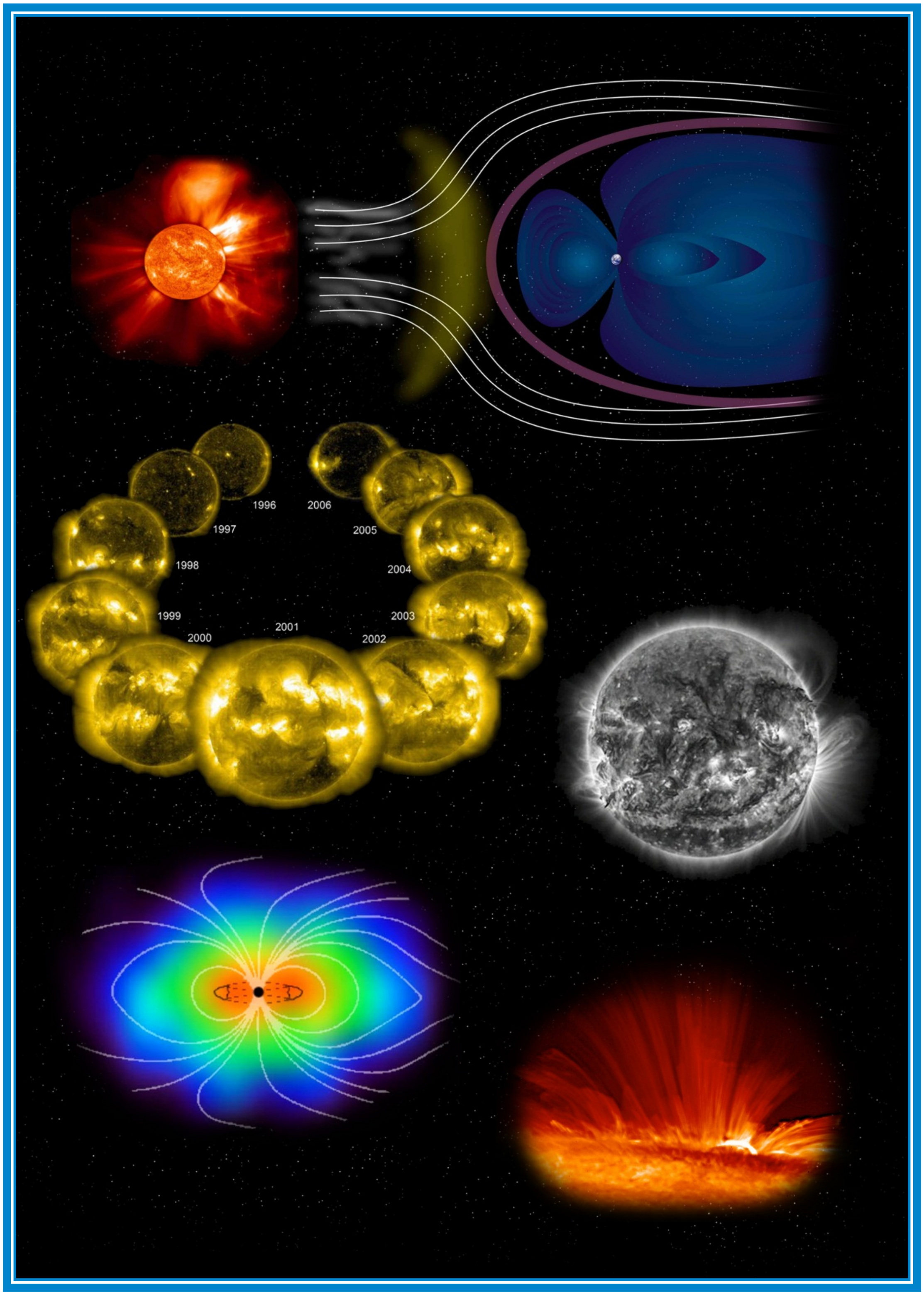
CESAR BOOKLET

General Understanding of the Sun: Magnetic field, Structure and Sunspot cycle



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Introduction to planetary magnetospheres and the interplanetary medium

Most of the planets in our Solar system are enclosed by huge magnetic structures, named magnetospheres that are generated by the planets' interior magnetic field. These magnetospheres form the biggest structures in our Solar System with their size being 10-100 times bigger than the planet itself. This if the heliosphere is not included. The solar wind moves around these magnetic "bubbles" and interacts with them. A planet's magnetosphere can either be induced by the interaction of the solar wind with the ionosphere (comets, Venus) of the body or via a dynamo process (Mercury, Earth or giant planets).

