Tony Fairall - AST 1000F - PART 5
THE NEAREST STAR

INSIDE THE SUN

The Sun is a spherical incandescent body, with diameter 1,4 million km (over a hundred times the Earth's diameter) and mass 2 million million million million million Kg (300 000 times the mass of the Earth). Its surface temperature is 5700K. At that temperature, all known substances are gaseous. Since the interior temperatures are much higher, the Sun is gaseous throughout. Whilst there is no direct way to explore the Sun's interior, the laws of physics enable us to accurately predict pressures, temperatures, densities, from which we can determine how it manages to generate its energy.

Let's start with density. At its 'surface' the density of the solar gas is well below that of the air we breath. But the density increases dramatically as we penetrate the interior. A few percent of the way down, it exceeds the density of our air (about a kilogram per cubic metre). Astonishingly, by 50% down, it increases a thousand fold to the density of water. While being that dense, the material is nevertheless gas, not liquid. Deeper still, and the density soars, denser than iron, lead and gold, to about fifty times denser than water at the centre. Yet it is still gas, not liquid. So the Sun has its mass strongly concentrated towards its centre.

The composition of the interior of the Sun is presumably the same as we measure at its surface, about 70% hydrogen, 30% helium and 2% heavier elements.

Now to temperature. The low-density outer layers of the Sun are opaque and act much like the jacket of a thermos flask, so much so that the surface of the Sun is almost stone cold, compared to its interior. Well 5700 degrees is hardly stone cold, but only 10% of the way in, the temperature is up to a million degrees. A pinhead at that temperature would emit so much radiation that nobody could approach closer than 100 km to it! The central temperature of the Sun is around 15 millionK. This means the solar interior has a tremendous reservoir of heat and effectively only a trickle escapes from its surface - so much so that the Sun could easily "coast" on its energy reserves for a couple of million years. However, there is evidence of the Earth having liquid water (i.e. not ice or vapour) for billions of years - so apparently the Sun's output has been fairly constant and energy must be generated in the interior. The only possible source of energy, that could be sustained over such a long time, is nuclear fusion.

PHYSICAL CONDITIONS AND NUCLEAR POWER

As gas gets hotter, its atoms gradually lose their electrons - the gas is said to be ionised. The solar interior is so hot that the gas is completely ionised, the electrons completely freed from the atomic nuclei. Since atomic nuclei are minute compared to atoms, instead of 'bulky' atoms, we have small nuclei and free electrons, moving at high speeds. Most of the atomic nuclei are the nuclei of hydrogen atoms, i.e. simply single protons. Protons do not normally bump into one another because their positive charges repel. However, under the very extreme temperatures in the core of the Sun, their speeds are so very high that they overcome the repulsive forces, and nuclear reactions result. Deuterium, tritium and eventually helium result. Effectively, the nuclei of hydrogen are fused to become the nuclei of helium. The process is conveniently described as 'hydrogen burning' (though it is not the chemical 'burning' process we experience on Earth).

For every 4 kg of hydrogen 'burnt', 3.97 kg of helium results. The 0.03 kg mass lost is converted into energy according to Einstein's famous equation E = mc**2. In other words, the fusion of hydrogen into helium produces the energy that keeps the Sun shining, at a cost of a small amount of mass. The Sun loses an incredible 4 million tons of mass per second, to achieve 100 million million million million watts of power. The Sun has so much mass that the mass loss is insignificant.

