The Sun

Introduction

Lying on a picturesque beach soaking up the warmth from that little disk in the sky, it's quite hard to visualise what the Sun really is. It is a giant body, an enormous ball exhibiting complex, turbulent, violent internal motion. Its size is hard to appreciate, being well over a million times the volume of the Earth. If the Earth is scaled to the size of a tennis ball, then the Sun is a ball about 7 m across, about the floor to ceiling height of our large lecture theatre. H. G. Well's famous story of rapid exploration was called "Around the World in 80 Days". At the same speed, it would take 24 years to travel around the circumference of the Sun, if you could withstand the heat.

When you are sleeping next to an elephant, it's wise to know how it will behave. We are living next to a giant. Is it a big, friendly giant? That remains to be seen. It's wise to learn how it will behave.

The Sun is a star. There are hundreds of thousands of millions of stars in the sky; indeed a lot more. They are all so far away as to appear just points of light, except one – the Sun. The Sun is our neighbourhood star. The nearest star to the Sun that we have discovered is about 250,000 times as far away. How do we know all this? By the application of physical measurement and reasoning. The next few slides show how such knowledge has been built up.

Sun's distance and diameter

How far away is the Sun? Historically this question has not been as easy to answer as you might have expected. The Moon's distance was found by parallax. The parallax of the Sun is tiny (~8.8" arc on a baseline equal to the equatorial radius of the Earth), too small to measure directly with any accuracy. Kepler's laws don't tell us how far away the Sun is. They give only the relative size of solar system, not its scale in metres or km. Several different kinds of historical attempts have been made to measure the Sun-Earth distance indirectly. One of these methods is based upon measuring the details of the transit of Venus across the face of Sun – an event that happened in 2004 for the first time for over 120 years. The method essentially measures the parallax of Venus as seen from different places on Earth. The 5 previous transits that have been observed over the past few centuries have all been pretty significant in the history of Astronomy and the method has historical connections with Aberdeen. That, though, was in the past. The scale of solar system, and hence the distance to Sun, is determined nowadays by timing radar reflections to planets. Astonishingly, the answer is now known to a better accuracy than 1 km. You remember that we call the average Earth-Sun distance the Astronomical Unit and it's about 150×10^6 km.

Given the distance, the size of the Sun is easily calculated from the angle it subtends. The diameter is $\sim1.39\times10^6$ km. In truth, the distance to the Sun may seem huge in km but it's only about 100 solar diameters. Draw a modest sized circular dot on a sheet of paper and then measure out 100 diameters distant and put a pencil dot there. You're now looking at a rough scale drawing of the Sun-Earth configuration.

Sun's mass from Kepler's laws

This argument is really a combination of the ideas of Kepler & Newton. Newton had deduced the inverse square law of gravitational attraction from the nature of planetary orbits. You might like to know how he did it.

Watching an apple falling to the ground doesn't tell you that gravity varies as the inverse square of the distance between bodies. The distance involved isn't the height of a body above ground but its distance from the centre of the Earth. Most of the problems involving gravity near the surface of the Earth, such as projectile problems, are worked out on the assumption of constant gravity. How did Newton know to put in the inverse square of distances?

First, he was imaginative enough to see a similarity between the Moon going around the Earth and a projectile curving around under the influence of gravity. He was able to work out, and it's not difficult, that if the Moon experienced the same gravity as something thrown on Earth, then its orbit would take only around 650 minutes, whereas in fact it takes just over 650 hours, or 27.3 days. The orbit, then, was about 60 times slower and for this to happen he could show that gravity at the distance of the Moon must be about 3600 times weaker. Now the Moon is about 60 times as far from the centre of the Earth as a body on the surface of the Earth and $60^2 = 3600$, exactly the figure he was looking for. This suggested very strongly the inverse square law of gravity.

That is not the end of the story. In 1684, the law of gravity was a hot topic of conversation with the Royal Society in London. The most able men of the time there, Hooke, Halley, Wren and others were trying to reconcile Kepler's elliptical orbits with the proposed inverse square law of gravity. No-one in London could work out what kind of orbits the inverse square law implied. It was a tough problem at the time. The Physics was new; the mathematics was new. Hooke was sure he had shown that the inverse square law produced elliptical orbits but in spite of being given several months to produce his reasoning, he could not do so. Finally, Halley (Edmond Halley of comet fame and one of the sharpest scientists of his day) said that he would go to see Mr Newton in Cambridge. Halley arrived at Cambridge and put the problem to Newton. "Most certainly the orbits are elliptical", said Newton, "I showed it some time ago". He went to look for the sheets with the calculation but his rooms were untidy and he couldn't find them. [Newton had the advantage over everyone else in that not only were they his laws of motion and his law of gravity but he had co-invented the differential calculus, the ideal mathematical tool needed for the job. It's little wonder that his contemporaries viewed him as the master, and successive generations have continued to be astonished at his perception and creativity.] Halley returned to London with the news and, sure enough, a few months later Newton sent down his working in the form of a 9 page Latin document and the result was agreed by all. It was this result that convinced everyone, not just the Royal Society, that the inverse square law held. Since then, experimental checks on the accuracy of the law have all confirmed it. [Halley's visit also resulted in Newton publishing one of the most famous books in the whole of science, his *Philosophiæ Naturalis Principia Mathematica*, usually just called "The Principia", the expense of which Halley himself underwrote.]

