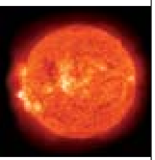
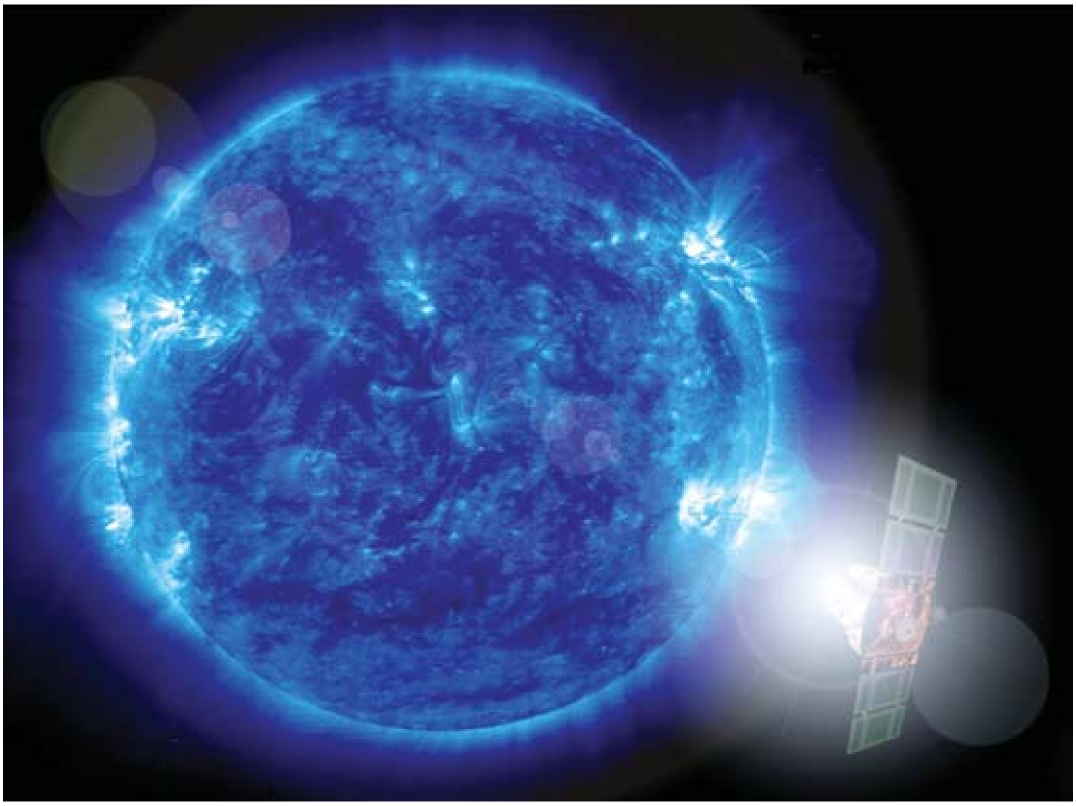


Thanks to new astronomical observation techniques, our view of the Sun's interior is undergoing a marked change. From being regarded as a hot, stable, trusted heavenly body, the Sun has turned into a true physics laboratory, presenting temperature and density conditions that are not yet obtained on Earth. This has made possible to push back the frontiers of our understanding of matter, in the areas of plasmas and particle physics. Understanding stars opens new fields of investigation, as power reactors and lasers. Current issues include the relationship between the different timescales involved, and new questions about the role played by the rotation and the magnetic field, and their contribution to the interaction between the Sun and the Earth.

Static and dynamic views of the solar interior

The decisive contribution of helioseismology to our understanding of the Sun

A number of disciplines have contributed to decisive advances, over the past few years, in our understanding of our own star. Among these, the investigation of "sunquakes" has played a major part in ensuring a new consistency for models of the source of daylight.



SOHO (ESA-NASA)

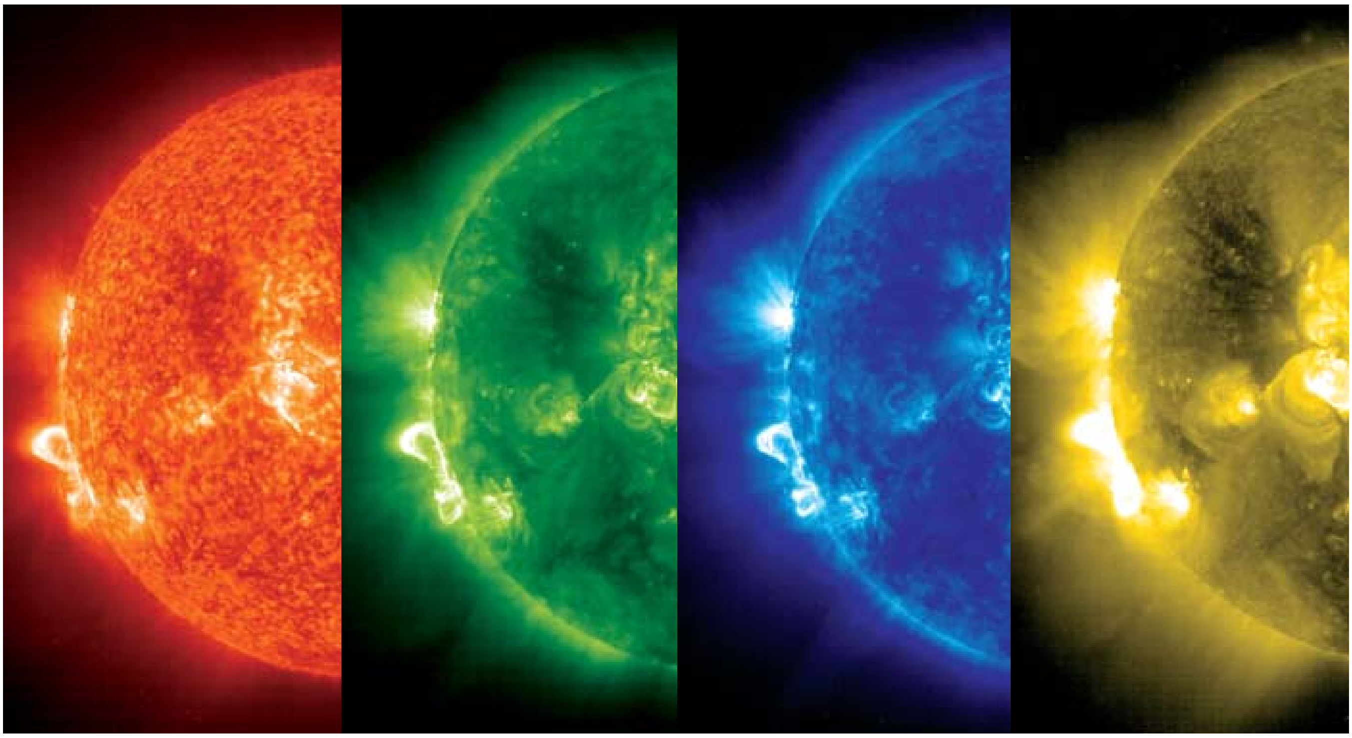
The SOHO satellite, with its twelve instruments on board, is constantly watching the Sun.

There is often a major gulf between understanding how a heavenly body works, and being able to describe it with sufficient precision to allow turning it into a laboratory, to expand our knowledge of fundamental physics.

The Sun, a reference for astrophysics

That gulf was traversed with regard to the Sun. The astrophysicist complements the observational astronomer, by interpreting the latter's observations. His role is to look for the main processes, then adding other secondary processes, until the observations can be reproduced. For a long time, owing to the restriction of observations to the **visible spectrum**, astrophysics was seen by other fields of physics as an approximate, or order-of-magnitude, science. This however was a key stage, and a decisive one. Our understanding of the Universe, as the number of processes involved is huge, necessitates an overall consistency daunting and a large range of highly specific tools. They are extremely useful to select the main processes among all the possible avenues. Nowadays, the whole **electromagnetic spectrum** has been opened up, thanks to orbiting instruments in space, along with the development of specific sensors.

As far as the Sun is concerned, this makes it possible to show up particle ejections, winds, **X-radiation, ultraviolet radiation**… Launched in 1995, the SOHO (SOlar and Heliospheric Observatory) satellite, a collaborative project of the European Space Agency (ESA) and the US National Aeronautics and Space Administration (NASA), is wholly dedicated to solar observation. Its superiority lies in its bringing together twelve instruments on board, looking at the Sun at a variety of **wavelengths**. Five instruments are dedicated to investigation of the **solar atmosphere**, thus probing the **corona**, the **chromosphere** and the **photosphere**, characterized by different temperatures and thus exhibiting diverse aspects of stellar **plasmas** (see Box A, ***Spotlight on the Sun***). Four others are designed for the investigation of the solar wind. And three solar-seismology instruments enable probing of the **star**'s interior, thus affording a unique opportunity finally to build up a complete view of it. The CEA teams have played an active part in the design and construction of the GOLF (Global Oscillation at Low Frequencies) helioseismology instrument, and in interpreting its observations (see *Solar seismic measurements*, Box). This yields quite astounding pictures of the Sun, evidencing the wealth of views of the Sun at our disposal (see Box B, ***Tell-tale spectra***).



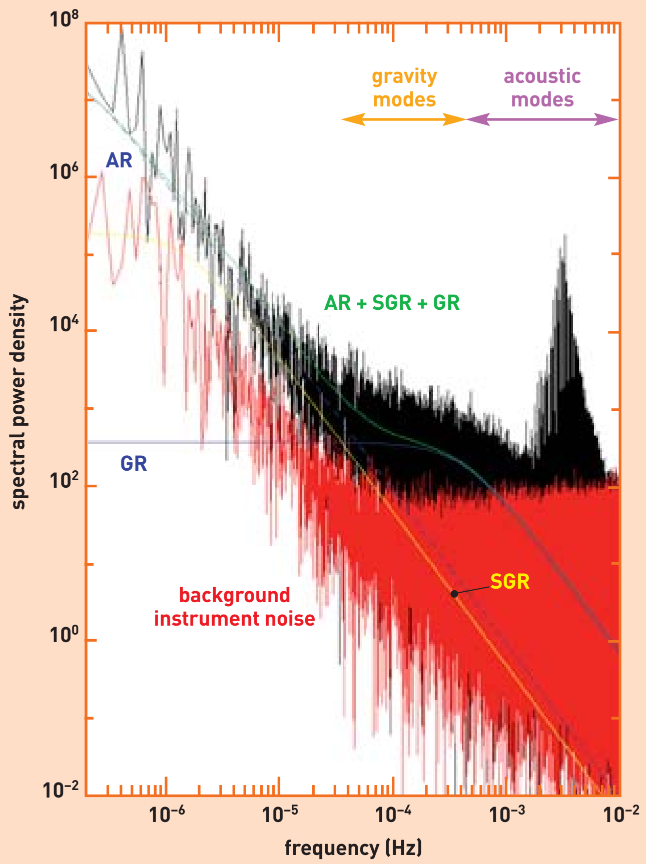
The Sun, seen at a variety of wavelengths by the EIT (*Extreme-ultraviolet Imaging Telescope*) instrument mounted in SOHO. Observation of several absorption lines enables probing of the temperatures of the granulated photosphere (5,800 K) at left, up to the corona, where the plasma is again heated to millions of degrees (right), through the chromosphere, whose position is close to the temperature minimum. This allows monitoring the signs of solar activity, originating below the photosphere, in the convective zone.

A star under the scrutiny of seismology

Resolution of the structural equations (see *The nuclear Sun*, Box 3) calls for introduction of a rich, complex physics, describing the thermodynamic conditions for the star that is to be modeled. In the years 1960-85, an accelerated survey of stellar conditions took place, and it emerged that stars evolve via highly diverse evolutionary paths (see *The nuclear Sun*, Figure 1) depending of their mass. A further advance has occurred, over the past twenty years, owing to the rise and development of **helioseismology**, which truly saw this science shift from the qualitative to the quantitative. This technique, taken from the geophysicists, is characterized by the wealth of information it provides. The astrophycist appears to be doubly in luck. On the one hand, the Sun is a gas, and it may be assimilated to a sphere, making for easily described wave propagation. And, on the other hand, the excitation process for the various modes is permanent, and generated by the Sun itself (see *Solar seismic measurements*). There is thus no further source calling for description, no perturbing interaction, and there is a continuous signal. All of the information carried by these waves thus directly relates to the solar plasma.

