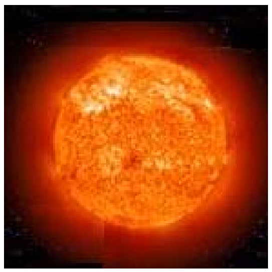
Main Sequence Stars



Credit: *NASA*
The Sun

The majority of stars in the galaxy, including our Sun, Sirius and Alpha Centauri A and B are all main sequence stars. The Sun's relative longevity and stability have provided the conditions necessary for life to evolve here on Earth. Our understanding of the processes involved and characteristics of this key group of stars has progressed in parallel with our understanding of nuclear physics.

Properties of Main Sequence Stars

Main sequence stars are characterised by the source of their energy. They are all undergoing fusion of hydrogen into helium within their cores. The rate at which they do this and the amount of fuel available depends upon the mass of the star. Mass is the key factor in determining the lifespan of a main sequence star, its size and its luminosity. Stars on the main sequence also appear to be unchanging for long periods of time. Any model of such stars must be able to account for their stability.

Hydrostatic Equilibrium

The simple model of any main sequence star is of a dense gas/fluid in a state of *hydrostatic equilibrium*. The inward acting force, gravity, is balanced by outward acting forces of gas pressure and the radiation pressure. Apart from the extremely hot but tenuous corona , the pressure and temperature of stars basically increases as you approach the core.

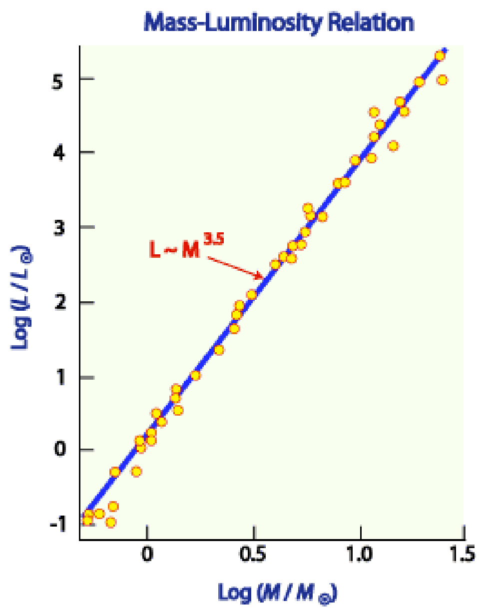
Main sequence stars essentially have a fixed size that is a function of their mass. The more massive the star, the greater its gravitational pull inwards. This in turn compresses the gas more. As you try and compress a gas it exerts a gas pressure back, it resists the compression. In stars this gas pressure alone is not sufficient to withstand the gravitational collapse. Once the core temperature has reached about 10 million K, fusion of hydrogen occurs, releasing energy. This energy exerts an outwards radiation pressure due to the action of the photons on the extremely dense matter in the core. The radiation pressure combined with the gas pressure balances the inward pull of gravity preventing further collapse.

Stellar Mass

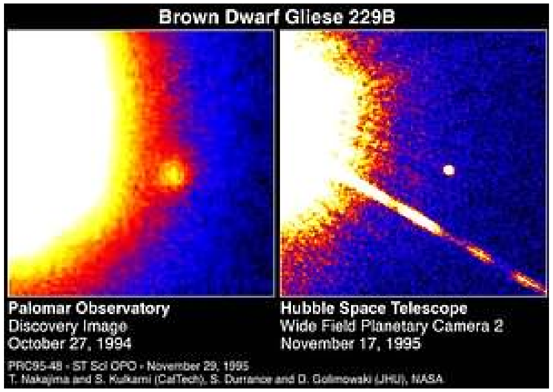
As was apparent from the evolutionary Hayashi tracks on the previous page, a star's position on the main sequence its actually a function of its mass. This is an incredibly useful relationship, called the *mass-luminosity relation*. If we know where on the main sequence a star is we can infer its mass. In general the more massive a star is, the further up the main sequence it is found and the more luminous it is. Mathematically this relation is expressed by:

$\log(L/L_{Sun}) = n \log(M/M_{Sun})$ or
$L/L_{Sun} = (M/M_{Sun})^n$ (Equation 6.1)

where *n* is about 4 for Sun-like stars, 3 for the more massive stars and 2.5 for dim red main sequence stars. (*Note this formula is not required for HSC exams). A 0.1 solar mass star has only about one-thousandth the luminosity of the Sun whereas a 10-solar mass star is has a luminosity 10,000 × that of our Sun.