You will remember that Kepler's 3rd law was written $P^2 = a^3$, in units appropriate to the Earth. Newton developed the relationship as $(M+m)P^2 = (4\pi^2/G)a^3$. The presence of both the masses in the relationship is not surprising. Two masses both equal to the Sun's mass are going to orbit each other at a different rate from two masses at the same separation but each equal to the Earth's mass. The light pair will orbit more slowly under their gravitational attraction than the massive pair. For example, if the Sun had only the same mass as the Earth, then a body 1 AU away would take 406 years to orbit. If the two masses are unequal, then the greater mass has the dominating effect. If you think this through, you'll realise that we know the mass of the Earth and how long it takes to orbit the Sun and hence we should be able to deduce the mass of the Sun, which is the dominating mass swinging us around. That is quite an achievement. In Newton's day there was a hitch in this idea, because there was no good measurement of the value of G. However, our predecessors were pretty bright and overcame this difficulty by the following argument.

The 'trick' is to eliminate the constant k (shown on the slide as equal to $(4\pi^2/G)$) by applying the relationship to two different orbital systems controlled by different central masses and then take the ratio of the results. If you know the ratio of 'P' and 'a' for two different systems, you can find the ratio of masses involved.

The *next slide* shows how, by comparing the Sun/Earth system with the Earth/Moon system, the mass of the Sun can be found as 1.97×10^{30} kg.

Applying Kepler's 3rd law

Kepler's 3rd law is written out first for the Sun/Earth system and then for the Earth/Moon system. In the two mass terms on the left-hand side, the smaller of the masses can be ignored in relation to the larger one without making much of an approximation. By dividing the first left-hand-side by the second, and likewise for the right-hand-sides the unknown constant k is eliminated, leaving an expression that involves the mass of the Sun (M_{Sun}) and other quantities all of which are known. Filling in the numerical values for the known quantities gives the answer of 1.97×10^{30} kg for the mass of the Sun. The use of Kepler's law is the best and really the only way of finding the mass of the Sun.

Solar radiation

Luminosity of a star is one of the quantities that can be determined for any individual star that can be seen. It is the total power output in watts. How big a power station do you think the Sun is? A good sized power station in Britain produces over 1000 MW. The Sun is obviously much more powerful. How about 1 billion MW? In fact that answer is nowhere near the truth. Even 1 billion, billion MW (10^{24} W) is not a big enough number. There's no need to guess, however, for we can work it out correctly.

We can determine the output of the Sun accurately because we know how far the Earth is from the Sun and we can measure the amount of radiation reaching the Earth (average ~1380 W m^{-2}). That's a lot. Why did Icarus' wings melt? Is the Sun's radiation really hotter high up? It is, but not because Icarus went significantly nearer the Sun but because high up you escape from the absorbing effect of the lower atmosphere. Anyway, take the amount of radiation arriving per square metre on the Earth and work out how many square metres there are all the way around the Sun at the same distance. Multiply up by this figure and you have the total energy output of the Sun. The answer is phenomenal: ~3.9×10^{26} W.

Notice that since the area of a sphere is $4\pi r^2$, the total radiation from the Sun decreases as the inverse square of the distance from the Sun. Thus, at 2 AU the radiation is spread over 4 times the area and hence the radiation per unit area is only $1380/2^2$. At 10 AU the radiation is spread over 100 times the area and hence the amount falling on unit area is only $1/10^2$ of that falling on the Earth, namely 13.8 W m^{-2}.

Deducing the Sun's temperature

In daily life we seldom pause to think how stupendously bright the Sun is. It takes a significant amount of technology and power to light a lecture room brightly. Candles and torches certainly won't do it. To floodlight the modest frontage of King's College at night takes several kW of power. Yet when the Sun comes out it floodlights the entire landscape, horizon to horizon, mountain top to sea, brighter than anything we do. No artificial light mankind has made can approach the Sun's performance. Artificial lights are always close to the scene they illuminate but the Sun is a staggering 150 million km away. The Sun occupies a tiny fraction of the whole sky. The tip of your little finger at arm's length is more than enough to cover it, yet it floods the whole of the landscape with light and heat. No wonder our distant ancestors considered the Sun a God. The Sun, though, is a completely natural object, one that is mind-bogglingly bright. Imagine how intense the radiation would be if you got closer than 150 million km.

Knowing the luminosity the Sun and its size, we can work out the energy per square metre at the surface of the Sun as 6.43×10^7 W m^{-2}, 64.3 MW m^{-2}. Toast isn't on offer – simply complete evaporation of any material known to mankind. Using the Stefan-Boltzmann law $6.43\times10^7 = 5.67\times10^{-8}\times T^4$ gives the temperature T as 5800 K, about five and a half thousand degrees Celsius.