Two types of waves propagate inside the Sun. *Acoustic waves* are generated by the pressure fluctuations induced by the surface **granulation**. *Gravity waves* mainly originate at the interface between **convection** and **radiation**, and are governed by gravity (see Figure 1). Only the acoustic modes, so far, have yielded information amenable to processing. The wealth of data they yield is due to the unique ability to **resolve** the Sun into a large number of pixels - 1,024 x 1,024 for the MDI (Michelson-Doppler Imager) instrument carried by SOHO, used to measure waves closest to the surface - or to take a global look at the star, as can be done with GOLF, which detects modes reaching down to the **core**. Million acoustic modes are reachable to observation. This makes it possible to reconstitute the solar plasma's properties, from the surface down to within a fraction of the nuclear core, by relying on two quantities: the sound speed, and the decomposition of modes into components linked to rotation, on the one hand, and to the magnetic field of the layers traversed, on the other.

Armed with such tools to confront data, it becomes possible to resolve the structural equations, and thus go from a purely theoretical view to a quantitative, numerical, verifiable vision. Thus ongoing intellectual stimulation between theorists, numerical analysts and observers has enabled answers to be given to such concrete questions as: What are the actual **neutrino** flows emitted by the Sun? What is the Sun's central temperature? How old are the oldest stars?…



R. García/CEA

Figure 1.
Frequency domains for the two types of mode. Acoustic modes appear above 0.5 mHz; the domain of gravity modes occurs between 50 μHz and 0.5 mHz. Superimposed on the GOLF observations, instrumental noise, and solar noise associated to granulation (GR), active regions (AR) and supergranulation (SGR) may be seen. The sound speed in the medium is derived from the measurement of acoustic propagation time for the different modes. This calculation is facilitated by the knowledge of a close solar model useful to define traversed cavity size. This speed is directly linked to thermodynamic quantities through the equation $c^2 = \gamma P/\rho$, where γ, P and r respectively stand for the gas's **adiabatic** index, pressure and density. Investigation of these modes also allows insight into internal rotation and magnetic-field effects.

A rich laboratory of complex physics: the state of matter

The Sun's composition derives from that of the cloud from which it was born. This determines the amount of hydrogen that was to be available for the nuclear core. The radial profile of the speed of sound is indicative of the thermodynamic state of matter, and of abrupt changes in it. Regions may thus be identified where the state of major **elements** changes (see Box 1): the locus where **helium** becomes partly **ionized**, the locus where transport no longer occurs through radiation, but through convection, owing in particular to the altered ionization state of oxygen (see Box 2). In the central region, the profile for the speed of sound is also highly sensitive to the main pp (proton + proton) reaction, and thus to its interaction **cross-section**, as also to the other major **fusion** reactions.

Precise extraction of the speed of sound, now obtained to within a few 10^{-4}, provides the ability to observe the solar plasma in situ. Thus, helioseismology has made it possible to evaluate the amount of helium in the photosphere, which was not given by direct measurement, and hence, indirectly, the hydrogen content. The value found is close to the **primordial** one, whereas the Sun was born some 8 billion years after our **galaxy** was formed. This finding highlights the requirement for a slow **gravitational** migration, relative to hydrogen, of all elements, and to quantify its effects; over 4.6 billion years, relative content in helium, referred to that in hydrogen, is lowered by 8-9% in terms of **mass fraction**, compared with its initial value, while for heavier elements such as carbon, nitrogen and oxygen, this reduces by some 10%. A trifle, or so it might seem, one however with a major impact as regards the age of the older stars, which thus found themselves rejuvenated by several billion years. The sound speed profile showed up also that abrupt, if tiny, change in slope that marks an alteration in energy transport, from convection to radiation, with a highly specific behavior over an extent of a few percent of the radius (see Figure 3).

In the radiative region, taking into account detailed composition, and **photon** interaction cross-sections, enabled a better evaluation to be made of central temperature, and hence of nuclear-reaction rates. It took the various teams, at work in the United States and in France on photon-matter interaction, over ten years to estimate the processes contributing to the photon advance from the Sun's center to the surface (see Box 2). Probing the nuclear core is only feasible if scientists correctly master the outermost regions. This justifies a specific effort

B Tell-tale spectra

The various categories of radiation are distributed across the electromagnetic spectrum according to their wavelength, from the shorter, more energetic wavelengths (gamma radiation) to the longer ones (radio waves) through visible light. The spectrum of the latter domain, for instance, may be obtained by passing light through a prism, which decomposes it into its various components, from red to purple (see Figure a). A rainbow likewise exhibits a spectrum of the visible light emanating from the Sun, through refraction in, and reflection on, water droplets.

The same principle is applied for the whole range of electromagnetic radiation, through the use of spectrographs, which analyze the spectral energy distribution of such radiation, and spectrometers, which record each component of the spectra by means of photoelectric sensors and measure radiation intensity, plotted against wavelength.

In astrophysics, spectroscopy consists in the remote investigation of bodies from the radiation emitted by them, or the alterations induced in that radiation as it encounters other bodies in its path. Spectra exhibit, between wide, continuous bands (each of which is termed a spectral continuum), discrete lines, each corresponding to a specific wavelength and, ultimately, to an energy level of an atom or molecule in the body observed. These spectral lines are of two types, emission lines and absorption lines.

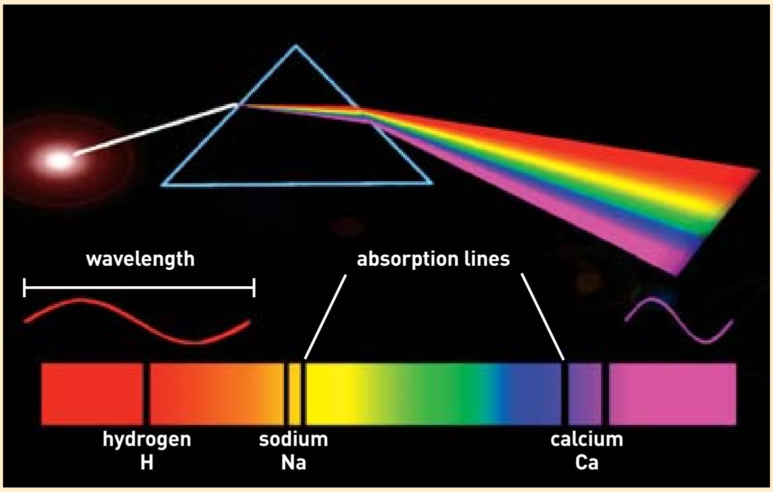


Figure a.

Bright emission lines correspond to radiation directly emitted by a body heated to a very high temperature. An emission spectrum thus allows detection of the presence of certain atoms or molecules in the emitting body.

Dark absorption lines also correspond to a specific wavelength, this being due, however, to the process whereby a radiation's intensity decreases as it goes through a material medium, to which it transfers all or part of its energy. Thus, the composition of a hot, radiating source such as the Sun may be analyzed from the absorption by its atmosphere of part of the electromagnetic radiation emitted (absorption spectrum).

Matters do not end there: analysis of spectral shift allows the relative motion of the emitting body to be estimated, thanks to the Doppler effect, [1] on the selfsame principle whereby the sound of an approaching vehicle gets higher-pitched, and lower-pitched for a receding vehicle. The apparent change in frequency (higher even as wavelength is shorter) is thus proportional to the relative velocity of observer and source. For a light source, this effect implies that lines in that source's spectrum will be shifted towards blue (blueshift), i.e. to shorter wavelengths, if it is approaching, or towards red (redshift), corresponding to longer wavelengths, if it is receding (see Figure b).

The Doppler effect is used in astrophysics, particularly to establish the radial velocity of stars or galaxies, for their perspective motion causes a shift in the lines emitted, relative to their nominal positions, or compared to the same lines emitted by a terrestrial source.

Finally, the splitting of spectral lines induced by a magnetic field (*Zeeman effect*) is used to measure the intensity of the magnetic fields associated to astronomical objects, the Sun in particular.

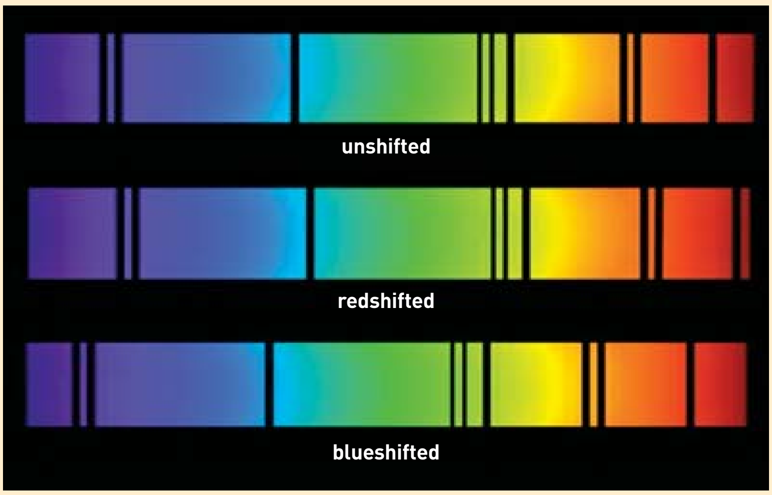
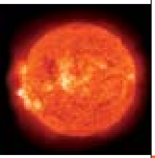


Figure b.

(1) Or, more accurately, Doppler-Fizeau effect. Discovered by Austrian physicist Christian Doppler for sound waves, the effect was extended to optics by French physicist Hippolyte Fizeau.



Solar plasma characteristics

1

Gas is in the form of **plasma** throughout the solar interior. The term plasma applies to a gas in a state where **electrons** are found to be dissociated (or partly dissociated) from **protons**. Thus, whereas an **atom** is electrically neutral (with as many positively-charged protons as there are negatively-charged electrons), a plasma is an ensemble of charged constituents. An **element** may be fully or partly ionized, this state depending on temperature and density. The higher the values for the latter, the more **ionized** the plasma is.
To take the example of oxygen. In the atomic state, its atom comprises a **nucleus**, consisting in 8 protons and 8 **neutrons**, and peripheral electrons which remain bound to the nucleus. At the center of the Sun, with temperature and density reaching values of $15 \cdot 10^6$ **K** and 150 g/cm^3 respectively, oxygen is wholly ionized, occurring in the form of a nucleus with an 8-fold positive charge, and 8 **free electrons** wandering at the rate of thermal agitation. Oxygen is in this plasma state throughout the **radiative region**, however, as temperature and density decrease, electrons will break free less and less from the influence of the nucleus. At around a few million degrees, one electron will remain bound to the oxygen atom, then two, then three, until oxygen appears in the atomic form by the time it reaches the Sun's surface.
In a plasma, motions of the various constituents are linked to thermal agitation, but equally to collective motions imposed by the gas's rotation. The presence of negatively- and positively-charged particles will cause currents to arise, and ultimately **magnetic fields**.

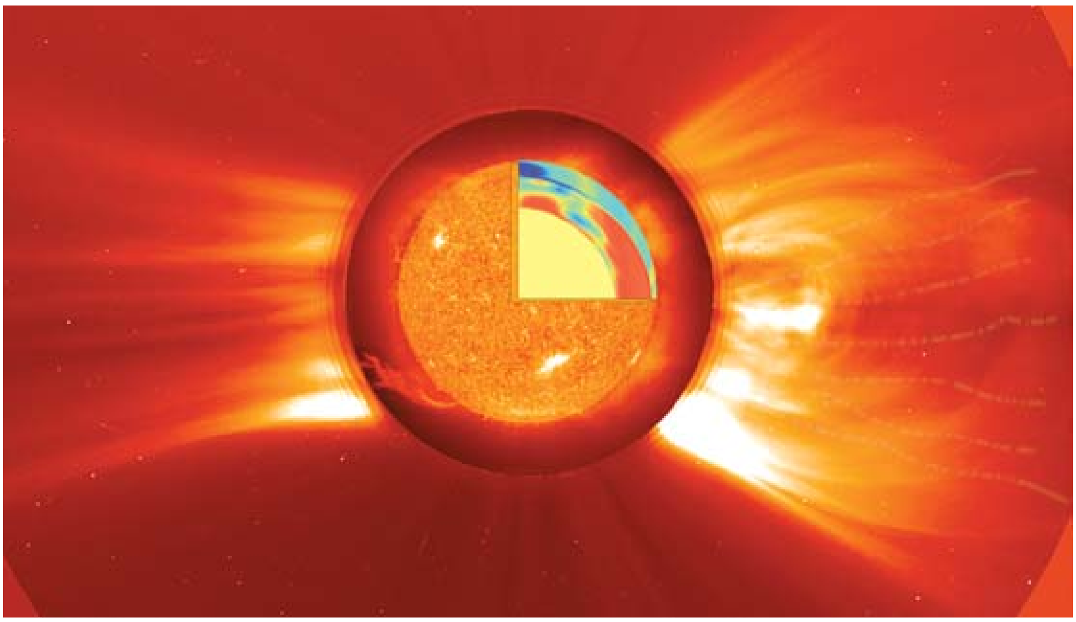
to determine precisely the mode-frequency extraction, and to understand the theoretical approach. The understanding of the Sun supposes a good adequation between the theoretical and seismic representations.

