## THE COLLECTION





Communication Division
Head Office
91191 Gif-sur-Yvette – *www.cea.fr*

ISSN 1637-5408.


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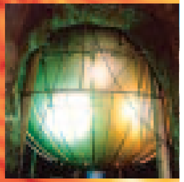
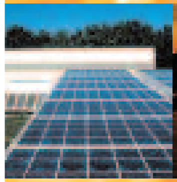
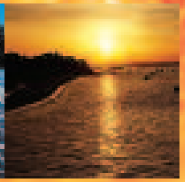
→ From the star to domestic energy

energie atomique • energies alternatives

FROM RESEARCH TO INDUSTRY

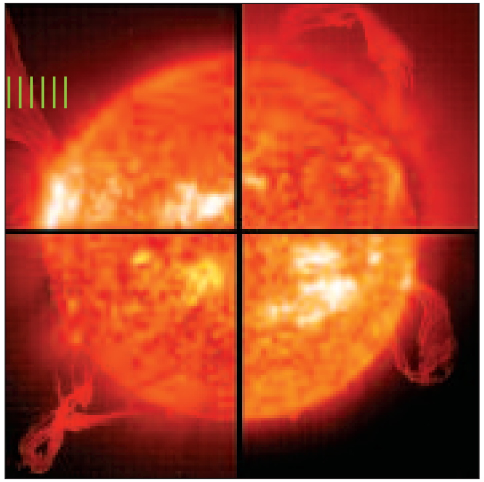
# 13 → The Sun

OUR STAR
VOYAGE TO THE CENTRE OF THE SUN
THE SUN TAMED

# The Sun





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Montage showing several views of solar flares.

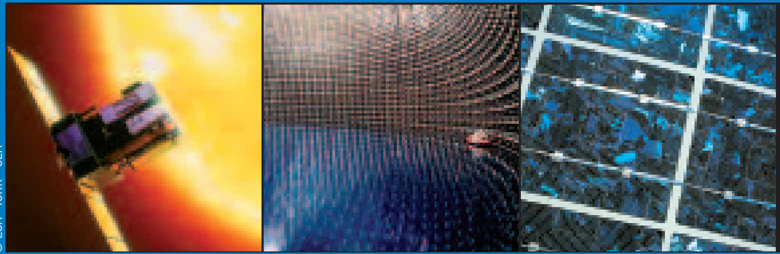
© Siemens Solar

Solar energy powers a telephone kiosk.

Design and production: Spécifique – *www.specifique.fr* – - Cover photo: © Soho (ESA/Nasa) - Illustrations: YUVANOE - Printing: Imprimerie Sénécaut - Summer 2011







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From left to right: The satellite SOHO, a neutrino detector in Japan, a photovoltaic cell.

**“For the last 4.6 million years the Sun has being providing us with light and heat. Today it is man's ambition to control this energy source.”**

Considered as a star and a deity, for a long period of time the Sun was though to be another planet, whereas the word "star" was reserved for all the brilliant points of light in the night sky. The Sun's status as a star in the sense of "an astral body producing and emitting energy" was firmly established only at the beginning of the 20th century. Today astrophysicists are revealing more and more secrets of the fusion burning region located in its core.
It is thanks to the Sun that life has appeared and evolved on Earth; it controls the cycle of the seasons and provides us with heat and light. But what exactly is the nature and origin of this prodigious energy source, with which man attempts to provide warmth and produce electricity?
What is happening in this gigantic ball of fire, impossible to observe without protective glasses? And finally, how long will it continue to shine? Questions such as these took many centuries to be solved and will continue to be the subject of research for a long time to come.

**ASTROPHYSICS HAS TAUGHT US THAT THE SUN IS A GIGANTIC NUCLEAR REACTOR.**

# Our star

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## A STAR IS BORN

The Sun is a star; an enormous ball of hot gas which produces and radiates energy. The Sun is the closest star to the Earth (150 millions kilometers). It is one of the billions of stars which make up our galaxy, the Milky Way, which is several light-years away. In spite of the fact that it has a radius of 700,000 kilometers, (more than 100 times the radius of the Earth) and a mass 330,000 times greater than that of the Earth (2 billion billion billion tons!), the Sun is a relatively small star: for example, the radius of Betelgeuse, in the constellation of Orion, is 1,100 times greater than that of the Sun.

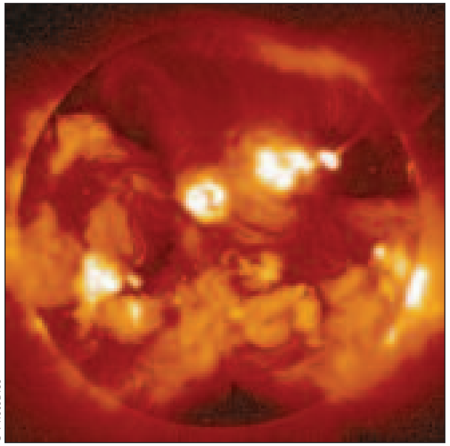
An astronomical unit of length, corresponding to the distance travelled by light in vacuum during one year. The speed of light in vacuum is 300,000 kilometers per second and the light emitted by the Sun requires only eight minutes to reach our planet, whereas light from the next nearest star to us, Proxima Centauri (a distance of 4.2 light-years from the Earth), takes more than four years.

But how was our star born?

The Sun was born 4.6 billion years ago, out of a gigantic interstellar cloud composed of hydrogen, helium with less than 2% of heavier elements. This cloud fragmented to give, among other celestial objects, a star surrounded by planets, comets and dust: the solar system. The Sun has been the subject of many studies in a scientific discipline known as astrophysics, where the fields of astronomy and physics (see the leaflet from this collection entitled "Nuclear Astrophysics").

This science helps us to understand the phenomena occurring in the Universe. Hence, we know that the Sun is in an enormous condensation of gases: why doesn't this hot gas disperse into the inter-planetary vacuum? Its cohesion results from the gravitational attraction which exists between particles of matter and tends to bring them closer together. Therefore, a star is a self gravitating body, with a spherical shape imposed by its own gravity.

But if gravity tends to bring particles closer together, why doesn't the Sun simply collapse in on itself? We need also to consider the stellar gas pressure, which is the result of incessant collision and rebounding of the particles with each other. Overall, this pressure balances the action of gravity. If this pressure was suddenly removed, the Sun would completely collapse in on itself in just three minutes!



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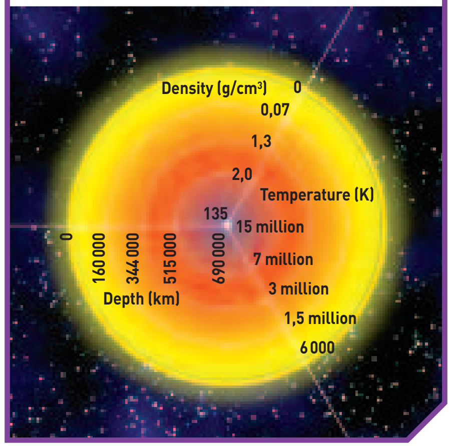
"The temperature imbalance within the Sun creates radiation."

> **“The temperature imbalance within the Sun creates radiation.”**

## WHAT CAUSES THE SUN TO SHINE?

It is well known that a compressed gas warms up: you only need to rapidly inflate a bicycle tire and then touch the end of the pump to realize this. Stellar material therefore becomes hotter the deeper we go into the Sun, since it is compressed by the mass of the layers which weigh down on it from above, acting rather like a piston. Hence, the closer we get to the core of a star, the higher the pressure and the hotter it becomes: the pressure at the core of the Sun is 200 billion times atmospheric pressure on the surface of the Earth and the core temperature is around 15 million degrees. With a surface temperature close to 6,000 °C, the Sun is subject to a large temperature difference arising from its own gravity. This temperature imbalance gives rise to a heat transfer which, flowing primarily from the hot region to the cold region, tries to make the temperatures more uniform. When it finally arrives at the surface, this flow of thermal energy escapes in the form of radiation which is then dispersed into interplanetary space: the Sun shines!

**Temperatures and densities within the Sun**




## WHAT TYPE OF ENERGY!

The radiated energy must be coming from somewhere: indeed "*Nothing is created or destroyed, it is all transformed*", as the great chemist, Antoine de Lavoisier (1743-1794), said 200 years ago. This assertion applies to **thermodynamics**.

> **thermodynamics:** The branch of physics which studies the phenomena involved in heat exchange.

How then, does the Sun maintain its heat generation? Indeed, if it were simply passively emitting its heat in the form of radiated energy, it would cool down inexorably and then die out. However, its longevity proves that it must have a way of replacing this lost energy; these days we know how this is achieved.