Now we know that there are magnetic structures. The second question is: what they are and how do we know about their shapes? The shape of it is determined by the strength of its magnetic field. Furthermore, as the flow of the solar wind passes the field, the motion of a solar charge particle goes in the direction of the magnetosphere's lines. Charged particles are present in all magnetospheres, though the composition of the particles and density varies from one planet to another. The particles in the magnetosphere may originate from the ionosphere of the planet, the solar wind or on satellites or ring particles whose orbits are entirely or partly within the magnetic field of the planet.

The motion of these charged particles increases to great scale electric fields and currents, which affect the magnetic field and the motion of the particles through the field. It may perhaps not be unexpected that the interface of magnetic field, charged particles and electric fields generates very complex physical processes which are frequently not well understood.

While most of the information and data we have is derived from in situ spacecraft measurements, atoms, and ions in certain magnetospheres have been detected from Earth through the discharge of photons at visible and ultraviolet wavelengths. Electrons that accelerate are known to discharge photons at radio wavelengths, visible at frequencies reaching from some hertz to gigahertzes. Emissions like those were studied from Jupiter in the 1950's, and shaped the first indication that planets other than ours may have magnetic fields that are strong.

A short introduction to magnetic fields

We can first introduce the term magnetic field and what it really is. An area of effect that is exerted by a magnetic force has a magnetic field. This field is usually focused along two poles, a south and a north. To create a magnetic field, one needs to have a magnetic matter, for example iron magnets, or by moving charged particles to create a force. This is a push or pulls force.

Here are some fundamentals about a magnetic field. First, it is not possible to divide a magnetic field. It is a dipole and will always be one. Dipole is as it sounds something that has two poles. It will simply change in its strength. If a magnetic field is small enough, it can be turned around in its orientation by a larger and stronger magnetic field. Additionally, a magnetic field is the cause of electric currents. Electric currents are simply electric changes that are moving in a distinct path. This movement is the reason why a magnetic field is created. The current can produce a magnetic field that is as large as the magnetosphere of our Sun and as small as the domain of the atom. The other thing to know when it comes to a magnetic field is that opposites attract to each other. Similar to poles in magnets, they will repel each other every time, while at the same time, poles that are opposite in nature will be attracted each other.

The structure of the Sun

The Sun as other stars is a huge spherical object made by hydrogen and helium. Its diameter reach 1.500.000 km that is 109 times the Earth's diameter but is 4 times less dense than the Earth due to its composition. The Sun is not only made of the burning gas that we see with a telescope. It has, exactly like the Earth, different layers at different temperatures. Every layer has its own features which makes them interesting. Below is a figure of the structure of the Sun with all the different layers and components named.