A partly mastered nuclear core

Knowledge of the nuclear reactions involved in stellar evolution is not enough to give a proper description of the nuclear core, owing to the very high temperature dependency of most of these reactions. The Sun is the unique plasma available, to date, for testing **weak interactions** with neutrino production (see Box 3), and the specific characteristics of plasma. A great deal of physics is required to describe the innermost 25% of the radius, which hold over half of the Sun's mass. The Sun owes its longevity to the fact that the interaction between two protons, which is the initiating reaction for the fusion process, is a weak interaction. It is why it is not accessible to laboratory checks. This interaction is directly linked to **neutron** lifetime - being estimated at 8 minutes - since one proton transforms into a neutron; the interaction is thus of fundamental importance. Moreover, the pp reaction, governed as it is by weak interaction, is the main source of the Sun's neutrino emission. A good understanding of solar plasma is equally crucial for the characterization of the plasmas, physicists are endeavoring to create further, to achieve fusion energy, for the plasma's thermodynamic conditions are similar, even though the reactants and the type of interaction be different (see Chapter II).

Complex laboratory measurements

To specify at what rate protons transform into helium nuclei through the reactions defined in Box 1 of the paper on The nuclear Sun, cross-sections for the various ppI, ppII, and ppIII chains, as well as for the **CNO cycle**, must be known. Only those governed by **strong interaction** are accessible for experiment, and many nuclear physics laboratories have worked on such measurements. US astrophysicist William Alfred Fowler collated all findings in this area, being awarded the Nobel Prize for Physics in 1983 for his considerable efforts. However, laboratory conditions are not those prevailing inside stars. Experiments are usually carried out at higher energies than those encountered in the solar plasma, since the **Coulomb barrier** often precludes entering this domain, ranging as it does from 1.5 **keV** for pp interaction to a few tens of keV for CNO-cycle reactions (Z_1Z_2 variation, where Z is the number of protons of the reac-



SOHO (ESA-NASA)

The SOHO satellite samples the Sun from its innermost parts up to the corona, where eruptions can be tumultuous, shooting away hundreds of tonnes of solar plasma. The asymmetry of such ejections, clearly visible here, is of importance for the understanding of the magnetic life of a star like the Sun.

tants). Moreover, most laboratory measurements are of interactions between **atoms**, rather than ions. Laboratory findings thus have to be extrapolated for the low energies prevailing in solar conditions, experiments must be corrected for the Coulomb effects encountered, and Coulomb effects reinjected for the solar-plasma ions under consideration. Finally, the acceleration effect on nuclear interactions from **free electrons** and spectator ions must be factored in at the theoretical level. It is owing to such complexity that laboratory measurements have extended over some thirty years, with some very nice findings coming up of late, aimed at taking on some of the aforementioned challenges. Thus, the ^{3}He-^{3}He measurement involved ions, and represents the sole case to have been carried out at stellar energies. Further, the cross-section for the $^7Be + p \rightarrow {}^8B + \gamma$ reaction, which is very difficult to measure, and a determining factor for the prediction of neutrinos as detected by the Super-Kamiokande and SNO experiments, has been tested by various methods, in particular by the French CSNSM [1] team, at Orsay.

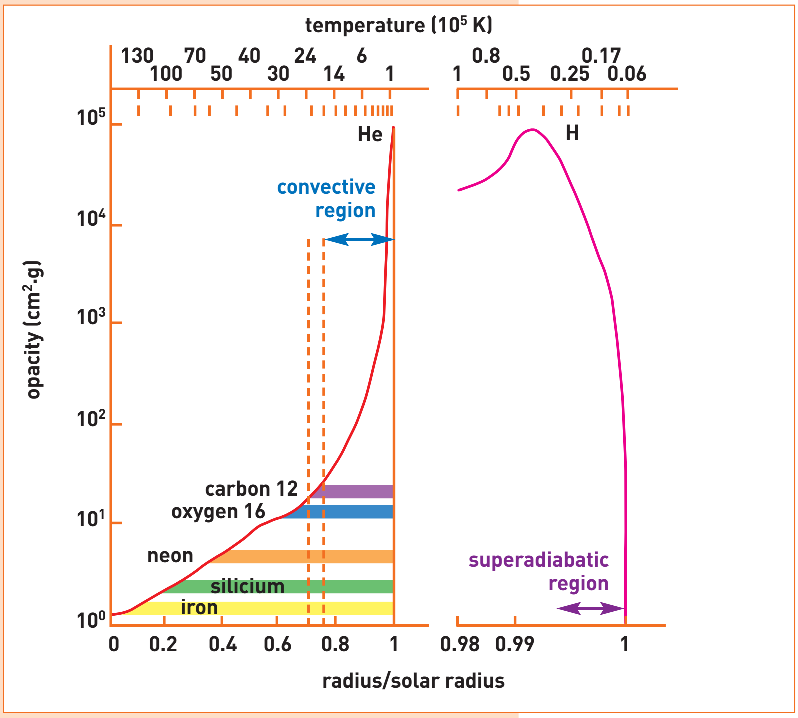
The decisive role of helioseismology

In this complex approach, some elements of the nuclear calculation might escape the physicist's acumen. Hence, coupling the theoretical approach with helioseismology turned out to be priceless. Extracting very precisely the speed of sound profile from GOLF and MDI, down to 6% of the radius from the Sun's center, astrophysicists at CEA were able to characterize the solar

(1) Nuclear Spectrometry and Mass-Spectrometry Center (CNRS-IN2P3-Paris-Sud University).

Energy transport: photon-matter interaction

2



S. Turck-Chièze/CEA

Interaction cross-section of photons with stellar plasma as a function of solar radius.

For every nuclear reaction that occurs, energy is released in the form of **photons**. Typically, the transformation of 4 **protons** into a **helium** nucleus releases 27 **MeV**. The energy thus generated contributes to the **star**'s equilibrium, by compensating for that emitted at the surface. From its emission in the **nuclear core** up to 0.71 of the solar radius, this energy is transmitted by photons: this is so-called radiative radiation. Photons are messengers, with an erratic, complex progression, ranging from simple scattering - known as *Thomson scattering* [1] - on **free electrons** to interactions with bound **electrons**, either causing the latter to go from one electronic level to another, or freeing the electron. During such interactions, the photons shed energy and separate out into photons of lower energies. These many interactions are characterized by interaction **cross-sections (opacity coefficient)**, and depend on the **plasma**'s state, for each chemical species present. Cross-sections vary widely, according to which processes are considered. Some are proportional to Z (the number of protons in the **nucleus**), others to Z^2, others yet to Z^4. This leads to attributing specific roles to each species. Indeed, to compare a **hydrogen ion** to an iron ion is tantamount, when the interaction is of the bound electron-bound electron type, to comparing $Z^4 = 1$ to $Z^4 = 457{,}000$. This entails directly that, to achieve a correct computation of energy transfer, the Sun's detailed composition will need to be known. Even though hydrogen and helium jointly account for over 99% of ions initially present in the Sun, the few remaining parts per thousand will play a considerable part in this transfer, thus restricting the rapid rise in core temperature, and hence impacting directly on the Sun's longevity. At present, only iron remains partly ionized, i.e. still retaining a number of peripheral electrons, in the central solar plasma (see Figure). Going from the center to the outer regions, more and more species, such as silicium, neon, oxygen... are found to be partly ionized, and interacting with travelling photons. At about 0.71 solar radius, oxygen, the most abundant **element** after hydrogen, becomes partly ionized. Photons now find themselves practically blocked, owing to the multiplicity of interactions they undergo, and energy transport becomes almost impossible. As temperature continues to get lower, carbon and nitrogen in turn become partly ionized. **Convection** then takes over, taking off energy to the surface with greater facility, even as it homogenizes the star's composition. Photons, of course, continue on transporting energy away, but now with extremely low efficiency. Near the surface, it is the turn of helium, and then of hydrogen, to recover their electrons, further increasing **opacity**. Photons, as they get closer to the surface, finally encounter species that are neutral, or even in the molecular state. The photon-matter interaction cross-section reverts to being low, and, finally, photons with energies corresponding to the **visible spectrum** escape from the **photosphere**.

(1) Thomson scattering: elastic scattering at high energy, with no change in wavelength.

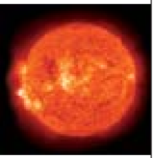
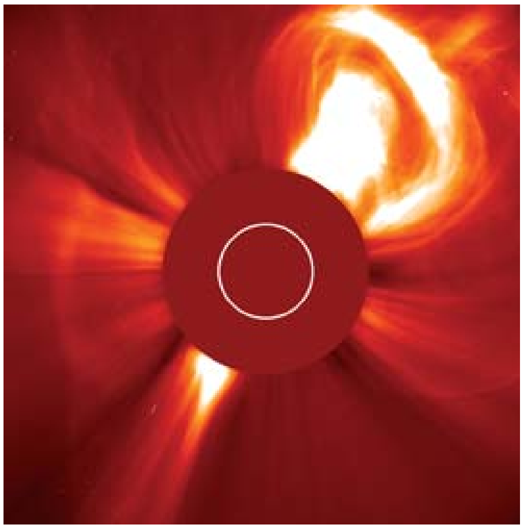


Table 1.
Characteristics
of the seismic model.

central temperature	T_c = 15.71·10^6 K
central density	ρ_c = 153.13 g/cm^3
hydrogen content at center	X_c = 0.3385 in mass fraction
surface temperature	T_{eff} = 5,800 K
surface helium abundance:	0.251 in mass fraction
initial helium abundance:	0.272 in mass fraction

plasma. In particular, the p + p cross-section, which had only been determined theoretically, is now ascertained to within 1%.
What, then, are these mysterious properties of stellar plasma? How is the Coulomb barrier between two positively charged protons to be overcome? Particles achieve this in nature through their initial velocity, and the **tunnel effect**. The interaction energy is not at thermal energy levels, but much higher. This effect, understood by Russian-born US physicist George Anthony Gamow, reduces the number of protons involved in these nuclear reactions. Were this not the case, the Sun would burn off its fuel inside a few million years! Indeed, all protons do not move at the thermal velocity relevant for the gas. They conform to a Maxwellian velocity distribution. (2) This property is a determining factor when counting the number of interactions, and for the specification of interaction energy, especially for strong interaction, which is so highly energy (or temperature) dependent. Moreover, free electrons act as accelerators for the interaction, the so-called "screening" phenomenon. For many years, doubts were entertained as to the accuracy of that velocity distribution. Could this distribution be perturbed by the plasma itself, or by the presence of other species of particles? Here again, helioseismology yielded decisive answers. If the velocity distribution is not fully Maxwellian, this has a major impact on the interactions involved for elements with a number of protons greater than 3, and the sound speed is directly affected by this in the central region. No signature has been found of such effects by seismic measurements.

(2) Maxwellian distribution: in a gas, particles (protons) do not all have the same velocity, but velocities randomly distributed on either side of a mean. Mean velocity is equal to $(8/\pi\ k_B T/m)^{1/2}$, where m is the proton mass, T is the gas's temperature, and k_B the Boltzmann constant, equal to 1.38·10^{-23} joules/degree K.



SOHO (ESA-NASA)

Coronal mass ejection observed by the LASCO (*Large-Angle and Spectrometric Coronagraph*) instrument on board SOHO. High-energy particles are suddenly released, with mean velocities of over 300 km/s, into the interplanetary environment, and can interact with the Earth's atmosphere.

