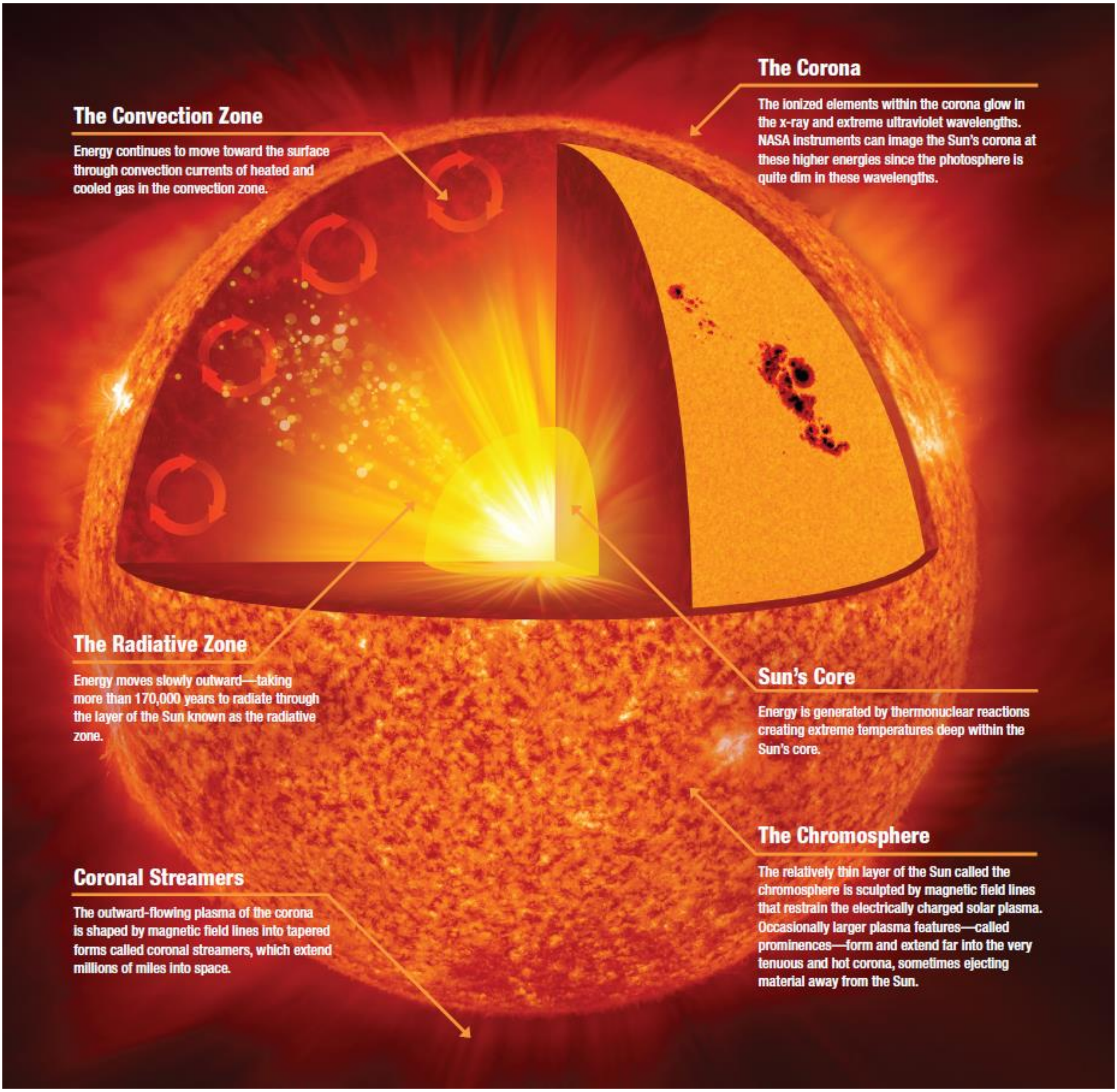
# The Structure of the Sun

## CESAR’s Booklet



**The Convection Zone**

Energy continues to move toward the surface through convection currents of heated and cooled gas in the convection zone.

**The Radiative Zone**

Energy moves slowly outward—taking more than 170,000 years to radiate through the layer of the Sun known as the radiative zone.

**Coronal Streamers**

The outward-flowing plasma of the corona is shaped by magnetic field lines into tapered forms called coronal streamers, which extend millions of miles into space.