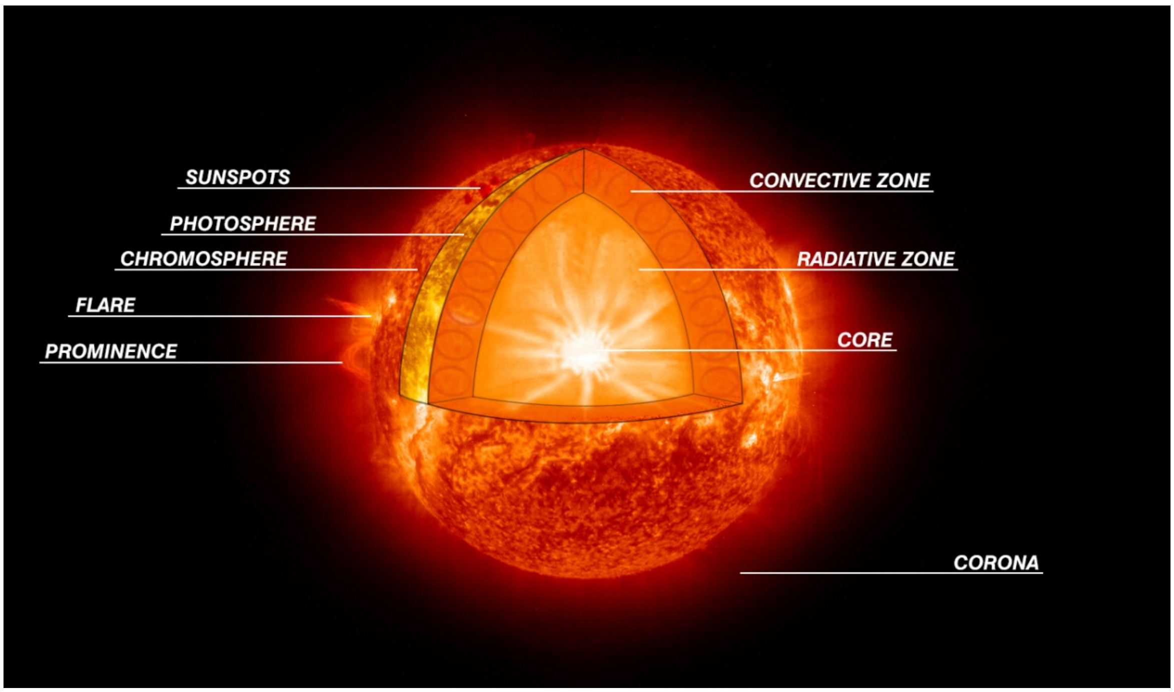

Figure 1: *A slice of the Sun. The nuclear fusion reactions occur in its center.* *Credit: CESAR*

A short description of the different layers seen on Figure 1 can be read below:

i. **The core:** The core of the Sun is the source of all its energy. The amount of energy produced is nearly continuous, so we do not see a considerable variation in its brightness nor the heat that is given off. The core has a very high temperature and the material it is composed of is very dense due to the extremely high pressure. It is due to the combination of these two properties that creates an environment where nuclear reactions can take place. These nuclear reactions always produce heavier elements on the periodic table.

ii. **The Radiative zone:** The transport of energy from the Sun's core (where it is produced) to the regions that surrounds it can be done by transferring it by radiation. This is how it travels from the center of the Sun to the outer regions, hence the name "radiative zone". Through this area of the solar interior, the energy (in the form of radiation) is transmitted by its interaction with the atoms in the surrounding. Some atoms are able to remain intact in the radiation zone, since the temperature is slightly cooler than what it is in the core. These atoms are capable to absorb energy, stock it for a short time, and then later release that energy as new radiation. In this way the generated energy in the core is passed from one atom to another through the radiation zone.

iii. **The convection zone:** The energy that is initially created in the core needs a new transport mechanism to carry on its passage to the Sun's surface once it is out of the radiation zone. This is necessary since the temperature is relatively cool outside of the radiation zone (2 million degrees Kelvin compared to 5 million in the radiation zone). The atoms will absorb energy at this temperature, but they do not release it so readily since their surrounding is cool and dense. Therefore the energy transfers by radiation slow down considerably.

iv. **The corona:** It is the biggest and less dense structure of the Sun and it surrounds it. Composed of plasma ejected from the Sun that reach 1.000.000 kelvin but with a very low density. Furthermore the solar wind transports the material of the corona to the interplanetary medium. From Earth, the corona is only visible during a total solar eclipse.

v. **The photosphere:** The photosphere is also named the apparent surface of the Sun. Since the Sun is wholly made of gas, there is no solid surface (like there is on Earth). However, when we observe the Sun, there is a depth past which the density of the gas becomes so high that we cannot see through it. This region is called the photosphere, or as mentioned the apparent surface. This is the disk that one sees in the sky when one looks at the Sun through a telescope that has a filter, or as a projection on for example a paper.

vi. **The chromosphere:** The chromosphere is the layer above the photosphere and is thicker than it. With a very low density, it´s impossible to observe it without narrowband filters or during a total solar eclipse due to the brightness of the photosphere. Furthermore it's less dense than the photosphere.

vii. **The flares:** The Sun usually ejects material through its surface. This material contains a huge amount of energy that the Sun releases in form of flares. From Earth, these flares are observed as a flash of light that increase the brightness of the Sun in that region. Sometimes, these flares are extremely powerful and the material ejected (typically electrons or hydrogen atoms) escape from the Sun´s gravitational field so they are free to travel through the Solar System.