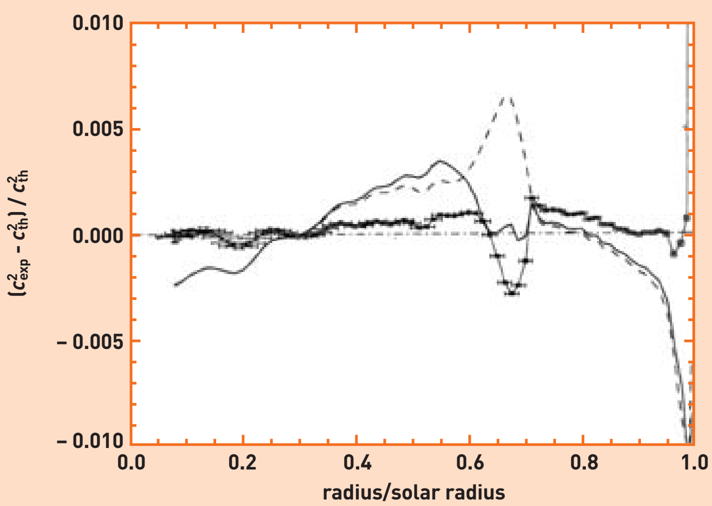


Figure 2.
Difference between the square of the sound speed as extracted from acoustic waves observed by GOLF and MDI, and that from solar models, for a purely theoretical model with no macroscopic effects (dotted line); for a model including mixing linked to treatment of the radiation-convection transition region (continuous line); and for a seismic model with adjustment of certain physical quantities, within the bounds of uncertainty, to reproduce optimally observations in the radiative region.

Converging models

With ongoing theoretical refinements and advances in seismic techniques, the quality of the solar models gained widespread acceptance, and the physics thus brought in nowadays affords a wealth of possibilities. Over the years, discrepancies between the sound speed, as extracted from acoustic modes, and that resulting from solar models have narrowed (see Figure 2). After twenty years' work, the seismic model has become a representative model of the Sun, for the radiative part. Its characteristics are shown in Table 1, and the information obtained for the 2,000 layers may be viewed on the website of CEA's Astrophysics Department. (3)
In 2001, precision on the sound speed proved sufficient to allow inference, from a "seismically" representative model, of the neutrino flows emitted by the Sun, for the various reactions involved. A few months later, the SNO experiment showed, for the first time, a flux resulting from the sum of various kinds (or flavours) of neutrinos that agreed perfectly with these predictions (see Box 3). Stellar physics had become a quantitative science, allowing reliable predictions of neutrino fluxes to be made. Particle physics has highlighted a peculiar property of neutrinos: they turn from

(3) To be found at the website: http://www-dapnia.cea.fr/Phys/Sap/Documents/soleil/solarmodel.html.

Neutrino production and the solar-neutrino puzzle

Energy production from weak interaction between two protons takes place with the transformation of a proton into a neutron, accompanied by the release of a neutrino. This being the fundamental reaction in the fusion process, the number of neutrinos thus generated may be derived directly from the total luminosity and the energy released in the transformation of 4 protons into one helium. A steady 65 billion neutrinos/cm^2/s reach the Earth. As early as the 1960s, Italian-born physicist Bruno Pontecorvo instantly grasped the importance of detecting these mysterious particles. Unfortunately, their energy is low, at under 0.4 MeV, and, as of now, only partial detection can be achieved. In gallium detectors, they account for 60% of accessible neutrinos. Fortunately, there are other reactions that yield more energetic neutrinos. Easiest to detect, since their energy can be as high as 14 MeV, are neutrinos released by the reaction $^7Be + p \rightarrow {}^8B \rightarrow 2\,{}^4He + \nu_e$ (see *The nuclear Sun*, Box 1). On the other hand, their flux is 10,000 times less intense, and temperature dependence is high, T^{24} at the center of the Sun. Their flux thus strongly depends on central conditions in the Sun, since they are emitted very close to the star's center (see Figure a). Thus, a 2% error for central temperature results in variations by a factor 2 in the flux of ^8B-associated neutrinos, as measured by the Super-Kamiokande experiment, in Japan, and the SNO experiment, in Canada. These neutrinos are of great interest for a better understanding of the Sun, and mainly for a better understanding of the neutrino properties. For over 40 years, the theoretical estimate for the number of neutrinos emitted remained higher than the neutrino numbers detected by the various dedicated facilities, by a factor as high as 2 or 3 for some of them. This finding proved highly stimulating, since, the Sun being a reference for all other stars, it was important to find out whether there was some problem with the estimate. Aside from the advances this query brought about in fundamental physics, helioseismology spurred on quantitative computation, and validated the various assumptions and ingredients in the calculations. It provided the means to converge to a prediction that was supported by seismic measurements (see Figure b). Helioseismology also made it possible to discard some hypotheses that had been suggested in order to lower significantly the numbers for some of the fluxes, such as species mixing owing to central convection, or the presence of WIMPs (candidate particles for dark matter) in the Sun's core... Every process, introduced into the theoretical models, could be tested to within a few percent, and, ultimately, it proved possible to determine precisely the neutrino flux released by each reaction, and to derive from this flux predictions for each facility (see Table).

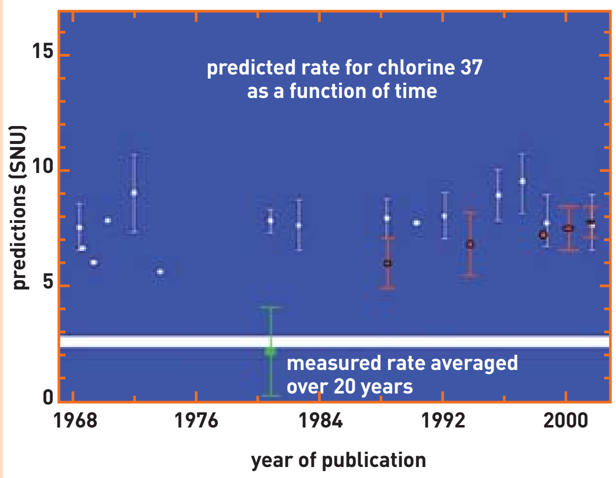


Figure b.
Time evolution of the neutrino flux prediction for the historic Homestake detector, set up by US chemist Raymond Davis Jr (1 SNU = 10^{-36} captures/atom/s). Shown in white, predictions by US physicist John Bahcall; in red, CEA predictions making use of seismic measurements to guide computations of the solar model. The green error bar corresponds to the uncertainty for each series of measurements. In the interaction with this detector, ^8B neutrinos account for 71% of neutrinos emitted by the Sun. The initial prediction that had convinced Raymond Davis to embark on this investigation was of 22 SNU!

	Gallex/Sage	Homestake	Super-Kamiokande (SK)/SNO
seismic predictions	123.4 ± 8.2	7.6 ± 1.1	5.3 ± 0.6
seismic predictions including neutrino oscillation parameters	66.5	2.76	
detected fluxes	68.1 ± 4	2.56 ± 0.23	2.4 ± 0.08 (SK) 5.21 ± 0.5 (SNO)

The first two fluxes are expressed in SNUs, the third one in 10^6/cm^2/s (1 SNU = 10^{-36} captures/atom/s).

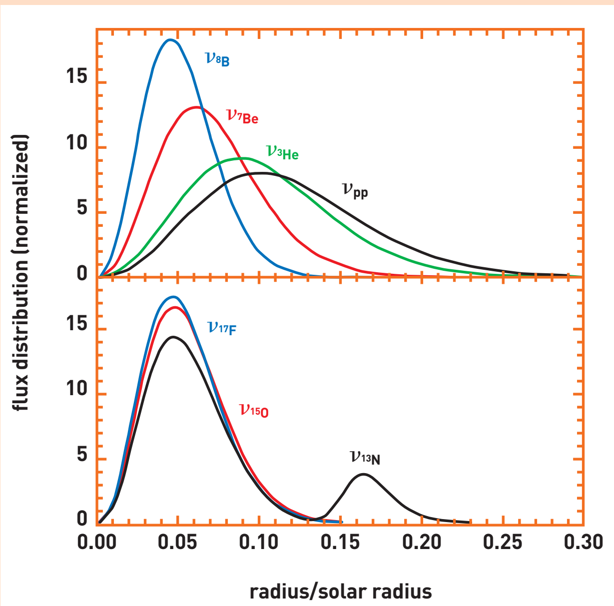
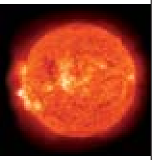
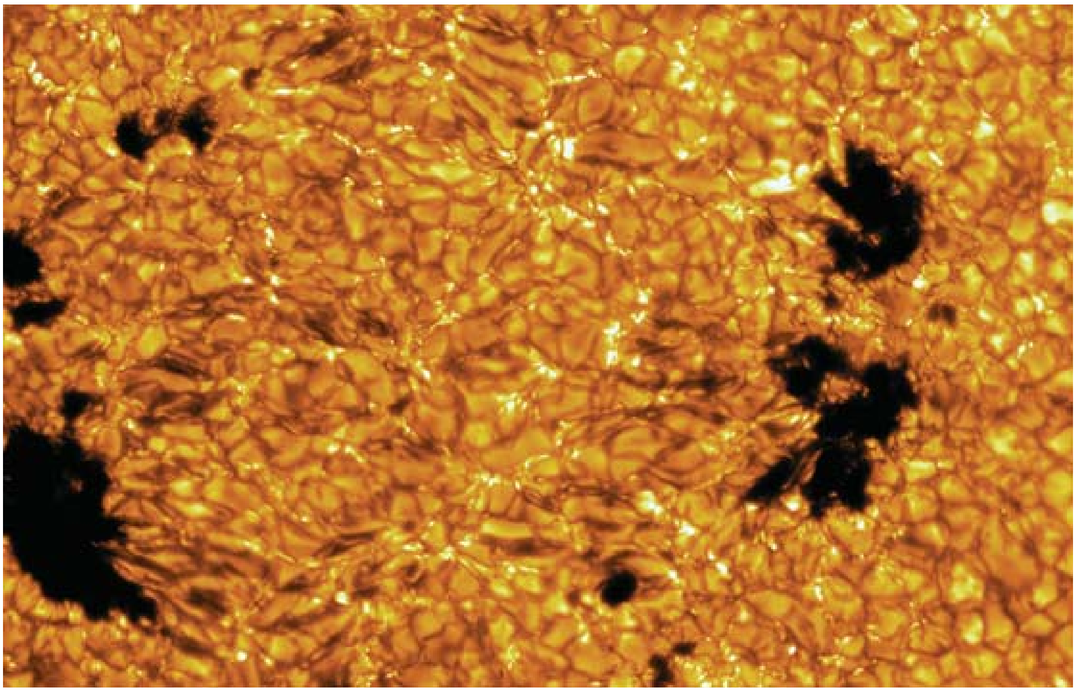


Figure a.
Emission region for neutrinos associated with the pp, e$^-$ + ^{7}Be, p + ^{7}Be, ^{3}He + p reactions inside the Sun. Other neutrinos are released by the CNO cycle, linked to elements ^{13}N, ^{15}O and ^{17}F. Except for those corresponding to the fundamental pp reaction, all are emitted close to the Sun's center.

The agreement with SNO is remarkable. Such good agreement is due to the unique ability of this heavy-water detector to count the three flavors of neutrinos, so the corresponding number includes in the comparison the fact that electron neutrinos transform into another flavor. Adding the three flavors, agreement between prediction and detection is outstanding. The Japanese Super-Kamiokande light-water facility does not have that ability, and the shortfall compared to prediction is apparent (see *Solar neutrinos: a puzzle finally solved*). Recently, another ingredient in the model was altered: oxygen content was scaled down by 30%, which has a real impact on central temperature, two nuclear reaction rates have been reestimated. However, neutrino flux having been determined by seismology, our predictions have been only slightly modified and stay in extremely good agreement with all the neutrino detections, if we introduce a reduction of flux due to the disappearance of electronic neutrino (deduced from the different experiments) when only this flavor is detected as it is the case in gallium and chlorine detectors (see Table). The Sun is a veritable laboratory for complex physics, which also contributes probing the neutrino's properties.





Lockheed Martin Solar and Astrophysics Laboratory/Tom Berger

The Sun's surface exhibits a granulated aspect. Millions of gas granules, heated to a temperature of several thousand degrees, are subject to agitation, inducing waves that propagate inside the Sun. In this region, darker spots appear, corresponding to **active regions**.

one flavour into another, and thus have mass (<u>see *Solar neutrinos: a puzzle finally solved*</u>). Interaction between these two disciplines is ongoing. It is currently focused on neutrino transport in matter with possible electromagnetic interactions, or on **spin**-resonance processes that could be associated with sharp density discontinuities in various solar regions and also to the search of dark matter (or neutralinos) in the central part of the Sun. A European network is being set up to resolve these new issues, as also further issues, linked to another neutrino source: **supernovae**.