Source of the Sun's energy

The problem of accounting for the Sun's energy output isn't just a matter of accounting for its sheer size but also for its longevity. 250 years ago, the standard belief in Christian countries was that the world, by which was meant everything, was 6000 years old. That intelligent people would defend this belief to the death, to the death of disbelievers branded as heretics, I find incredible. Perhaps that just shows how difficult it is to get into the mindset of times past. Such was the prestige of James Ussher's chronology, not only in his day but for a long time after, that his posthumous portrait gazes down from above the heads of the throngs who pay homage to the religious treasures in Florence's Uffizi galleries. Few look up to meet his stern gaze. What is astonishing is that he is placed among the royalty and savants of Europe, including such rightfully brilliant men as Newton, Leibnitz and Descartes. Fortunately, we have come a long, long way since Ussher's day and the accumulated knowledge of the past 400 years tells us that the origin of the world, and indeed the Universe, is a far, far more intricate, involved and interesting story than was believed then.

All the evidence points to the Sun and the Earth being about 4.6 billion years old. To me that adds to the wonder of being alive today, knowing that the world about us, the complexity of biological life, the stunningly sophisticated materials we find in nature are all the product not of 6000 years of history but of over 4 billion years of evolution. That's a staggering amount of time and it's hardly surprising that we don't yet understand how it's all come about. Mankind is working on it, as a collective enterprise and that's what science is all about. To return to the Sun, the evidence of the comparative stability of conditions on Earth for the majority of this time suggests that the Sun hasn't changed much over that time. Our present-day knowledge of how stars work reinforces this view. Astrophysics tells us that the Sun has slowly brightened over that time-span by around 20%. So how can you produce energy at the rate of around 10^{26} W for 4.6 billion years? Not by chemical energy, the kind we use for most purposes – burning coal, oil, wood, etc.

What about gravitational collapse? When a stone is dropped from a height it speeds up, acquiring kinetic energy that is converted into heat when the stone hits the ground, bounces a little and then comes to rest. Water cascading over a waterfall is a little warmer when it churns around at the bottom than when it left the top. The famous scientist James Joule who hit upon the concept of conservation of energy measured this effect with a sensitive thermometer. At the surface of the Sun gravity is about 28 times that on the surface of the Earth. Atoms falling back acquire 28 times more energy in falling a short distance than they do on Earth. It's a lot more, **and** the Sun has a huge surface area of 6.1×10^{18} m^2 for this falling to take place. If the entire Sun were collapsing, falling in on itself, would that produce enough energy to sustain its energy output? A calculation shows that it need only shrink at the rate of 36 m per year to create its energy output. This is a viable mechanism. However, it couldn't sustain the output of the Sun for more than a few hundred million years. We probably couldn't measure such a shrinkage. However, our modern view of the Sun is that it is pretty well in equilibrium and not shrinking. Another mechanism for energy production is needed.

When radioactivity was discovered, people though that this could be fuelling the Sun. It's not a far-fetched idea. Radioactivity does in fact keep the centre of the Earth warm. However, neither radioactivity nor the more extreme form of nuclear disintegration, nuclear fission produces solar energy. The Sun is not a fission reactor. The Sun is a nuclear fusion reactor, **making** elements, not splitting them up.

The story of the Sun takes us into the realm of modern particle physics and nuclear physics.

Mass to energy

Einstein's famous equation $E = mc^2$ has adorned many a million T-shirts. Why is this relevant? Radiation is energy. Einstein's equation gives the intrinsic energy content of a given mass. Before Einstein we had a fundamental rule called the conservation of mass. If you wanted to create a certain amount of mass at a given place, you had to provide that mass from elsewhere. Mass couldn't be created out of nothing. Einstein agreed that mass couldn't be created out of nothing but realised that mass could be created out of energy and, more importantly for our story, the reverse could happen and mass could be turned into energy. How much energy? Take the mass in kg, multiply by the velocity of light squared, which is 9×10^{16} in $(ms^{-1})^2$ and you will obtain the energy in Joules. The crucial feature of this relationship is not only that energy can be obtained from mass but also that the multiplying factor is so large. If you want to obtain 100 MW-hours, enough power to keep a fair sized city going for an hour, then you need 'only' 4 micrograms of mass, an amount quite a lot less than a grain of salt in a salt cellar. Compare that with the amount of coal needed for a power station that produces a hundred megawatts for an hour.

In the lecture you can hear Einstein himself describing his equation, courtesy of a voice-clip.

Nuclear concepts

Isotopes of hydrogen. Frederick Soddy, who was a lecturer at the University of Aberdeen from 1914 - 1919, worked before he came here with Ernest Rutherford, the father of radioactive studies and the originator of nuclear physics. Soddy devoted himself to understanding more about radioactivity and in 1913 realised that the same chemical species could exist with different atomic weights. He called these species isotopes. Soddy won the Nobel Prize for Chemistry in 1921, not long after he left Aberdeen, "for his investigations into the origin and nature of isotopes". Since the chemical species is determined by the number of protons in the nucleus, which are positively charged, then the different atomic weights must be caused by variations in the uncharged or neutral component of the nucleus. This neutral component is due to elementary particles called *neutrons*, a fact that was discovered many years after Soddy devised the concept of isotopes.