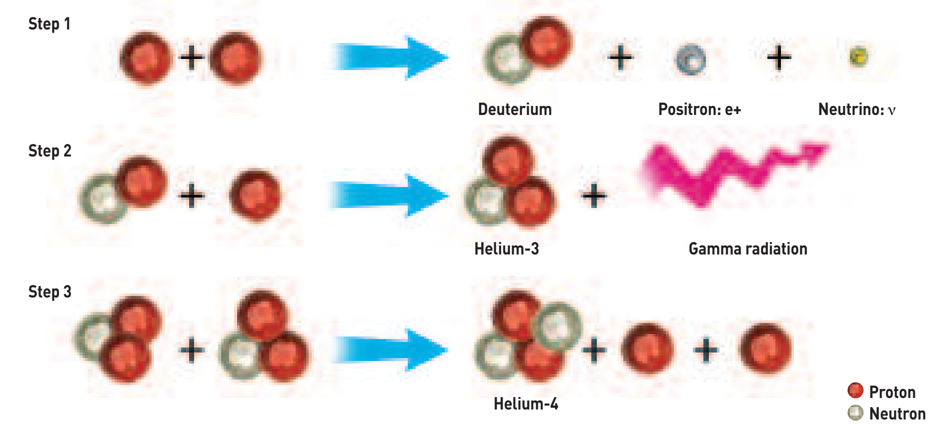
In 1921, the physicist **Jean Perrin** provided an explanation by proposing that nuclear reactions were the source of energy production, i.e. reactions between atomic nuclei.

> **Jean Perrin:** Jean Perrin (1870-1942) was one of the pioneers of atomic theory and obtained the Nobel Prize for physics in 1926 for his work on the structure of matter.





**The transformation of hydrogen into helium in the Sun**




Like any other star, the Sun is a gigantic nuclear reactor. Nuclear fusion reactions transformed hydrogen into helium in its core, releasing energy. The temperature at the center of the Sun is fifteen million degrees and the density is one hundred and fifty times that of water (150 g/cm³).

The transformation of hydrogen into helium is complex; the following are the most common steps:

- Step one: two protons interact to form a deuterium nucleus. During this process, one proton is changed into a neutron by emitting a positron (or positively charged electron) and a neutrino, a particle from the same family as the electron, which carries energy but has an unknown, very low mass.
- Step two: one deuterium nucleus combines with a proton to form helium-3, releasing energy in the form of a gamma ray (or photon).
- Step three: two helium-3 nuclei combine to form helium-4 by ejecting two protons.

This idea was proposed again and developed several years later by the German, Hans Bethe, who explicitly described the nuclear reactions produced in the core of the Sun. This physicist showed that, during the major part of its life, a star draws on its nuclear reserves to compensate for its constant loss of energy.

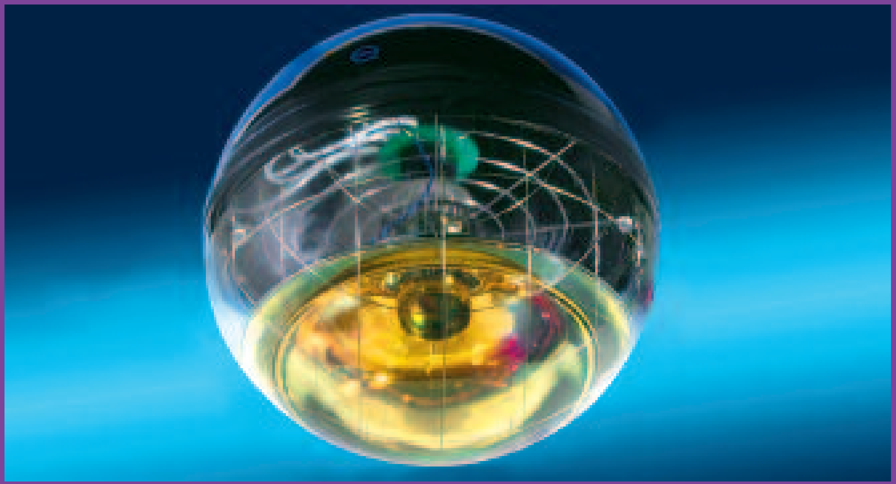
In the densest and hottest central regions of the Sun, **fusion** reactions transform four hydrogen nuclei (protons) into a helium nucleus, $^{4}He$, an element which is particularly stable, and release energy which compensates for that lost at the Sun's surface. This energy is emitted and transported in the form of photons (massless fundamental particles with no electric charge) and neutrinos (very low mass particles with no charge).

> **fusion:** Nuclear reactions in which two lighter nuclei combine to form one heavier nucleus. Such reactions are accompanied by a large energy release.

## THE SUN, A SELF-REGULATING NUCLEAR FUSION REACTOR

A fusion reaction releases energy because the mass of the nucleus produced is less than the sum of the masses of the initial nuclei. This mass difference is transformed into energy according to Einstein's famous equation, $E = \Delta m \times c^2$. These reactions cannot take place unless the temperature and pressure are suf-

> **$E = \Delta m \times c^2$:** The energy produced is equal to the mass difference multiplied by the speed of light squared.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Optical module from the Antares neutrino detector.

## NEUTRINOS

The core of the Sun is the region where hydrogen is transformed to helium by nuclear fusion reactions. The process also produces ghostly particles called neutrinos. At the central part of our star, the temperature is sufficiently high to ignite fusion reactions between pairs of protons, the first step of a nuclear chain reaction which leads to the formation of helium. This reaction produces a deuterium nucleus (a hydrogen isotope), a positron, the positive alter-ego of the negatively charged electron, and of course energy. In 1930, the American physicist, Wolfgang Pauli (born in Austria in 1900 - dead in Switzerland in 1958), in order to save the principle of conservation of energy, suggested the need for an additional, unobserved particle with an assumed zero mass. A Japanese team provided the experimental proof of the existence of the neutrino mass in 1998; this discovery, a foundation stone in the edifice of particle physics, brought its author, Masatishi Koshiba, the Nobel Prize for physics in 2002. Having no electrical charge and an almost zero mass (less than 10 to the power of -33 grams), the neutrino interacts only very weakly with matter. Every second, 65 billion neutrinos strike each square centimeter of the Earth's surface and almost none are stopped! This is why large scale detectors have been constructed, and installed in mines (such as that at Sudbury in Canada), underwater (the Antares project in the Mediterranean Sea) and even in a tunnel (Gran Sasso, under Mont-Blanc), to shield them from other types of cosmic radiation. A thick covering of earth or water acts like a sieve, only allowing the most penetrating particles to pass through. Scientifically these experiments have been impressive. They have allowed observation of neutrinos emitted from the supernova which appeared in the Large Magellanic Cloud in 1987 and it was possible to follow this remote explosion (170,000 years later!) using the Hubble space telescope.





ficiently high that the two protons, stripped of their electron and thus positively charged, fuse. This limits their field of action to the regions closest to the core of a star like the Sun. The stars must also have sufficient mass, greater than one tenth of the Sun's mass, to compress the core sufficiently and ignite the nuclear reactions. In the core of the Sun, 620 million tonnes of hydrogen are transformed into 615.7 million tonnes of helium every second; the difference is converted into energy which radiates towards the outside. This nuclear energy reserve enables us to calculate the lifespan of the Sun as being around 10 billion years. Furthermore, thanks to measurements of radioactivity in terrestrial rocks, we know that our planet, and hence the Sun, are 4.6 billion years old. The Sun will shine, therefore, for another 5 billion years!

Finally, we note that these fusion reactions are self regulating. We know that the Sun, like all other stars, is: a nuclear reactor operating in the fusion mode.

Here on earth, man is attempting to master fusion reactions, to exploit this fantastic energy source. Currently two types of processes are being studied in the laboratory.

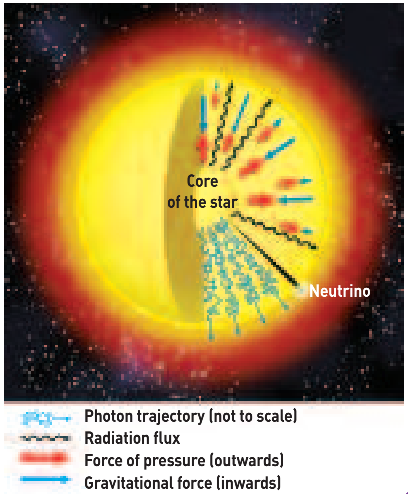
- At low concentrations, fusion gas mixtures are contained by immaterial walls created by magnetic fields: this is the subject that will be investigated by the future international experimental reactor ITER.

*International Thermonuclear Experimental Reactor.*

- At higher concentrations, the fusion reaction can be ignited by irradiation with very high power laser beams: this subject will be studied by the Megajoule laser which is under construction at the CEA Cesta centre near Bordeaux, as well as at the LIL prototype which is already in operation. This laser, assisted by the very short impulse laser, Petal, will produce plasmas similar to solar plasma but in very small volumes and will enable certain cosmic processes to be studied in the laboratory.