From a microscopic to a macroscopic view of the Sun

It took less than a century to formulate hypotheses on the way stars function, put them into equations, compute the ensemble of internal thermodynamic quantities, and verify them with great accuracy for the specific instance provided by the Sun. Taken together, these results provide a stable foundation for all stars. The so-called "microscopic" view, concerning itself with the infinitely small, referred back to the tremendous size of a star, has been mastered. In this representation, the star leads a separate inner life, independent from its turbulent, **eruptive** outside life, showing as it does calmer periods, and more convulsive ones. Stellar modeling was built up in economical fashion, by ignoring two essential ingredients: the rotation, and the **magnetic field**. Indeed, as the Sun's rotation is slow - one full rotation in 28 days - asphericity deformations remain minimal. This, however, does not allow a unified vision of the Sun to be achieved, nor a proper understanding of young stars or of the explosion stages, for which consideration of such processes is a prerequisite. Moreover, the Earth is affected by the phenomena occurring on the Sun's surface.

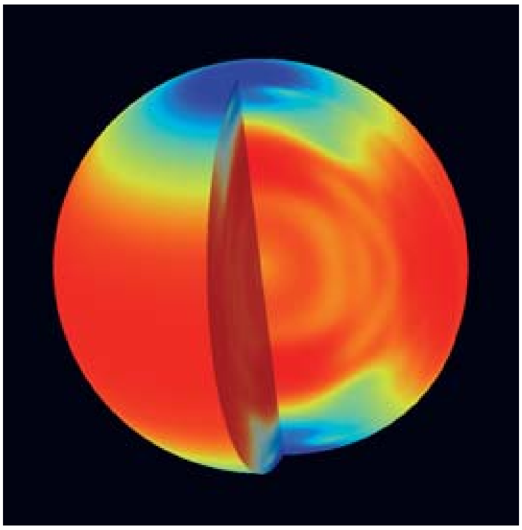
Hence, it is imperative to endeavor, as of now, to define the "macroscopic" view of the Sun, changing over periods that are not to be counted in billions of years, but in hours, days or years. Helioseismology was to enable this conceptual leap, by seeking below the surface the source of those phenomena that had been observed for over three centuries, whether on the surface or in the corona. In the 17th century, French astronomer and geodesist (and clergyman) *abbé* Jean Picard would count every day the number of **sunspots** appearing on the Sun's surface. Nowadays, scientists seek to understand why these darker regions have a more intense magnetic field than the surrounding areas, and why the spots migrate from the polar regions to the equator (<u>see *Magnetohydrodynamic simulations of the Sun*</u>). First, however, such internal motions must be measured.

Rotation of the convective region

According to whether the acoustic wave propagates in the direction of the Sun's rotation, or in the opposite direction, mode frequency will be altered. Rather than having a single value, this mode will show up as a multiplet, and the distance between the components will carry information, not only as to surface rotation, but also internal rotation traversed by the wave (<u>see *Solar seismic measurements*</u>). From the great number of modes observed, and the time these modes spend in the less dense regions, it is possible to extract the rotation profile according to latitude, for the convective region (<u>see Figure 3</u>).

Differential rotation at the surface (25 days at the equator, 35 days at the poles), clearly evidenced by the sunspots, extends to the entire convective region. This finding had in no way been anticipated theoretically. Scientists believed rotation to be dependent on distance from the center, and flow of matter, in the convective region, to be laminar. (4) The new finding, the outcome of the US MDI experiment, thus entails strong constraints on the interaction between rotation, convection and **turbulence**. Further, helioseismology has highlighted a region, known as the **tachocline**, where there is an abrupt change from convective differential

(4) Laminar flow: a flow where the layers, or laminae, of the fluid glide one against the other, with no particle exchange between layers.



SOHO (ESA-NASA)-Stanford University

Image obtained from the MDI instrument, mounted in SOHO, exhibiting in schematic form differential rotation of the Sun's surface. Higher velocities are shown in red, slower velocities in dark blue. It is apparent that the equatorial band is rotating faster than the poles.

rotation to radiative rigid rotation. This region corresponds to a horizontal-shear zone, resulting in element mixing. Introducing this hydrodynamic instability into the structural equations restricts the mainly gravitational diffusion described above, enabling photospheric helium abundance, as obtained from acoustic modes, to be perfectly reproduced, as shown in Table 1. This transition region is thus, as of now, "visible" macroscopically. It should be added that it appears to exhibit a periodic behavior, as yet unexplained, over a time interval of some one year and a few months. This transition, crucial as it is for the understanding of the **dynamo effect**, inside the Sun, sustains and reorganizes the magnetic field, causing the cyclic, eruptive processes observed on the Sun's surface, with a switch in polarity between poles every 11 years. Seismic observation of internal rotation thus contributes to the understanding of dynamic surface processes.

Rotation of the radiative region

The dynamics of the radiative region is harder to extract, since the number of acoustic modes penetrating into that region is smaller, as is the number of components of the multiplets. Moreover, stochastic (5) excitation makes extraction of information difficult, over limited observation spans. However, observations amassed over twenty years and instrument-based comparisons made it possible to obtain, incontrovertibly, the rotation profile for the radiative region. Five years' accumulated data from SOHO with the GOLF instrument gave the ability to use only low-frequency modes, exhibiting weak perturbation from stochastic excitation and the effects of the **solar cycle**. The outcome is the finding that the radiative region rotates rigidly, in uniform fashion, right to the edge of the nuclear core, with a period of some 27 days, i.e. a value intermediate between that for the poles and the equator (see Figure 3).
Bearing in mind that young stars rotate much faster than the Sun does presently, such a profile entails strong constraints on the loss of angular momentum (6) over the Sun's lifetime. It would seem that the main agent responsible for this profile is the magnetic field. Which also allows an upper limit to be set for its current value: no higher than a few hundred megagauss (MG) at the center of the radiative region.
In the nuclear region, measurement uncertainties are of the same order of magnitude as the information originating from the region considered. A full picture of rotation thus requires detection of gravity modes, exhibiting as they do very high sensitivity to this region. Measuring the components of just 2 or 3 of these modes would already allow an answer to be given to a number of major questions.

(5) Stochastic: involving one or more random variables.

(6) Angular momentum: product of mass by rotation speed by distance to the axis of rotation.

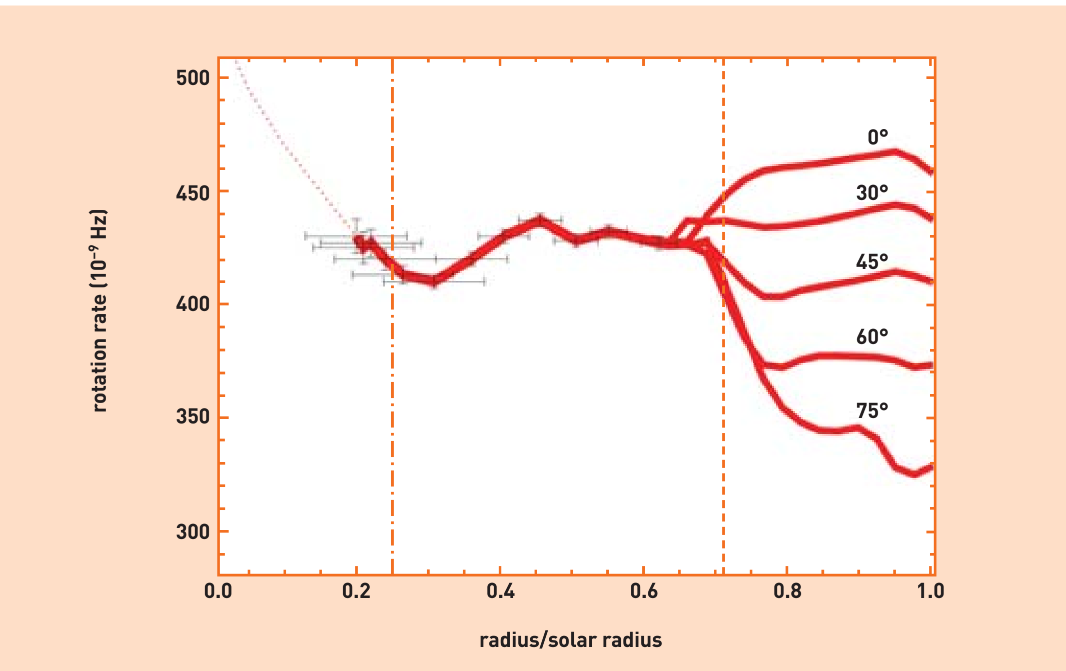


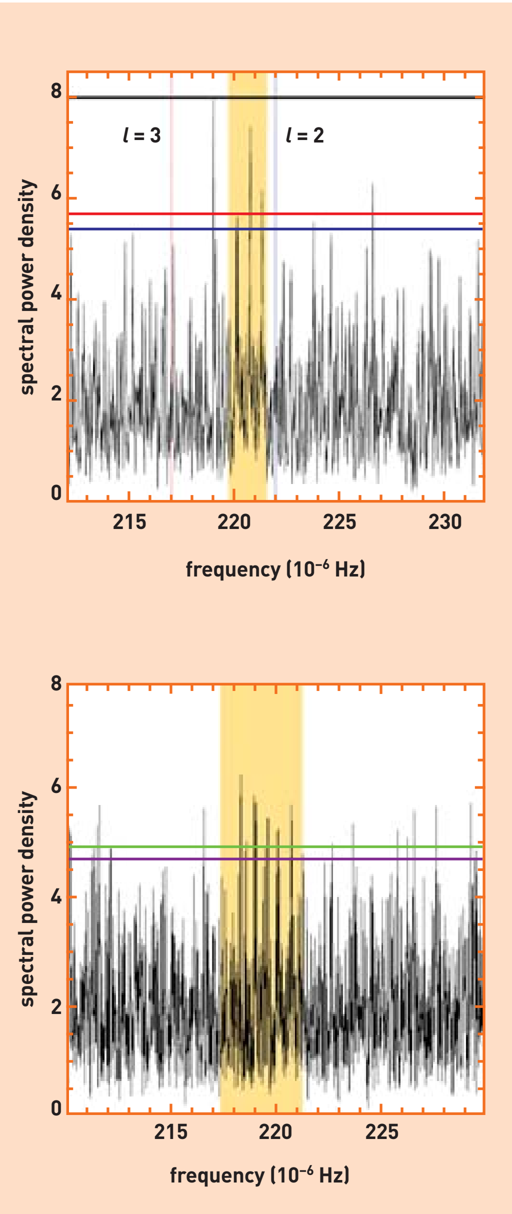
Figure from the MDI and GOLF experiments

Figure 3.
Rotation speed as a function of radius inside the Sun. In the outermost segments, rotation speed depends on latitude, this being specified for each curve. Below the tachocline (0.7 solar radius), the radiative region exhibits uniform, rigid rotation. An increase of the rotation in the nuclear core is not excluded by the present gravity mode observations.

Gravity modes

These waves, which as a whole remain trapped in the radiative region, exhibit a vanishing behavior in the convective region. Thus, at the level of the photosphere, their velocity is very low, making detection highly difficult. Endeavors pursued over the past twenty years with ground-based instrument networks remained unsuccessful. The SOHO satellite thus represents an exceptional opportunity, due to its being positioned at **Lagrangian point L1**, where temperature and **radiation** conditions are very stable, as well as to its longevity - some 11 years - and the presence on board of three seismology instruments carrying out continuous observation of the Sun.

No detection has been logged, to which any confidence could be attached, in the quest for single peaks. That for multiplets is more promising, since it lowers the detection threshold, and has the potential of yielding information on core rotation. Current efforts have allowed identification, with confidence levels of over 90%, of candidate structures for gravity modes (see Figure 4). Velocities measured are as low as 2 mm/s on the surface of the Sun. At such velocities, this is tantamount to identifying, from the Earth, a swinging cherry on the surface of the Moon. Hence, observational conditions, in such an investigation, are of paramount importance. As a matter of fact, at the Lagrangian point, the greatest perturbing agent is the Sun itself, since surface granulation and solar activity perturb measurements. For which reasons astrophysicists at CEA are hopeful they can confirm, or dismiss, these possible detections in quiet solar conditions, before SOHO is halted - this being scheduled for 2007-2008 - once solar activity decreases (next mimimum in 2007). Currently identified signatures relate to signals that have been present for 5 years. Were they to be validated, they would provide evidence for a rapidly rotating central core, with an axis inclined at a different angle than the rest of the star. Such a finding would open up a new page in solar history, for the nuclear core would thus have preserved some traces of initial conditions. This is both an exciting field of investigation for the years ahead, and equally an opportunity for all the engineers and technicians of capping this success by building a new generation of instruments, of even higher performance, to measure the nuclear core's dynamics over time…



Turck-Chièze et al. in *Astrophysical Journal*, 20 March 2004

Figure 4.
One of the candidates for gravity modes, detected with 90% confidence as a triplet, after 1,200 days' observation (bottom figure, orange and blue lines), then as a quintuplet after 2,000 days (bottom figure, green and purple lines). In the top figure, theoretical positions for 2 gravity modes of **degrees** $l = 2$ and $l = 3$, corresponding to the seismic model, are shown superimposed.