**The Corona**

The ionized elements within the corona glow in the x-ray and extreme ultraviolet wavelengths. NASA instruments can image the Sun’s corona at these higher energies since the photosphere is quite dim in these wavelengths.

**Sun’s Core**

Energy is generated by thermonuclear reactions creating extreme temperatures deep within the Sun’s core.

**The Chromosphere**

The relatively thin layer of the Sun called the chromosphere is sculpted by magnetic field lines that restrain the electrically charged solar plasma. Occasionally larger plasma features—called prominences—form and extend far into the very tenuous and hot corona, sometimes ejecting material away from the Sun.

# How stars work

In order to have a stable star, the energy it emits must be the same as it can produce. There must be an equilibrium. The main source of energy of a star it is nuclear fusion, especially the proton-proton chain, which can transform hydrogen into Helium.

The energy generated in the core is transported outside by two main mechanisms: radiation and convection. The radiation process consists just of photons emitted by the Sun, and the convection means huge movements of material all throughout its interior, as you can see on the cover.

Scientists call this balance “**hydrostatic equilibrium**”. There are two main forces acting in a star:

- **Gravitational contraction:** it is due to the higher layers, this force pushes mass to the center.
- **Radiation pressure:** it is produced by the inner layers, and it forces material upwards.

# The different layers of the Sun

The Sun, like other stars, is a huge spherical object made of hydrogen and helium. Its diameter reaches 1.400.000 km, or 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 glowing 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.

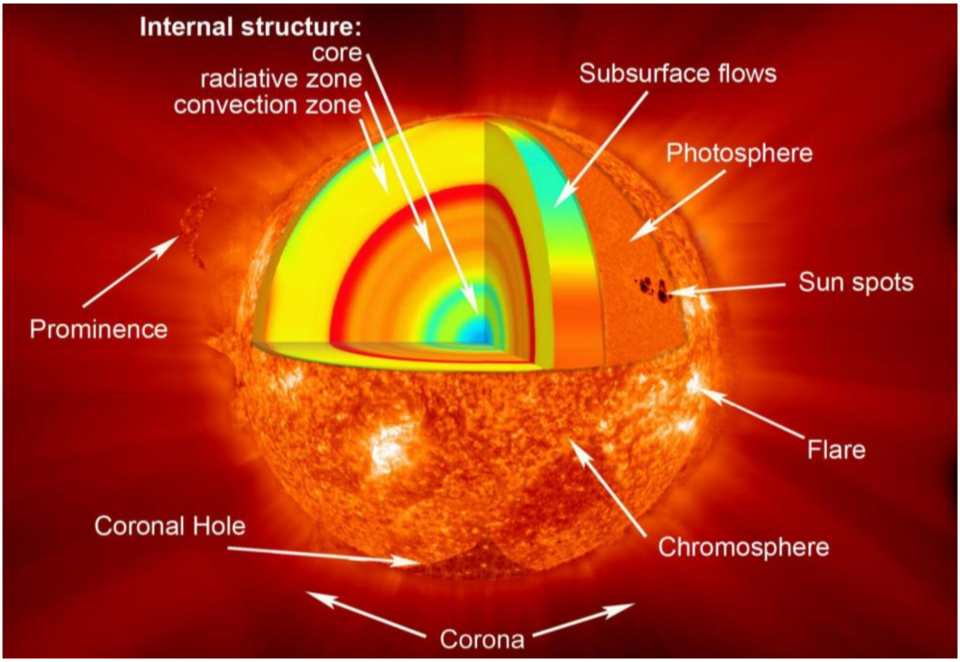


***Figure 1:*** *A slice of the Sun. The nuclear fusion reactions occur in its center* *Credit: NASA*

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

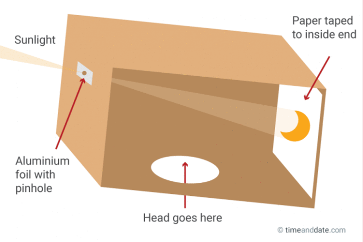
**The core:** The core of the Sun is the source of all its energy. The amount of energy produced is nearly continuous, so we do not see a considerable variation in its brightness nor the heat that is given off. The core has a very high temperature and the material it is composed of is very dense due to the extremely high pressure. It is 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.