The lower mass limit for a main sequence star is about 0.08 that of our Sun or 80 times the mass of Jupiter. Below this mass the gravitational force inwards is insufficient to generate the temperature needed for core fusion of hydrogen and the "failed" star forms a brown dwarf instead. The first such object discovered in 1995 was Gliese 229B at 0.05 solar masses.



Gliese 229B, the first brown dwarf, discovered in 1995.

Limits on the upper mass of stars is thought to be somewhere between 150 and 200 solar masses based on theoretical modeling. Such stars are extremely rare and short-lived.

The greater the mass of a main sequence star, the greater its effective temperature. This, combined with the larger radius of higher mass main sequence stars accounts for their much greater luminosity. Remember, $L \propto T^4$ and $L \propto R^2$ so even a small increase in effective temperature will significantly increase luminosity.

Main-Sequence Lifespan

The main sequence is the stage where a star spends most of its existence. Relative to other stages in a star's "life" it is extremely long; our Sun took about 20 million years to form but will spend about 10 billion years (1×10^{10} years) as a main sequence star before evolving into a red giant. *What determines the main sequence lifespan of a star?*

Main sequence stars vary in mass. You may imagine that a more massive star has more fuel available so can spend more time on the main sequence fusing hydrogen to helium. You would be wrong - the opposite is true. More massive stars have a stronger gravitational force acting inwards so their core gets hotter. The higher temperatures mean that the nuclear reactions occur at a much greater rate in massive stars. They thus use up their fuel much quicker than lower mass stars. This is analogous to the situation with many chemical reactions, the higher the temperature the faster the reaction rate.

Lifespans for main sequence stars have a vast range. Whilst our Sun will spend 10 billion years on the main sequence, a high-mass, ten solar-mass ($10M_{Sun}$) star will only last 20 million years (2.0×10^7 years) on the main sequence. A star with a only half the mass of Sun can spend 80 billion years on the main sequence. This is much longer than the age of the Universe which means that all the low-mass stars that have formed are still on the main sequence - they have not had time to evolve off it.

Key Properties of Main Sequence Stars

Mass/M_{Sun}	**Luminosity/L_{Sun}**	**Effective Temperature (K)**	**Radius/R_{Sun}**	**Main sequence lifespan (yrs)**
0.10	3×10^{-3}	2,900	0.16	2×10^{12}
0.50	0.03	3,800	0.6	2×10^{11}
0.75	0.3	5,000	0.8	3×10^{10}
1.0	1	6,000	1.0	1×10^{10}
1.5	5	7,000	1.4	2×10^{9}
3	60	11,000	2.5	2×10^{8}
5	600	17,000	3.8	7×10^{7}
10	10,000	22,000	5.6	2×10^{7}
15	17,000	28,000	6.8	1×10^{7}

Mass/M_{Sun}	Luminosity/L_{Sun}	Effective Temperature (K)	Radius/R_{Sun}	Main sequence lifespan (yrs)
25	80,000	35,000	8.7	7×10^6
60	790,000	44,500	15	3.4×10^6

Composition

Although there are 92 naturally occurring elements and a few hundred isotopes, the composition of stars is remarkably similar and simple. Stars are composed almost entirely of hydrogen and helium. A star such as our Sun is about 73% hydrogen by mass and 25% helium. If determined by number of nuclei then it is 92% hydrogen and 7.8% helium. The remaining 2% by mass or 0.2% by number is all the heavier elements. Historically astronomers termed these elements with atomic numbers greater than two as *metals*. These include elements such as carbon and oxygen. The use of "metals" is not to be confused with the more common chemical meaning of the term.

Metallicity is a measure of the abundance of elements heavier than helium in a star and is expressed as the fraction of metals by mass. It can be determined or at least inferred from spectroscopic and photometric observations. In general stars with higher metallicities are inferred to be younger than those with very low values. This is due to the fact that elements heavier than helium are made inside stars by nucleosynthesis and released into interstellar space by mass-loss events such as supernova explosions in the late stages of stellar evolution. Early generations of stars

Stars found in the spiral arms of galaxies, including our Sun, are generally younger and have high metallicities. They are referred to as Population I stars. Population II stars are older, red stars with lower metallicities and are typically located in globular clusters in galactic halos, in elliptical galaxies and near the galactic centre of spiral galaxies.