Towards modeling at different scales

Astrophysicists at CEA are currently looking to **modeling** the different scales involved in a star's history, through numerical simulations with large, **massively parallel computers**. However, other space projects are taking shape, in particular the ILWS (International Living With a Star) program, and the European Solar Orbiter satellite, for which collaborations involving US and European teams may be set up. The ensemble of microscopic and macroscopic processes will then be quantitatively measured, and set into equations. For obvious reasons, namely intimate knowledge of the solar plasma, CEA teams have been strongly engaged over the past twenty years, and will remain major protagonists in this page in the history of science.

The relationship between Earth and Sun

The Sun interacts with the Earth, and particles released during powerful **eruptions** may interfere with electrical installations, or orbiting vehicles. While it is clearly established that the Earth's mean temperature, some 16-17 °C, is directly linked to the energy sent out by the Sun, the part the latter plays with regard to current climate is poorly understood as of now. Of 1,365 **W**/m^2 emitted, the amount reaching the ground, ultimately, is 240 W/m^2. Cyclical variations in the Earth's temperature have been found in the past, and have been directly attributed to effects due to the Earth's orbit around the Sun (see *When the Sun meets the Earth*). The current issue is whether there are other sources of variation originating in the Sun. Since the Sun started burning hydrogen, solar luminosity has increased by 30% over 4.6 billion years, and thus, in human terms, changes to be expected over 100 years are negligible. That is why scientists speak of the "solar constant," which for over ten years has undergone systematic measurement. A variation in energy has been found, of the order of 1 watt over the 11-year cycle. This phenomenon is due, in part, to redistribution of energy in the convective region, in the form of magnetic and mechanical energy, this being accompanied by movements of matter, and the presence of **faculae** close to the sunspots.

A number of issues are beginning to be raised. How does differential rotation change over time? What variation does the magnetic energy escaping from the Sun exhibit? Has it varied by a factor of 2 over 100 years, as current measurements would seem to suggest? Does this have an impact on climate? What is the actual interaction between charged particles released during **coronal mass ejections** and the Earth's **magnetosphere**? Do these particles significantly alter the composition of clouds in the upper atmosphere?

These questions may not be answered as of now, however all the techniques relevant to supplying parts of the answers are available. Be that as it may, it also seems reasonable to assume some recent climate changes may be attributed to emissions on Earth, which thus require curtailing with some urgency.

Some crucial observations will come from the instruments mounted on SOHO, and on the four Cluster satellites investigating the Earth's magnetosphere. The observational strategy has now been defined, and theoretical and numerical support is being set up (see *Magnetohydrodynamic simulations of the Sun*), to answer these questions over a timescale of ten to twenty years. One reality to be dealt with is that the Sun has a major impact on communications, and the ever-more sensitive technology being developed. SOHO is the first satellite to provide information, on a daily basis, on "solar meteorology," with specifications of solar wind speeds, and matter ejections that may be associated on Earth, 2 or 3 days later, to motions of our own magnetosphere, and to Northern lights, or **aurora borealis**.[7] Astronauts and pilots are certainly not the only ones to have an interest in these matters…

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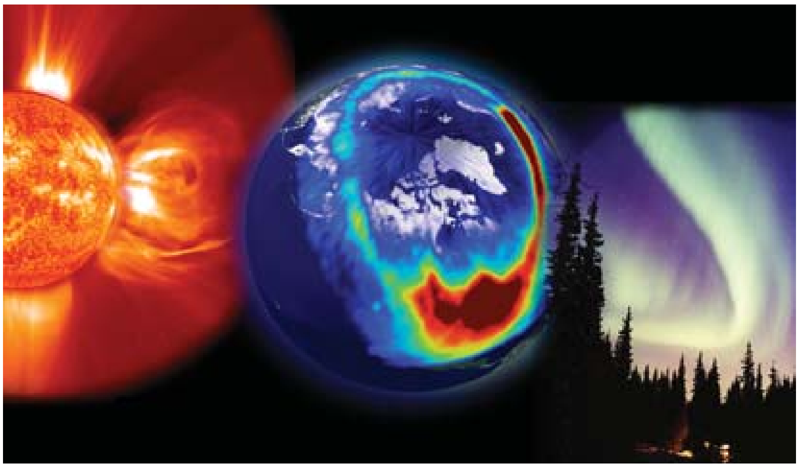
(7) For further information, see the website: http://sohowww.estec.esa.nl/.



SOHO (ESA-NASA)

Solar activity, interfering as it does with telecommunications and causing unusual aurora borealis phenomena, may have more important consequences on Earth, such as climate modification, or bringing about ice ages.

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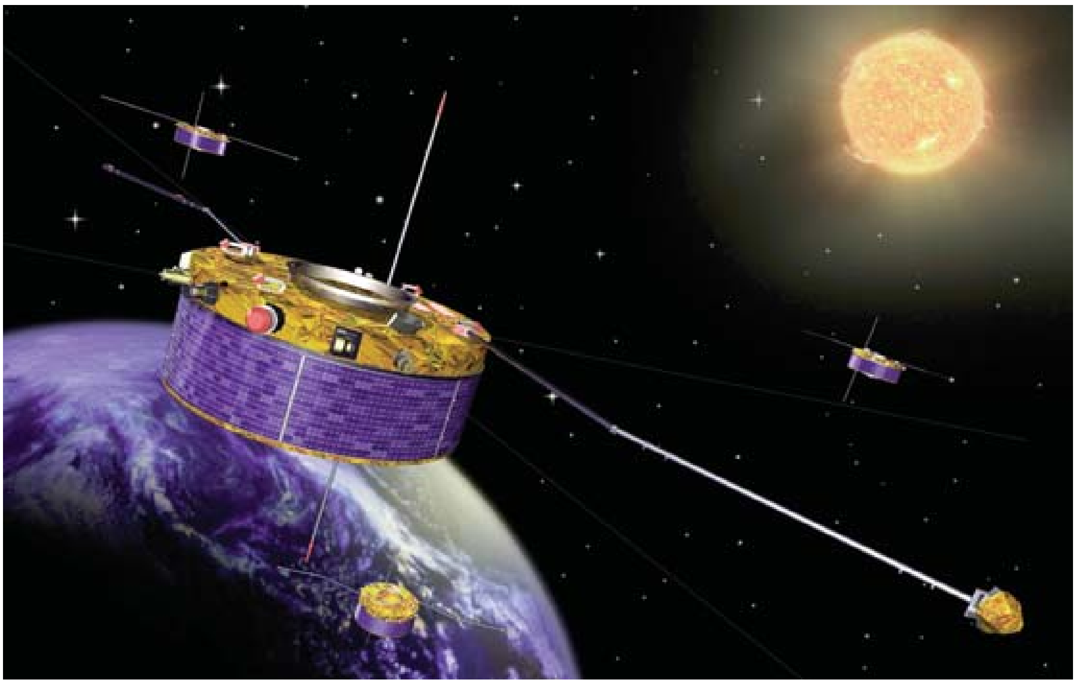


ESA

The four European Cluster satellites, launched in 2000, are intended to investigate the Earth's magnetosphere, and interactions of the solar wind and coronal mass ejections with it.

A Spotlight on the Sun

The largest object in the solar system, the Sun accounts for some 99.8% of its total mass. Initially consisting in over 70% hydrogen and more than 25% helium, the Sun is a huge rotating gas ball.

The Sun's internal structure comprises four distinct regions (see Figure). The core, where the prevailing temperature and density conditions are extreme, is host to numerous nuclear reactions, turning hydrogen into helium. The energy released will end up as visible light at the surface.

In the radiative region, extending from the core to a distance equal to 0.71 of the solar radius, energy is transported to the Sun's surface through photon-matter interaction (radiative transport). Photons are absorbed and re-emitted millions of times in countless collisions with the atoms they encounter, which are highly ionized. It takes over one million years for photons to reach the tachocline, which is a thin transition layer, between the radiative and convective regions, that plays an essential part in the solar magnetic field.

In the convective region, owing to the lower temperature, the environment, consisting in partly-ionized atoms and neutral atoms, is more opaque. The photons' progression becomes arduous. Moreover, local density varies by a factor of one million between base and surface. Such steep temperature and density gradients cause convective motions that are observable on the surface, such as the granules (with a life span is of the order of a few minutes), or the supergranules, with sizes of the order of 1,000 km and 35,000 km respectively.

The solar atmosphere comprises four regions (see Figure). The surface, or photosphere, only some 400 km deep and with a temperature close to 5,800 K, thus presents a granulated aspect, featuring more or less dark areas. Darker areas, known as sunspots, occurring singly or in clusters, are at a temperature of 3,800 K. They appear to be black, owing to the difference of temperature with adjoining areas. They are subject to an 11-year cycle, and are associated to regions where the magnetic field is much more intense (several thousand gauss) than for the Sun as a whole (1 gauss). These sunspots may reach a diameter of 50,000 km. They can last from a few days to several months. Lighter, hotter areas, known as faculae, which may occur in isolation, but are as a rule located around clusters of sunspots, may also be observed.

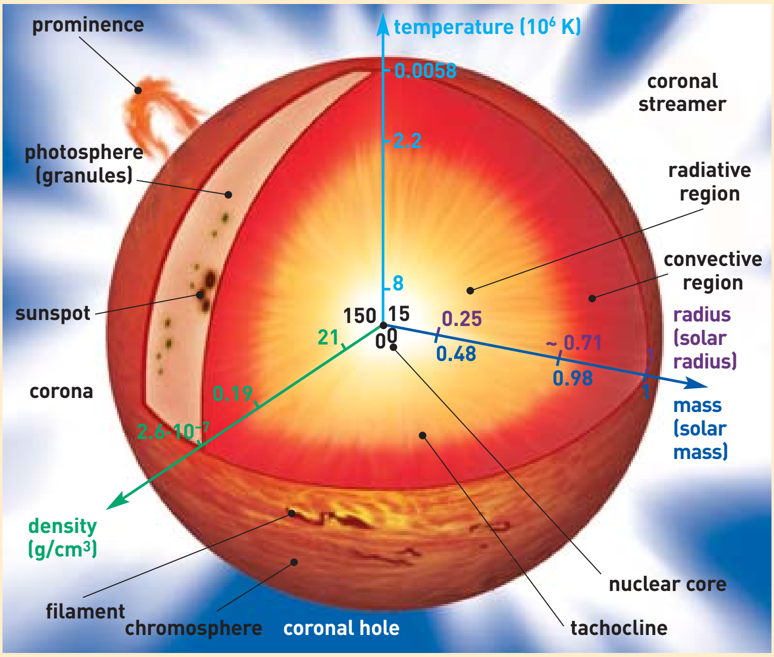


Figure.

Beyond the photosphere, extending for thousands of kilometers, is the chromosphere, where density goes on falling off rapidly, while temperature reaches 20,000 K. In this region are to be found plages, bright regions characteristic of the strong magnetic fields occurring with sunspots, prominences, or filaments (when seen against the Sun's disk), magnetic structures that are denser and cooler (10,000 K) than the surrounding medium, and spicules, small, short-lived (5-10 minutes) jets of matter shooting out towards the corona, at velocities of up to 20 km/s.

Between the chromosphere and corona lies the transition region, a thin, irregular layer where temperature rises abruptly.

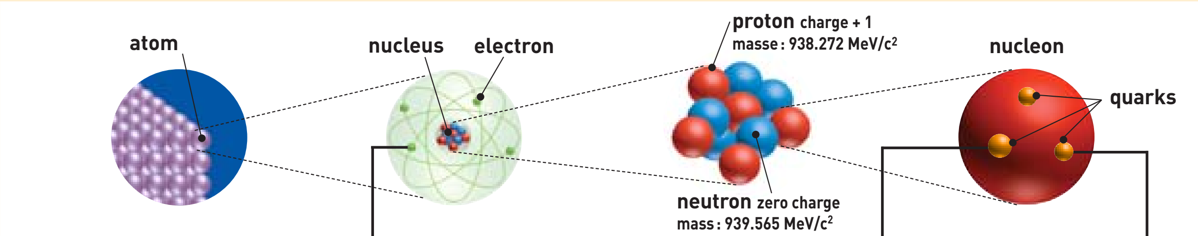
The corona, where gas is rarefied, reaches out for millions of kilometers, and is characterized by a temperature of over 1,500,000 K, and low density. It features numerous magnetic structures, or structures associated with magnetic structures, such as coronal loops, coronal holes, bright points... In this constantly-changing region, the prominences, or filaments, appear as huge plumes of hot gases, originating in the chromosphere.