In reflective mood, Soddy wrote *Nature can be sardonic at times, when you come to think of the hundreds of thousands of alchemists in the past few thousand years roiling and broiling over their furnaces, spending laborious days and sleepless nights trying to transmute one element in to another, a base into a noble metal, and dying unrewarded in the quest, whilst we at McGill, by my first experiment, were privileged to see, in thorium, the process of transmutation going on spontaneously, irresistibly, incessantly, unalterably! There's nothing you can do about it. Man cannot influence in any respect the atomic forces of Nature.* Soddy was alluding to his early experiments with Rutherford at McGill University in Canada. He over-estimated the number of alchemists in the past but he was right that nature transmutes elements spontaneously through radioactivity, though it doesn't turn lead to gold. Back to the theme!

Deuterium is the isotope of hydrogen that is crucial to the Sun's energy production system. The contents of this bottle of heavy water that I'll pass round would have won me the Nobel prize about 80 years ago. 'Heavy water' is D_2O, ordinary water is H_2O. Harold Urey won the Nobel Prize for Chemistry in 1934 for separating hydrogen and deuterium.

Positrons are antimatter, anti-electrons in fact. Antimatter may appear in science fiction stories but it also appears in the real universe. Aberdeen infirmary has a PET scanner that does excellent work in diagnosing deep seated cancers. It may sound cuddly but PET stands for Positron Emission Tomography and you'll recognise the word positron. To use the technique, the patient is injected with a radioactive isotope that emits positrons, or positive electrons. Isotopes used may be ^{22}Na, ^{18}F or ^{15}O, amongst others. The isotopes are incorporated into chemicals that circulate in the body and, for cancer diagnosis, those that particularly accumulate in a cancer. When the radioactive decay takes place, a positron is emitted. Being an anti-electron, it soon meets an electron and the two mutually annihilate their own masses, producing electromagnetic energy in an amount given by Einstein's $E = mc^2$. In fact two γ-rays are produced that travel at the speed of light in exactly opposite directions. They pass right out of the patient and into detectors on opposite sides of the patient. The line joining the two detectors that received the two γ-rays shows the line on which the positron decay occurred. The intersection of lots of these lines locates the cancer. Sophisticated analysis allows some mapping of the extent of the cancer where the isotope has accumulated. The point of this digression is just to say that anti-matter does exist and is even put to good use in high-tech medicine.

The **neutrino** is another neutral particle of great importance. Indeed, there is a small family of neutrinos. The neutrino's story also begins with a study of radioactivity, the so-called β active isotopes, named by Rutherford, like the ones mentioned above. Some β active isotopes emit positrons, the majority emit electrons. The puzzle with these isotopes is that you can start with a large number of identical radioactive atoms, say ^{14}C, that undergo β disintegration producing an equal number of atoms of the final product, say ^{14}N. When you look at the electrons produced, you find that they cover a whole spectrum of energies and momenta. This fact was discovered by James Chadwick, who later on won a Nobel Prize in Physics (in 1935 "for the discovery of the neutron"). The fact seemed to contradict two of the basic principles of physics, the law of conservation of energy and the law of conservation of momentum. Physicists as eminent as Neils Bohr even said the unthinkable, that these laws might have to be re-thought. However, Wolfgang Pauli, another physicist who was to win the Nobel Prize (in 1945), sowed the seed of a possible way out of the difficulty. Pauli suggested in 1930 that there was an unseen neutral particle that could account for the missing energy and momentum and hence preserve the conservation laws.

4 years later, Enrico Fermi, yet another physicist who would win the Nobel prize (in 1938), laid out the modern quantum theory of β decay. Fermi introduced the word “neutrino”, meaning little neutral one, for the unseen particle. His theory pictured the neutron and the proton as being two states of an entity called a nucleon. In changing from one state to another, for example a neutron to a proton, the nucleon emitted an electron and a neutrino, in a way not too different from an energetic atom emitting a quantum of light as it decays to a state of lower energy. Likewise, in some nuclei, the nucleon could change from a proton to a neutron, emitting a positron and a neutrino. The neutrino started life in theoretical physics as a ‘fix’ for an awkward fact about β decay but over the following decades people realised that neutrinos are fundamental constituents of the stuff of the universe.

There you have it, our small menagerie of nuclear concepts necessary to understand how the Sun generates its energy.

The contributors

This slide shows the several great scientists who have created the understanding needed to build a coherent theory of nuclear concepts.

James Chadwick was of the generation that experienced two world wars. Just before the first world war he worked with Rutherford at Manchester University where Hans Geiger was developing the first Geiger counters. Chadwick decided to spend a year with Geiger in Berlin when Geiger returned to Germany. The year was 1914. You can guess his huge mistake. Chadwick had not long got to Berlin when war broke out and he was interned as a prisoner of war for the next 5 years in a camp near Berlin. He did at least end the war alive, which was more than many did.