Nucleosynthesis and Fusion Reactions

Nucleosynthesis simply refers to the production of nuclei heavier than hydrogen. This occurs in main sequence stars through two main processes, the proton-proton chain and the CNO cycle (carbon, nitrogen, oxygen). Primordial nucleosynthesis occurred very early in the history of the Universe, resulting in some helium and small traces of lithium and deuterium, the heavy isotope of hydrogen. Fusion processes in post-main sequence stars are responsible for many of the heavier nuclei. Other mechanisms such as neutron capture also occur in the last stages of massive stars. Both discussed in later pages.

Main sequence stars fuse hydrogen into helium within their cores. This is sometimes called "hydrogen burning" but you need to be careful with this term. "Burning" implies a combustion reaction with oxygen but the process within stellar cores is a nuclear reaction, not a chemical one.

The nuclear fusion in the cores of main sequence stars involves positive hydrogen nuclei, ionised hydrogen atoms or protons, to slam together, releasing energy in the process. At each stage of the reaction, the combined mass of the products is less than the total mass of the reactants. This mass difference is what accounts for the energy released according to Einstein's famous equation: $E = m\,c^2$ where E is the energy, m the mass and c the speed of light in a vacuum. This is better expressed as:

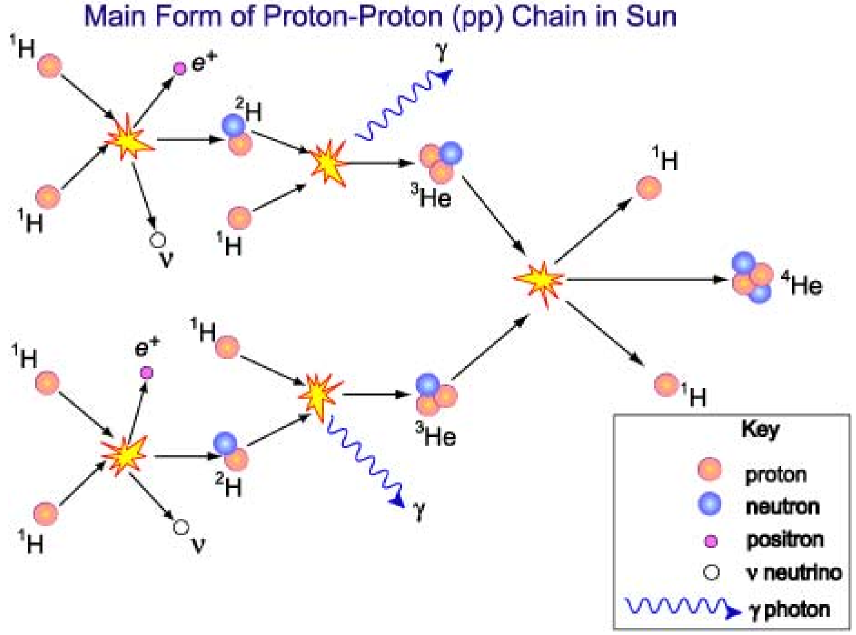
$E = \Delta m\, c^2$ where Δm is the change in mass. (Equation 6.2)

In conditions such as those on Earth, if we try to bring two protons (hydrogen nuclei) together the electrostatic interaction tends to cause them to repel. This coulombic repulsion must be overcome if the protons are to fuse. The actual process whereby two protons can fuse involves a quantum mechanical effect known as *tunneling* and in practice requires the protons to have extremely high kinetic energies. This means that they must be traveling very fast, that is have extremely high temperatures. Nuclear fusion only starts in the cores of stars when the density in the core is great and the temperature reaches about 10 million K.

There are two main processes by which hydrogen fusion takes place in main sequence stars - the proton-proton chain and the CNO (for carbon, nitrogen, oxygen) cycle.

Proton-Proton (pp) Chain

The main process responsible for the energy produced in most main sequence stars is the proton-proton (pp) chain. It is the dominant process in our Sun and all stars of less than 1.5 solar masses. The net effect of the process is that four hydrogen nuclei, protons, undergo a sequence of fusion reactions to produce a helium-4 nucleus. The sequence shown below is the most common form of this chain and is also called the ppI chain. It accounts for 85% of the fusion energy released in the Sun.