Solar activity is not constant. Repeatedly, and with intensities that are cyclical, violent eruptions occur in the active regions. These are sudden releases of high-energy particles into the interplanetary environment. Such coronal mass ejections (CMEs) may on occasion attain a height of 100,000 km, for a length of 200,000 km. According to the direction in which they are ejected, the high-energy particles thus released may interact with the Earth's atmosphere.

The Sun also expels a constant flow of charged particles, mainly protons and electrons, forming a plasma, the so-called solar wind. This propagates right out of the solar system, with a velocity of some 450 km/s. The Sun thus depletes itself by about one hundred thousand-billionth of its mass every year.

C Elementary particles and fundamental interactions

Neutrinos are the stealthiest particles in the standard model of particle physics, the theoretical framework describing all known elementary particles and the fundamental interactions they mediate (see Table).
The basic constituents of matter, fermions, are partitioned into two main categories: leptons, which do not respond to strong interaction, and quarks, which are subject to all of the interactions. The six quarks form three pairs (up/down, charmed/strange, beauty/top). In the lepton category, the charged leptons (electron e^-, muon μ, tau τ) are involved in the electromagnetic interaction and the weak interaction, while neutral leptons (electron neutrino ν_e, muon neutrino ν_μ, tau neutrino ν_τ) are only subject to weak interaction. In the standard model, neutrinos have zero mass, however experiments have shown they do have some mass, though very small, the exact value of which is as yet unknown. Involvement



		leptons able to move freely		quarks held captive in larger particles, they are not observed separately	
Fermions Common matter is made up of particles from this group.	first family	**electron** Responsible for electricity and chemical reactions. Charge: – 1. mass: 0.511 MeV/c²	**electron neutrino** Has no electric charge, and interacts very seldom with the ambient medium.	**down** Electric charge: – 1/3. The proton holds one, the neutron two. mass: 5 – 8,5 MeV/c²	**up** Electric charge: + 2/3. The proton holds two, the neutron one. mass: 1,5 – 4,5 MeV/c²
	second family	**muon** A more massive companion to the electron. mass: 105,658 MeV/c²	**muon neutrino** Properties similar to those of the electron neutrino.	**strange** A heavier companion to “up.” mass: 80 – 155 MeV/c²	**charmed** A heavier companion to “down.” mass: 1 000 – 1 400 MeV/c²
Most of these particles were around just after the Big Bang. Presently only to be found in cosmic rays, and around accelerators.	third family	**tau** Heavier still. mass: 1 777 MeV/c²	**tau neutrino** Properties similar to those of the electron neutrino.	**beauty** Heavier still. mass: 4 000 – 4 500 MeV/c²	**top** Heaviest in the family (observed in 1985): 180 times the proton mass. mass: 174 300 ± 5 100 MeV/c²

Vector Bosons Fundamental particles carrying out transmission of all natural forces.	**photon** Elementary grain of light, vector for the electromagnetic force.	**gluon** Bearer of the strong force between quarks.	**$W^\pm$, Z^0** (W^+, W^-, Z^0) Bearers of the weak force, responsible for some forms of radioactive decay.

Higgs Boson? Responsible for “electroweak symmetry breaking.”

Tableau.
Constituants élémentaires.

of the various elementary constituents in the fundamental interactions is governed by their quantum numbers, or interaction charges (electric charge, color charge [(1)]...). To every constituent of matter is associated its **antiparticle**, a particle having the same mass and opposite charges. The **gravitational force**, which is not included in the standard model, acts on all fermions in proportion to their mass. The table of elementary constituents of matter manifests another classification – independently from their involvement in fundamental interactions – into three generations, or families. From one family to the next, charged quarks and leptons having the same charges only differ by their mass. The electron, up quark and down quark, which all belong to the first family, are the lightest massive particles. They are stable particles, and the constituents of common matter. For instance, the **proton** is made up of two up quarks and one down quark; the **neutron**, of two down quarks and one up quark. Particles in the other two families are unstable, and rapidly decay into stable first-generation particles. This is why all the stable matter in the Universe is made up from constituents from the first family.

According to quantum mechanics, for an interaction to take place, at least one elementary particle, a **boson**, must be emitted, absorbed or exchanged. The **photon** is the vector for the electromagnetic interaction, the **W^+**, **W^-** and **Z^0** mediate the weak interaction, and **gluons** act as messengers for the strong interaction.

Quarks and charged leptons exchange photons, but conserve their electric charge after the exchange, the photon having no electric charge. Since the photon's mass is zero, the electromagnetic interaction's range is infinite. Having no electric charge, neutrinos are the only elementary fermions that are not subject to electromagnetic interaction.

In the electroweak theory (a unification of the weak and electromagnetic interactions), the weak interaction has two aspects: charged-current weak interaction, for which the interaction vectors are the W^+ and W^-; and neutral-current weak interaction, for which the mediator is Z^0. These two forms of weak interaction are active between all elementary fermions (quarks, charged leptons and neutrinos). The mass of these bosons being very large (80,000 MeV/c^2 for $W^\pm$, 91,180 MeV/c^2 for Z^0), the range of the weak interaction is tiny – of the order of 10^{-18} m. Since $W^\pm$ bosons have a non-zero electric charge, fermions exchanging such bosons undergo a change in electric charge, as of nature (flavor). Conversely, since the Z^0 boson has no electric charge, fermions exchanging one undergo no change in nature. In effect, neutral-current weak interaction is somewhat akin to exchanging a photon. As a general rule, if two fermions are able to exchange a photon, they can also exchange a Z^0. On the other hand, a neutrino has the ability to exchange a Z^0 with another particle, though not a photon.

Only those quarks that have a color charge exchange gluons, these in turn being bearers of a color charge. Thus, when a gluon exchange takes place between quarks, the latter exchange their respective colors. Gluons have zero mass, however, since they do bear a color charge, they are able to interact. The range of the strong interaction is consequently very restricted – of the order of 10^{-15} m.

The graviton, the vector for gravitational interaction, has not so far been observed.

Theory predicts that another fundamental interaction mechanism exists, responsible for the mass of elementary particles, for which the messenger is the Higgs boson, which remains as yet undiscovered. This boson makes it possible to assign a mass to elementary fermions of zero mass that interact with it.

(1) Color charge: a quantum number that determines whether a particle is involved in strong interaction. The color charge can take on three values: "red," "green," or "blue" – such colors bearing no relation to visible colors. Every quark bears one of the three color charges, every antiquark one of the three anticolor charges. Gluons bear double color–anticolor charges (eight possible combinations).

fundamental interaction	messenger	actions
gravitational	graviton?	responsible for the mutual attraction of any two masses and for the law of falling bodies
electromagnetic	photon	responsible for the attraction between electrons and atomic nuclei, hence for the cohesion of atoms and molecules
weak	W^+, W^-, Z^0	the root cause of **thermonuclear fusion** inside the Sun, ensuring its longevity. β^- and β^+ radioactivity, and reactions involving neutrinos are weak interactions
strong	gluons	ensures the cohesion of the atomic nucleus

Table.
Fundamental interaction and elementary constituents.

One Sun, four equations

3

The Sun is a set of equations, essentially comprising four equations. These equations describe the star's equilibrium, its mass distribution, energy production, and energy transfer, from core to surface. These coupled differential equations are solved by means of powerful computers. The physical parameters (mainly initial composition, nuclear reaction rates and opacities) are worked out by entire communities of experts, astronomers and geophysicists, nuclear physicist and electronic-structure physicists. As for chemical composition, this only alters in the combusting regions: the surface remains unchanged, except for lithium.

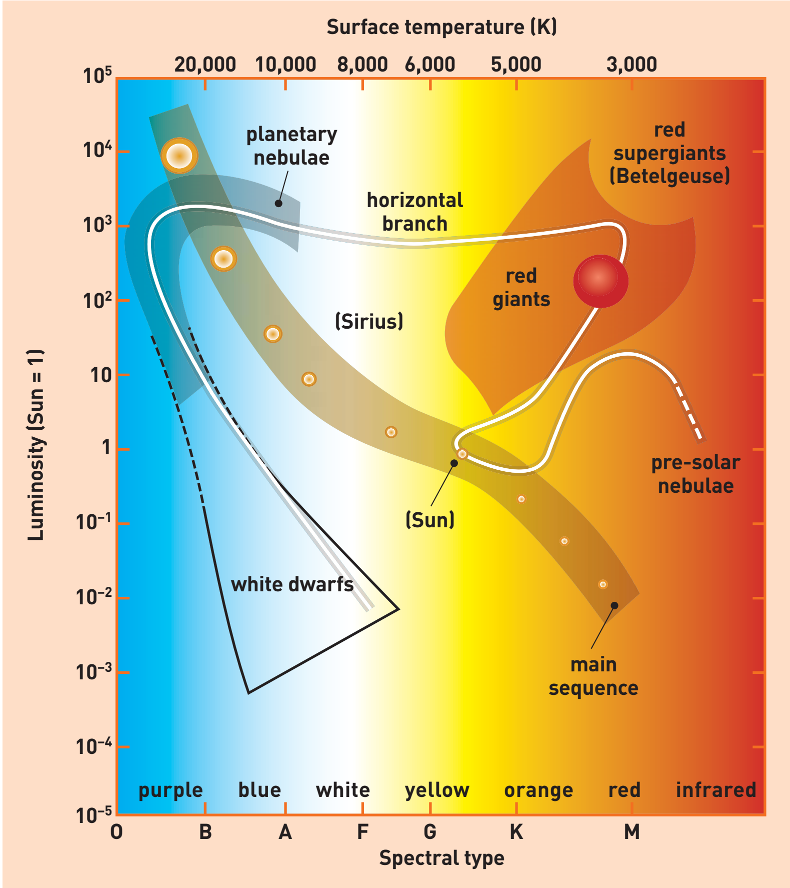


Figure 1.
The Sun is located at the very heart of the **main sequence** of the Hertzsprung–Russell diagram. Stars are classified, from hottest to coolest, on the basis of their **spectral lines**, which allow an estimate of their surface temperature. Star designations include a letter (from the sequence O, B, A, F, G, K, and M) and a digit, referring to a subdivision within the main class, followed by a Roman numeral, indicating its luminosity class. Thus, the Sun is of type G2 V, being a *yellow dwarf* of average age.

Solar nuclear reactions

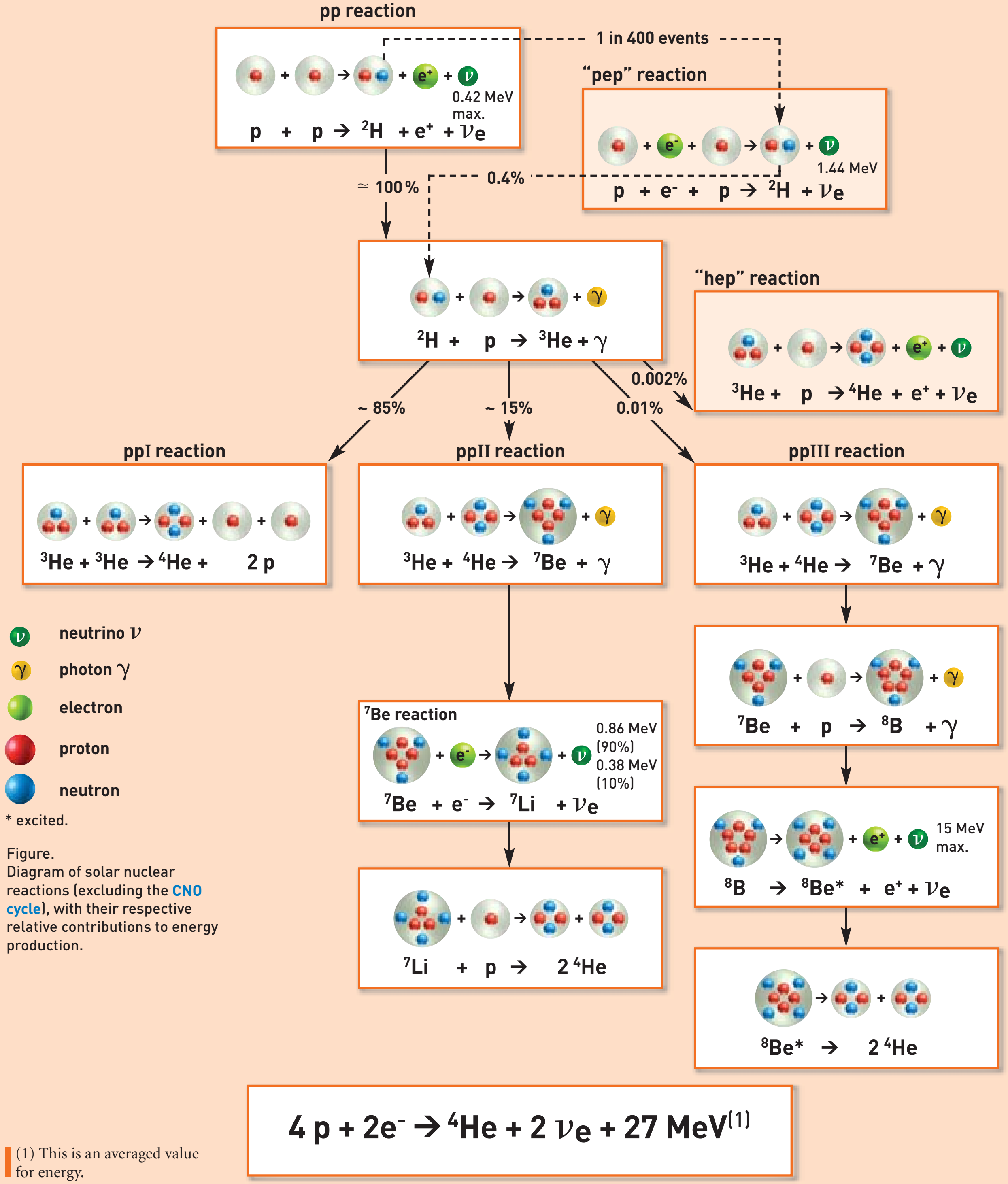


Figure.
Diagram of solar nuclear reactions (excluding the CNO cycle), with their respective relative contributions to energy production.