**The Radiative zone:** The transport of energy from the Sun's core (where it is produced) to the regions that surround 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 particles 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 particles 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, wandering on an upwards path, through the radiation zone.

**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). Atoms will absorb energy much more easily at this temperature, but they do not release it so readily since their surrounding is cool and dense. Therefore, the energy transfer by radiation slows down considerably. The atoms are heated up by absorbing the and rise through the convection zone, bringing this energy (heat) towards the surface.

## Do it at home

You can build your own observatory for watching a solar eclipse at home in a safe way. You just need a cardboard box with a tiny hole in it, the Sun's light will go through it and will project inside the box.



For further information of how to build one you can visit:
https://www.timeanddate.com/eclipse/box-pinhole-projector.html

**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 sheet of paper.

**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 behind it. Furthermore it's less dense than the photosphere.

**The corona:** It is the biggest and least dense structure of the Sun and it surrounds it. Composed of plasma escaping from the Sun that reaches 1.000.000 kelvin, but with a density even lower than the chromosphere. Furthermore, the solar wind transports the material of the corona out to the interplanetary medium. From Earth, the corona is only visible during a total solar eclipse.

| Type of radiation | Temperature | Thickness of the layer | Density |
|---|---|---|---|
| **Photosphere** | 8000 – 4500 K | 500 km | ~$10^{-4}$ kg/ m$^3$ |
| **Chromosphere** | 4500 - 20000 K | 1600 km | ~$10^{-8}$ kg/ m$^3$ |
| **Transition Zone** | 20000 – $10^6$ K | 100 km | ~$10^{-10}$ kg/ m$^3$ |
| **Corona** | $10^6$ - 3x$10^6$ K | >$10^7$ km | ~$10^{-13}$ kg/ m$^3$ |

*Table 1: Temperature, density and size of every layer of the Sun* *Credit: (CESAR)*

Neither their temperature nor their composition are the same, so the solar activity on these layers is very different. These different features are:

1. **The sunspots:** When looking at the Sun through an adapted 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. This happens because the temperature of the sunspots vary from 3000 to 4500 K, meanwhile in the rest of the photosphere the temperature is usually around 5780K. Moreover, a very high concentration of magnetic field lines go outside and inside the Sun through the sunspots. Sunspots usually pop up in pairs or in groups, and they usually appear in belts to the north and south of the Sun's equator.


Active regions

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Solar Eclipse 2017 | Slide 16

European Space Agency

*Figure 2: Magnetic Field's lines of the sun visualized* *(Credit: CESAR)*

2. **The flares:** Not only the sunspots indicate the Sun's activity, also solar flares do. The Sun usually ejects material from its **chromosphere and corona.** 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 and hydrogen atoms) escape from the Sun´s gravitational field so they are free to travel through the Solar System.

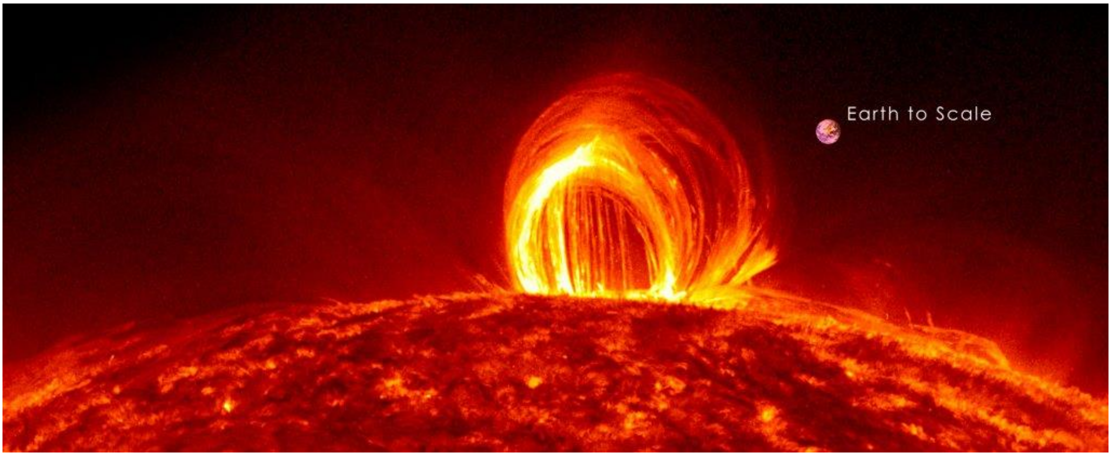

***Figure 3**: Solar "coronal rain" – some of the material released from a solar flare – falling back down to the Sun. Earth to Scale (Credit: NASA)*

3. **The prominences:** They are also called filaments, and they are formed in the **corona.** A prominence is a huge structure of gas at a very high temperature that is held up by magnetic field lines above the surface of the Sun. We often observe them with long, twisted shape.

