VIII. Understanding the Sun Our Star

1. Interior of the Sun

After we have exhausted our first round of information gathering about the Sun through observations, we will have to resort to scientific reasoning in order to learn more. This is particularly true, if we want to know about the inner workings or the interior of the Sun. The first natural question that comes to mind is: What is the tremendous energy source of the Sun that has kept it going for such a long time?

A) Energy source

According to what we have derived before, the Sun needs to maintain an energy flux of $\approx 4 \times 10^{26}$ Watt (equivalent to its luminosity) for $> 4.5$ billion years. Over the age of our solar system this sums up to a total energy of $\approx 2 \times 10^{37}$ kWh. The age is known from the oldest rocks on Earth and on the moon. In the last century it was already known from fossils that the Earth was at least several 100 million years old. This created a puzzle for astronomers, since they had no idea, what the energy source of the Sun might be that could last so long. (The commercial with the Energizer Bunny was not popular yet at that time.) The maximum amount of possible fuel was of course known through the total mass of the Sun.

Slide VIII.1

a) The first idea was a Sun of pure coal and oxygen. The Sun spots were thought to be ash from the burning of coal. But this would have only lasted for $\approx 10,000$ years, much to short!

b) Kelvin and Helmholtz proposed shrinkage of the Sun under its own gravity. What does this mean? The Sun is a huge gas ball. Shrinking it means that the pressure of the gas must rise. If you squeeze a balloon you increase the pressure. This might be done, until it ruptures. But increasing the pressure has also another effect. You may have felt it, when you were pumping air into the tire of your bike. The pump gets warm. If you increase the pressure by squeezing, the gas inside also increases its temperature. Let us see this in a little demonstration: I have a little bit of cotton wool in this glass cylinder. When I push the piston into the cylinder hard enough, the air gets so hot that the cotton is ignited and burns.

Demo Syringe

View VIII.1

<table>
<thead>
<tr>
<th>Source</th>
<th>How?</th>
<th>How Long?</th>
<th>Adequate?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal, Oxygen</td>
<td>Chemical Reaction (Burning)</td>
<td>10,000 Years</td>
<td>No</td>
</tr>
<tr>
<td>Gravity</td>
<td>Sun shrinks</td>
<td>100 Million Years</td>
<td>No</td>
</tr>
<tr>
<td>Hydrogen Nuclei</td>
<td>Nuclear Fusion 4 H $\rightarrow$ He + 2 Positrons + Photons + Neutrinos He weighs less than 4H $E = mc^2$</td>
<td>10 Billion Years</td>
<td>Yes</td>
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</table>
For the Sun this means: When it shrinks -> it increases pressure -> this increases the temperature -> it radiates more energy
This would lead to a life of the Sun of about 100 million years. But this is still by far not enough for the known age of the Earth. Thus this approach doesn’t work either. However, as we see below gravity and pressure play an instrumental role in what does work, and we will come back to this issue.

c) Nuclear Fusion (Bethe: Nobel Prize)
As a consequence of his theory of special relativity Einstein found that energy and mass is made from the same stuff and can be converted into one another. He came up with the famous relation:

\[ E = M \times c^2 \]

If we use this formula, it means that 1 kg of matter, if converted, produces \( 2.5 \times 10^{10} \) kilowatt hours of energy.

\[ E(1\text{kg}) = 1 \text{kg} \times (3 \times 10^8 \text{m/s})^2 = 9 \times 10^{16} \text{kg m}^2/\text{s}^2 (\text{Ws}) = 9 \times 10^{16} \text{Ws}/3600 \text{ s/h} = 2.5 \times 10^{10} \text{kWh} \]

Or perhaps more meaningful to you: You can burn a 100 W light bulb for 250 billion hours or for 25 million years. This is a very powerful energy source. Still the Sun has to convert \( \approx 4 \) million tons of matter every second in order maintain its luminosity. This sounds like a lot, but it is peanuts for the huge mass of the Sun.

