400,000 m s^{-1}. Due to conservation of angular momentum as the star shrinks, neutron stars spin extremely quickly, having rotational periods ranging between around a millisecond and several seconds.

In some cases, where the mass is large enough, the gravitational force overcomes the degeneracy pressure of the neutrons, after which nothing can stop the collapse. It continues unabated until an object of zero volume and infinite density is created.The gravitational field of such an entity is so strong that even light itself cannot escape. These objects are known as black holes.

The distance from within which nothing can escape a body is called the Schwarzschild radius and is given by

$$r_{\text{Schwarzschild}} = \frac{2GM}{c^2}$$

where G is the universal graviational constant, M is the mass of the object and c is the speed of light in a vacuum. For a non-rotating black hole the surface at the Schwarzschild radius forms an *event horizon*, a region from beyond which nothing, including light, can escape to influence the outside universe. Interestingly in the case of a sufficiently massive black hole it would be possible to fall within the event horizon without suffering any ill-effects or necessarily being aware of one’s impending doom.

This collapse itself is a sudden and very rapid event, lasting a fraction of a second and releasing enormous amounts of energy. This energy release blows away the outer layers of the star into space and releases a massive burst of radiation known as a supernova, which for a brief moment can outshine an entire galaxy. From Earth, relatively nearby supernovae are seen as a sudden brightening of a star, which lasts from several days to months before gradually fading away. However, the debris from such explosions can remain visible for much longer.

An example of this is found in the Crab Nebula (Figure 19). This nebula arose from a supernova observed in China in 1054 AD and modern observations confirm that there is a neutron star at the centre of the nebula surrounded by clouds of stellar material expanding at thousands of kilometres per second.

Figure 19 *Crab Nebula.*

The closest red supergiant to Earth at 310 light years is Betelgeuse in the constellation of Orion. It is not possible to know exactly where it is in its life cycle but if it happens to have gone supernova during the 18th century you may yet see the visible evidence arriving on Earth.

The death of a high-mass star, from the point at which the hydrogen runs out until it goes supernova, is of the order of one million years, compared with a five million year main-sequence lifetime. This is roughly three orders of magnitude shorter than the lifetime of a Sun-like star.

Material ejected during a supernova includes all the elements formed by the fusion processes so that when, ultimately, this material condenses to form a new star it will already have some of the heavier elements present within it. However, the quantity of energy available in a supernova is sufficient to bring about the formation of elements heavier than iron and, together with the S process, supernova nucleosynthesis is responsible for the production of elements up to and including uranium, including many of the elements necessary for human life. The atoms which your body is currently borrowing have existed for billions of years and were once part of a supernova explosion.

References

Bennett J, Donahue M, Schneider N, Voit M (2008) *The Cosmic Perspective*, 5th edition, Pearson Addison-Wesley, San Francisco.

ITER (2011) http://www.iter.org/ (accessed 14 March 2012).

Monteith JL (1973) *Principles of Environmental Physics*, Edward Arnold, London.

Moore P (ed.) (2002) *Astronomy Encyclopedia*, Philip's, London.

SIDC (2011) SIDC-team, World Data Center for the Sunspot Index, Royal Observatory of Belgium, *Monthly Report on the International Sunspot Number*, online catalogue of the sunspot index, http://www.sidc.be/sunspot-data/, 1700–2010 (accessed 14 March 2012).

Singh (2004) *Big Bang*, Fourth Estate, London.

Wolfram Alpha (2011) http://www.wolframalpha.com/entities/calculators/luminosity-absolute_magnitude_formula/7m/06/j3/ (accessed 14 March 2012).

Young HD, Freedman RA (1996) *University Physics*, 9th edition, Addison-Wesley, Reading, MA.

Glossary

Term	Definition/ Comment
Absolute brightness	The absolute brightness is the brightness a celestial body would have were it to be placed at a distance of 10 parsecs from Earth.
Absolute magnitude	The apparent magnitude of a celestial body is a measure of how bright it is as seen by an observer on Earth. There are no units. Allows direct comparison of actual luminosities as it ranks stars by their brightness as if placed 10 parsecs or 32.6 light years from Earth. There are no units.
Apparent Brightness	The apparent brightness of a celestial body is how much energy is coming from the body per unit area per unit time, as measured on Earth. The units are watts per square metre (W m^{-2}).
anthropic principle	A range of philosophical arguments which broadly assert that we find ourselves in a universe capable of supporting intelligent life because only in such a universe would intelligent life exist to ask the question.
astronomical unit (AU)	149,597,870 km; the average distance from the Earth to the Sun.
Big Bang theory	A theory of cosmology in which the expansion of the universe is presumed to have begun with an explosion hence the term ‘Big Bang’.
Brown Dwarfs	An object similar to, but smaller than, a star which is not massive enough to burn hydrogen in its core. Brown dwarfs have a mass less than $0.08M_{\text{Sun}}$, and usually give off infrared radiation.
Chemical species	Chemical species are chemically identical atoms, molecules, molecular fragments, ions, etc subjected to a chemical process or to a measurement.
corona (plural: coronae)	The outer layer of a star’s atmosphere. In the Sun, the corona has a temperature greater than 1,000,000 K and a low density.
deuterium	An isotope of hydrogen containing one proton and one neutron.
Luminosity	This is a measure of the total power output of a star (W).