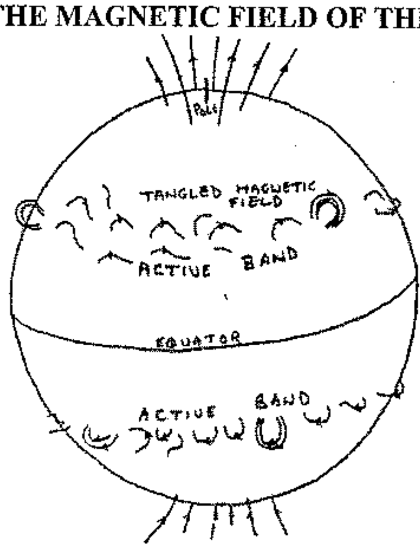
Surprising its takes a long time for the energy produced in the core to work its way out to the surface. Energy can be carried by conduction, convection and radiation. In the Sun's interior, energy is carried out from core via radiation transport (repeated absorption and re-radiation). The outer layers of the Sun, however, are remarkably opaque (mainly due to H+ - hydrogen atoms that have acquired a second electron) and turbulent convective transfer takes over. In convection - like the boiling of water in a saucepan - hot 'chunks' rise upward carrying the heat with them. When they reach the surface, the heat is radiated off into space. Once cooled, the material sinks back into the interior.

THE PHOTOSPHERE

Effectively, the surface of the Sun is boiling and bubbling, and the typical size of the hot 'chunks' is comparable to the size of the Earth. The Sun appears to have a surface, the photosphere, below which the gas is opaque, and above which the gas is almost transparent. The opaque material - like clouds in the Earth's sky - is not totally opaque. When you look at the centre of the Sun's disk, you see about 100 km into the interior to where the temperature is slightly higher. When you look near the edge of the disk of the Sun, your line of sight is slanted and does not penetrate so deep, the temperature is slightly lower and the disk appear slightly darker (limb darkening).

The surface brightness of the solar disk is such that its image inside the human eye cannot be sustained without possible damage, albeit temporary. Safe ways of viewing the disk of the Sun are to look through plastic coated with a very thin metallic foil (as used to wrap tea bags), or to project its image from the eyepiece of a telescope. Never look directly at the Sun's disk through a telescope or pair of binoculars, as these devices enhance its surface brightness.

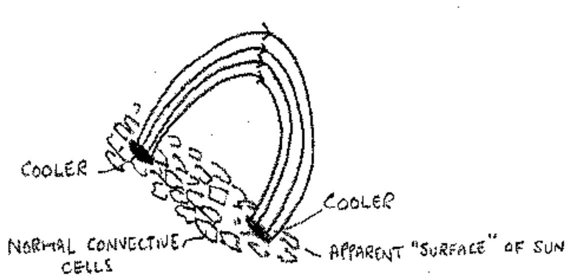
THE MAGNETIC FIELD OF THE SUN AND THE 11-YEAR CYCLE



The Sun possesses a generally weak magnetic field, but complications arise because the Sun does not rotate as a solid body. The equatorial regions rotate once in about 25 days, whereas polar regions rotate in about 30 days. The gaseous material of the Sun, being ionised, drags the field with it and the uneven rotation tangles the field as suggested in the diagram.

The "active bands" move slowly towards the Equator. Over an ll-year cycle, new bands start around latitudes 40° north and south, grow to a maximum, and eventually fade out at latitudes 5° north and south, just as the next new pair of bands begin.

Much of the disturbance in the active bands consists of magnetic loops breaking the surface of the Sun. If the magnetic field in these loops is strong enough it will divert the heat flow from the interior.



The cooler regions appear darker; thus a pair of sunspots, with opposite magnetic polarities, is created. The sense of polarity is reversed from northern to southern hemisphere, and one cycle to the next. The next solar maximum - when the greatest number of sunspots are visible on the photosphere - will be around 2012.

OUTER LAYERS OF THE SUN AND THE SOLAR WIND

The magnetic disturbances extend well above the photosphere - great 'prominences', some showing the loop structure, can occur. Energy is also released, partly as short-duration flares of light - or by heating the outer 'corona' of the Sun to temperatures of millions of degrees. At such temperatures, the tenuous gas is no longer held by the Sun's gravitational attraction, but streams outward through the solar system. In general this SOLAR WIND may "blow" at speeds of a few hundred kilometres a second, but can be enhanced in speed and strength during "storms". Occasionally, flares may be followed by 'mass corona ejections', with enormous bubbles of material eruptive from the solar surface.