How does the Sun manage to convert mass into energy? Most of the energy sources we use on Earth deal with chemical reactions: For example Coal and oxygen of the air is burnt into CO\(_2\).
This provides only very little energy, since only the shell of the atoms with the flyweight electrons gets involved. The lion share of the mass of an atom (99.98%) rests in its nucleus. We need to get involved with nuclear reactions, if we want to tap this mass and energy reservoir. The nuclei of atoms consist of protons (positive charge) and neutrons (no charge):

\[
\begin{align*}
\text{H} & : 1 \text{ proton} \\
\text{He} & : 2 \text{ protons, 2 neutrons} \\
\text{C} & : 6 \text{ protons} + 6 \text{ neutrons}
\end{align*}
\]

Some nuclei have less or more neutrons than protons, but represent the same element. The number of protons determines the element; the neutrons don't matter. The most abundant element on the Sun is \( \text{H} \), next comes \( \text{He} \). Thus the energy source should involve these 2. A nuclear reaction means that one element is transformed into another element. Helium has 4 individual nucleons: if we fuse 4 \( \text{H} \) nuclei into 1 \( \text{He} \) nucleus, what then?
We find: 4 H nuclei weigh more than 1 He nucleus. The difference is 0.7 %

Thus in this process 0.7% of the mass has vanished. It was transformed into energy. And this is what happens in the Sun

\[
4 \text{H} \rightarrow \text{He} + \text{gamma} (\gamma) \text{photons} + \text{positrons} + \text{neutrinos}
\]

Thus energy escapes with the \( \gamma \)-s and neutrinos.
The resulting \( \text{He} \) that contains less mass remains inside the Sun.

The gamma photons carry most of the energy, the other particles a tiny bit of it. The positron is like an electron with positive charge, it leaves the proton when this is converted into a neutron (for He we need 2 neutrons) and carries the positive charge away. The positron will quickly meet an electron, which then will convert into two more gamma photons. The last particle, the neutrino, is a very elusive particle, which leaves the interior of the Sun with almost no interaction. We will come back to this particle soon, because it provides an interesting tool to take a look inside the Sun.

There is a lot of hydrogen on the Earth, but it does not readily fuse into helium. The reason is that the positive charges of the protons repel each other. A high energy of the protons or a temperature of the matter is needed to overcome electric repulsion between positively charged nuclei ("fusion ignition temperature"). And a high density is needed for lots of collisions to occur in order to provide the energy.

On Earth so far only nuclear fusion bombs (ignited by another nuclear bomb) could be built. The fusion reactor is still very far in the future. A nuclear fusion reactor is very difficult to make: hot stuff flies apart too fast and there is no time for the fusion reaction to start. In laboratories magnetic containment is used to trap energetic ions like in the Earth's radiation belt, but there is still a long way to go.

Now we may ask: How does the machinery work in the Sun's interior? We need:

- high temperature
- and
- high density

The temperature of 5500 K on the surface is by far not high enough. We need \( \approx 15 \text{ million Kelvin} \) and densities much greater than that of water.

B) Hydrostatic equilibrium:

If we go deeper and deeper into the Sun, there is more and more matter above, which must be carried. Thus an increasing pressure is needed to balance the weight of the overlying stuff.

Demo Pressure

In this demo I show you how I try to push up and keep up a column of water with the pressure of the air in my lungs. I can only push the water up by \( \approx 2 \text{ m} \). If I would add more and more water on top, I would have to increase the pressure even more or it
would be pushed down. This is the reason, why divers need pressurized air to breathe in deep water. The overlying water increases the pressure on the lungs from outside.

How can we increase the supporting pressure in the depth of the Sun? Pressure means: many particles hitting a surface with a certain velocity. Thus pressure increases inwards, which means:

Density increases inwards (more particles in the volume).

This is also natural, since heavier stuff sinks.

and

Temperature increases inwards (particles hit with higher energy).

This is again natural, the energy of the Sun is transported outward, and it goes from hot to cold. We have already seen that gas under pressure gets hot (like in the pump for the bicycle).

Thus the center of the Sun is the most dense and hottest place. The pressure must sustain all the material above, and that is a lot as we have seen from the mass of the Sun. The Sun is stable, i.e., it is in equilibrium. We call this pressure balance hydrostatic equilibrium. From the knowledge of the mass above and the gravity force we deduce that the pressure in the interior of the Sun is \( \approx 1.3 \times 10^9 \) times the atmospheric pressure on the Earth (or \( \approx 1,000,000 \) times the pressure at the deepest ocean floor).

The energy from the fusion reactions maintains the temperature and the pressure in the center of the Sun. If the fuel runs out, the Sun were to shrink further, since the pressure would decrease. However, the Sun can burn 10% of its H, before it runs out of fuel. This is good for another 4.5 billion years. The Sun is just in its best years!

Finally, there is another question: why does the Sun not explode like a nuclear bomb? The answer is that the Sun has a built-in safety valve and thermostat, which provides protection against overheating and explosion:

With the pressure balance in place, the Sun has a built-in safety feature. Let us consider the following situation: If there were more fusion than necessary

- \( \rightarrow \) temperature increases \( \rightarrow \) pressure increases \( \rightarrow \) core expands

As a reaction:

- \( \rightarrow \) density decreases \( \rightarrow \) less fusion reactions

Ergo: the temperature will decrease again
The core has to shrink, until the nuclear fusion balances the pressure overhead. In this way a fine balance is established.