Term	Definition/ Comment
neutrino	A fundamental particle produced by nuclear reactions, including those in stars. They are therefore produced in huge numbers by the Sun. The overwhelming majority of them pass through the Earth without interacting, making them extremely difficult to detect. All neutrinos are part of the lepton family of particles. There are three types of neutrino: the electron neutrino (νe), the muon neutrino ($\nu\mu$) and the tau neutrino ($\nu\tau$), plus their associated antiparticles, making a total of six.
Nucleosynthesis (stellar)	The process by which elements heavier than helium are created by nuclear fusion in stars.
parsec	A common distance unit used in astronomy that is short for parallax of one arc second. One parsec equals 3.26 light-years, or 3.1×10^{16} m.
parallax	The apparent motion of a relatively close object compared to a more distant background as the location of the observer changes. Astronomically, it is half the angle through which a star appears to move as the Earth moves from one side of the Sun to the other.
plasma	Often referred to as the fourth state of matter. A low-density gas in which the individual atoms are ionized (and therefore charged). The overall electric charge on the plasma is neutral as the total number of positive and negative charges is equal. The vast majority of matter in the Universe exists as a plasma.
positron	The positively charged antiparticle to the electron. The positron is identical to the electron, with the exception of charge and lepton number.
solar flares	A solar flare is an intense change in brightness on the surface of the Sun due to violent eruptions the Sun's surface. The flare ejects clouds of electrons, ions, atoms and electromagnetic radiation across the whole spectrum into space. Flares occur in active regions around sunspots, where intense magnetic fields infiltrate the photosphere.
Solar Neutrino Problem	The problem facing scientists, astrophysicists and nuclear physicists alike for more than 30 years, in that the number of solar neutrinos predicted did not match with the number predicted from the theories of how the Sun produced its energy. This was resolved when more sensitive ways of measuring all three types of neutrinos were produced.

Term	Definition/ Comment
Stefan-Boltzmann constant;σ (sigma)	The constant of proportionality present in the Stefan–Boltzmann law. It is equal to 5.6697 × 10^{-8} W m^{-2} K^4).
Stefan-Boltzmann law	The radiated power P (rate of emission of electromagnetic energy) of a hot body is proportional to the radiating surface area, *A*, and the fourth power of the thermodynamic temperature, *T*. The constant of proportionality is the Stefan–Boltzmann constant.
stellar classification	Stars are given a designation consisting of a letter and a number roughly dependent on their surface temperature. The main classes are O, B, A, F, G, K, and M; O stars are the hottest, M the coolest. Stars are further subdivided into numbers in each of the major classes, for example the Sun is classified as G2. The classes are oddly sequenced because they were assigned before the science behind the concept was fully understood. O and B stars are rare but very bright; M stars are numerous but dim.
sunspots	Visible dark regions on the photosphere of the Sun. These are cooler regions on the Sun where the magnetic field loops up out of the solar surface.

Useful websites

The H–R diagram
http://www.astro.ubc.ca/~scharein/a311/Sim/hr/HRdiagram.html
http://astro.unl.edu/naap/hr/animations/hr.html

Background to early models and measurements of our Universe
http://www.splung.com/content/sid/7/page/earlymodels

Fusion
http://www.splung.com/content/sid/5/page/fusion

The Big Bang time machine
http://resources.schoolscience.co.uk/STFC/bang/bang.htm

Brown dwarfs
http://starchild.gsfc.nasa.gov/docs/StarChild/questions/question62.html

Sunspots
http://solarscience.msfc.nasa.gov/feature1.shtml#Sunspots
http://www.eaas.co.uk/news/solar_features.html

CCDs
http://www.mssl.ucl.ac.uk/www_detector/optheory/ccdoperation.html#basics
http://www.explainthatstuff.com/howccdswork.html
http://www.britastro.org/vss/ccd_photometry.htm
http://www.maths.qmul.ac.uk/~svv/MTH725U/Lecture2.htm
http://www.opticstar.com/Run/Astronomy/Astro-Editorial-Articles-General.asp?p=0_10_19_1_6_200_30

Neutrinos
http://www.particleadventure.org/neutrinos.html
http://astronomyonline.org/SolarSystem/SolarNeutrinoProblem.asp
http://imagine.gsfc.nasa.gov/docs/science/know_l2/stars.html

Nucleosynthesis
http://helios.gsfc.nasa.gov/nucleo.html

anthropic principle
http://www.allancrossman.com/ap/anthropic.html
http://www.np.ph.bham.ac.uk/history/nucleosynthesis

Luminosity and brightness
http://www.frankswebspace.org.uk/ScienceAndMaths/physics/physicsGCE/astrophysics2.htm

Parsec
http://www.splung.com/content/sid/7/page/magnitude.