Nuclear Fusion & the Sun

The Sun's 'low' density - 1410 kg/m^3 - indicates that it is most composed of hydrogen and helium, a fact confirmed by analysis of its stellar spectrum.
For a core temperature of 1.5×10^7K all atoms are ionised and so the core is composed of a rapidly moving 'soup' of e^- H (p^+) and He nuclei.

The P-P reaction

[See Fig 18.2 & Box 18.1]
This is the dominant reaction that powers Main Sequence stars of ∼solar mass
To understand this remember that the overall charge of ingredients and products must remain constant (i.e. you can't create or lose charge). Likewise the total sum of matter and energy remains constant.
Stage 1: 2 protons (H nuclei) fuse to form an H isotope with one proton and one neutron.
Additionally, a positron - a positively charged version of an electron, sharing the same mass - is created to conserve the total charge in the reaction.
The positron quickly reacts with a free electron to annihilate both, with the energy being released in the form of gamma ray photons.
Finally, a neutral, nearly massless particle called a neutrino is formed as a byproduct of the fusion of the two protons. We can detect these on Earth and they provide us with information on the Sun's core.
Stage 2: The ^{2}H nucleus reacts with another proton to form an isotope of Helium - ^{3}He, consisting of 2 protons and one neutron - and releases another γ ray photon.
Stage 3: Two ^{3}He nuclei react to form a stable ^{4}He nucleus and two protons.
The overall effect of Stages 1-3 is therefore:
4 H → ^{4}He + energy + neutrinos.
With the 2 positrons also formed quickly reacting with ambient electrons and annihilating to release additional energy.
But the mass of the ^{4}He nucelus is slightly *smaller* than the sum of the masses of the 4 H nuclei (an effect due to the way that the strong nuclear force that holds the nucleus together works).
The mass difference is
$4\ M_H = 6.69\times10^{-27}$kg – M_{He} ($=6.645\times10^{-27}$kg)
$\Delta M=0.048\times10^{-27}$kg (i.e. about 0.7%)
Energy released ($E=mc^2$) $=4.3\times10^{-12}$ J
This is about 10^7 times greater than the energy of a chemical reaction.
Still, to produce the Sun's luminosity requires the fusion of $\sim5\times10^{11}$ kg of hydrogen *per second* - very large, but so is the Sun...
Indeed, given that 10% of the Sun's mass is within its core we can power it for ∼10 billion years.
The P-P chain is the easiest reaction that can occur, since it requires the lowest temperature and density to overcome the ionic electric repulsive forces between nuclei.
In other, more massive stars the core density and temperatures are higher than in the Sun, so other nuclear reactions can occur.
One example is the CNO cycle, which also converts hydrogen to helium.
Likewise in later stages of stellar evolution, when all the interior H has been burnt, further reaction can occur, ie.
He burning → C, and hence carbon burning, oxygen burning etc. → Fe (iron) core.
This is the main source of elements up to iron, and are returned to the ISM via Supernova explosions.

The Structure of the Sun

Whilst the solar surface is visible to us, we cannot directly see what conditions are like throughout the Sun, from surface to core.
However we know for the P-P chain to work that $T_{core} \sim 10^7$K, while $T_{surface}$=5800K, and thus there is a decrease in T(r) from the core to the surface.
Also, via the same argument we know that the density of the Sun decreases and hence pressure must also fall as you travel from the core to the surface.
The nuclear burning core is found within the innermost ~20% of the Sun, but outside this radius the luminosity is constant (i.e. what is produced in the core has to escape at the surface...).
We would like to know how density, temperature and pressure varies in the interior of the Sun, but to do this astronomers need to solve how energy is transported through the star, and also make use of some very basic observations.

Energy Transport

To understand how the Sun work we must recognise the three ways it may transport energy from its core to its surface:
1) **Conduction:** Energy is transferred by the interaction of adjacent atoms - *not* important in the Sun since it requires particles to be very close to one another.
2) **Convection:** Energy is transfered via the bulk motion of matter from one location to another - e.g. hot air rising.
3) **Radiation:** Energy is transfered directly via photons.
In the Sun (and stars in general) only the latter two mechanisms are important.

The Sun is Stable

We also need to make use of the fact that the Sun is stable - it is neither shrinking or growing (**Hydrostatic Equilibrium**) nor is it heating up or cooling down (**Thermal Equilibrium**).
Since the star isn't heating up, all the energy that is produced at the core must be lost at the surface - but no more! If more energy is lost than is generated it would cool down... And this energy can only be transported by convection and radiation.
But what is **Hydrostatic Equilibrium**?
Hydrostatic equilibrium basically means that if we look at a layer of material in the stellar interior it will on average neither move up nor down - and hence the Sun will neither expand nor contract.

