Chapter 16 The Sun

Physical Properties of the Sun

The Sun is the source of energy for life on the Earth. It is a star just like all the others. It is held together by gravity and the energy is produced by nuclear fusion. It lies right in the middle of the HR Diagram which makes us rather typical.

Overall Properties

The radius of the Sun is approximately 700,000 km and the mass is 2 x 10^{30} kg. The mass is determined by the motion of the planets and Kepler's 3rd Law. The average density is 1400 kg/m^3. The rotation was determined by watching the sunspots on the surface. It was found that the equatorial rotation was in 25 days while above 60° N or S latitude it is 31 days. This is called *differential rotation*. This is just like Jupiter and Saturn. The rotation at the very poles of the Sun is not known precisely, but it is thought to be around 36 days. By doing blackbody studies of the Sun the surface temperature has been determined to be 5800 K. The Sun is 109 Earths in diameter and has a mass 300,000 times greater than the Earths.

Solar Structure

The Sun has a surface, but it is not a solid like the Earth. The Sun's surface is the part that emits the radiation we see. It is called the *photosphere*. The photosphere is probably only 500 km thick. Just above the photosphere you will find the *chromosphere*. This is about 1500 km thick. From 1500 km to 10,000 km you find the *transition zone*. Here you find that the temperature rises quickly. Stretching above the transition zone out to about 12 solar radii you find the *solar corona*. At much greater distances the corona becomes the solar wind. Out here the temperature is about 2 million K. What is strange about that?

Now if we go the other direction we find other layers. Extending down some 200,000 km from the photosphere you find the *convective zone*. This is where the hot material is brought up from the interior to the surface and the cooler material drops back down inside. Below the convective zone you find the *radiation zone*. Here the energy is transported by radiation rather than convection. Below that you have the *central core* which is about 200,000 km in diameter. This is where the nuclear fusion occurs.

Luminosity

There are many things about the Sun that makes it great. The most important is that the Sun radiates energy. It is radiated outwards in all directions evenly. If we hold a detector at the top of our atmosphere that is 1 m^2, we can measure the energy we receive. This quantity which is known as the *solar constant* is 1400 W/m^2. Of that, 60 – 70 % of that energy reaches the surface. The amount that is lost is lost to the atmosphere or the clouds reflecting it away. On a clear day a sunbather receives about 500 W of energy, the energy of 5 100 W light bulbs. Having solved this, let's determine the total amount of energy radiated away. That energy is the *luminosity*. It is just less than 4 x 10^{26} W. Every second it generates the energy of 10 billion 1 megaton bombs.

The Heart of the Sun

What is going on to power the Sun for billions of years? Let's take a look.

Solar Energy Production

We can determine how efficiently the Sun produces energy. It produces about 2×10^{-4} W/kg. A piece of burning wood puts out about 1 million times more energy. The difference is that the wood will not burn for billions of years. Only one method of energy production will continue to produce that energy for billions of years: *nuclear fusion*.

Nuclear Fusion

Basically the formula for the production of energy is this: 4 H ‡ 1 He + energy You will find that 1 helium atom weighs less than the 4 hydrogen atoms. That means that some of the mass was converted into energy. That is what Einstein's formula says: $E = mc^2$. This is why the *law of the conservation of mass and energy* works. If you lose mass in the reaction it has to become something else.

The Proton-Proton Chain

Since the nuclei of all the atoms are positively charged, they repel each other. It is only through high temperatures and extreme pressures that the 2 nuclei will approach each other. As they get closer, the repulsion becomes much greater. If they can get within the *strong nuclear force* they will stick together. You need temperatures in excess of 10 million K to do this.

Proton + Proton -‡ Deuteron + Positron + Neutrino The particle is called a *deuteron* which is a form of *deuterium*. This is also called *heavy hydrogen*. On of the protons becomes a neutron to produce these particles. The *positron* is a positively charged electron. It is the antiparticle (or antimatter) of the electron. If they come together, they will destroy each other. The final product is a *neutrino*. The neutrinos are basically massless and carry no charge. They can pass through anything. Their interactions with matter are governed by the *weak nuclear force*. Now hydrogen and deuterium are called *isotopes*. They have the same number of protons, but their masses are different. This is the start of the *proton-proton chain*. At this point another proton will join with the deuteron making helium3. Eventually 2 helium 3's join making helium 4 and losing 2 protons.

Energy Generated by the Proton-Proton Chain

If you work out all of the math it means that 600 million tons of hydrogen is turned into 595.7 million tons of helium and 4.3 million tons are turned into pure energy. It is a slow and steady process that will power the Sun for billions of years.

The Solar Interior

Our knowledge of the solar interior comes from working mathematical models. Taking all of what we do know and applying that information we believe that we understand what is going on in the interior. From this we come up with the *standard solar model*.