We have seen that the Sun radiates energy: the earth only receives an extremely small part

### Internal structure of the Sun



## “Helioseismology studies the surface oscillations of the Sun and allows us to probe the interior of our star.”

of this which, nevertheless, amounts to 178 million billion watts! Thermonuclear fusion, the process generating this energy, compensates for the loss of energy at the surface and allows the Sun to burn sustainably; contraction causes an increase in heating providing the energy to remain in balance from its gravitational capital. In reality, these two phenomena are linked: since the nuclear resources are limited, gravitational contraction of the core will begin as they become exhausted. The resulting compression and heating will make it possible to start a new fusion cycle which burns the "ashes" of the present cycle at a higher temperature. This is what happens in stars more massive than the Sun: hydrogen transforms into helium until it is exhausted, then the helium, in its turn, becomes the fuel. It will be transformed into carbon. Following these processes, known as "nucleosynthesis", a series of elements - carbon, neon, oxygen, silicon – is created, until finally iron is obtained.

We have seen that electromagnetic radiation is emitted from the surface of the Sun and that this radiation takes eight minutes to arrive at the Earth. But, owing to the extreme density of the Sun, the light which is emitted by the core, takes several million years to reach the surface and escape into the sidereal vacuum; it has therefore lost all information concerning its origins in the core of the star.

This is the reason that astrophysicists prefer to study solar acoustic waves, which have the same characteristics as seismic waves and carry information on the internal structure of the star.

These waves propagate from the surface to the core and require only one hour for this whole travel, this providing almost live information on the internal microscopic and macroscopic properties of the Sun. These waves generate period motions at the Sun's surface and their study has given birth to a new discipline which allows us to probe the interior of our star: helioseismology.

© CEA

### THE GOLF INSTRUMENT

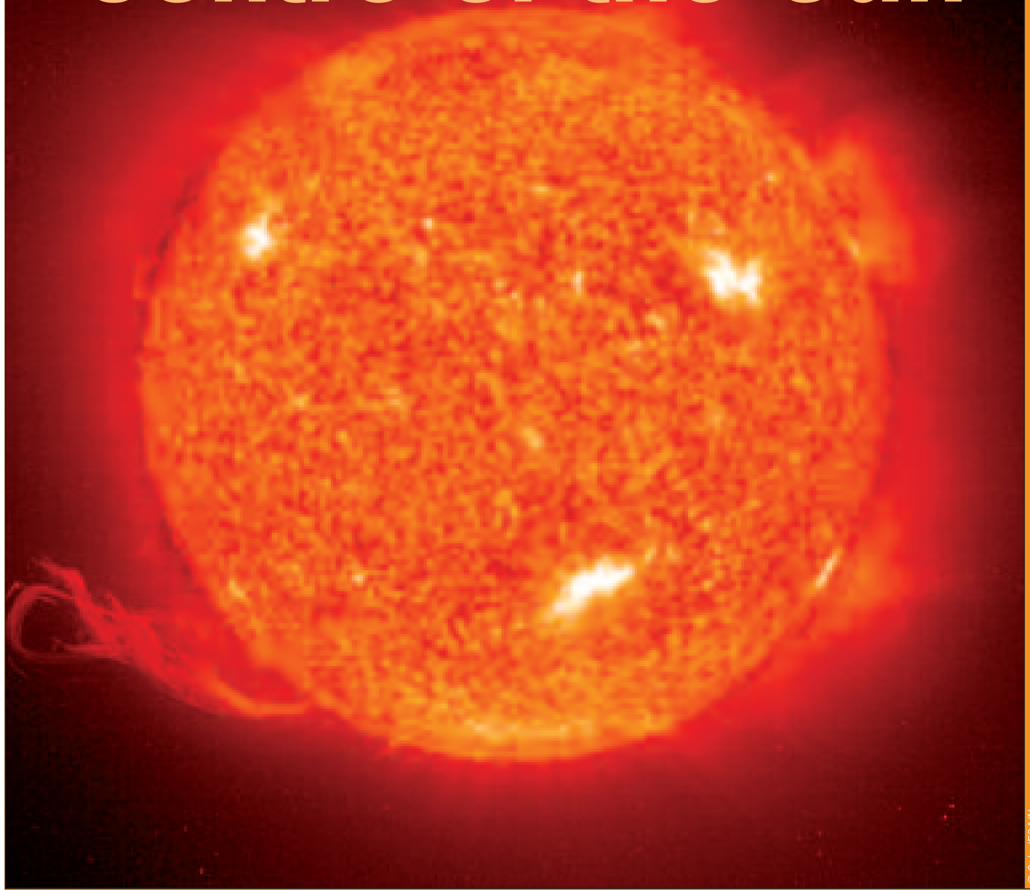
**The CEA made a large contribution to the production of the GOLF detector (Global Oscillations at Low Frequencies), an helioseismology instrument on board the SOHO satellite. With this tool, it is possible to make detailed studies of the internal structure of the Sun using global acoustic wave measurements; These data have led to determination of the sound speed profile from the surface to the core, where the nuclear reactions occur, and to the theoretical predictions of the solar neutrino fluxes.**





**PROMINENCES AND FILAMENTS, FLARES, EJECTIONS, GRANULES, SPOTS, FASTEN YOUR SEAT BELTS...**

# Voyage to the centre of the Sun



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# Solar topography: the opaque part

Today, it is possible to determine the fraction which is opaque to light by calculation or seismology.

It includes:
– **A zone, called "radiative"**, with includes the core where nuclear reactions transform hydrogen ions into helium; the core and radiative zone represent 98% of the mass of the Sun;
– **a zone, closer to the surface, which is called "convective"**.

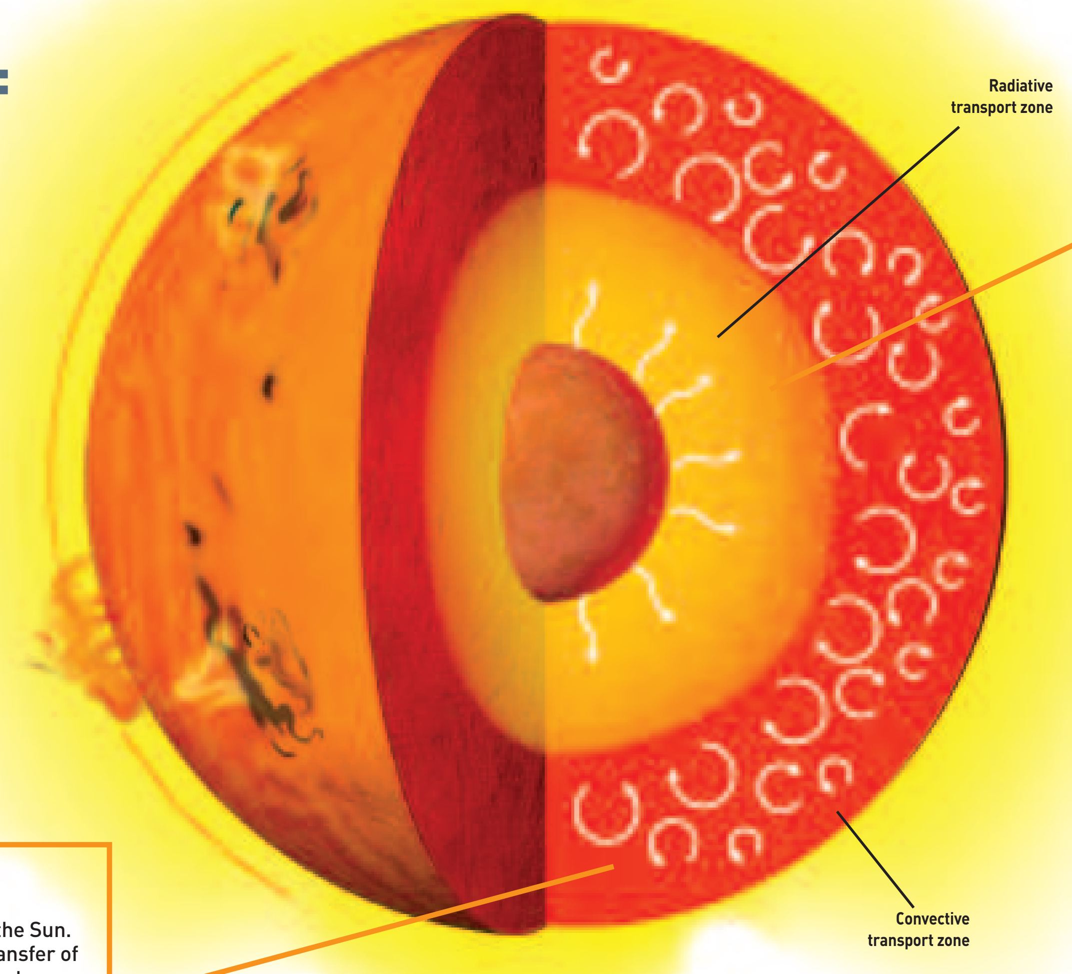
The names of these zones are linked to the mode of transport of the energy produced in the central part and then carried to the exterior of the Sun. Transport is either by radiation (propagating in the form of electromagnetic waves) or by convection (electric heater principle: heating causes the motion of particles, and this moving matter transports heat).