Fred Hoyle

It was the late, great Fred Hoyle and a few collaborators who worked out the important mechanisms through which stars created energy and made elements. He made other contributions to astronomy, too, and encouraged others into science.

Links in the proton-proton chain

- 2 protons make a deuterium nucleus that has less mass than that of the two protons. The difference in mass appears as a γ ray and a neutrino. This reaction is hard to get going, a point I’ll come back to.

- The deuterium nucleus and another proton combine to make a helium-3 nucleus. This produces yet more energy in the form of a γ ray. The deuterium reaction goes more easily than the first step, which is why if mankind develops a fusion reactor it will need to start with deuterium or indeed tritium, which is the isotope of hydrogen with 2 neutrons in the nucleus.
- The final stage is to take two helium-3 nuclei to form a helium-4 nucleus and release 2 protons back into the system for re-use. All that is produced here is kinetic energy for the helium nucleus.

The textbook has a diagrammatic version of this set of reactions.

Nuclear Energy

Summarising the result of the proton-proton chain, the production of one helium-4 nucleus releases 26.7 Mev of energy in the form of γ rays and neutrinos. Compare that with the few eV that come from chemical combination of one molecule with another. The loss of mass is ~0.7% of the initial mass of the 4 protons.

The net result is that the conversion of 1 kg of hydrogen produces about 6.3×10^{14} J of energy and hence the Sun needs to convert 6×10^{11} kg s^{-1} of hydrogen to sustain its energy output by this means. At this rate the Sun could produce its output for more than 10 billion years but in fact the Sun's output will gradually increase so the expected lifetime of the Sun is more like a further 5 billion years.

Nuclear reactions

We are made mostly of hydrogen (~62% of atoms by number – next is oxygen (24%), carbon (12%), nitrogen (1.2%) and the rest). Why don't we go thermo-nuclear? Because of their positive charge, protons naturally repel, with a force that gets increasingly strong as the protons get close together. Fortunately, our protons haven't enough energy to overcome that repulsion.

To achieve the fusion of two protons needs very high temperatures and pressures, such as you'll only find in the inner tenth of the radius of the Sun. The model of the Sun's interior is called the 'standard model' and it attempts to put numbers on how the pressure, temperature, density and so on increase as you look deeper into the Sun.

One complication is that close to the centre of the Sun the temperature is high enough for some other thermo-nuclear reactions to go on. One of these is known as the 'carbon cycle', in which carbon acts as a catalyst in converting more hydrogen to helium. This process generates about 7% of the Sun's energy.

A digression

These two quotations highlight that the role of nuclear power has not always been obvious, even to those who should have appreciated what was going on. When Einstein first investigated his relationship $E=mc^2$, he did not appreciate the application to the generation of power, either by fission – the breakdown of heavy elements – or by fusion – the building up of lighter elements. This was entirely understandable since the mass differences between elements and their constituents weren't then known. Churchill, though, should have been better advised before making public pronouncements in an area where his knowledge was insufficient.

Inside the Sun

Pressure is force per unit area. Inside the Sun the pressure increases because of the weight of overlying material. The average density of the Sun is a bit greater than that of water on Earth (about 1.4×10^{3} kg m^{-3}). You might be surprised then that the material of the Sun can be treated pretty well as an 'ideal gas'. The reason is that all the particles (ions and electrons) are so hot that they move about quite independent of each other and the space between particles is much larger than the particles themselves. In much of the Sun, the nuclei have no bound electrons at all and hence all the particles are around 10^{-15} m across and even at the centre of the Sun the average distance between particles might be 10^{-11} m. This is just the situation that the ideal gas law works for. Hence pressure, P, volume, V, and temperature, T, are related by $PV \propto T$.

The model that represents the pressure, temperature and density within the Sun is called 'the standard model'. It predicts that the temperature for fusion will only be high enough at the very centre of the Sun, within a fraction of 0.1 of the Sun's radius.

The whole Sun is in *hydrostatic equilibrium*. This means that at any depth the inward pressure created by the weight of overlying material is balanced by the outward pressure of the gas within. The Sun is a very stable system. If it were to start to shrink a bit, then the interior would get hotter and the rate of fusion reaction at the centre would increase, creating a greater pressure inside than there was before. This increased pressure would act to expand the Sun out again. Likewise, if the Sun were to expand a bit on its own, the core would cool and the pressure there would decrease, resulting in the overlying mass winning the pressure balance and making the Sun contract. In practice the balance of pressures is very stable, keeping the Sun stable to a high degree. Measurements of the Sun's output of radiation show that it's not changing over most of the spectrum by more than 0.1%.

The standard model of the Sun

Three plots show how important quantities that relate to the working of the Sun vary from the centre of the Sun to its surface.