4. **The coronal mass ejections (CMEs):** It may occur that the twisted magnetic field holding up a prominence becomes unstable and rises up very suddenly and quickly. If that occurs, the material of the prominence could be released out of the Sun, reaching a speed of 1000 km/s. This is known as a CME. They sometimes happen at the same time as flares, but where the flare releases light, a coronal mass ejection releases material. They usually last several hours, until all the twisted magnetic field lines are finally broken and rearranged. These ejections release huge amount of matter and electromagnetic energy (EM radiation) when this occurs, and if the ejection is pointed at the Earth, in 2–5 days an intense flux of particles will arrive to Earth. The CME also brings twisted magnetic field with it, which can play a little with the magnetic field of the Earth, causing aurorae and other effects.

All the phenomena mentioned are closely related to the solar cycle.

# Solar Cycle

Astronomers have noticed that the sunspot cycle relates to activity 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. The northern lights are a strong example of that.

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

Numerous methods are used for predicting the activity of the Sun (number of sunspots, especially) Normally, as soon as the new cycle is started, the quantity 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 thanks to Hathaway and his research team.

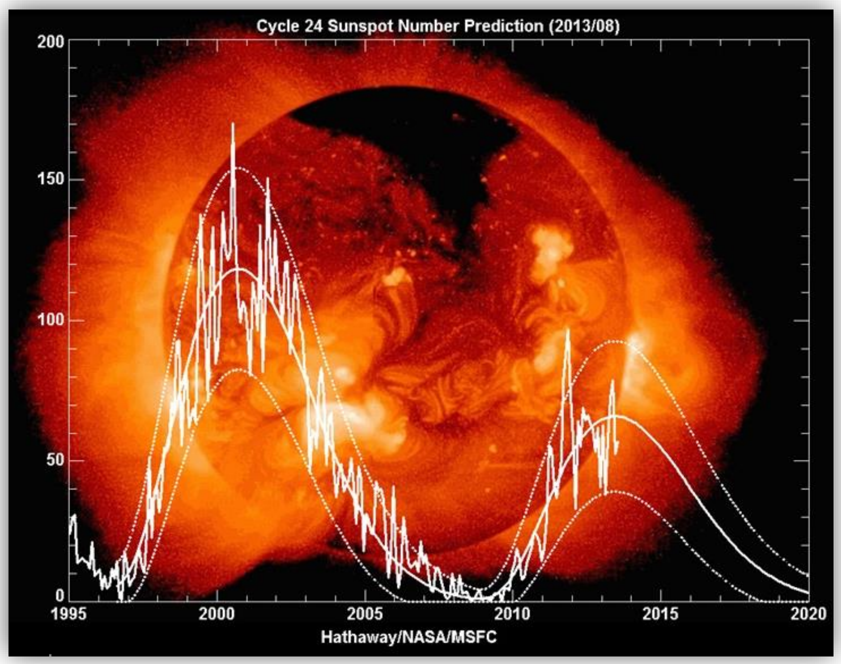

***Figure 4:*** *The solar cycle, 1995-2015. The "noisy" curve traces measured sunspot numbers; the smoothed curves are predictions.*
*Credit: D. Hathaway/NASA/MSF*

The methods for forecasting sunspot activity are generally designed around the time close to and before sunspot minima and give emphasis to the relation between the level of activity at minimum, the size of the previous cycle and the duration of it, all in relation to the size of the next cycle minimum. Constructing and inferring this type of modelling over many years has permitted scientists to make quite trustworthy forecasts of the timing of the next cycle.

Changes in the electromagnetic field of the Earth because of solar storms are verified and compared against sunspot activity. A reliable connection is assumed between sunspot activity , the magnetic field of the Earth, and resulting solar storms, but the precise relationship is unidentified. Different methods using the geomagnetic variations that is caused by solar storms have been established to predict subsequent sunspot activity.