If you study the diagram above you will note that six protons are used in the series of reactions but two are released back. Other products include the He-4 nucleus, 2 neutrinos, 2 high-energy gamma photons and 2 positrons. Each of these products carries some of the energy released from the slight reduction in total mass of the system. The overall reaction can be summarised as:

ppI: 4H-1 → He-4 + $2e^+$ + 2ν + 2γ
The neutrinos are neutral and have extremely low rest masses. They essentially do not interact with normal matter and so travel straight out from the core and escape from the star at almost the speed of light. About 2% of the energy released in the pp chain is carried by these neutrinos.

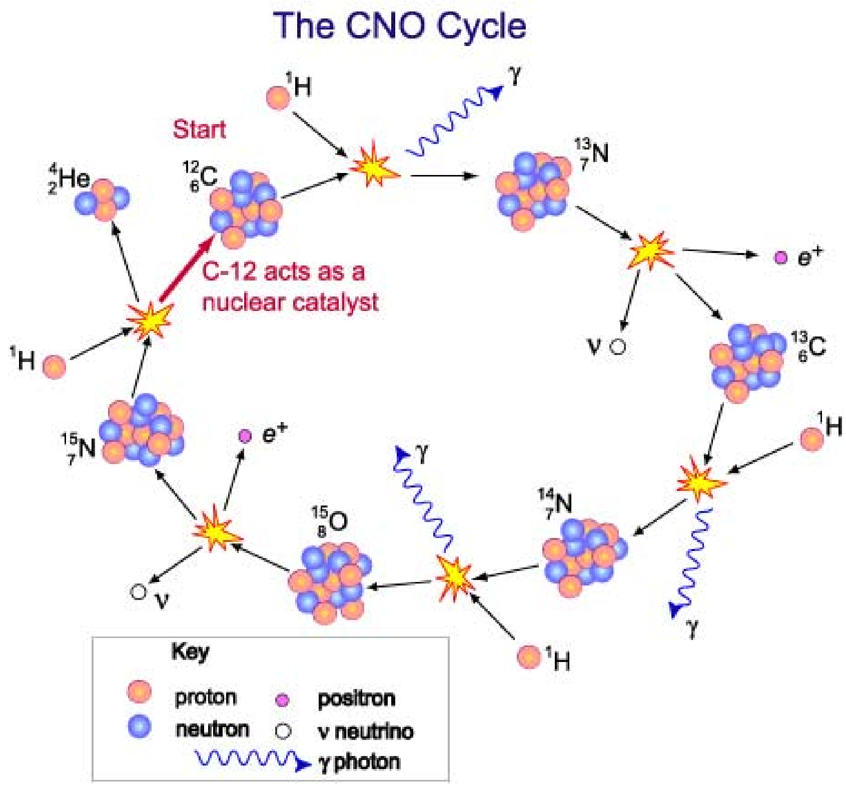
Positrons are the antiparticle of electrons. Although the pp chain involves the fusion of hydrogen nuclei, the cores of stars still contain electrons that have been ionised or ripped off from their hydrogen or helium nuclei. When a positron collides with an electron, an antimatter-matter event occurs in which each annihilates the other, releasing yet more high-energy gamma photons.

Two other forms of the pp chain can occur in stars and contribute about 15% of the energy production in the Sun. In the ppII chain, a He-3 nucleus produced via the first stages of the ppI chain undergoes fusion with a He-4 nucleus, producing Be-7 and releasing a gamma photon. The Be-7 nucleus then collides with a positron, releasing a neutrino and forming Li-7. This in turn fuses with a proton, splitting to release two He-4 nuclei. A rarer event is the ppIII chain whereby a Be-7 nucleus produced as above fuses with a proton to form B-8 and release a gamma photon. B-8 is unstable, undergoing beta positive decay into Be-8, releasing a positron and a neutrino. Be-8 is also unstable and splits into two He-4 nuclei. This process only contributes 0.02% of the Sun's energy. These forms are summarised as:

ppII: 4H-1 + e^- → He-4 + e^+ + 2ν + 2γ
ppIII: 4H-1 → He-4 + $2e^+$ + 2ν + 3γ

CNO Cycle

Stars with a mass of about 1.5 solar masses or more produce most of their energy by a different form of hydrogen fusion, the CNO cycle. CNO stands for carbon, nitrogen and oxygen as nuclei of these elements are involved in the process. As its name implies, this process is cyclical. It requires a proton to fuse with a C-12 nuclei to start the cycle. The resultant N-13 nucleus is unstable and undergoes beta positive decay to C-13. This then fuses with another proton to from N-14 which in turn fuses with a proton to give O-15. Being unstable this undergoes beta positive decay to form N-15. When this fuses with a proton, the resultant nucleus immediately splits to form a He-4 nucleus and a C-12 nucleus. This carbon nucleus is then able to initiate another cycle. Carbon-12 thus acts like a nuclear catalyst, it is essential for the process to proceed but ultimately is not used up by it.

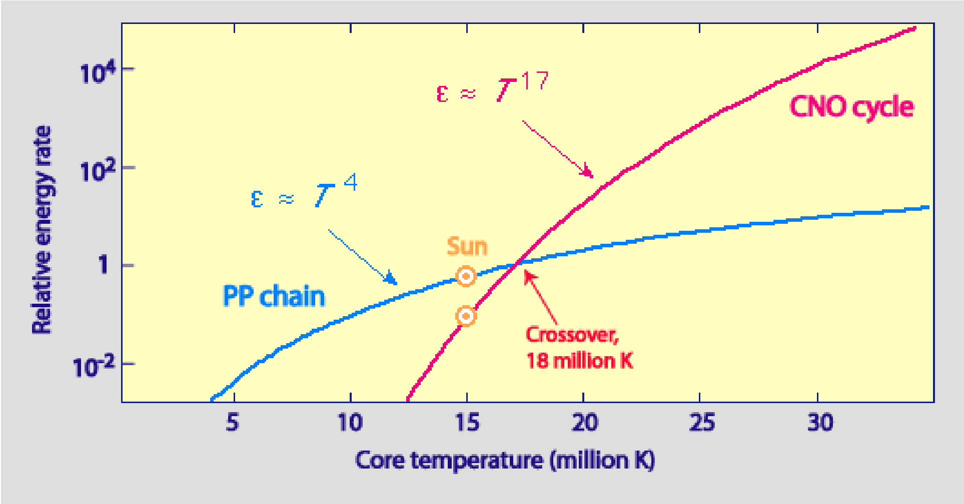


As with the various forms of the pp chain, gamma photons and positrons are released in the cycle along with the final helium and carbon nuclei. All these possess energy. The overall reaction can be summarised as:

CNO: 4H-1 → He-4 + $2e^{+}$ + 2v + 3γ

Why does the CNO cycle dominate in higher-mass stars? The answer has to do with temperature. The first stage of the pp chain involves two protons fusing together whereas in the CNO cycle, a proton has to fuse with a carbon-12 nucleus. As carbon has six protons the coulombic repulsion is greater for the first step of the CNO cycle than in the pp chain. The nuclei thus require greater kinetic energy to overcome the stronger repulsion. This means they have to have a higher temperature to initiate a CNO fusion. Higher-mass stars have a stronger gravitational pull in their cores which leads to higher core temperatures.

The CNO cycle becomes the chief source of energy in stars of 1.5 solar masses or higher. Core temperatures in these stars are 18 million K or greater. As the Sun's core temperature is about 16 million K, the CNO cycle accounts for only a minute fraction of the total energy released. The relative energy produced by each process is shown on the plot below.



Credit: *Adapted from an image by Mike Guidry, University of Tennessee.*
Relative energy production for the pp chain and CNO cycle. Note that at the temperature range typically found in main sequence stars, the contribution due to the pp chain is dependent on T^4 whereas that from the CNO cycle is T^{17}. Above 18 million K the CNO cycle contributes most of the energy and any further slight increase in core temperature leads to a greater increase in energy output.

Calculating the Sun's Main Sequence Lifespan

As we have already seen, the Sun has a main sequence lifespan of about 10 billion (1×10^{10}) years. How do astronomers calculate such a value? A first order approximation for this value is surprisingly easy to derive.