**CONVECTIVE ZONE:**
**from 480,000 to 690,000 km**
This zone represents 2% of the mass of the Sun. Turbulent plasma movements ensure transfer of energy towards the outside. Bubbles of hot matter rise, cool down and then descend back. This convective transport is analogous to that observed in a saucepan of hot water. These movements cause the granulation observed on the photosphere (see p. 14).





## "The Sun is divided into two zones: the opaque part and the visible part."




**RADIATIVE ZONE:**
**from 0 to 480,000 km**
Internal part of the Sun including the core.

**THE CORE OF THE SUN:**
**from 0 to 210,000 km**
It represents 50% of the mass of the Sun. This is the region where nuclear fusion reactions take place. The temperature is 15 million degrees at the centre, dropping from the center to the extenal layers. When the plasma (see p.17) reaches 7 million degrees, there is insufficient heat to support fusion reactions.

In this zone, energy is transported by radiation. There are numerous interactions between photons and the various elements present. It results also absorption-reemission phenomena which slow down and degradate their energy.
Photons diffusion times are very long, on the order of a million years, whereas the light emitted from the surface takes only eight minutes to reach the Earth. The temperature at its frontier is 2 million degrees.

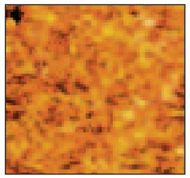
# The visible part

This part of the Sun is directly observable. It consists of the **photosphere** (boundary with the opaque zone), **chromosphere** and the **corona**. These latter two are only visible during total eclipses (natural or man-made) of the Sun.

### THE PHOTOSPHERE

The photosphere contributes 99% of solar radiation. The surface, several hundred kilometers thick, is a virtual boundary between the interior of the Sun (the radiative zone including the core and the convective zone) and its atmosphere (chromosphere and corona). Its temperature is around 6,000 °C.

### Granules



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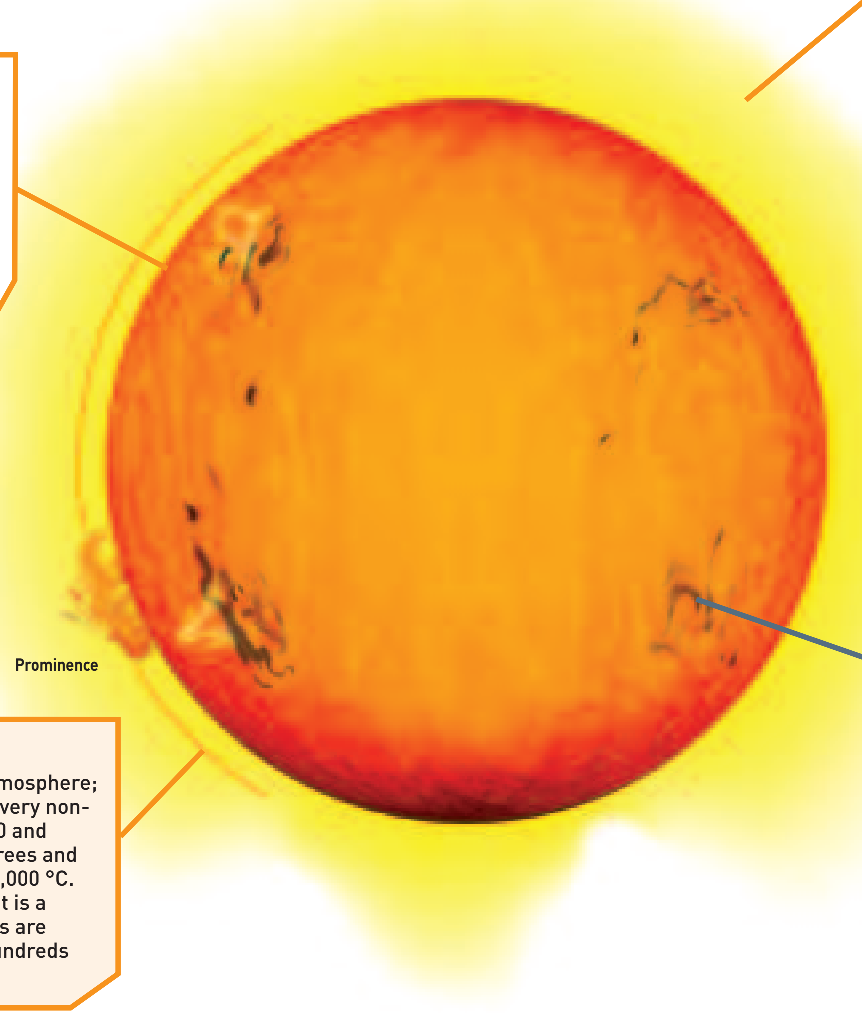
Observation of the photosphere shows granules whose centers are more brilliant than their circumference. These zones, with a diameter of around 1,000 km, have an individual surface area comparable to that of France. Their lifespan is several minutes. This granular structure reflects the motions of the hot material which is bubbling in the convective zone; the darker edges of the granules correspond to cooled matter. These are the descending streams which produce the acoustic waves which penetrate down to the core of the Sun.

### TRANSITION ZONE

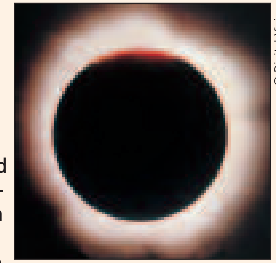
Between the chromosphere and the corona, there is a transition zone, exhibiting an abrupt rise in temperature of up to 1 million degrees towards the exterior. This temperature rise is linked to magnetic field effects. These complex mechanisms are being studied, today, using many satellites, including SOHO.




### THE CHROMOSPHERE

The chromosphere is the lower part of the solar atmosphere; it contributes only slightly to solar radiation. It is a very non-uniform layer with a mean thickness between 2,000 and 3,000 km. Its temperature is several thousand degrees and increases towards the exterior where it reaches 20,000 °C. It is visible for short periods during total eclipses. It is a theatre of intense activity. It is here that solar flares are born. These violent phenomena can spread over hundreds of thousands of kilometers in several minutes.

### THE CORONA



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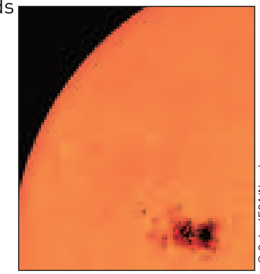
The corona is the outermost layer of the solar atmosphere. It has a temperature of around 1 million degrees and its density is 100 million times lower than that of the Earth. It extends to a distance of several solar radii and blends into the interplanetary medium. The photosphere is so brilliant that it prevents the corona being observed, except during total eclipses of the Sun. At other times, coronagraphs must be used, devices which screen the light from the disk of the photosphere.

### Sunspots

Seen as wide dark areas, sunspots may be up to several hundred thousand kilometers in diameter. They appear and disappear in groups and return regularly, with a period of around 11 years. Their observation makes it possible to measure the superficial rotation of the Sun; this fact allowed Galileo to discover, in 1613, that the Sun rotated on its own axis. Today, we know that sunspots correspond to areas which are the seat of magnetic fields several thousand times larger than the Earth's magnetic field. These magnetic fields decelerate the motion of charged particles, the temperature drops (4,000 °C) and the area becomes darker. The diversion of particles by these fields, associated with the creation of local magnetic fields, leads to extremely violent motions of solar material.

**This cycle is today known as the solar cycle and is linked to solar magnetism, the polarity of which inverts every 11 years.**



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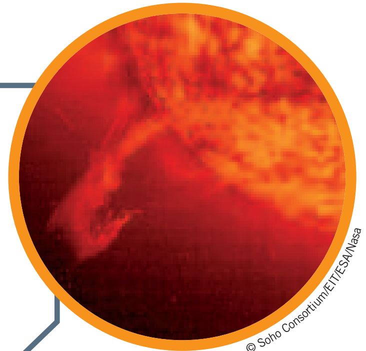
### Prominences and filaments

Prominences or filaments are dense, cold pockets of plasma (10,000 degrees nevertheless!) in the hot, dilute solar corona. These gases, which are mostly hydrogen, leave the surface in the form of columns which stretch out into space or which return to the surface of the Sun, forming loops. An intense magnetic field lifts the dense matter and brakes its motion, leading to cooling. Prominences can rise to altitudes of several hundred thousand kilometers.



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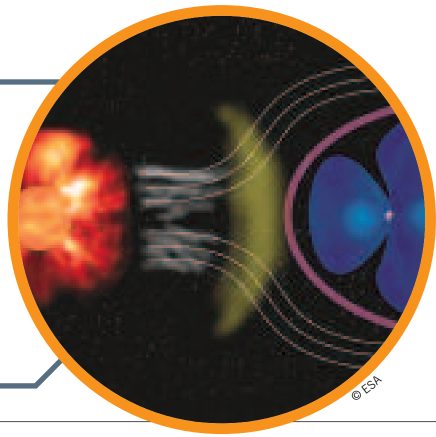
### IN THE CORONA AND BEYOND: THE FURIES OF THE SUN

**In the upper, low-density layers of the solar atmosphere, charged particles (ions and electrons) are sensitive to electromagnetic forces. These forces may be stronger than gravity and can keep the matter in altitude, or even eject it out of the corona, sending it off into interplanetary space. The corona can therefore presents very varied aspects, resulting from the magnetic activity of the Sun: prominences, solar flares or coronal holes.**

### Solar wind

Beyond a certain distance, gravitational forces are insufficient to hold on to the matter. This matter escapes along the magnetic field lines into interplanetary space. This is the solar wind. Its mean velocity is around 400 km/s. It is more rapid near the poles of the star than it is at the equator.