viii. **The prominences:** Not only the solar flares indicate the Sun's activity, also the solar protuberances do. A protuberance is a huge structure of gas at a very high temperature that follows the magnetic field lines outside the surface of the Sun. For this reason we observe them with a loop shape. It may occur that the loop breaks into two parts. If that occur, the material that follows the magnetic field lines could be released out of the Sun, reaching 1000km/s of speed.

ix. **The sunspots:** When looking at the Sun through a telescope (or by projection), dark spots can sometimes be observed. These dark, continuously changing areas are called sunspots and they are generated on the photosphere. They appear darker to the eye for the reason that their temperature is not as high as the neighbouring gas. Moreover, the magnetic field lines go outside and inside the Sun through the sunspots.

Magnetic field of the Sun/Stellar magnetic field

Our star is very magnetically active. It has a strong and shifting magnetic field that differs from year-to-year. It reverses the direction of its poles after every solar maximum. This happens during one solar cycle. As far as we know, one solar cycle takes about 11 years to be completed.

Also, the magnetic field of the Sun leads to many effects that are together named solar activity. This contains solar flares, prominences, sunspots, and difference in the solar winds that carry material through our Solar System.

The effects of solar activity also can be seen from Earth. These refer to the auroras, or northern lights, at reasonable to high altitudes. Also, the disturbance of radio communications and electric power is often due to the stellar magnetic field. It also changes the structure of Earth's outer atmosphere. Lastly, it is believed to have played a huge role in the formation and development of the Solar System.

The matter in the Sun is all in the form of charged gas at high temperatures, also known as plasma. This then makes is possible for the equators of the Sun to rotate faster than it does at higher latitudes.

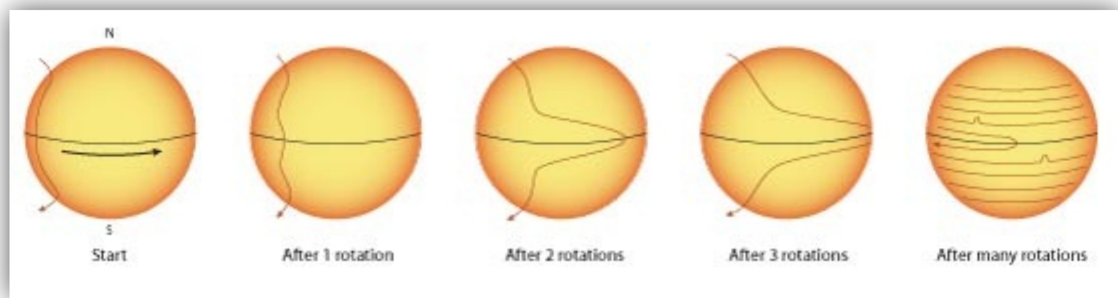

Figure 2: *The rotation of the Sun's magnetic field.* *Credit: NASA/ IBEX*

Look at Figure 1. The Sun´s equator takes 25 days to complete a rotation compared to 35 days at higher altitudes. With the equator moving in a faster pace than the other areas of the Sun, the magnetic field lines will twist together over time. This will then produce loops in the magnetic field, which in turn will erupt from the surface of the Sun and create the formation of the Sun's intense sunspots and other known solar events as we have seen before.

The twisting action also creates the solar dynamo and the 11-year solar cycle of magnetic activity as the magnetic field of the Sun reverses itself around every 11 years (polar shift).

The magnetic field of the Sun is not only surrounding the Sun, its field ranges beyond the Sun itself. The plasma from the Sun transmits its magnetic field into space, producing what is known as the interplanetary magnetic field. The interplanetary magnetic fields are at first stretched radially away from the Sun due to the plasma moving alone the magnetic field. The fields below and above the solar equator have different polarities that points away and towards from the Sun leads to an existing of a thin layer of current in its equatorial plane. This is called the heliospheric current sheet. As the distance from the Sun increases, the rotation of the Sun twists the current sheet and magnetic field into a structure that looks like the Archimedean spiral structure called the Parker spiral. Below is a figure showing this phenomenon.