You will recall that the mass of a helium-4 nucleus is slightly less than the sum of the four separate protons needed to form it. In nuclear physics, the masses dealt with are so small that the atomic mass unit or amu is used instead of the kilogram where 1 amu = 1.66×10^{-27} kg. A proton has a mass of 1.0078 amu so four protons add up to 4.0312 amu. A helium-4 nucleus has a mass of 4.0026 which means that the mass defect, the difference between the two total masses, is 0.0286 amu or only 0.7%. From equation 6.2:

$E = \Delta m\, c^2$ so substituting in values gives
$E = 0.0286(1.66 \times 10^{-27})(3$ &times $10^8)^2$
$\therefore E = 4.3 \times 10^{-12}$ J
The production of each helium nucleus releases only a small amount of energy, 10^{-12} J which does not seem a lot. We know though measurement that the Sun's luminosity is 3.90×10^{26} J.s^{-1}. To produce this amount of energy, vast numbers of helium, $(3.90 \times 10^{26})/(4.3 \times 10^{-12})$ = 9 &times 10^{37}, must be formed every second. Each second, 600 million tons of hydrogen fuse to form 596 million tons of helium. This means 4 million tons of matter is destroyed and converted into energy each second.

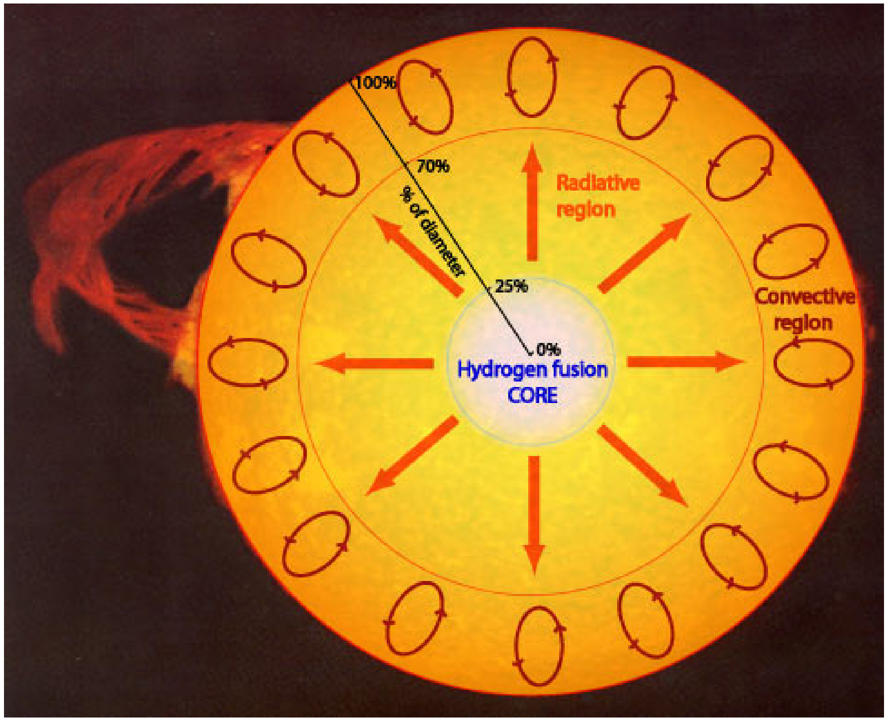
The high temperature needed for hydrogen fusion is only found in the core region of the Sun. This comprises only about 10% of its total mass. The energy potentially available from this mass of hydrogen is roughly:

E_{total} = (mass defect per He nucleus produced) × c^2 × (mass of H in core)
$\therefore E_{total} = 0.0071(9$ &times $10^{16})(0.1 \times 2.0 \times 10^{30})$
$= 1.28 \times 10^{44}$ J
Given that the Sun's energy output is currently 3.90×10^{26} J. s^{-1} and assuming that it will be roughly constant for its main sequence lifespan, then the Sun has enough core hydrogen for about 10 billion years. As it is currently about about 5 billion years old this means it is half way through its main sequence life.

Energy Transport in a Star

We have now seen how energy is produced in a star such as the Sun. *How, though, does this energy escape from the star?* Two processes, radiation and convection, play a vital role.