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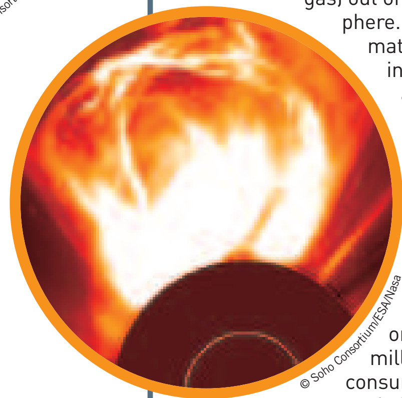
### Solar flares or coronal mass ejections

Solar flares or coronal mass ejections occur when the magnetic fields are sufficiently strong to overcome gravitational attraction and eject the matter (plasma and neutral gas) out of the solar atmosphere. Billions of tons of matter are transported in this way. The flares are characterized by an abrupt release of an enormous quantity of energy in the form of radiation (visible, UV, X-ray and radio waves). The energy brought into play is considerable, on the order of several million times the annual consumption of electrical energy in France.



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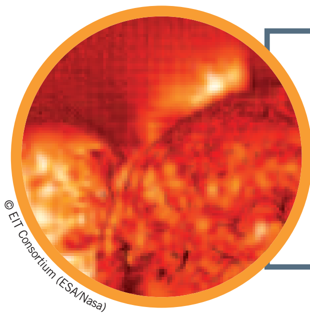
### Coronal holes

Coronal holes are less luminous, cooler regions, where the magnetic field enables matter to escape. In these regions, the magnetic field lines do not return to the Sun but project radially away from the Sun.



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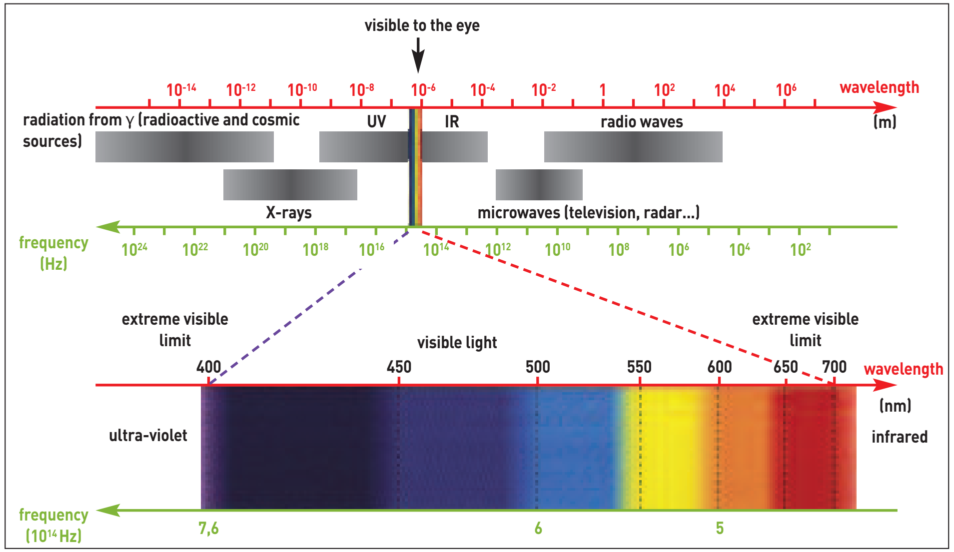
Under the conditions of temperature and pressure found on the earth, matter is present in three states: solid, liquid and gaseous. Passage from one state to another corresponds to a reorganization of the molecules or atoms in the matter. Take water as an example: in the solid state, as ice, water has a very organized structure, in which the molecules are strongly bound to each other. Following application of heat, the molecules become agitated and move away from each other and the water moves into the liquid phase. At higher temperatures still, the structure becomes completely disorganized and the water molecules scatter in the form of a gas; this is boiling.

## THE SOLAR PLASMA

Under conditions of extreme pressure and temperature a new state of matter appears in which the atomic structure itself becomes totally disorganized: a plasma. At the core of a star a great agitation reigns among the atoms. These atoms normally exist as a nucleus, which itself is made up of neutrons (with and neutral electric charge) and protons (with positive electric charge), accompanied by a stream of electrons (with negative electric charge). Overall, the atom is electrically neutral: it contains as many electrons as protons. At very high temperatures, the atom can lose or gain one or more electrons, thus becoming a positively or negatively charged ion, respectively.

**This word first appeared in the 1920s in the work of the American Irving Langley, Nobel Prize winner for chemistry in 1932, on ionized gases. Today the plasma is present in our daily lives with plasma television screens, plasma torches and neon tubes.**




**Electromagnetic waves divided into various frequency and wavelength families. The distribution of energy from radiation is called the electromagnetic spectrum and extends, in decreasing wavelength order, from low frequency radio waves to gamma rays, passing through the microwave region, the infrared, visible and ultraviolet, and X-ray regions.**

In the core of the Sun, the energy is sufficiently high to strip the electrons from the hydrogen atoms, which normally consist of one proton and one electron. Hence, the hydrogen atoms become positively charged ions called protons. Stellar gas is in the form of dense plasma, made up of ionized atoms. Almost all of the mass of the galaxy is found in the form of plasma.

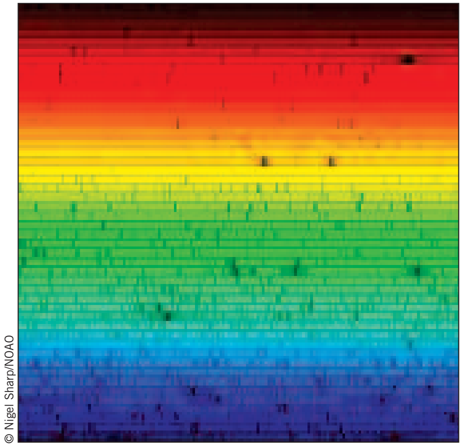
From the core to the periphery, the solar plasma contains elements in various states of ionization, depending on their temperature and density. These variations stratify the Sun into several layers with very different behaviors. Various theoretical and experimental methods make it possible to study the Sun, its composition, structure and properties.

## AN IDENTITY CARD FOR THE SUN

For a long time, information about the Sun could only be gained from its light. We know from the work of Isaac Newton (1642-1727) that light which appears to us as white is in fact made up of all colors, or "of all wavelengths" as physicists would say. One just has to look at a rainbow, or to observe a light source through a prism, to be convinced of this. Two centuries later, spectroscopy would be born from this discovery (see illustration above): the rainbow, "the scarf of Iris" according to the poets, is also a solar spectrum for physicists! The tungsten filament in a light bulb is a good example of a body which, at high temperature, emits visible light over a broad range of wavelengths: it provides an emission spectra consisting of a wide continuous band of frequencies. In 1814, the German physicist Joseph von Fraunhofer (1787-1826), the founder of spectroscopy, studied the spectrum from the Sun and discovered the presence of dark bands superimposed on the continuous spectrum, each corresponding to a specific wavelength. At the time, he didn't have the means to interpret this curious phenomenon. Later physicists noticed that when a gas is illuminated by white light source, it will absorb certain colors. The appearance of dark lines superimposed on the electromagnetic spectrum is the manifestation of this absorption: it is providing an absorption spectrum.