Besides the techniques mentioned above, 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 turbulence from the sunspot cycle and the amplitude of the coming maximum.
- The second method is to develop an index that helps us conclude the value of geomagnetic fields at sunspot minimum which the geomagnetic field correlates to during the (following) minimum.
- And the third method is to create/develop a geomagnetic index which has one component in phase with the sunspot number, and an additional component which stays as the signal and happens as a magnetic maximum close to the sunspot minimum.

# How astronomers study the Sun

Astrophysicists study the Sun in very different ways, and they are complementary: they use ground-based and satellite telescopes. Every layer of the Sun is very different, and requires a distinct instrument, and as they study it in all the electromagnetic spectrum, scientists obtain as much information as possible from the Sun.

Just as we previously said we can get information from:

- Inner Sun
- Photosphere
- Chromosphere
- Corona

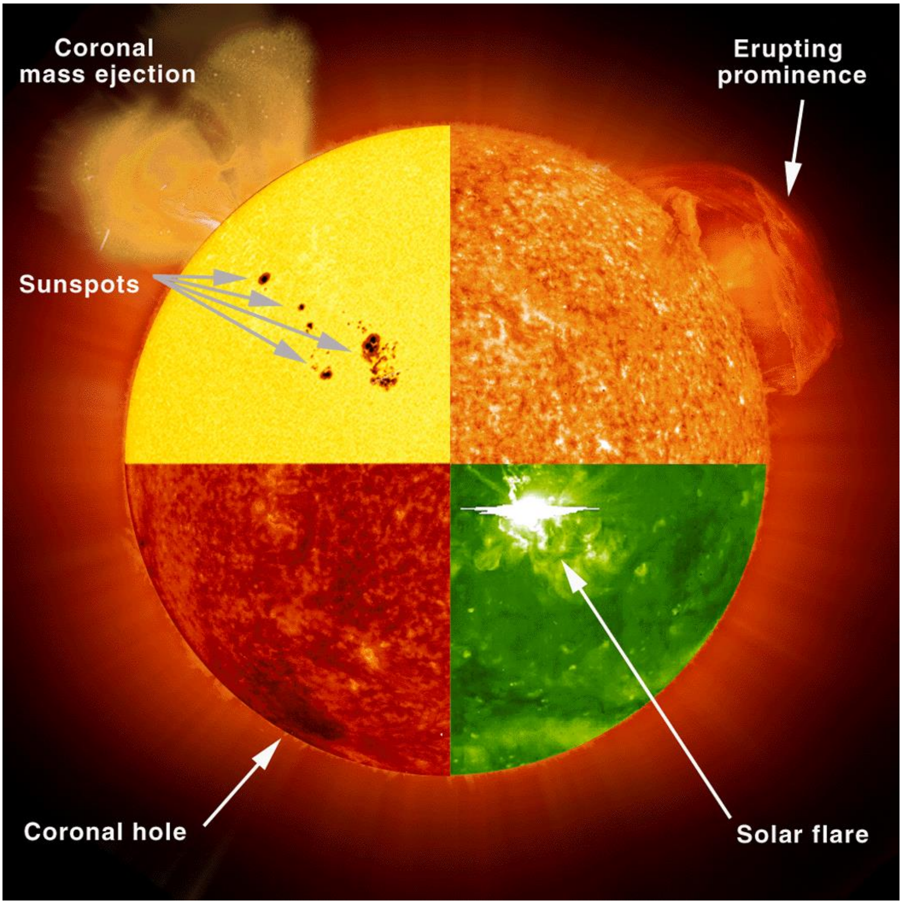

***Figure 5:*** *Different views of the Sun* *Credit: SOHO (NASA/ESA)*

## 1. Inner Sun

The core of the Sun is the most dense part of it. It is so dense that photons take more than 2000 years, following the “random walk” movement, until reaching the convection region. Scientists use helioseismology to study this part of the Sun, just as in Earth we study the interior by measuring earthquakes (seismology).

Most of the information we know about the core of the Sun has been studied with ESA’s SOHO mission. In particular with GOLF (**G**lobal **O**scillations at **L**ow **F**requencies) instrument.