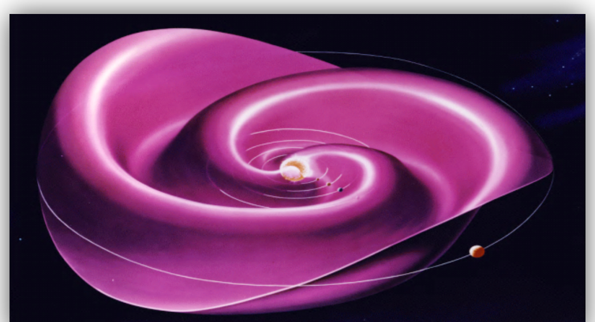

Figure 3: *The purple are is the Heliospheric current sheet, with the planets crossing it.* *Credit: Wikipedia*

The dipole component of the solar magnetic field is much weaker than the interplanetary magnetic field. To compare them, the dipole magnetic field at the photosphere is roughly 50–400 μT. It then reduces with the distance in cube to approximately 0.1 nT at the Earth's distance. On the other hand, some spacecraft's has observed the interplanetary field at the location of the Earth and the results was that its value is about 5 nT in strength. This is roughly hundred times more than the strength of it close to the Sun. Why does it behave like this? Well, the dissimilarity is due to the magnetic field that is produced by the electrical currents in the plasma that is surrounding the Sun.

Geomagnetic storms

A geomagnetic storm, also recognized as a magnetic storm, is a disruption in the magnetic field of the Earth. This disruption is triggered by coronal mass ejections (shortly CMEs) or solar flares that come from the Sun. These are in other words huge outbreaks from the outer layer of the atmosphere of the Sun, that is, from the corona. The material related with these solar outbreaks contains mostly of electrons and photons, with energy of a few thousand electron volts.

A geomagnetic storm usually begins between 24 and 36 hours after a CME, when an enhanced stream of solar plasma reaches the magnetosphere of the Earth, causing changes on it. Usually, a magnetic storm then continues for 24 to 48 hours, but some can even last as long as days. Once every decade (more or less), some really powerful storms can happen, with the most severe happening once every century. They happen when particles with high energy from a solar storm interact with the ionosphere and magnetosphere, generating a flow of energetic particles and disturbing the magnetic and electric currents in the atmosphere. Some effects of a magnetic storm include induced fluxes in power lines, powerful auroras, harm to satellites etc.

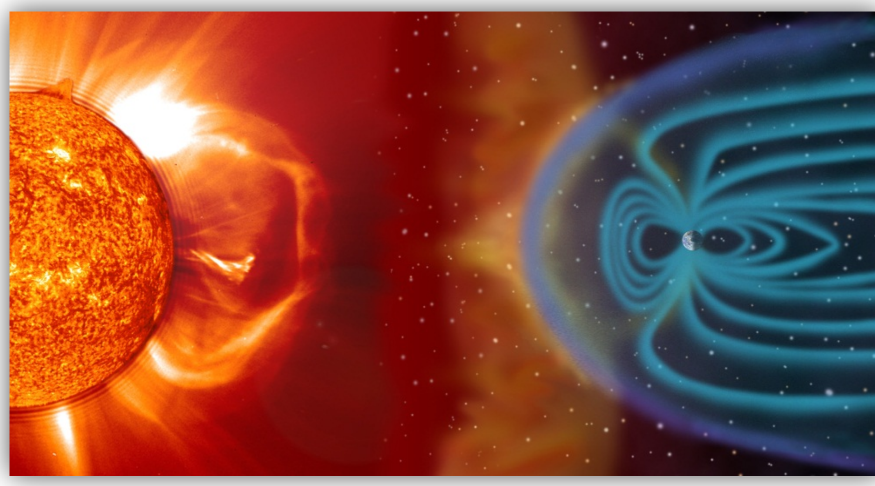

Figure 4: *An image of a Coronal Mass Ejection. Basically, CMEs are huge gas bubbles bounded by the magnetic field lines of the Sun, ejected from it over the course of several minutes – sometimes even a couple of hours. The cloud of charged solar particles that is travelling towards the Earth can interact with the magnetosphere and cause anything from radio interference to failure of sensitive electromagnetic equipment, or even increased aurorae activity.* *Credit: ESA/NASA*

Sunspots

As we mentioned, a sunspot is part of the photosphere that is disturbed by powerful magnetic activity, this magnetic activity prevents mater convection that happens below, thus decreasing its surface temperature in that area. These areas have a magnetic field that is about 2,000 times more powerful than the one Earth has, and much higher than anywhere else on the Sun.