Hydrostatic Equilibrium

For a layer of material not to move all the forces acting to pull it down must balance the forces pushing it up.
Downwards forces: Pressure from material above the layer + weight of own layer (gravitational attraction).
Upwards forces: Pressure from material below the slab.
Hence the pressure from below must be greater than the pressure from above.
We also known that the density of the slab must be just right - too light and it will rise - too dense and it will sink.
Finally we include what we know about how gases behave...
When you compress gases by placing them under increased pressure they become denser and hotter.
So as we travel through the Sun, since the pressure increases the nearer you get to the centre, so both density and temperature also increase.

So we can see that the density and pressure of the solar interior is also related to its temperature - we have linked the structure of the Sun to how energy is transported through it.
In fact to understand the structure of the Sun, astronomers must solve 7(!) equations governing hydrostatic & thermal equilibrium and energy transport through the Sun.
Some summary points:

- Inner $0.25R_\odot$ is 'core'
- 94% of mass is in inner $0.5R_\odot$
- from $0 \rightarrow 0.7R_\odot$ energy is transported by radiative diffusion.
- closer to surface, where hydrogen and helium have recombined, energy i s transported by *convection*, in the convective zone.

Note that convection is the transport of energy by the bulk motion of gas (or liquid - c.f. a pan of water boiling).

But What's Radiative Diffusion?

If the Sun were completely transparent the photons from the core could escape to the surface at the speed of light in about 2secs.
However the inner region of the Sun is very dense and so the photon will interact many, many times with matter, constantly being absorbed and re-emitted.
On average, a mean free path for a photon (the distance between photon/matter interactions) is only 1cm!
This has several effects:
Firstly the average energy of the photon goes down over time. This is because not all the energy will be re-emitted every time - some goes on heating the matter present.
In fact by the time it reaches the surface of the Sun, the original γ (Gamma) ray photon has 'become' an optical - UV photon.
Secondly the direction the photon is re-emitted in is random.
This means that photons take a very circuitous route to the surface - *the drunkard's walk* - and instead of reaching the surface in 2secs, on average they take $\sim$170,000yrs!
The net result is that they carry no information on the inner structure of the sun by the time they reach the surface.
So how can we test our theories of how the Sun works?

The Solar Interior

So far we have constructed theoretical models for the interior of the Sun and have observed the outer layers, but can we observe the interio *directly*
The answer is yes - by **Helioseismology** and observing the *Neutrino flux.*
Helioseismology works by listening to the way the Sun wobbles.
In 1960, Robert Leighton discovered that part of the Sun's surface oscillates up and down 10m every 5s.
Other periods were subsequently found, with periods between 20-160mins.
These pulsations are exactly analogous to sound waves and seismic waves in the Earth's interior generated by earthquakes.
In the same way geologists use seismic waves to study the structure of the Earth so we may probe the Suns interior by the way it vibrates.
This is because changes in the internal properties of the Sun such as density affect the way these 'sound waves' propogate.

This has enabled us to refine estimates of the quantity of He present in the Solar Core and convective zone, as well as determining the thickness of the transitional zone between the radiative and convective zones (where the magnetic field is thought to form).

Solar Neutrinos

Remember our discussion of the p-p chain? One of the byproducts of the fusion of H→He was the production of *neutrinos* - ghostly particles with almost no mass that interact *very* weakly with matter. Each second the Sun produces 10^{38} neutrinos, which escape from the Sun without undergoing the random walk of the photons. Consequently, if we could detect these particles, we would directly probe the conditions in the Suns's core.

Despite the fact we might expect 10^{14} neutrinos per second to pass though every square metre of the Earth, its still *very difficult* to detect *any.*

One possible detection process is

neutrino+neutron→proton+electron

The Davis experiment in the 1960s used a huge tank of C_2Cl_4 and this reaction to detect neutrinos. Every now and again a neutrino will react with a neutron in the ^{37}Cl atoms, producing a proton and hence a radioactive atom of Argon (^{37}Ar).

The rate of production of ^{37}Ar is therefore proportional to the flux of neutrinos - by measuring one we may infer the other.

Big problem: The flux of solar neutrinos was only 1/3rd of that expected from theory... the *Solar Neutrino Problem.*

The Solar Neutrino Problem

- The Solar model is wrong. The rate of production of neutrinos is sensitive to the internal conditions of the Sun. If the core temp was 10% lower the problem would disappear - however the Sins size and surface temp would then differ from that observed.
- Neutrinos 'oscillate'. Neutrinos come in 3 flavours, and the Davis experiment is only sensitive to one flavour. If neutrinos can change flavour (i.e. oscillate) from a detectable to non detectable type between the Sun and Earth the problem would be solved.

Newer experiments such as Super-Kamiokande & Sudbury Neutrino Observatory suggest that the latter may be the correct explanation.