At the top left, the temperature inside the Sun increases to just over 15 million degrees K at the centre. Of course you can't put a thermometer there to see if the answer is right but the rate of the fusion reaction depends crucially on temperature and we can tell that the predicted temperature profile produces just the rate of energy production observed in the Sun. The nuclear physics tells us that the Sun is only producing energy in the first 10% of its radius, which is actually only a thousandth of its total volume. Also, there are millions of stars like the Sun but a bit different in their mass and in how far through their cycle of evolution they are. Our 'standard model' works for millions of other stars too. It describes the general picture of how conditions change within the Sun, without giving the finer details. The is still a lot of solar physics carried on throughout the world aimed at understanding the very important detail, such as the rôle played by the Sun's complex magnetic field in controlling possible variability of the Sun.

You can see at the top right that both pressure and density vary together by many orders of magnitude, as the meteorologists in the class might expect. The central density of the Sun exceeds 10^5 kg m^{-3} and the pressure is very high, all of which helps the fusion process. In comparison, remember the earlier figure for the average density of the Sun, namely 1410 kg m^{-3}, not much more than the density of sea water. The lower plot shows that most of the mass of the Sun is within the inner 50% of the radius, as you might expect for a ball that is compressed by its own weight.

Heat transfer outwards

The intense radiation generated near the Sun's centre doesn't travel straight out. If it did, it would take less than two-and-a-half seconds. In fact it takes over 100,000 years, some estimates going as high as a million years. The energy finally radiated at the surface of the Sun to us was generated within while primitive Man lived in caves. In the inner part of the Sun, the energy is propagated by 'radiative transfer', which is a fancy word for saying that the photons are continually absorbed and re-emitted in random directions. It's as if they were in a mega pin-ball machine, only in a pin-ball machine at least the balls maintain their identity whereas a photon is absorbed and a new one re-emitted by each 'pin'. The pins in the Sun are the nuclei and electrons.

When the photons have finally drifted out to about 0.7 times the radius, at a pace that would lose any race with a snail, the temperature has fallen low enough for hydrogen atoms to form and these absorb photons very effectively. A hydrogen atom is just a bound proton and electron. Hydrogen may seem pretty transparent stuff to you and me but in thick enough layers it is effectively black and the radiative transfer mechanism becomes even slower. The atomic hydrogen heats up and convection transfers the energy to the surface. The convection cells can be seen on the surface of the Sun. The cooler regions at the edge of each cell where material is sinking back into the interior show dark on the bright surface.

The Sun's composition

We can measure by spectroscopy the composition at the Sun's surface. The light we see comes from only the first few thousand km into the Sun, a very small fraction of the 696,000 km radius. However we do know that the outer 30% of the Sun is stirred by convection and hence well mixed. We have to infer the composition of the interior.

Telling you the composition of the Sun is so matter-of-fact these days that we're apt to overlook what a feat of observation and deduction this is. Less than 200 years ago, in 1835, the famous French philosopher Auguste Comte, who was well informed on the science of his day, wrote summarising what was known about the stars *On voit comment on peut déterminer leurs formes, leurs distances, leur masses, leurs mouvements, mais nous ne pourrons jamais connaître quelque chose à propos de leur structure chimique ou minéralogique.* "….we will never be able to know about the chemical and mineralogical structure of the stars", he asserted. Comte didn't know about the power of spectroscopy. Joseph Fraunhofer had laid the foundations of this subject 20 years previously but the connection between spectral lines and the elements that produced them had not been properly worked out. The moral of the story is that our own ignorance is seldom due to laws of nature.

The Sun is still mainly hydrogen, in spite of the fact that it has been converting hydrogen to helium for 4.6 billion years. In fact the percentage of hydrogen isn't much different from the percentage of hydrogen created in the Big Bang, 13.7 billion years ago. However, the Sun contains about 2% of heavier elements, none of which were created in the Big Bang and have only been created in the interior of massive stars. We know it's not hot enough inside the Sun to create the elements like those we see commonly in our surroundings, including iron, lead, gold, silver, silicon and lots more. All such elements were made in the exceedingly hot interior of stars towards the end of their lives. We are made of star stuff, the star of another solar system or a lone star. Our Sun has a lifetime of about 10 billion years. Less massive stars could last 100 billion years and massive stars only a few hundred million years. The Sun was created about 9 billion years after the Big Bang and is usually described as a third generation star.

The great neutrino puzzle – solved

The standard model of energy generation within the Sun has long predicted the neutrino flux expected at the Earth. Neutrinos with a range of energies are produced by different fusion reactions within the Sun. The total flux is huge. Some 6.6×10^{14} neutrinos are passing through every square metre of you per second – and me. 'Passing through' is the right phrase because neutrinos interact so weakly with the matter we're made of that not one of the 6.6×10^{14} is likely to interact with any atoms in your body. Indeed, almost every neutrino will pass straight through the Earth as if it were but a ghost in the near vacuum of space. How then can we detect the neutrino flux coming from the Sun? If we could measure the flux and find it to be what the standard model predicts, then that would be strong confirmation that we understand what's going on in the Sun.