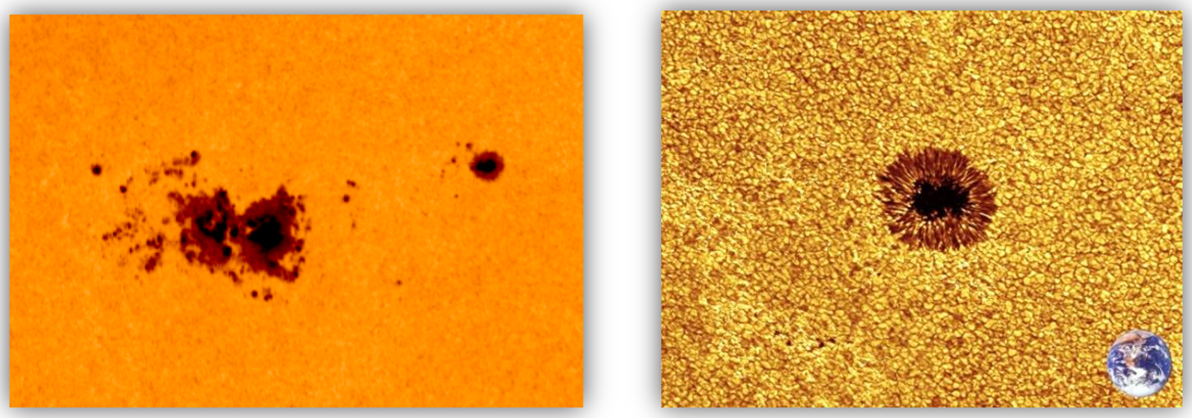

Figure 5: *Pictures of sunspots. The one to the right is a close-up image of one spot, with the size of the Earth in comparison. Credit: ESA/NASA*

Because of the strong magnetic field, the magnetic pressure grows, while at the same time, the surrounding atmospheric pressure drops. This then decreases the temperature compared to its surroundings since the concentrated magnetic field stops the flow of new, hot gas from the Sun's internal to the surface. Even if the sunspots are still extremely hot and bright, they look darker since they have a cooler temperature than their surroundings. The black areas of the sunspots are titled an "umbra" (shadow is the translation) and the surrounded or lighter area is titled the "penumbra" (almost shadow is the translation).

To put in numbers, the photosphere has a normal temperature of about 5500 Celsius degrees, whereas the temperature of a sunspot is approximately 4000 Celsius degrees. The temperature difference leaves them visibly as noticeable dark spots. Sunspots have a habit of being in pairs that have magnetic fields pointing in opposite directions (as a magnet does).

The average sunspot is about the size of our planet. Yet, sunspots come in diverse sizes reaching from hundreds to tens of thousands of kilometres across.

Scientists that observe the sun often measure the total area (size) of all the sunspots seen on the Sun every day. This is to get an idea of how active the Sun is. Lastly, sunspots seem to be permanent but they are not. The spots appear and disappear on the Sun's surface in regular cycles.

To measure the solar activity in terms of number of sunspots we use the "Wolf number". This number is given per day and counts both the number of sunspots and the group of sunspots on the Sun's surface. Plotting the Wolf number in a diagram is possible to visualize the solar cycle too.

Sunspot Cycle and predictions

Could solar cycles possibly relate to activities or unusual behaviour of the Sun? Actually, astronomers have noticed that the sunspot cycle even relates with activities on the Sun, including powerful coronal mass ejections, the size and extent of the outer reaches the Sun (the corona), and the intensity of light and exciting particles the Sun discharges out into the Solar system and space. These particles then affect the magnetic fields and atmospheres of numerous planets in the solar system, specifically Earth. Northern light is a strong prove of that.

As mentioned, the Sun has cycles and right now, it is currently in cycle 24 which began on the 4th of January 2008. We call it the 24 number because the first solar sunspot activity was documented in year 1755. Since then, 24 cycles has been recognized.