FORMATION OF THE SUN

The Sun is believed to have formed towards 5 billion years ago from a dense cloud of interstellar matter (gas and dust). (By comparison the Universe is 13.7 billion years old.) The 2% heavy elements show that the matter it is made of came from earlier generations of stars. The gas cloud may have been compressed by the action of a shock wave from either a supernova explosion or from the spiral compression waves in the galaxy. Probably the Sun did not form alone, but the gas cloud was massive enough to form a cluster of proto-stars, one of which eventually became our Sun. Once collapse is initiated, gravity ever more rapidly assists the collapse towards stellar dimensions. In the collapse, conservation of angular momentum may "spin up" the proto-stars so that they fragments into smaller pieces, or split to become a binary systems, or simply spin off a disk of material, as did our Sun.

The contraction released gravitational energy which heated the proto-Sun and the dust particles with it. The dust particles are highly efficient radiators and the proto-Sun would have become highly luminous in the infra-red (since it was not yet hot enough to emit visible thermal radiation). As the temperature increased still further, the dust was vapourised and the luminosity decreased. Convection may aid fairly rapid cooling on the outside, allowing the star to collapse further and the core to grow hotter. Convection then decreases, and the proto-Sun shone by the slow release of gravitational energy. The central temperature gradually increased until nuclear reactions (Hydrogen burning) started in the core and the Sun no longer required gravitational contraction as an energy source. At this point the Sun reached stability, its size and luminosity much as we find it today.

THE LIFETIME OF THE SUN

By stellar standards, the Sun is burning its hydrogen fuel at a modest rate, such that it ought to stay as it is for almost 10 billion years. The Sun is therefore only halfway through its lifetime.

THE DEMISE OF THE SUN

When the hydrogen in the core of the Sun finally runs out, the core will contract slightly and in so doing raise its temperature slightly. Hydrogen burning will then proceed at an accelerated rate in a shell surrounding the core.

The increased energy production will cause the surrounding envelope to gradually inflate and the size of the Sun will gradually increase. Eventually it will ends up as a 'red giant' with an enormous surface area, a lower surface temperature and a very high luminosity. So large will the Sun then become - hundreds of times its present diameter - the Earth will no longer be habitable and may possible even be vaporised. Though the outer layers have expanded, the core will contract further and its temperature will climb higher. Eventually it will begin 'Helium burning" - the most common reaction being the "triple-Alpha" where three colliding helium nuclei fuse to become carbon. In time, the helium too will be exhausted and a further core contraction and temperature increase will initiate even higher forms of burning. Thus heavier and heavier elements will be synthesized in the core. Iron will be the end point since, only for elements ligher than iron, does fusion generate

energy. Beyond iron, it would cost energy to make nuclei fuse (hence energy could be only extracted by fission - a la Koeberg).
Due to very high luminosity the Sun will then have, its life as a red giant is very short. It is more like a "last fling". Eventually the Sun will have no further energy resources available to it its core will collapse to a very dense state. However, in these very late stages of the giant phase, the energy generation is such not just to inflate the envelope but to blow it off, thereby revealing the hotter interior. Thus a significant portion of the star is blown away and forms a shell around the dying Sun - such shells are known as planetary nebulae (since their 'disks' seen through telescopes resemble the disks of planets. The expelled material is mainly hydrogen, but it does contain some of the heavy elements generated in the core. Thus it is not only a process that recycles material to the interstellar m~dium to be re-used in making new stars, but it gradually enriches the interstellar medium with heavy elements. Old stellar populations are found to be 'metal-poor', The contracting core has no further energy and it ends up as a white dwarf. A white dwarf is not much larger than the Earth, so its densityis an incredible 100 000 times that of water. It is so-called 'degenerate' matter, where normal atomic structure has been destroyed and only electron repulsion prevents further collapse.
A white dwarf has no means of generating energy, but is still hot from the last stage of energy generation and gravitational contraction. Because its surface area is very small, it will take a very long time to cool off - far longer than the current age of the universe.