Detecting neutrinos isn't easy. You need a large volume of material, specially chosen so that a reaction with a neutrino generates something that can be detected. Interactions are so rare that the detectors need to be well shielded from penetrating cosmic rays that can also generate a signal. That shielding is not simply a metre or two of concrete but the whole equipment needs to be something like a km or more underground. The original neutrino detector built in the 1950s by Raymond Davis was a 100,000 gallon tank of dry cleaning fluid (CCl_4) full of ^{37}Cl atoms that occasionally absorbed a neutrino as a neutron turned into a proton and the Cl changed into radioactive ^{37}Ar that could be detected. It was a *tour de force*. [Davis shared the 2002 Nobel Prize in Physics for his work on neutrino detection over many years]. Davis only expected to be able to detect some of the solar neutrinos. The signal wasn't strong but enough neutrinos were detected to enable the detection rate to be worked out as only a third of what the solar physicists predicted. Other neutrino detectors were built to cover a larger range of energies but no-one found much more than half the neutrinos expected. Solar physics appeared to be in trouble. This state of affairs became known as the solar neutrino problem.

Particle physicists realised that there was more than one type of neutrino – in fact there are 3 types: electron, tau and mu neutrinos depending on whether they are created in reactions that involve electrons, or heavier particles called tau and mu mesons. Solar neutrinos are electron neutrons. Neutrinos were predicted to have no 'rest mass', just like packets of light energy. They either travel at the speed of light or are absorbed and cease to exist. One consequence of this prediction is that once a neutrino is created it keeps its identity and can't change into one of the other types of neutrino. However, the particle physicists realised that if neutrinos had a small rest mass then they could change from one kind into another, a phenomenon known as neutrino oscillation. Davis and subsequent experiments looking for solar neutrinos detected electron neutrinos. What if the some of the solar neutrinos changed into meson neutrinos in-flight from the Sun? That would account for the failure to detect them. What was needed was an experiment that could detect all the different kinds of neutrinos.

Such an experiment was designed and constructed deep in a nickel mine in Sudbury in Canada. Known as SNO – the Sudbury Neutrino Observatory – it was 2 km deep and used heavy water as the main interacting medium. The first definitive results came in 2001 and 2002. They clearly demonstrated that the total flux of neutrinos from the Sun **did** agree with the standard solar model and confirmed that neutrinos oscillated from one type to another. The measured oscillation allowed an estimate for the rest mass of the neutrino to be made and currently it is about 0.1eV. That might not seem much but at 10^{14} per second per m^2, that's a lot of rest mass energy coming not only from the Sun but also from all the other stars, filling the universe. It's quite fitting that the Sudbury experiment provided the confirmatory evidence for the standard model of the Sun, and other stars, because the nickel mine is centred around the nickel deposit created by a mountain-sized metallic meteorite that struck the region much earlier in the Earth's history.

The Sun's outer reaches

Above the photosphere that generates the sunlight we see is a thinnish layer of a few thousand km called the chromosphere. Normal sunlight blinds our view of it but seen during a total solar eclipse it is predominantly red (from hydrogen light emission) and has an extraordinary temperature profile. The bottom of it is about 6000 K but gradually through this layer the temperature rises to well over 1 million degrees K. The layer is full of 'spicules' of energetic matter projecting from the photosphere through the chromosphere and from it come huge flares sending material far out away from the Sun's surface.

Beyond the chromosphere lies the **corona**. Its temperature is typically millions of degrees K. It extends our several solar diameters and is in one sense the most extensive body of matter in the solar system. How can an atmosphere at 6000 K, hot though that is, heat up its exterior to well over one million degrees K? That is a question of real practical importance because the outer atmosphere of our Sun directly influences conditions on Earth. You can learn more about this dependence in our level-2 *Space Science* course.

Another topic you can learn more about in our *Space Science* course is the solar wind. The solar wind pours out of coronal holes, a plasma of positively charged ions, mainly protons, and negative electrons. The next slide summaries some of its influence

The solar wind

You may think that the Earth at 150 million kilometres distant from the Sun is a long way away. On the astronomical scale of stars, it's pretty close, close enough to smell the breath of the Sun once you escape from the Earth's atmosphere. I'm speaking figuratively, of course, because the Sun isn't exactly breathing but it's certainly belching out material in all directions. Solar wind particles are typically travelling at several hundred kilometres per second by the time they reach the Earth, in spite of streaming out against the Sun's gravity. 400 km s^{-1} is here to London in 2 seconds, impressively fast. The solar wind was first suspected by its influence in stretching out comet tails. Comets have two tails, one curved and one almost straight. The straight tail is called the 'ion tail' and is straight because the ionised material generated by the comet interacts with the charged material of the solar wind and is accelerated by it to speeds of ten times the speed of the comet around the Sun. The comet tail is dense enough to make the solar wind visible.

More importantly for us, the solar wind interacts with the upper reaches of our atmosphere the details of which are only now being appreciated. The interaction first takes place at distances as far as about 10 earth radii and the Earth's magnetic field is an essential ingredient in the process. One consequence of the process is the production of a permanent auroral display around the Earth, which sometimes moves far enough south for us to see it. Currents induced in the upper atmosphere can affect radio communication, sometimes blocking out normal channels of communication for hours on end.