How do we predict the behaviour of the sunspot cycle? Well, numerous methods are used for predicting the activities of the Sun during this event. Normally, as soon as the new cycle is started, the quantities and behaviour of spots are not that difficult to foresee. The predictions have been confirmed to be best precise about 3 years following the sunspot minimum (Hathaway et al. 1994).

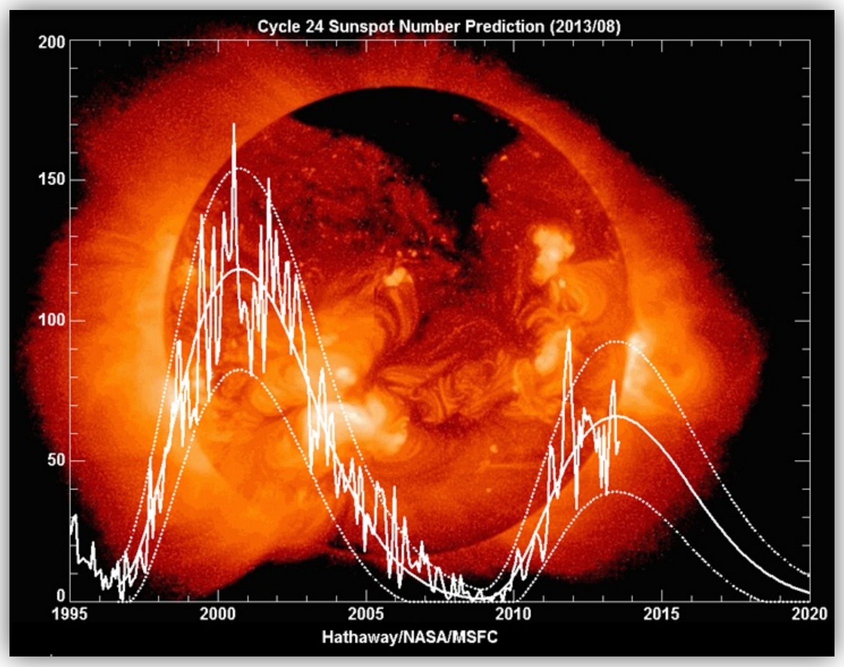

Figure 6: *The solar cycle, 1995-2015. The "noisy" curve traces measured sunspot numbers; the smoothed curves are predictions.* *Credit: D. Hathaway/NASA/MSF*

The methods for forecasting sunspot activity are generally designed around the time close to and before sunspot minimums and give emphasis to the relation between the level of activity at minimum, the size of the previous cycle and the time interval of it, all in relation to the size of the coming cycle minimum. Constructing and inferring on years of this type of modelling has permitted scientists to make exceptionally trustworthy forecasts.

Also during this time, changes in the electromagnetic field of the Earth because of solar storm are verified and compared against sunspot activity. A very reliable connection is assumed between the electromagnetic field of the Earth, solar storms and following sunspot activity, but the precise relationship is unidentified. Different methods neighbouring the geomagnetic variations that is caused by solar storms have been established to predict subsequent sunspot activity.

Besides the techniques mentioned above, also three more methods have been proven to be useful. One is to relate the connection between the number of days the Earth is affected by geomagnetic turbulences from the sunspot cycle and the amplitude of the coming maximum. The second method is to develop an index that help us conclude the value of geometric fields at sunspot minimum which the geomagnetic field correlates to during the (ensuring) minimum. And in conclusion, the third method is to create/develop a geomagnetic index which has one component in fraction and one in phase to the sunspot number, and an additional component which stays as the signal and happens as a magnetic maximum close to the sunspot minimum.

i. The Maunder Butterfly Diagram

Sunspots usually appear at the beginning of every new solar cycle and can often be seen in groups. We can conclude that groups of sunspot mostly show up in a particular belt between the heliographic latitude of 5° and 35°. There are much smaller number of groups out of these belts, and above 40° there is almost no presence of them. These sunspots have latitudes that differ with a remarkable pattern during the solar cycle. When the cycle reaches a minimum (small number of sunspots), sunspots appears even closer to the Sun's equator, and as a new cycle starts again, sunspots again appear at high altitudes (new maximum). As mentioned, a noticeable pattern occurs and we get the "butterfly" pattern, a pattern that was first discovered by Edward Maunder in 1904.