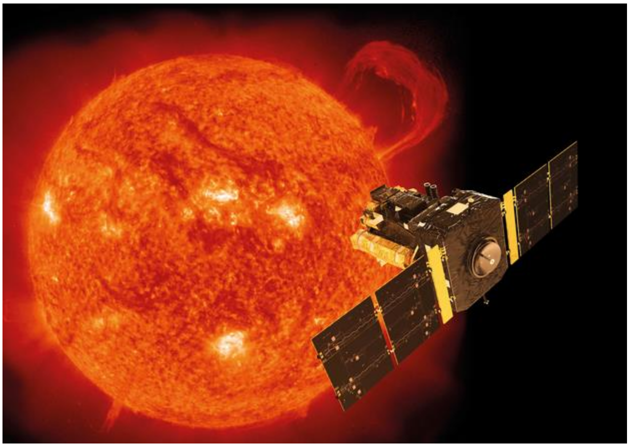

*__Figure 6:__ Artist's impression of SOHO. (Credit: ESA/ATG medialab)*

## 2. Photosphere

The photosphere is also known as the Sun’s surface, so it was the first part scientists started to study, as it can be seen even with our eyes (WARNING: ALWAYS WEAR PROTECTION WHEN LOOKING AT THE SUN). Everything that occurs in this layer is strongly responsible for what happens in the atmosphere above, so is vital to study the photosphere.

ESA also study this region of the Sun with SOHO mission, but with other instruments: MDI (**M**ichelson **D**oppler **I**mager) and VIRGO (**V**ariability of Solar **IR**radiance and **G**ravity **O**scillations) are in charge of the photosphere.

There are many ground telescopes pointing at the Sun studying the photosphere as well. For example, ESA uses the HELIOS Observatory placed on ESAC (Madrid, Spain) and fully operated by CESAR.

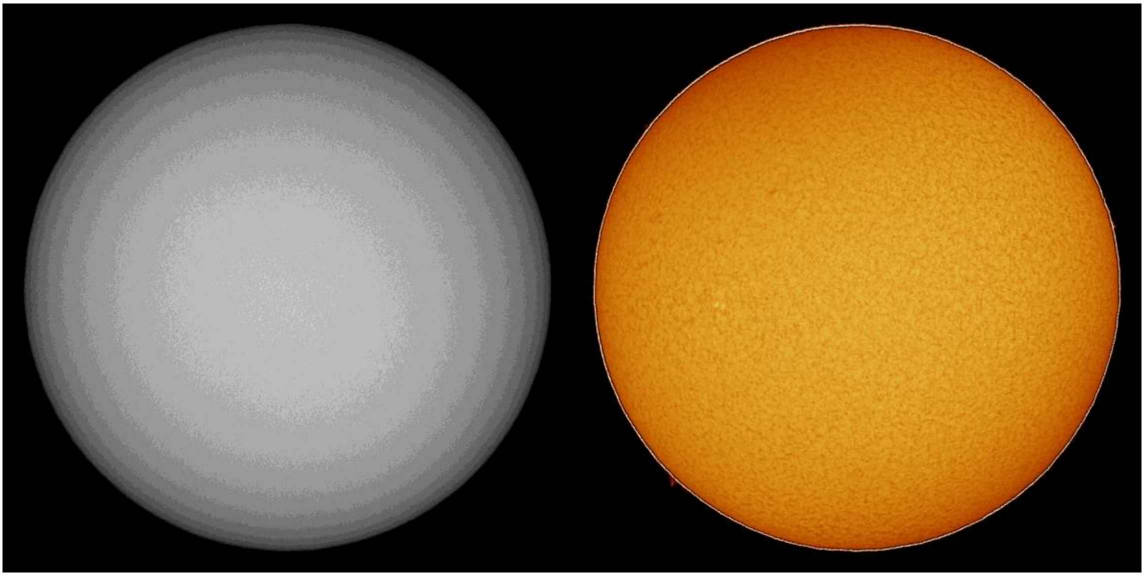

*__Figure 7:__ Sun photos from CESAR observatory, processed by Abel de Burgos (ESA/CESAR). The image on the left shows the photosphere, while the image on the right shows the chromosphere, which looks red*

## 3. Chromosphere

The chromosphere starts at the coolest point above the sun (4000 degrees), but gets much hotter (8000 degrees), so light of other wavelengths is emitted, and using special filters lets us see this light from the ground. A typical filter is one that looks at the red light emitted by hydrogen and other instruments are required. Solar physicists need instruments capable of detecting ultraviolet light. SOHO carries EIT (Extreme ultraviolet Imaging Telescope).