**View VIII.4**

**C) Information from the interior**

The clues shown above were all very indirect. Can we get some more direct information about the interior of the Sun? There are indeed 2 possible tools:

1) the **neutrinos** from the nuclear reactions which leave the Sun and

2) we can use a similar tool as for the Earth: **seismology** like the waves triggered by earthquakes (Sun rings like a giant bell)

**a) Neutrinos** come directly from the fusion reactions and thus they constitute a direct proof of these reactions. However, since the neutrinos make through the matter of the Sun so easily, they also go easily through the Earth and through our detectors without being noticed. Only very, very few can be captured in special reactions. These detectors have opened **neutrino astronomy** (this is no electromagnetic radiation!)

*Solar Neutrino Problem*: We detect fewer neutrinos than predicted from the energy output of the Sun (only $\approx 30\%$ of how many are expected). This is a huge effect!

Possible answers (?):

**Problems** with the detector?
This has been checked again and again and with different detectors.

**Interaction Cross-Sections** provided by Nuclear Physics are incorrect
They have been measured precisely at particle accelerators.

This leaves us with two more interesting possibilities:

**Neutrinos change identity on their way** to Earth?
This may mean neutrinos have a small mass?
The model of the Sun's interior is not correct?
If this is the case, we would learn something new about the Sun’s interior, but at first only neutrinos of a relatively unimportant side reaction could be observed.

The last two possibilities both would have profound consequences:
As far as the neutrino mass goes: Our universe is full of neutrinos. Thus the question arises:
Can neutrinos with mass solve the missing mass problem?
For these two reasons another big detector set which works with a large amount of gallium has been operated.

Deep in the Appenin mountains in Italy the detectors are buried to be shielded from cosmic rays, which create false signals. There are only a few signals per day!! Scientists have to be very patient here. Only very few Ga atoms are converted into Ge, which then can be extracted and detected.

The results from the first few years seem to show that
- The original results from the other detectors were correct, but
- In addition, this detector measures the important neutrinos of the main H -> He reaction!! The number of these neutrinos is closer to what is expected, but still by far not enough!!
- The neutrinos seem to have no or very, very low mass. Thus it does not solve the missing mass problem in the universe. However, they appear to oscillate between different identities and do seem to have mass!

Even more recent observations with the Japanese Kamiokande detector and the US-Canadian Sudbury Neutrino Observatory (SNO) show strongly that neutrinos change their identity on their way. Quantitatively, indeed only 1/3 of them are the easily detectable e-neutrinos. According to the standard model of elementary particles there are also μ-neutrinos and τ-neutrinos, i.e. associated with the cousins of the electron, the μ-meson and the τ-meson. The new detectors make use of tons of water to detect neutrinos. Using the heavy variety of water (water that has 2 deuterons instead of 2 regular hydrogen atoms) the SNO has just recently been able to detect directly all of the neutrinos. Indeed, the combined flux of all neutrino varieties meets the expected value from the known energy production of the Sun, and thus this important question appears to be settled.

b) Helioseismology (like earthquakes)
The second method to probe the interior of the Sun is helioseismology, similar to the earthquake tracing on Earth. Since the Sun is a gas ball, only sound waves travel through its interior. As a
result of these waves the **Sun's surface moves up and down** (like the ocean) with a period about 5 minutes ("5 minute oscillations"). They represent sound waves, which are trapped inside the Sun. We can measure the up and down **motion** of the surface with the **Doppler effect**. The propagation of sound waves depends on density and temperature, and therefore we can learn about these parameters inside the Sun from the recording of the solar oscillations.

The results: Do not contribute to the neutrino problem and so far Do not agree with models of the generation of the Sun's magnetic field. More work is needed. In collaboration between ESA and NASA the project SOHO a spacecraft was launched in December 1995, which has the instrumentation on board to monitor the solar oscillations continuously from space. It will also have many other diagnostic instruments on board. I am part of a team to determine the composition of the particles, which come from the Sun.

**D) Energy transport to surface**

Let us now see, how the energy comes out of the interior of the Sun to the surface. All energy transport requires that the temperature decreases outwards, which is the case. We have two competing mechanisms:

**a) Energy flow by photons:**

This is like the thermal radiation from the Sun. The only difference is that photons undergo many collisions with matter on their way out. As a result the photons "degrade" to lower energies or longer wavelengths on the way out:

- From gamma (from the nuclear reactions) to X-rays to UV to visible.

