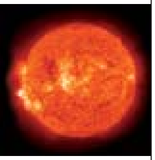
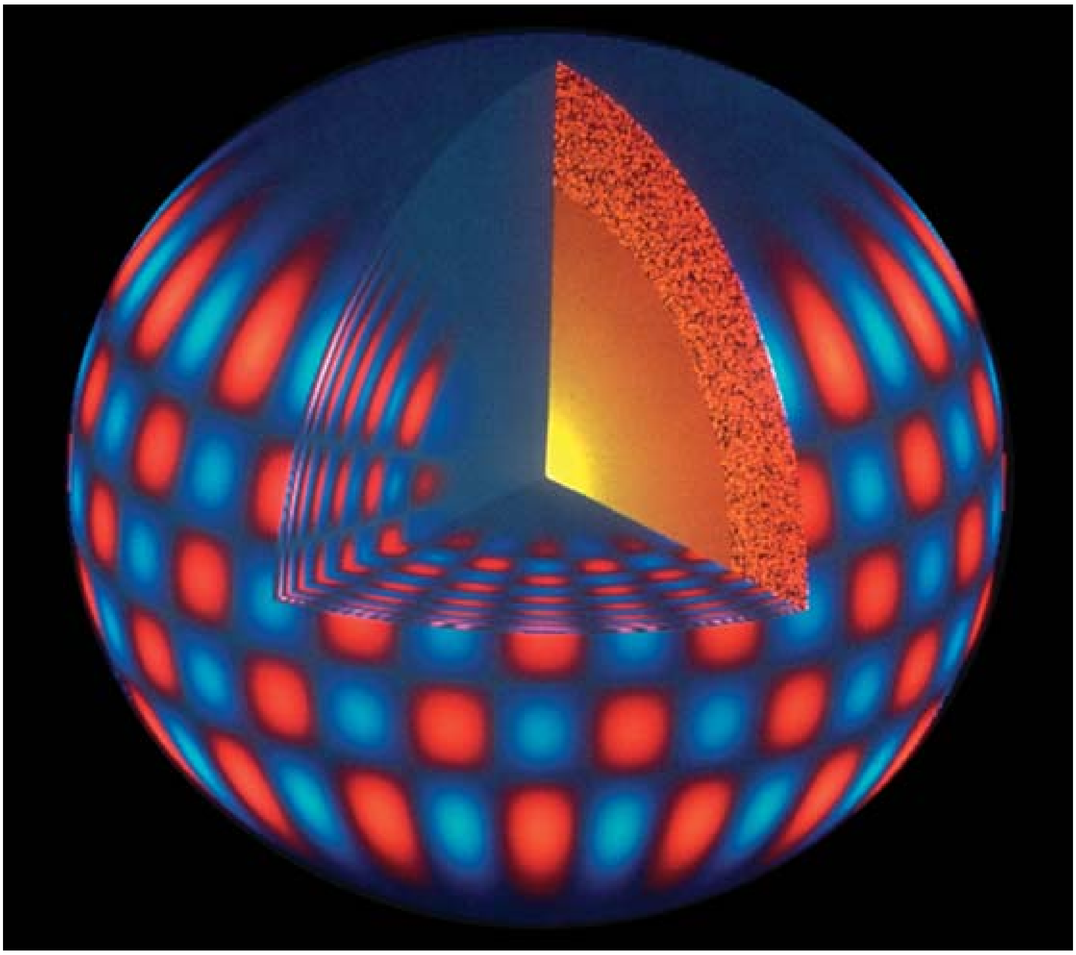


Solar seismic measurements

Rising in a few decades to the status of a fully-fledged discipline within astrophysics, helioseismology allows investigation, virtually in real time, of the Sun's interior, since acoustic waves only take about one hour to propagate from the core to a surface that is now under constant watch.



NSO/AURA/NSF

The constant motion observed on the Sun's surface is due to the combined action of millions of distinct oscillation modes. Each mode is characterized by the number of times the wave is reflected on the Sun's surface. The figure shows, in schematic form, one oscillation mode, with the regions affected by displacement towards the observer shown in blue, those receding from him being shown in red.

Investigation of the solar interior cannot proceed by looking at the **electromagnetic radiation** emitted by the Sun's surface. Admittedly, that light only takes 8 minutes to reach the Earth, however, it will first have taken it several million years to cross the 700,000 km separating the Sun's center from the **photosphere**, owing to the extreme **opacity** of the matter it has to traverse. The light we receive, after so long a journey, has thus lost all information as to its origins, and the layers encountered. Exploration of the solar interior, however, is made possible by the existence of acoustic waves that propagate from the surface right down to the **core**, this taking about 1 hour. The first observation of such waves dates from 1962, though it was not until the 1970s that their nature was understood, and that a new discipline arose, focusing on their investigation: **helioseismology**.

Wave generation

The astrophysicist is faced with a similar problem to that of the geophysicists, when they seek to investigate the Earth's interior. "Terrestrial" seismologists make use of the seismic waves travelling through the Earth as a source of information on the Earth's internal structure. The seismic waves known as *P waves* are of the same kind as sound waves: these are waves that propagate by compressing, then decompressing in turn the medium in which they travel. Consequently, seismologists speak of compression waves, or acoustic waves, or even sound waves. Solar acoustic waves are likewise termed *P waves*. However, there is no solid crust on the Sun's surface, liable to rupture as a result of the deformations generated by seismic events. In contrasting fashion, the Sun's photosphere undergoes local oscillation as a result of the waves reflecting on it. It is these oscillations of the photosphere that are detected. They yield information about the waves propagating inside the Sun.