The aurora

Two pictures of the aurora, which can be seen particularly outside Aberdeen every winter but you need to look at the right times and right days. From 8 pm to midnight, October to March are the highest probability times. Conditions that tend to favour aurora visibility are monitored by space probe and if you subscribe to the auroral notification mailing list you will receive alerts. See http://www.dcs.lancs.ac.uk/iono/aurorawatch/cgi-bin/subscribe.

Current auroral oval

The extent of the auroral oval from the POES satellite data.

Space weather

The solar wind is monitored continuously, particularly by the ACE probe sitting at the first Lagrangian point, L1. The corona and coronal mass ejections are monitored by the Soho probe, also at L1.

Monitoring the Sun – 1

The two images show the Sun in the extreme UV and in the visible. In visible light the Sun can be imaged at the wavelength produced by glowing hydrogen. Choosing other wavelengths the Sun can be imaged in the extreme UV, where it is much more irregular and more variable. We have a lot more on the Sun in our level 2 course PX2011 '*Space Science and Remote Sensing*'.

The solar cycle in UV

This montage from the SOHO team shows the Sun over almost a complete solar cycle. Notice the quiet Sun at the back in 1996 and 2006 (also in 2007) and the much more active Suns near the front.

Monitoring the Sun – 2

It's possible to obtain detailed magnetic images of the Sun through spectroscopy. Some spectral lines are subdivided very finely if the light emitting atoms are in an electric field. The effect is known as the Zeeman effect, after its Dutch discoverer. The amount of subdivision depends on the strength of the magnetic field and hence if you can measure how far apart the components of the spectral line are, then you can measure the Sun's magnetic field. Doing this right across the Sun’s image you can create a *magnetogram*, or map of the Sun’s magnetic field. The magnetic field turns out to be intense near sunspots, reaching several thousand times the magnetic field that affects our compasses on the surface of the Earth.

Sunspots themselves are visible as apparent blemishes on the otherwise fairly featureless face of the Sun seen in visible light.

Sunspots

Sunspots are hotter than the hottest filament lamp but they appear dark against the background of the even hotter surface of the Sun. They are also conspicuously depressed relative to the surrounding surface. Sunspots are regions where the strong magnetic field is inhibiting convection and hence inhibiting the supply of hot gas from within that keeps the surface at its normal temperature in spite of the fantastic rate the Sun is radiating energy. They occur in pairs of opposite magnetic polarity and last from a few days to several months. The nest slide will show how the number of sunspots fluctuates over the years. This fluctuation has a distinct correlation with climate changes, for reasons that are at the moment only speculation.

There is also a correlation between sunspot activity and the solar wind. The solar wind contains a magnetic component that has a significant effect in deflecting cosmic rays from reaching the Earth. Cosmic rays produce isotopes in the upper atmosphere, including the famous ^{14}C that is used for dating historic objects containing carbon. The stronger the solar wind, the less ^{14}C occurs in the atmosphere, by a small amount. The correlation is sufficiently good that we can deduce sunspot activity in years before the telescope was invented. This helps us see if there is a connection between climate and sunspot activity. It seems that there is.

Longer term fluctuations

Looking at the sunspot record is a good reminder that the Sun isn’t a body that is guaranteed to behave constantly with time. The 11.3 year sunspot cycle is conspicuous but there are other periodicities in the record. The *Maunder minimum c*overing the second half of the 17th century is a period where there were no sunspots. It coincides with an exceptionally cold period in Europe, and possibly in other parts of the world too but records of that time are much the best in Europe.

Daily sunspot area averaged over solar rotations – the butterfly diagram

The bottom chart shows in finer detail the sunspot activity over more than a century. Sunspots reduce the solar energy output, but at the level of a few parts in a thousand. This effect is insufficient to explain a climate correlation with sunspot number. The top chart shows that sunspots don’t appear at random on the Sun’s disk. After the minimum when the Sun is almost free of spots, they start to appear round about latitude 30° north and south. Gradually over the next 11 years they appear on average nearer and nearer the equator, giving rise to this famous ‘butterfly diagram’. Solar physicists are still working on the explanation of this characteristic behaviour.

Sunspot polarity changes

The slide shows how the polarity of sunspots switches every 11.3 years. When the next cycle appears, the sunspots in a given hemisphere are of opposite magnetic polarity. More work for the solar physicists to do.

Hairy Ball Model of Sun's Magnetic Field

The Sun's magnetic field is immensely complicated compared with that of the Earth, which is rather like that of a simple bar magnet. The magnetic field originates in the motion of the convective region of the Sun and is influenced by the rotation of the Sun. The pictures from the TRACE programme shows plasma following the field lines, lighting up the otherwise invisible magnetic structure near the Sun's surface. There is no difficulty in seeing the Sun as the violent, complex, turbulent, body mentioned at the start of this chapter.

JSR