(1) This is an averaged value for energy.

The nuclear reactions start off with the fusion of two protons, and end in production of helium 4, one chain being by way of helium 3, the other by way of beryllium 7, this being followed, according to the reaction, by production of further light elements (lithium 7, or beryllium 8 by way of boron 8). These proton–proton reaction chains are known as ppI, ppII, and ppIII (see Figure).

In the initial basic reaction, one of the two protons transforms into a neutron through weak interaction. Conjunction of the two particles gives birth to a variety of hydrogen, deuterium (D, or ^{2}H), whose nucleus thus comprises one proton and one neutron; at the same time, one anti-electron, or positron, and one low-energy (electron) neutrino are released.

The deuterium nucleus captures a proton, yielding a helium 3 nucleus and a gamma photon. Two helium 3 nuclei react to produce one helium 4 nucleus, releasing two protons, thus available to initiate a new chain. In some 85% of instances, such is the end of the **ppI chain**. This chain is prolific in neutrinos: some 65 billion of these pass through every square centimeter of our skin in any second. However, these low-energy neutrinos are hard to detect. It took all the sensitivity of the Gallex detector and similar devices to record them (see *Solar neutrinos: a puzzle finally solved*).

In the 15% of remaining instances, one helium 3 undergoes fusion with one helium 4, yielding one beryllium 7 and one gamma photon. Then, either the beryllium 7 transforms into lithium 7 by capturing an electron, this lithium 7 in turn capturing one proton to yield two helium 4 nuclei directly (**ppII**); or, by capturing one proton, the beryllium 7 yields the same outcome indirectly, by way of boron 8, this disintegrating, with the release of a high-energy neutrino, into beryllium 8, which instantly breaks up into helium 4 (**ppIII**).

The **ppIII** chain thus ends with the disintegration of boron 8 into beryllium 8, this yielding high-energy neutrinos, greatly prized by solar-neutrino hunters.

Reaction rates inside the solar plasma must be corrected for the screening effect of free electrons (see *Static and dynamic views of the solar interior*).

The energy generated in the guise of gamma rays goes to keeping the solar furnace hot, thus precluding it from collapsing, and to making it shine. This energy, in the guise of photons, filters through to the surface. It is scattered, absorbed, re-emitted by ions and electrons. The neutrinos alone pass right through the Sun, in a straight line, this taking some two seconds.

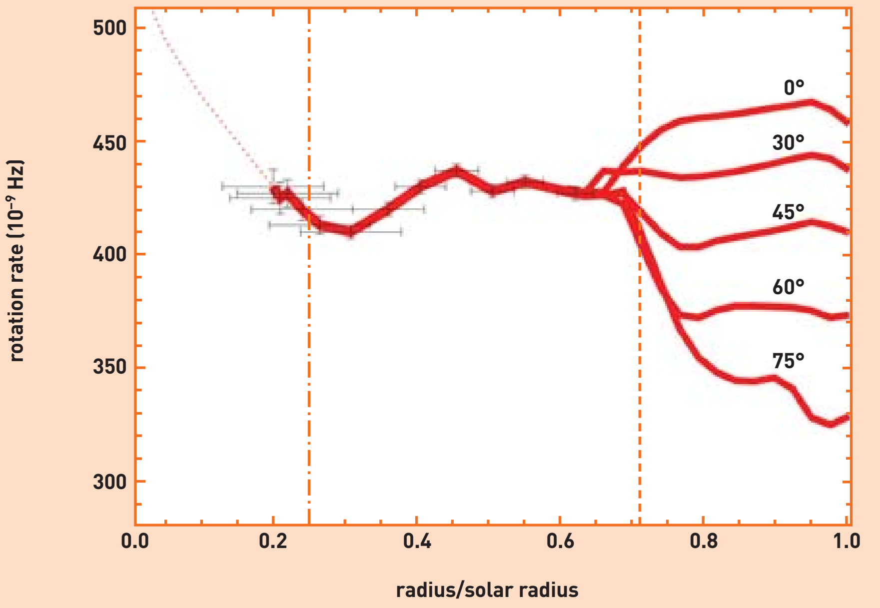


Figure from the MDI and GOLF experiments

Figure 3.
Rotation speed as a function of radius inside the Sun. In the outermost segments, rotation speed depends on latitude, this being specified for each curve. Below the tachocline (0.7 solar radius), the radiative region exhibits uniform, rigid rotation. An increase of the rotation in the nuclear core is not excluded by the present gravity mode observations.

The GOLF instrument in space: a resonance spectrometer

The best way to find out about the internal waves penetrating down to the Sun's core is through use of a resonance spectrometer. This records periodic variations in Doppler velocity (see Box B, *Tell-tale spectra*). In the case of the GOLF (Global Oscillations at Low Frequencies) instrument, mounted in the SOHO (SOlar and Heliospheric Observatory) space probe, use is made of the shift velocities of sodium lines, forming at about 500 km above the photosphere. Interference of the ensemble of acoustic waves is detected, superimposed on the displacement velocity of the Sun, relative to the observer. Then, through the Fourier transform, the frequency spectrum is obtained (see *Static and dynamic views of the solar interior*). After filtering the Sun's light around the sodium wavelengths (589 nm), the sensors count the photons resonating with those of a cell holding gaseous sodium at about 200 °C. This atomic process makes it possible to define a very narrow strip within the sodium line. Selecting a suitable entry polarization and placing the cell in a 4-kG magnetic field, a measurement is made on the left wing of the line, then, by changing polarization, on the right wing. From the count asymmetry, the Doppler velocity between the Sun and the instrument is extracted. Measurements at regular intervals (every 10 s) allow investigation of fluctuations in that velocity, and to derive from this the frequency of each mode. The greater the number of reiterated measurements, the higher the precision, since this is given by the inverse of observation time. It is thus necessary to follow the Sun constantly, either through networked instruments around the Earth (French IRIS network), or by putting into orbit an instrument such as GOLF, positioning it at Lagrangian point L1. After several years' observations, precision as to frequency stands at a few 10^{-5}, and the speed of sound is extracted to within less than 10^{-3}, making it possible to ascertain physical processes to within a few percent.

A new instrument is being built at CEA's Department of Astrophysics, Particle Physics, Nuclear Physics and Associated Instrumentation (DAPNIA: Département d'astrophysique, de physique des particules, de physique nucléaire et de l'instrumentation associée), involving the Astrophysics (SAp), Electronics, Sensors and Computer Science (SEDI) and Systems Engineering (SIS) services, in collaboration with the Bordeaux and Nice observatories (France) and the Canary Islands Institute of Astrophysics (IAC, Spain). The aim is to improve sensitivity, by a factor 10, for the instrument, in order to measure a greater number of gravity modes, and their variation over time. The goal is to achieve detection of superficial velocities of 0.1 mm/s.

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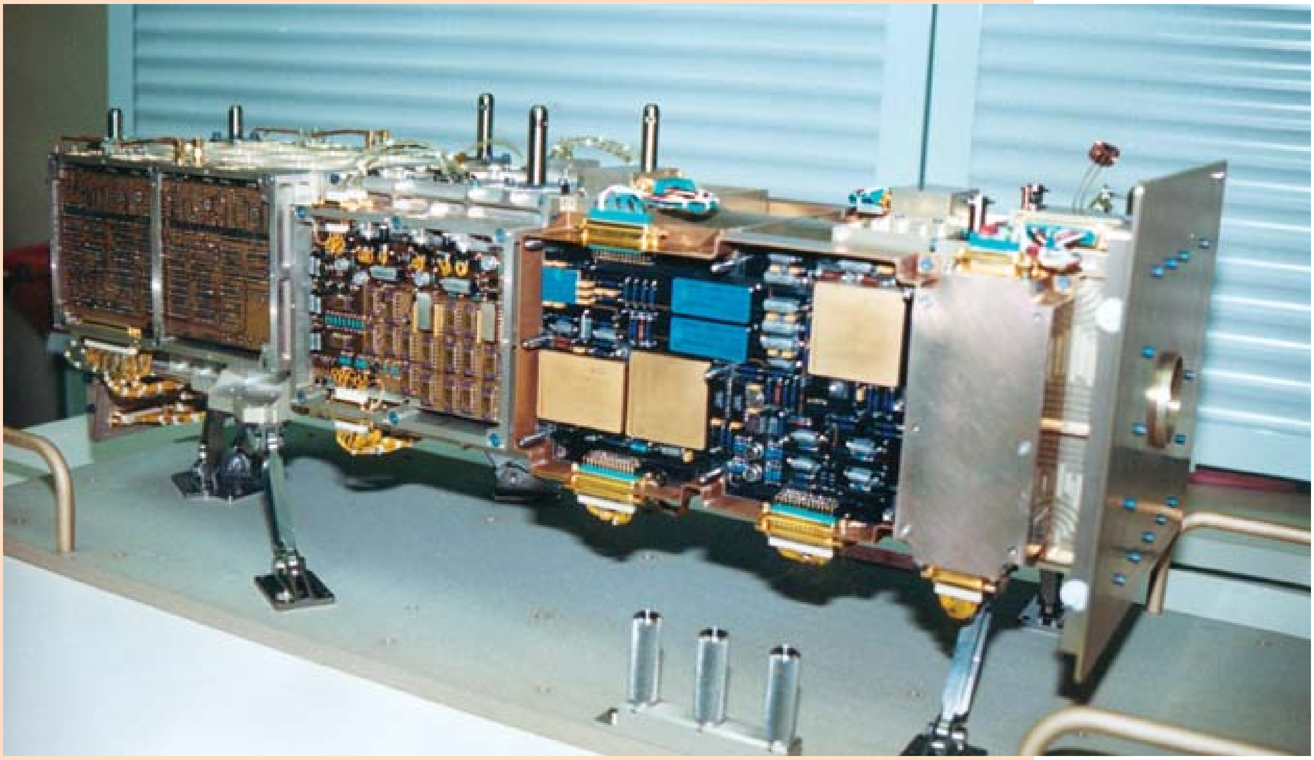

Institut d'astrophysique spatiale

The GOLF space instrument was constructed by the Space Astrophysics Institute at Orsay (near Paris), DAPNIA at CEA, the Canary Islands Astrophysics Institute (Spain), and the Bordeaux and Nice observatories (France): some fifty scientists, engineers and technicians collaborated in this. It is used for the investigation of the Sun's internal structure, by measuring the spectrum of global oscillations in the 10^{-7}–10^{-2} Hz frequency range.

Table 1. Characteristics of the seismic model.

central temperature	$T_c = 15.71 \cdot 10^6$ K
central density	$\rho_c = 153.13$ g/cm^3
hydrogen content at center	$X_c = 0.3385$ in mass fraction
surface temperature	$T_{eff} = 5,800$ K
surface helium abundance:	0.251 in mass fraction
initial helium abundance:	0.272 in mass fraction