**The solar spectrum exhibits dark bands superimposed on a continuous spectrum.**

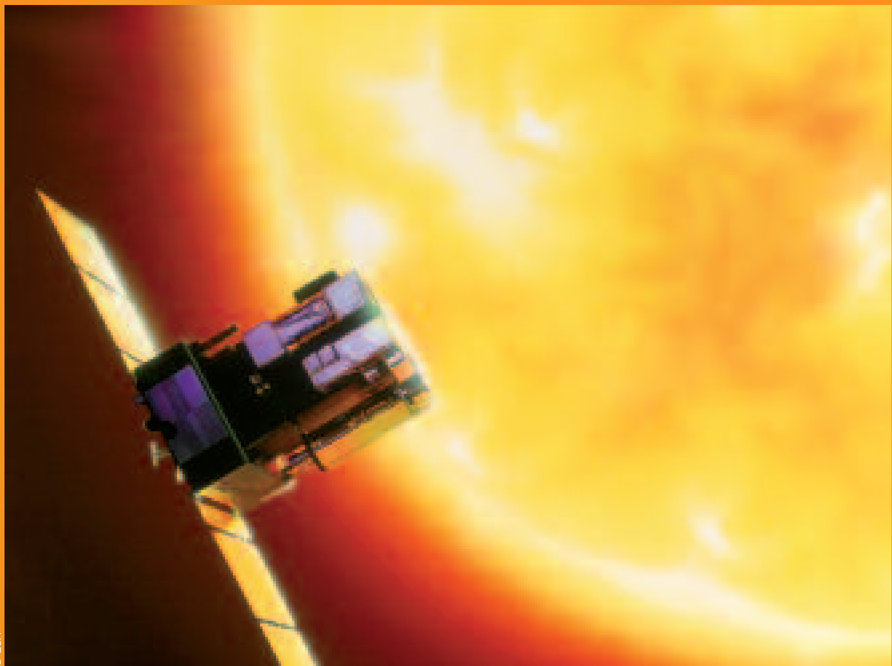
How is this phenomenon explained? Very simply by the fact that the intensity of radiation decreases as it crosses a material environment to which it transfers part of its energy. However, an emission or absorption of energy results in a modification in the electronic structure of the atoms concerned; this gives rise to a spectral signature which is characteristic of a given element. To put this another way, the spectrum is a chemical identity card of the material being studied. Hence, the French astronomer Jules Janssen (1824-1907) discovered, by spectroscopy, an element that was unknown at that time on Earth, helium, whose name is derived from the Greek word "Helios" referring to the Sun.

From all the wavelengths of radiation emitted by the Sun, the terrestrial atmosphere only allows visible light to pass (with a small amount of infrared and UV) together with radio waves. It is therefore necessary to go beyond the terrestrial atmosphere to measure other wavelengths of radiation (in particular X-rays and gamma rays). We can use instruments on board satellites such as SOHO.

Production of light and heat is not the only manifestation of the Sun: to these must be added periodic vibration which can reveal internal rotation and magnetism.

## HOW DOES THIS WORK?

In 1960, regular, low amplitude motions of the solar surface were discovered. Ten years later, theoretical work showed that in reality these





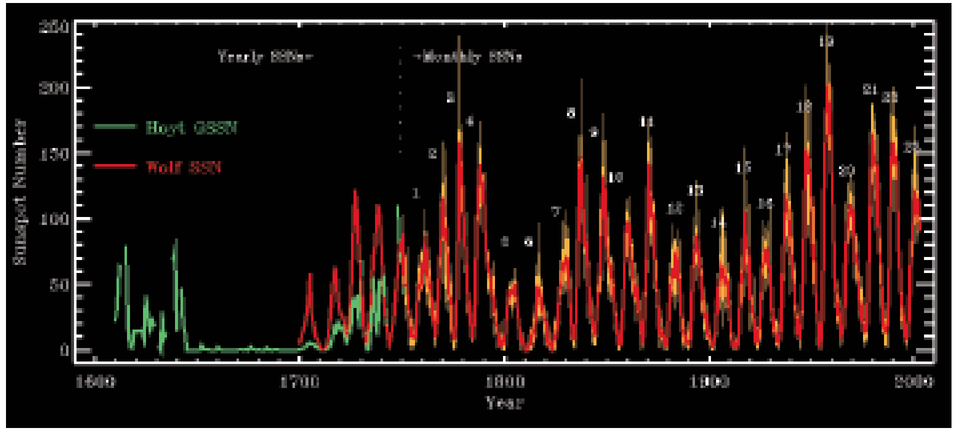
The SOHO satellite near to the Sun.

## THE SOHO SATELLITE

SOHO (Solar and Heliospheric Observatory) is the fruit of an European and American collaboration. The satellite was launched into space on 2nd December 1995, from Florida by NASA. It is located 1.5 million kilometers from the Earth at a very special location known as the Lagrange point. Here the gravitational pull of the Sun exactly matches that from the Earth.
From this favored location, it can observe the Sun without interruption and in remarkably stable conditions. SOHO is equipped with 12 observation instruments: three of these are dedicated to seismology, the rest, to all the other atmospheric phenomena of the Sun (solar wind, particle emissions, flares...). SOHO will continue to observe the Sun for many years to come, accompanied by other probes from Japan (HINODE), United States (STEREO, SDO) and by the CNES microsatellite, PICARD, to gain a better understanding of solar activity.

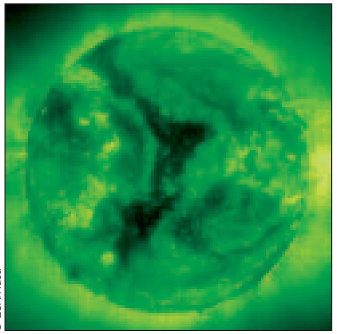







The evolution over time of the number of sunspots appearing on the solar photosphere. The approximately 11-year cycle is clearly visible but very variable.

motions were not simply superficial but reflected global motions which affected the whole of the Sun. These could be compared with a cavity in which sound waves develop at very low frequencies, inaudible to the human ear.
In fact, the sound waves produced by the Sun are 17 octaves lower in frequency than the sound produced by a tuning fork with a frequency set at 440 Hz: their frequency is of the order of 3 mHz, corresponding to a period of around five minutes.
Acoustic waves produced continuously by the granulation at the surface, like rain on the surface of a drum, are a fantastic means to probe the Sun throughout its opaque parts. The study of solar vibrations, which propagate from the surface and are reflected by the various interior layers, makes it possible to measure values such as the profile of the speed of sound or the profile of the rotation velocity.
Sound moves at a velocity of around 340 m/s in the air that we breathe; in the Sun, this velocity is 500 km/s at the centre and around 7 km/s at the surface.
An acoustic wave penetrating to the core of the Sun takes around one hour to traverse the star. This wave is very sensitive to the gaseous matter that it encounters: investigating the interior of the Sun by seismology makes possible live and continuous monitoring of the state of evolution of the Sun, in situ.
Everything in the Universe rotates and the Sun



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The solar corona in a period of strong activity.

**"Understanding the variation of the solar magnetic activity will enable better forecasting, over the coming decades, of its impact on the terrestrial environment."**

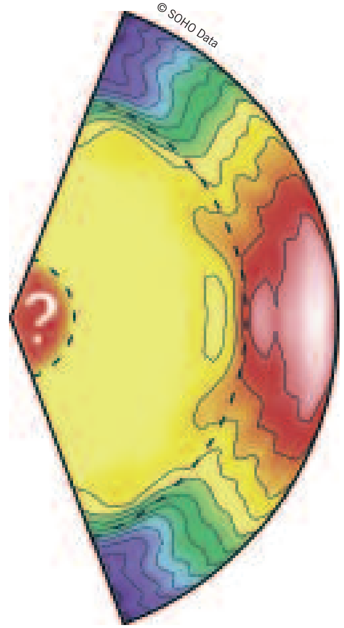
is also rotating; but it rotates in a differential way between the equator and the poles. We have seen that the surface of the Sun, the photosphere, is strewn with dark spots which one can follow over time: they provide a measurement of the rotational speed of the Sun. It is possible to determine that the equator rotates faster (with a period of around 25 days) than the poles (period closer to 30 days). However, there is a relationship between the surface rotation and the magnetic phenomena. We can speak of an activity maximum when the number of spots at the surface is at its highest: this is the time period when magnetic activity of the Sun is greatest, leading to strong solar flares. The SOHO satellite is well placed to monitor these activity phenomena, since it can continuously observe each region of the Sun. In periods of strong activity, large dark regions and flares of matter are clearly visible at the corona level (see above and p.16-17).

Helioseismology, carried out by SOHO, has revealed that this differential rotation of the surface is maintained over the entire convective region (the low-density region representing 2% of the solar mass), then disappears abruptly in the transition region located at the boundary between the radiative and convective regions. Indeed, this region is the site of strong shear forces which contribute to regenerate the magnetic field. Thus a large part of the solar mass (close to 50%) in fact rotates as a solid body. First observations of gravity modes, by contrast, favor a more rapid rotation of the nuclear core than of the rest of the radiative region. If this is confirmed, it would indicate that the Sun has retained at its core, which holds nearly 50% of its mass, a remnant of the rotation, which it acquired during its formation, including probably a fossil magnetic field.
Understanding this solar activity has today





© SOHO Data



Profile of the internal rotation of the Sun obtained by the Golf and MDI instruments on board SOHO: the red sections are rotating more rapidly than the blue sections. The increase in rotation at the core, in agreement with the signals from the first gravity modes, remains to be confirmed.

become a significant key in order to understand its effects on the human scale, as well as the effective role of the Sun on the terrestrial environment. In fact, the origin of external magnetic phenomena located under the photosphere, and its understanding, requires knowledge of the internal motions of matter all the way to the centre of the Sun. Scientists imagine meridional circulations for which the velocity varies from tens of meters per second (in the convective region), playing a determining role in explaining the 11 year cycle, to fractions of microns per second in the radiative region (hence suggesting one complete rotation of this region requires a billion years).