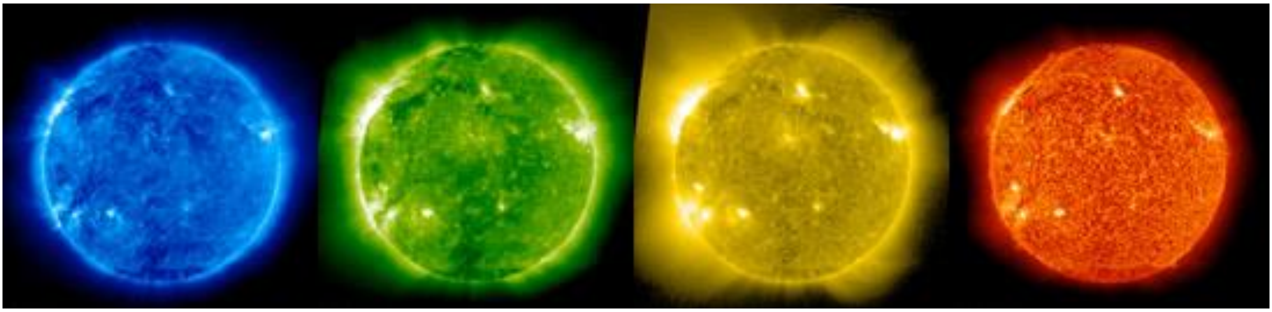

***Figure 8**: EIT images show the Sun's corona in 4 different wavelengths of ultraviolet light (Credits: ESA/NASA)*

## 4. Corona

For observing this last layer instruments capable of detecting ultraviolet and X-Ray radiations are needed. The Sun's corona can be seen in visible light, but it is 1 million times fainter than the photosphere, and still 1000 times fainter than the brightness of the sky. For this reason, Sun's light emitted from the surface need to be blocked, so that we can see the corona at all. This is why solar eclipses are the perfect opportunity for studying this phenomenon, because the photosphere is blocked and the sky is then also much darker; but we can block the surface of the sun as well with a coronagraph.

SOHO uses the EIT, CDS, UVCS and LASCO instruments for studying the corona, providing very useful and attracting images.

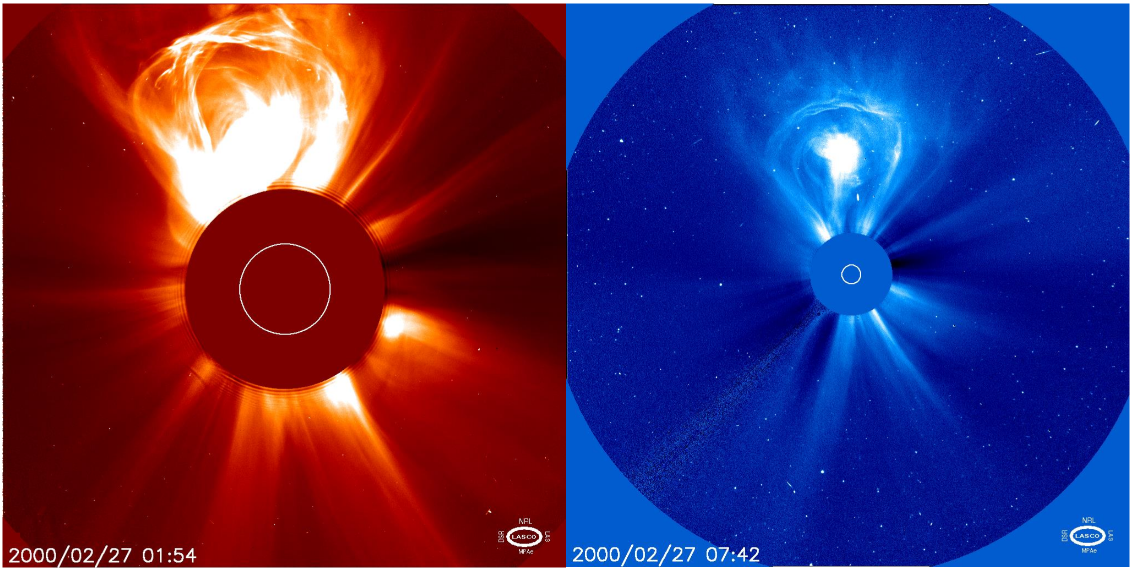

***Figure 9:** LASCO different images of the same coronal mass ejection Credit: NASA/ESA*