Modeling the Structure of the Sun

As we can see the Sun doesn't vary much from day to day or year to year. But this is on the human scale. Our models begin with the idea that the Sun is in *hydrostatic* *equilibrium*. That means that the inward pull of gravity is balanced by the outward push of the pressure. Since the Sun is so massive and has a large gravitational pull, this means that the core temperature must be very high to produce a pressure to balance the gravity. Since we can't see below the photosphere we must rely on indirect techniques to find the information. We observe Doppler shifts of the solar spectral lines and we see that the surface of the Sun oscillates. These oscillations are due to pressure waves in the Sun that reflect off the photosphere and bounce back and forth. Because they pass through the center of the Sun it allows us to understand the interior. This study is called *helioseismology*. There is much work going on around the world to watch the Sun and determine what is going on. One satellite is doing great work on the Sun: the *Solar and Heliospheric Observatory* or *SOHO*. It is permanently stationed between the Sun and Earth at a distance of about 1.5 million km from the Earth. Studies of the Sun reveal that the rate of rotation varies as you get deeper into the Sun. The puzzling thing is the complexity of the rotation. Any theory as to what is going on eludes scientists currently. As you move out from the core the density drops off. In the ore the density is probably about 150,000 kg/m^3 to an intermediate value of 1000 kg/m^3 to about 1/10,000 the thickness of our atmosphere at the surface. This means that about 90% of the Sun lies in the inner 50 %. Computer models say that the core must be about 15 million K which is consistent with what we believe.

Energy Transport

Since the core is so hot, there are violent collisions that are occurring constantly between the particles. At these high temperatures there are no photons left on the atoms, so they can not absorb any photons of light. This makes the interior very transparent. This means that energy travels outward fairly easily in the central part of the Sun. As you move outward, the temperature drops and electrons are found on their atoms. Now there are electrons to absorb the photons and the layer becomes opaque. At the outer edge of the *radiation zone*, which is 200,000 km below the photosphere, all of the photons have been absorbed. But what of the energy? This energy reaches the surface by *convection*. The hot solar gas moves upward while the cooler solar gas drops back into the Sun. This is how the energy reaches the surface. At the upper edge of the radiation zone the convection zone starts. The convection cells at the bottom are thought to be 10,000 km across. As you move outward the cells get smaller, but more numerous until they are about 1000 km across at the surface. Convection only has enough energy to carry the energy to the photosphere. The photons that reach the photosphere escape out into space.

Granulation

When you look at a close up of the Sun's surface you see all of these cells. This is called *granulation*. These granules are the tops of the convection currents. They measure about 1000 km across and last about 5 – 10 minutes. Spectroscopic measurements show that gases boil up at these points. The dark areas are where the material is dropping back down into the Sun. The granules have a variation in brightness and this is due to temperature differences.

The Solar Atmosphere

Composition

An enormous amount to information can be found in the spectrum from the Sun. You will see more than 600 Fraunhofer lines on the spectrum. These are due to the photosphere and the lower chromosphere. Below the photosphere the gas is sufficiently dense to interact with the photons. But this is due to the energy of the photons. If the energy of the photon doesn't match up with the transition energy in the atoms, it can escape. That means that when we look at the Sun, we look at different depths depending on what wavelengths of light we are seeing. Photons that have wavelengths near the absorption lines are more likely to be captured by an atom. This means that they escape from higher (cooler) levels in the Sun. The Fraunhofer lines are evidence that the temperature decreases as you move outward from the Sun. In all, there have been 67 elements identified in the Sun. There are probably more elements present but they are in such a small amount we can't see them. This type of analysis only allows us to determine what is going on in the photosphere and lower chromosphere.

The Chromosphere

The chromosphere is the layer that lies just above the photosphere. We only see it when there is an eclipse. It shows up as a red ring around the Sun, which is due to hydrogen alpha (H_). You will find that every few minutes a *spicule* erupts from the chromosphere. This is hot gas being expelled from the Sun. They blow off at about 100 km/sec. They usually accumulate around supergranules. The spicules are thought to be the result of stronger magnetic fields in the area.

The Transition Zone and the Corona

When the photosphere and the chromosphere are blocked the solar corona becomes visible. The spectrum of the Sun changed dramatically when we took the spectrum of the corona. The absorption lines disappeared and emission lines appeared. This was seen in the 1920's. This is due to the fact that the atoms in the corona are more highly ionized. Iron atoms have been identified that have lost as many as 13 of their 26 electrons. In the photosphere the iron has lost only 1 or 2 electrons. This is all due to the high coronal temperatures. The temperature varies with altitude above the Sun. At the surface the temperature is about 5800 K. Five hundred km above the Sun it drops to 4500 K and then at 1500 km the temperature starts to rise rapidly. At around 10,000 km the temperature reaches 1 million K. In the corona the temperature remains a constant 3 million K. What is goofy about that? We don't know what is really happening to cause that. Some think it has something to due with the magnetic field.

The Solar Wind

The Sun loses fast moving particles, mainly protons and electrons, and radiation all the time. The radiation moves at the speed of light while the particles move more slowly, about 500 km/sec. This stream of particles is called the *solar wind*. At 10 million km above the Sun the particles can escape the gravity. The Sun is evaporating, losing mass all the time. It carries a million tons per second from the Sun, which is only .1 % of the mass since the Sun formed 4.6 billion years ago.

