The Sun as a Star

In this part of the course we are going to examine the properties of the Sun.
(Chapter 18 in *Universe 7e* covers most of the material we shall study).
The Sun is the closest star to the Earth, and hence is an invaluable laboratory for stellar physics.
It *used* to be the only star we could spatially resolve - i.e. we can actually observe the Disk of the Sun and examine the surface properties - although new astrophysical techniques have allowed us to begin to accomplish this for other stars....

Basic Properties of the Sun

These are summarised in Table 18.1 of your textbook.
The Sun's angular diameter - 32 arcmin - is directly resolvable
The Earth Sun distance:
149,598,000km = 1 AU
From the distance to the Sun and its angular size we measure
$R_\odot = 6.96\times10^5$ km
Solar mass, from Newton & Kepler
$M_\odot = 1.98\times10^{30}$ kg
With the mass and radius of the Sun, we can determine the average solar density:
$\rho_\odot$=1410kg/m^3
We can measure the flux of solar radiation that arrives at the Earth, and hence infer the total solar luminosity:
$L_\odot$=3.86×10^{26}W
Parameters for other stars are typically given in terms of their size relative to that of the Sun, ie in units of $L_\odot$, $M_\odot$ and $R_\odot$.
We can measure the energy distribution of the Sun (i.e. the shape of the spectrum) and find a Black Body (or *Planck function*) fit to this to determine the average temperature of the Sun's atmosphere (*photosphere*)
$T_\odot$=5800K
(see Fig 5-11 for comparison between the stellar spectrum and a black body of 5800K)
However the core of the Sun is *much* hotter, at 1.55×10^7K
Also, the diffuse corona surrounding the Sun is hotter (10^6K) than the photosphere.
We may also use the Stefan-Boltzmann equation to calculate a mean temperature, given that we know the size of the Sun and its luminosity...

What Powers the Sun?

The Sun's luminosity is very large, producing an energy output that is vital to
1) provide a source of heat and light for the Earth and
2) to maintain the stability of the Sun against gravity, which is trying to force it to contract.
Understanding the basic, fundamental process that gives rise to the Sun's energy is therefore crucial - it, or variations of it, operate in all other stars.

We now know that this basic process is thermonuclear fusion in the *core* of the Sun, where the temperatures and densities are sufficiently high to allow such reactions to occur.
This is now taken for granted, but before its recognition in the 1930s other possibilities were considered and discounted.
The basic problem:
$L_\odot = 3.86\times10^{26}$ Watts
Age of the Earth - determined primarily from geology (and inferred from biology) - and hence of the Sun is $\geq 10^9$yrs ($\sim$4.6 Gyrs).
What process can keep the Sun shining for so long?
Previous theories included gravitational contraction & chemical burning.

Kelvin-Helmholtz (Gravitational) Contraction

As material (gas) contracts under its own self gravity it has to lose energy. This is primarily radiated as heat, and in fact powers young stars as they are born.
Simple calculations show that for the Sun, energy generated in this manner would provide $\sim 4\times10^{41}$ Joules of energy in total.

Kelvin-Helmholtz Contraction

Is this enough?
If it was the source of energy for the Sun *and* the luminosity of the Sun was constant over its lifetime, it would live for
$t_\odot = 4\times10^{41}\text{Joules}/L_\odot$
$t_\odot = 4\times10^{41}\text{Joules}/3.9\times10^{26}$ Watts
$t_\odot = 10^{15}$ sec $= 30\times10^6$ yrs!
Not nearly long enough - so gravitational contraction *cannot* power the Sun.

Chemical Reactions

Could simple chemical reactions power the Sun - i.e could it be on fire?
Lets try to guess-timate if this is possible...
1) We will assume that chemical reactions, such as burning give 10^{-19}J/atom
2) Number of atoms involved in chemical reactions required to power the Sun is
$\sim 3.9\times10^{26}/10^{-19} \sim 3.9\times10^{45}$ each second
3) From $M_\odot$ and its chemical composition, we know that the Sun has 10^{57} atoms
4) Therefore, if all these were involved in a chemical reaction releasing energy (i.e. burning) the Sun would live for
$10^{57}/3.9\times10^{45} \sim 3\times10^{11}$sec $= 10^4$ yrs
Again far too short a time period - the release of chemical energy cannot power the Sun.

<u>Nuclear Fusion</u>

Nuclear reactions differ from chemical reactions in that they affect the nuclei of atoms, while chemical reactions do not alter the number of protons and neutrons in atoms.
There are two type of nuclear reaction; *fission*, where heavy atoms split apart to form lighter atoms, and *fusion*, where light atoms fuse together to form heavier atoms. It is nuclear fusion that powers the Sun.
Note that astronomers often talk about stars 'burning' their fuel - this is *not* a chemical process but just 'short hand' for the nuclear reactions taking place.
Nuclear reactions *can* power the Sun since they generate far more energy per atom than either gravitational contraction or burning would for the Sun.

<u>Einstein & Nuclear Fusion</u>

The reason why nuclear fusion can power stars is that the end products are very slightly lighter than the ingredients.
This 'missing mass' is converted to energy - via Einstein's mass-energy relationship:
$E=mc^2$
where **m** is the mass converted to energy and **c** is the speed of light.
Because c^2 is such a big number this means that even tiny amounts of mass are equivalent to huge amounts of energy.
An example:
Take 1g = 0.001kg of material and 'convert' it to energy
$E=mc^2 = 0.001 \times 3 \times 10^8 \times 3 \times 10^8$
$E= 9\times10^{13}$ Joules!
Now exactly how much energy is this?
Consider an electric fire radiating at 1000J/s (=1 kilo Watt)
In a year it would radiate $\sim 3 \times 10^{10}$ Joules
So we could run our fire continuously for 3000 years by converting 0.001kg of matter to energy...!
So how does fusion work in the sun, and what fuses to make what?