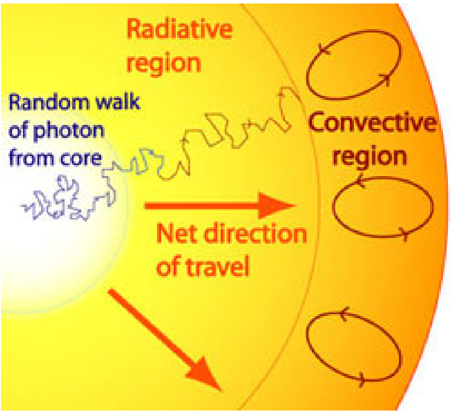
The Sun's interior comprises three main regions. The core, only 25% of the Sun's diameter, a radiative zone extending from the core to 70% of the diameter and the outer region where convection processes dominate.



Credit: *Background image of the Sun at 30.4 nm in extreme ultraviolet taken from Skylab in 1973 provided courtesy of the [Naval Research Laboratory](). Overlay adapted from "Observer's Guide to Stellar Evolution", M. Inglis, Springer, 2003.*

A cross-section of the three main interior regions of the Sun. Radiation dominates in the dense core and surrounding radiative region. Convection currents are responsible for transporting energy out to top of the photosphere where it then escapes as radiation into space.

High-energy gamma photons produced in the core do not escape easily from it. The high temperature plasma in the core is about ten times denser than a dense metal on Earth. A photon can only travel a centimeter or so on average in the core before interacting with and scattering from an electron or positive ion. Each of these interactions changes both the energy and travel direction of the photon. The direction a photon travels after an interaction is random so sometimes it is reflected back into the core. Nonetheless over many successive interactions the net effect is that the photon gradually makes its way out from the core. The path it takes is called a *random walk*. Photons lose energy to the electrons and ions with each interaction creating a range of photon energies. This process is known as *thermalisation* and results in the characteristic blackbody spectrum that forms the continuum background spectrum of stars.

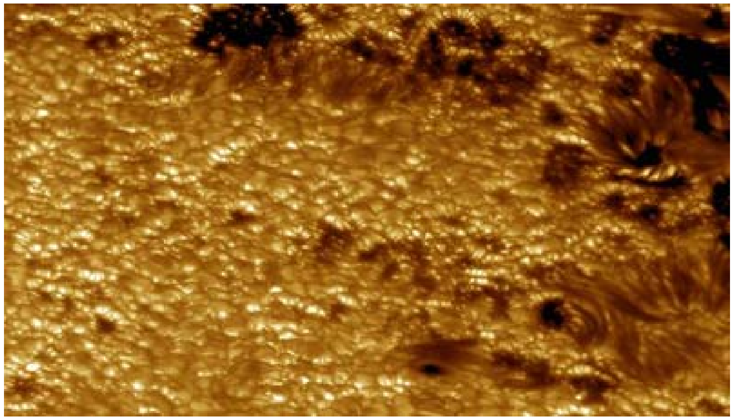


A random walk of a photon from the core of a star. The mean path length increases as it moves out from the core. The photon, initially a gamma-ray also loses some energy from each interaction so that by the time it reaches the convective region it is likely to be a visible light photon. On average a photon takes 23,000 years to make its way from the core of the Sun to the surface where it is radiated away into space.

Interactions between ions and electrons also produce many additional photons of various energies. These also contribute to the blackbody spectrum.

The electrons and nuclei formed in fusion reactions also carry kinetic energy that they can impart to other particles through interactions, raising the thermal energy of the plasma. Neutrinos produced by the various fusion and decay reactions travel out from the core at almost the speed of light. They are effectively unimpeded by the dense matter in the core of main sequence stars. They carry away about 2% of the total energy.

The outer 30% of the Sun is at lower temperature and density than the inner parts. Here, convection currents are responsible for transporting energy to the surface. Deep cells, 30,000 km across are responsible for supergranulation. The cells just below the photosphere are only 1,000 km across and are responsible for the granulation seen on the surface of the Sun as in the image below.



Credit: *G. Scharmer (Swedish 1-m Solar Telescope, Royal Swedish Academy of Sciences)*

The Sun's surface in 3D. Note the sunspots neat top right. Hundreds of solar granules, each about 1,000 km across are visible in the image.

What happens when a main sequence star runs out of hydrogen, the fuel in its core? This leads us to evolution off the main sequence which is discussed on the next page.

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