## HELIOSEISMOLOGY AND SIMULATION

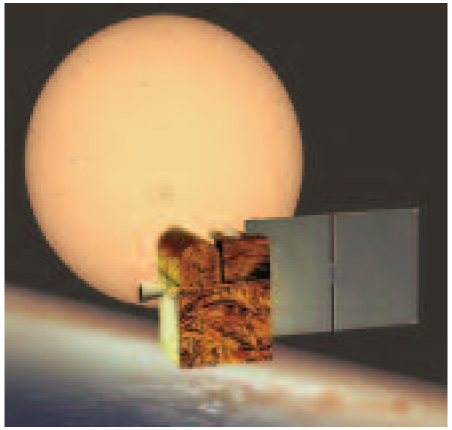
Helioseismology is a necessary tool for providing quantitative evidence of these large scale motions. Today, it is associated with numerical simulations which try to reproduce the observations in order to understand them. It has already been established that the differential rotation of the convective region contributes to the presence of a magnetic dynamo field which covers the whole convective zone and the transition region between radiation and convection, where this differential rotation disappears, known as the tachocline. An understanding of this complex physics will need to describe how the magnetic field organizes and regenerates itself. It must also explain the duration and intensity of solar cycles, which are not regular, having large maxima and large minima, as seen in the figure showing the evolution of cycles since they were first measured in the 17th century. These studies will, in the long term, make it possible to estimate changes in magnetic activity over the

**Rapidly changing speed of rotation.**

coming decades. This has two important consequences: understanding the Sun enables us to understand other stars; but understanding the Sun also enables us to forecast phenomena likely to affect the Earth, such as magnetic storms which can cause many disturbances, notably to electrical networks and to high-frequency radio and satellite communications.

## MEASURING ACTIVITY FROM THE CORE TO THE CORONA OF THE SUN

A new discipline has appeared to estimate the impact of solar activity on the Earth's atmosphere. The PICARD satellite will help SOHO, the Japanese HINODE satellite and the American SDO satellite, to track and record all the solar activity indicators from the Sun's nuclear core to its corona. These measurements make it possible to provide better estimations of the response of the stratosphere and the terrestrial atmosphere to solar perturbations, which develop from the visible domain to the UV and hard X-ray domains. Joint work on solar modeling and climatic modeling is in prospect, provided that continuous observations are maintained over one or two decades.
This rapid growth in our knowledge of the Sun shows how such plasma can inspire a large number of theoretical works, models and observations with many enthralling implications for society.



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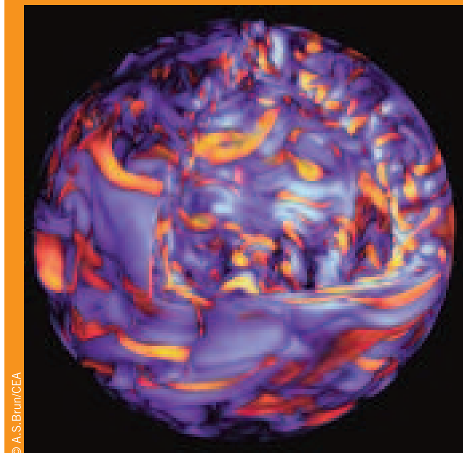
The CNES microsatellite, PICARD, will observe the Sun at several wavelengths and will observe its superficial deformations.



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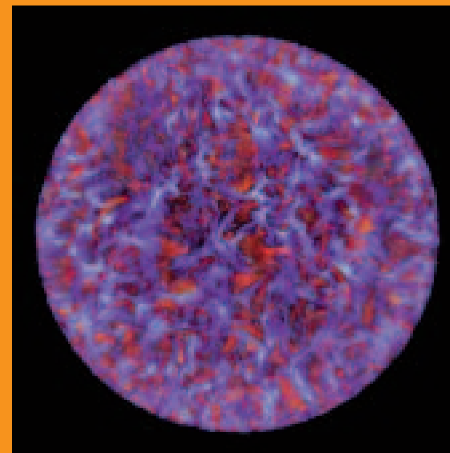
The magnetic field in a global non-linear simulation of the Sun's convective dynamo.



The radial velocity in the Sun's turbulent convective region. This convection is the source of heat transport to the surface of the Sun.

## THE COAST PROJECT

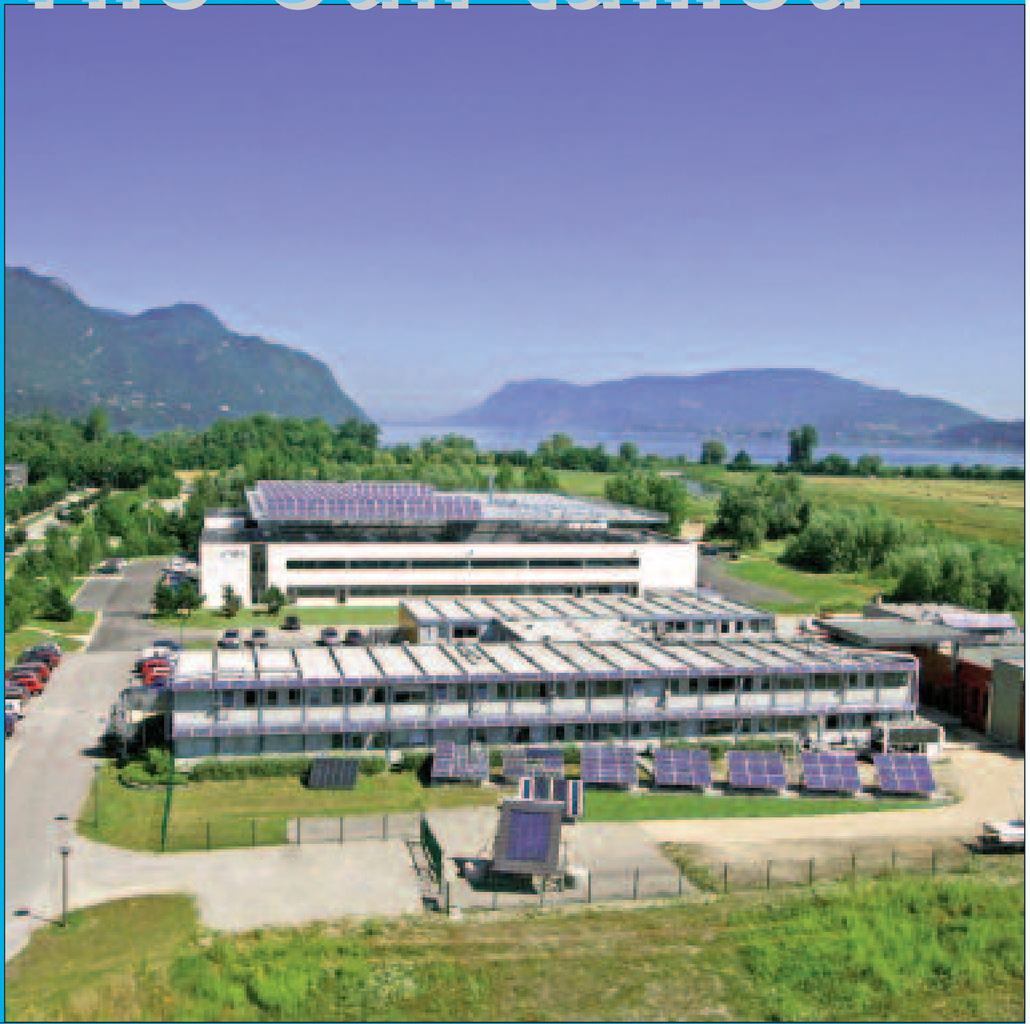
After instrumentation and observation, simulation is the third channel of research in astrophysics. The most beautiful images from astronomy only give a two-dimensional vision of the Universe. Thanks to the power of new super-computers, today, scientists can simulate the formulation and evolution of stars on a computer in sufficient detail to produce very high quality "virtual" images in three dimensions.

The aim of the Coast program is to model complex astrophysical phenomena, in order to confirm current theories on the physics of stars and to plan future astronomical observations. The main investigations which have benefited from this program are in the fields of cosmology, stellar physics, the study of proto-planetary discs and the study of the interstellar medium.

In stellar physics, stars are considered as large spheres of hot gas. They are turbulent objects, exhibiting many convection phenomena; they rotate on their own axis and are bathed in a self induced magnetic field. The ASH computer program, supported by the European commission via grant ERC-StG STARS2, calculates the evolution of stellar fluids.

## Solar energy for heating and electricity production...

# The Sun tamed



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The Sun constitutes an enormous source of energy in which we are permanently bathed. Man has understood for a long time the importance of exploiting this source of heat and light. However, in the past the problem has always been how to recover this energy, transport it, store it and transform it into electrical power. Exploitation of this energy source is recent. It is being developed, but it still remains very costly. Solar energy is one of the group of renewable energies. Currently, there are two channels of fire which solar energy is exploited, either directly transforming radiation into heat or into electricity, thermal and photovoltaic solar power, respectively.