It takes \(\approx 10\) million years for the radiation from the core to reach the surface.

**b) Energy flow by convection (outer shell).**

In the outermost shell of the Sun the radiation doesn't work that well and convection becomes more important. This is the effect known from boiling water.

- Hot (and less dense) material rises.
- Cool (and dense) material descends.

We see this effect on the surface of the Sun itself in the form of granulation. The bright interior of a granule is the hot (and thus bright) stuff, which rises. After it cooled down radiating away its energy it sinks at the edge of the granule where it is darker.

**2. Solar atmosphere**

Now we are in the Sun's atmosphere, or more precisely in the Photosphere of the Sun.

**A) Photosphere:**

**a) Definition**
The *photosphere* is where the Sun's energy (i.e., its visible light) comes from, i.e. what we see as its surface. From here on of course radiation is the energy transport again, because that is how we get the energy on Earth.

**b) Structure**

We can check, whether our idea of the energy transport in the uppermost layers of the Sun is correct with the Doppler effect (which I already mentioned). Remember hot material is flowing upward and cold material is flowing downward.

All *velocities can be measured with the Doppler effect*:
The reason is that the wavelength of waves changes when the source moves toward or away from the observer. This makes the spectral lines the key to Doppler measurements: We know the frequencies or the wavelengths when there is no motion and thus can compare wavelengths when sent out by moving objects with the laboratory wavelength.

- Away: wavelength increases = *redshift*.
- Toward: wavelength decreases = *blueshift*.
- Across: no shift.

Consequently, the spectral lines in the center of the granules are blue-shifted and red-shifted at their edge. On the Sun we can use the Doppler effect for several observations:

- **Granulation**: Solar super-granulation (was discovered via Doppler shifts).

 This is granulation on a larger scale. The flow pattern can be seen with a so-called Doppler-gram as obtained by SOHO:

**B) Chromosphere**: It is somewhat hotter and thinner above coolest layer of Sun

We can observe it in the light of the hydrogen line. In this way we can get photographs of many different layers of the solar atmosphere. The Chromosphere is \( \approx 10000\) K.

**C) Corona**: The atmosphere is even hotter in the corona above a few 1000 km in height. The hottest and outermost part of the solar atmosphere is at \( \approx \) few million K.

- Helium at \( T \approx 100000\) K
- Iron at 1-2 million K

**a) Temperature**

This high temperature is deduced from:

Highly ionized iron in the corona, i.e., iron which has lost many electrons, which means it must be extremely hot there. The sample image shows iron that has lost 14 electrons. It must be very hot to take away so many electrons from the Fe.

It seems strange that the cooking pot is hotter than the heater element underneath. We find additional heating by magnetic fields (wildly stirring in the atmosphere). We will come back to this later.
The corona can be observed during total solar eclipses or with a coronagraph, which produces a kind of solar eclipse. A small disk is used of the size of the image of the Sun in the focus of the objective of a telescope.

**b) Structure**
The corona is highly structured by magnetism: in lines and loops. It looks like the structure when you have iron filings in a magnetic field. Only now the hot plasma is tracing the field lines, since the charged particles of the plasma can only spiral around the field lines.

The coronal heating is still *a matter of intense research*. It needs strong motion and magnetism. We observe strong heating where there is strong magnetism, but how the magnetic energy is converted to heat energy is still not fully understood.

The large structures in the corona are much better understood now. Prominences with dense cool material (10000K, like in the chromosphere) are observed (more material than in neighborhood).

Hydrogen at $10^4$ K red emission.

How can such dense material stay there, without sinking down in the Sun’s gravity? Prominences are held up by magnetism.

The magnetic field lines levitate the plasma, which is attached to them, since the particles can only spiral around them. The ever-changing magnetic field structures on the Sun lead to magnificent spectacles.
There are always motions and sometimes eruptions, which through the material into space. Eventually it may hit the Earth and cause strong auroras. How does the Sun manage to move the material around? The magnetic field and currents flowing through the conductive solar atmosphere do that:

**Demo Motion by electromagnetic fields**

c) **Activity of the Sun:**

Let us now turn to the activity on the Sun. This image shows a giant sunspot group. It also shows the granulation, which is responsible for the energy transport to the surface. The granules are found all over the Sun except in the Sun spots. The sunspots are darker and thus have a lower temperature. The reason is that the energy transport is choked off by a strong magnetic field.

The magnetic field itself can be observed using the fact that spectral lines are split into 2 or more components by magnetic fields. Using this effect, called **Zeeman splitting**, maps of the magnetic field on the Sun are produced.