The Active Sun

Even though the Sun is quite steady, there is an unpredictable aspect to our Sun. Solar activity affects what are called coronal holes and the amount of matter in the solar wind.

Sunspots

Sunspots were first studied by Galileo, which led him to say that the Sun was not perfect, thus going against Aristotle. These areas are dark and usually measure 10,000 km across. They will quite often appear in groups. Sunspots show an *umbra* or the dark area and the *penumbra* which is the lighter area of the spot. The reason they appear dark is that they are cooler than the surrounding Sun. In the umbra the temperature is about 4500 K while in the penumbra it is about 5500 K. The sunspots seem to come and go at random. A single spot can last from 1 to about 100 days while a group will last for about 50 days.

Solar Magnetism

The magnetic field causes the sunspots. At the sunspot the field is typically 1000 times stronger than on the Sun. It is thought that the magnetic field causes the hot material in the convection current to be deflected from where it was going. Groups of sunspots are an indicator of the magnetic field. There is a *polarity* in the sunspots. Spots where the magnetic field comes out of the Sun are labeled S and where the field lines dive into the Sun are labeled N. Sunspots usually come in pairs at the same latitude. The leading spot in the pair have the same polarity, but it varies depending on which hemisphere it is found. Due to differential rotation the magnetic field lines get wrapped around the Sun many times until they kink like a garden hose and the pressure builds up. At some point it bursts through the atmosphere and forms a pair of spots.

The Solar Cycle

Not only do the sunspots come and go, but their numbers follow a cycle. It is called the *sunspot cycle*. The cycle takes about 11 years. As we move towards a minimum, like we are now, the spots will start to appear at higher latitudes. During the maximum you will find them closer to the equator. At *solar minimum* very few spots are seen. As we approach solar maximum, the numbers start to increase, reach a peak then decrease at minimum again. Making things more complicated still, there is a *solar cycle*. This cycle lasts 22 years. Every 11 years the polarity in the Sun reverses itself. So every 11 years the polarity reverses and we go from a minimum to a maximum and back to the minimum. This is thought to be due to the magnetic field wrapping itself around the Sun numerous times and finally snapping. From 1645 to 1715 we experienced what is called the Maunder minimum. The solar activity was at a minimum for 70 years. This can not been explained easily.

Active Regions

The surface of the Sun is a violent place with many *active regions* on it. One such region would be a *prominence*. Here you have a loop of hot material being ejected from the Sun and following a magnetic field line. *Quiescent prominences* last for a few days or weeks. An active prominence comes and goes much quicker, a matter of hours. They many reach 100,000 km in height. The largest prominences produce 10^{25} joules of energy. It would take all the power plants in the world a billion years to produce that much energy. A more violent event is the *flares*. They can flash across the Sun in minutes, releasing huge amounts of energy as they go. Temperatures here reach 100 million K. A flare releases the energy of a large prominence in minutes rather than weeks. Sometimes the flares can eject large amounts of matter into space. These are called *coronal mass ejections*. If aimed at the Earth they can cause havoc with communications and power disruptions.

The Sun in X-rays
The coronal gas emits in X-rays due to the high temperatures. In the 1970's we stared to see windows in the corona that we now call *coronal holes*. They aren't really holes, but rather regions where the corona is absent. When you look at this region it looks black underneath, but that is simply because there are no X-rays. This is where the material is streaming away from the Sun due to high energy disturbances below it. The largest coronal holes can be hundreds of thousands of km across. This only happens a few times per decade, but small holes that are a few tens of thousands of km across are more common.

The Changing Solar Corona
The corona varies in size with the sunspot cycle. At sunspot minimum the corona is very small and at maximum it is very big. Astronomers think that the corona is powered by solar surface activity. Small magnetic loops appear all over and break releasing large amount of energy into the corona.

Observations of Neutrinos
The Solar Neutrino Problem
In the Sun neutrinos are produced as a consequence of the proton-proton chain. The neutrinos interact with nothing as they stream out of the Sun. Several experiments have occurred to try and detect neutrinos. One of the first was in South Dakota where they placed a tank of about 100,000 gallons of chlorine containing material in a mine that was 1.5 km underground. When a neutrino interacts with the chlorine it produces argon and it would be detected. It was determined that we should detect 1 neutrino every day of 10^{16} neutrinos that passed through the tank. In reality about 2 per week were detected. Why? This came to be called the *solar neutrino problem*. Other experiments showed the same results.

Neutrino Physics and the Standard Model
Well there are only 2 reasons that we found fewer neutrinos than we thought: 1) fewer neutrinos are produced than thought or 2) not all of them make it to Earth. If the first one is true then we are in trouble because that means that what we think we understand about the Sun may have just gone out the window. If neutrinos have even the slightest mass they transform during the trip to the Earth. This called *neutrino oscillations*. They simply change form and we can't detect them.