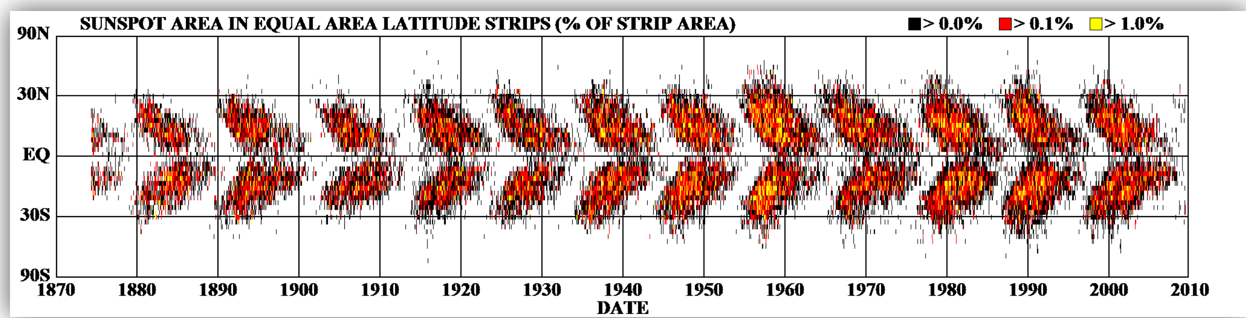

Figure 7: *The Butterfly diagram* *Credit: NASA*

He was the first person that noticed this pattern by plotting the position (latitude) of the spots versus time. The areas of the sunspots were not considered, and are still not.

A German astronomer named Samuel Schwabe, noticed in the middle of the 19th-century, that the number of visible sunspots on the disk of the Sun falls and rises in nearly regular 11-year cycle. This was concluded after many years of diligent solar observations. Now, we call this period a solar cycle.

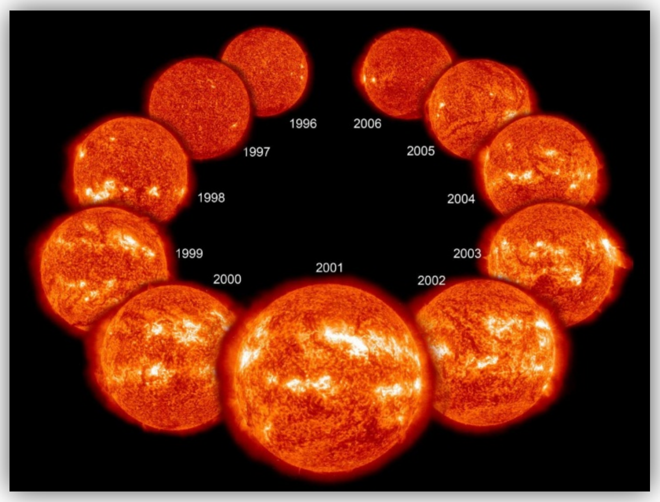

Figure 8: *This image shows a solar cycle, from 1996 to 2006. In 2001, there was a solar maxima and it is easy to see all the sunspots and active regions.* *Credit: ESA/NASA*

The magnetic poles of the Sun reverse almost every 22 years and it has two sunspot cycles that happen at 11 year intervals within each of its cycles.

This regular cycle was actually drawn back to the first telescopic observation of our Sun which happened in the 1600's, and has been documented in cumulative detail by modern astronomers right up to the current day.

ii. The Maunder Minimum

The prolonged sunspot minimum, also known as the Maunder Minimum, is the name used for the time period approximately covering the years 1645-1715 when sunspots became extremely infrequent, as documented by solar observers of the time. During this time span, North America and Europe experienced the coldest winter in many years, as it was called the little ice age. The reason why there were so few observed sunspot was not due to a lack of observations.

The name for the era originates from Edward Maunder, who first published the minimum in papers in the 1890s. It is good to know that the statistics from the period that were covered by the Maunder Minimum is not even complete. The known astronomer Galileo had merely started drawing sunspots via projection only a few years past to the beginning of the Maunder Minimum. There is also evidence that the Sun has had comparable times of inactivity far earlier.