**Image_7** *(Date_KittPeak_Ca_Magnetogram)*

This demonstrates that sunspots show a very strong magnetism. We see the strong signatures, where we saw the sunspots in the other images.

Over sunspots with complex magnetism we find another sign of the solar activity: Solar flares. These are violent eruptions on the Sun, now constantly observed by the SOHO spacecraft in UV light. **Video (8_SOHO_EIT...Flare_1)**

A wave ripples through the Sun’s atmosphere **Video (9_SOHO_EIT...Flare_2)** Finally, material takes off into space: **Video (9_SOHO_LASCO...Flare_3)**

(If there is time: **Laserdisc Sun and Universe, Ch.11**)

Here we encounter similar effects as in the Earth's magnetosphere:

In the complex magnetic fields field lines with opposite directions meet, and we get.

**Magnetic reconnection:**

![Diagram of magnetic reconnection](attachment:image.png)

- oppositely directed magnetic lines
- reconnected magnetic lines are kinked
- jets, heating, energetic particles

E. Mö. 4/2/04
This leads to particle acceleration and heating. The particles which are ejected outward can be measured in space. They reach very high energies. We are currently working on a detector for NASA’s ACE (Advanced Composition Explorer) Mission to be launched in fall of 1997, with which we can measure how many electrons these particles have lost. Then we can measure directly the temperature in these flares. The others, which hit the Sun's atmosphere, create gamma rays, which can be measured by the Gamma Ray Observatory.

The activity of the Sun varies very regularly. Indeed sunspots occur on an 11-year cycle. Fewer sunspots also mean that the Sun is less active and probably dimmer. That this seems to be the case can be seen from old climate records. During the 17th century it was much colder than today. During this time almost no sunspots (and also almost no auroras) were observed. This was the time of the 'little ice age' or the so-called Maunder minimum. The coincidence is intriguing. To date several more such periods have been found in the earth's history. Very recently, precise measurements of the solar energy flux for years, taken from satellites, have shown that the energy output of the Sun is higher when it is active.

D) Solar Wind

a) The corona is so hot that it overcomes solar gravity.
The result is constant outflow of this hot material form the Sun. The wind is so strong that it blows with supersonic velocity (several 100 km/sec). This flow is particularly strong where the magnetic field lines of the Sun seem to stretch outward. No magnetic force tends to hold the particles back. Thus a particularly strong solar wind should originate over the poles of the Sun, which were unreachable for long. The Ulysses spacecraft which was launched October 1990 has reached the polar regions of the Sun over the summer 1994 and has now scanned both poles for the first time. Indeed a particularly strong solar wind was found over the poles.

b) Solar wind carries Sun's magnetism to earth and beyond, since the flow is even stronger than the magnetic field lines. We have seen this already at the cometary tails, which are stretched out by this field.

The region governed by the solar wind and its imbedded interplanetary magnetic field is called the heliosphere. The solar wind is so strong that it blows with supersonic speed. What does this mean? It becomes clear when there is
an obstacle in the way. In the heliosphere there are many obstacles: the magnetospheres of planets comets, etc..

A whip is a classic example of effects at supersonic speed. The tip of the whip is so fast that it moves at supersonic speed!! The crack of the whip, which you all hear, is the shock wave, or the supersonic Boom created by the whip. You may know this: when a supersonic jet passes overhead, a tremendous Boom passes by.

Here you see the structure of this shock wave in a wind tunnel experiment for a jet. What happens at this shock wave is that the gas passing by abruptly is decelerated to subsonic speed. This means that behind the shock the density and thus the pressure increases tremendously, and we hear this pressure pulse as the Boom. The Earth's magnetic field creates such a Boom or shock wave (the bow shock) in the solar wind.

c) The corona and solar wind change

1) on the short scale:
Fast and slow SW follow rapidly depending on the conditions on the Sun
As shown above: prominences can erupt and leave the Sun. These are coronal mass ejections or ejection of solar plasma and magnetism

2) with the Solar cycle (number of sunspots).
The solar wind flows out to the earth and beyond. These changes impact the Earth's magnetosphere. We have talked briefly about the pressure of the solar wind on the earth's magnetism and the resulting aurora etc.

d) Shield against cosmic rays

However, the solar wind with its magnetic field makes it also hard for other plasmas and charged particles from outside the heliosphere to move in. Thus it constitutes the first shield against cosmic rays for the earth. Altogether we have a 3-layer shield:

1) the solar wind
2) the Earth's magnetic field
3) the Earth's atmosphere