**Renewable energies:** Solar, wind, hydraulic, biomass and geothermal energy sources.

© CEA-Coulon

**Polycrystalline silicon solar panels at the Cadarache research centre.**

The CEA took a particular interest in thermal applications, at the time of the first oil crisis, at the start of the 1970s. Since 1978, it has installed, in the Pacific, the first solar houses, hospitals and hotels in the world. Since the 1980s, the CEA has pursued thermal solar solutions for building applications and it has also focused research on solar photovoltaics, an area in which it has become a major player.

## SOLAR THERMAL ENERGY

Solar thermal energy is mainly used for water or space heating. Thermal collectors are employed. There are various types, but the principle is always the same: solar collectors absorb photons from the Sun and transform their energy into heat. The collecting material must be strongly absorbing, such as chromium oxide, for example. The heat is then transferred to a liquid or gas (known as a "heat transfer fluid") which carries it to a thermal store. Four square meters of heat collectors are enough to supply a family of four with hot water, and 10 m² are enough to heat a 100-m² house at the latitudes found in France. This type of technique is, for example, used for "direct solar floors". In this application, the heat transfer fluid is transmitted directly into the floor of the building at a temperature of approximately 25 °C, providing comfortable heating to the accommodation.
Electricity can also be produced from solar thermal energy using thermodynamic techniques. This requires high temperatures (of


© EyeWire

A solar power plant in California for a thermodynamic utilization of solar radiation.

order 1,000 °C) which are obtained by concentrating sunlight using mirrors. Indeed, which of us has not tried, at some time or another, to set light to a piece of paper using a mirror exposed to sunlight? This principle, known since antiquity, is used today on a larger scale. There are thermodynamic units containing hundreds of mirrors (heliostats) which act by reflecting solar radiation onto a boiler located on top of a tower. In this boiler, the heat exchange liquids will store heat (they can reach temperatures of several hundred degrees), then transport the heat to a water reservoir where they exchange the heat with the water. Once heated, the water turns to steam, then operates a turbine to produce electricity as in conventional thermal power plants. The power output from this type of facility is on the order of several megawatts; for comparison a nuclear power plant produces an electrical power output of 1,000 MW. A prototype power plant with tower was constructed in France on the site at Targasonne in the Pyrenees at the start of the 1980s. It provided power from 1983 to 1986. Power plants with troughs in parabolic collectors exist on the industrial scale; in this case, solar radiation is concentrated on an axis where the heat transfer fluid is heated by several hundred degrees. This technology is employed in the world's largest, thermal solar-energy plant which is situated in California and has attained an electrical power of 150 MW.





## PHOTOVOLTAIC SOLAR ENERGY

The advantage of this technique is to convert solar energy directly into electricity. This conversion, known as the "photovoltaic effect", was discovered in 1839 by Edmond Becquerel (1820-1891), but it was not until 1954 that the first photovoltaic cell with high output (6%) appeared. Output for current-day modules are of order 15-20 %.

**The father of Henri Becquerel, who was awarded the Nobel Prize for physics in 1903, jointly with Pierre and Marie Curie, for the discovery of natural radioactivity.**

**Collections of photovoltaic cells in series, assembled in a metallic framework with their mechanical structure.**

Photovoltaic cells are made from semiconductor materials, such as silicon, produced from very high purity raw materials. The "electronic" quality is order 10 billionths of the impurity ratio!

Currently, a third of the world's population does not have access to electricity, but the Sun is everywhere. This is why this technique constitutes such a good solution for low energy consumption applications: examples include lighting, powering water pumps, refrigerators, televisions, etc., in rural regions.

There are two rapidly growing markets: autonomous applications, where the energy is produced, stored and used at a single location, and applications connected to a network often referred to as "photovoltaic roofs".

The earliest applications, and the most widespread until 1990, appeared in the field of space technologies for satellites and then for telecommunications, for maritime and airborne beacons, roadside emergency telephones, domestic lighting, audio and visual applications and water pumps. But since the Sun is not present 24 hours a day, these applications require the use of batteries which can insure storage of energy for consumption outside of daylight periods.

At the CEA, research is being carried out on lead batteries, derived from automotive accumulators. In particular, work is focused on extending the lifespan of batteries, which are currently much less than those of photovoltaic cells (on the order of 10 and 30 years respectively). Recent work leads us to anticipate new technologies for storage, notably lithium batteries, which will have lifespans equivalent to those of other components.

### INES: FRENCH NATIONAL SOLAR ENERGY INSTITUTE

**INES was created in 2006 on the initiative of the public authorities, to promote and develop the use of solar energy in France and, in particular, to control energy use in buildings.**

**It was set up at Bourget du lac at the Savoie Technolac technology park, close to Chambéry. The Rhône Alpes region is a special area, with a particularly dense concentration of leading players in relevant fields: industrialists, researchers, local communities and associations.**

**A team of more than 150 researchers have developed solutions with industrial partners for solar, thermal and photovoltaic, power.**

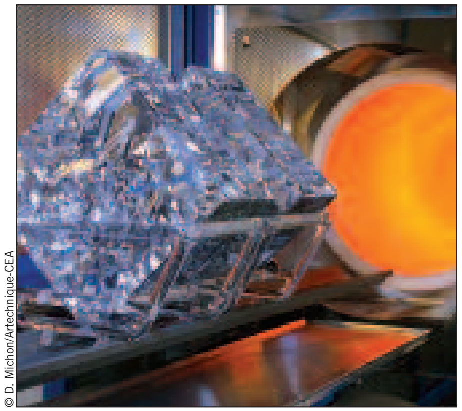
## “Production of unlimited, "clean" energy that is available in all regions of the world.”

The second application, with connection to the network, consists of integrating photovoltaic modules in the roofs and frontages of buildings and houses, producing electricity which will be either consumed on site or fed into the network.

In summary, the Sun constitutes a clean and almost inexhaustible energy source, which promises a bright, but still expensive, future. No doubt we will learn to control this energy source before it runs out in around 5 billion years time... indeed the time will come when, with its hydrogen running out, the Sun will burn helium and transform it into carbon. But the process will not go any further: the temperature will not permit this stellar alchemy to continue until the core was eventually reduced to iron. Rather, after the helium burning phase, gravity will compress the Sun to the size of the Earth and the Sun will become a white dwarf, a low luminosity star, which will fade away with a quiet death, unlike more massive stars which explode into supernova.


© Siemens Solar

An example of an autonomous application: telecommunications.



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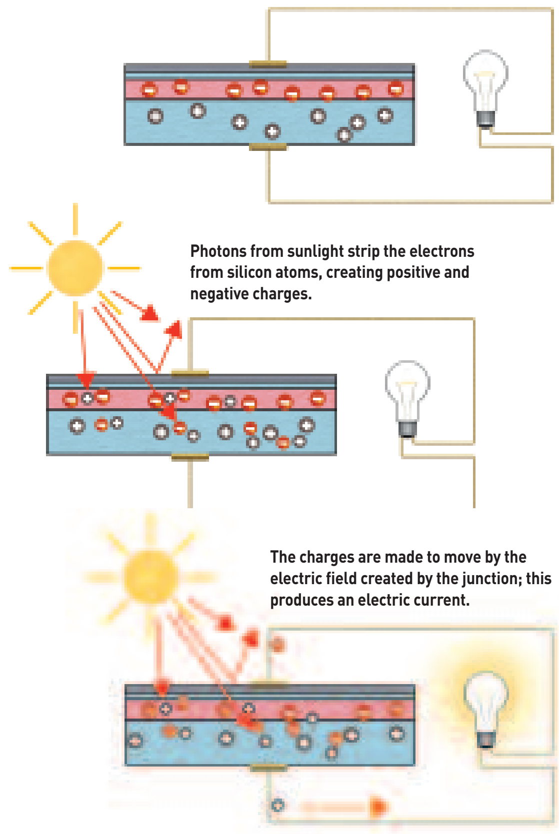
Silicon wafers are doped in this furnace, at a temperature between 700 and 900 °C to create junctions which will become the core of photovoltaic cells.





The photovoltaic cell contains electrical charges because of the doping: negative in n-type (an excess of electrons), positive in p-type (lack of electrons). These charges create an electric field across the junction.




## HOW DOES THIS WORK?

This technique profits from the optoelectronic properties of semiconductors which enable them, under certain conditions, to convert optical energy into electrical energy. The most advanced technologies use silicon as the base material.

A photovoltaic cell can be made up, for example, of two layers of silicon, the transport properties of which have been modified by doping.

The addition of boron atoms favors conduction by positive charges. The silicon becomes p-type.

Doping the silicone with phosphorus atoms improves conduction of negative charges. The silicon then becomes n-type.

Placing p-type silicon in contact with n-type silicon creates a so called p-n junction. When this cell is exposed to solar illumination, electrons and holes are generated at the p-n junction, which can be considered as the active area of the cell. These electrons and holes then move, respectively, across the p and n zones, to reach the electrodes. This series of processes, called the photovoltaic effect, leads to the production of a current which can supply a piece of electrical equipment.