Excitation of these acoustic waves is due to **convection**. In the outermost 30% of the Sun's radius, the **plasma** is churned violently by macroscopic movements of matter, convective motion. The energy generated by nuclear **fusion** in the core, enabling the Sun to shine, is not transmitted solely by electromagnetic radiation: it is essentially transported by convection in this outer region, commonly known as the **convective region**. These convective motions cause the well-known surface **granulation**, clearly seen in telescopes, giving that "orange peel" aspect to the photosphere. These motions are similar to those stirring the boiling water in a heating pan of water. The convection cells inside the Sun "hit" the surface, thus generating acoustic waves that go on to propagate inside the **star**, just as raindrops beating on a drumskin make a noise. Conversely to what happens with electromagnetic waves, these sound waves propagate from the surface to the core, making the journey in a little less than an hour (*acoustic ray*), thus providing information on the Sun virtually in "real time." This is because the speed of sound inside the Sun, being proportional to the square root of temperature, ranges from 7 km/s near the surface to 510 km/s in the core; high velocities, compared to the value found on Earth (barely 340 m/s in the atmosphere).

A musical analogy

The Sun is an awesome musical instrument. Just as a piano string only gives sounds of certain precise frequencies (the fundamental tone, and its harmonics), only certain waves are "allowed" inside the Sun, which acts as a resonant cavity. Waves of the appropriate frequencies are *oscillation modes*, vibrating for several days, or even several years (these being standing waves). Other waves are doomed to vanish quickly. Convection, acting as a piano hammer striking the string, is the excitation source for these modes. Now, to take our cue from the trombone. The player, adjusting, by means of the slide, the length of the air column inside the instrument, produces sounds of varying frequencies. The greater the length, the lower the note. Anybody caring to visualize the Sun as a cavity inside which sound waves propagate, with a volume one million three hundred times larger than the Earth's, will grasp intuitively that the Sun's acoustic waves must be of very low frequencies.
Thus, the Sun produces sound waves separated by 17 octaves from the middle La (A) note of a piano, tuned at 440 Hz, i.e. waves with frequencies centered around 3 mHz (corresponding to a period of 5 minutes). Now, think of the way it takes a few minutes to identify a musical number and the instruments playing in it. In analogous fashion, when it comes to the Sun, since its frequencies are some 150,000 times lower, it takes a much longer "listening" time to begin to extract some information: about one year's uninterrupted "listening."

Characterizing a sphere's oscillation modes

The Sun, however, is far more complex than a musical instrument, mainly because it is a three-dimensional, spherical object. Oscillation modes, then, cannot be characterized by a single number, they require two, designated as n (radial order) and l (harmonic degree of the mode). Order n is the number of nodes in the radial direction, i.e. the number of times wave amplitude vanishes to 0 between the surface and the Sun's center. **Degree** l corresponds to the number of node lines on the surface, in other words the number of times the mode is reflected on the Sun's surface. In the case of a guitar string, this being fixed at both ends, the oscillation modes are wholly determined by the sole given n, corresponding to the fundamental tone and its harmonics.
Furthermore, the Sun rotates, and thus exhibits a privileged axis of symmetry, namely its axis of rotation. For oscillations to be fully characterized, presence of this axis entails that a further number must be introduced, azimuthal order m, standing for the number of surface node lines perpendicular to the equator (see Figure 1).

Propagation of acoustic waves

Sound waves yield information on the Sun's structure, and its physics. In this respect, a number of quantities must be considered: the waves' frequency,

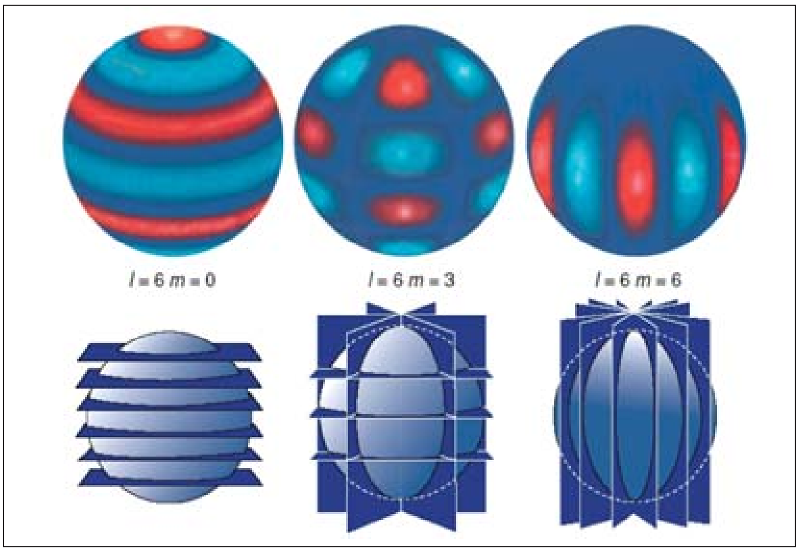
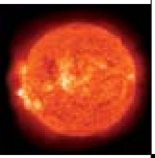
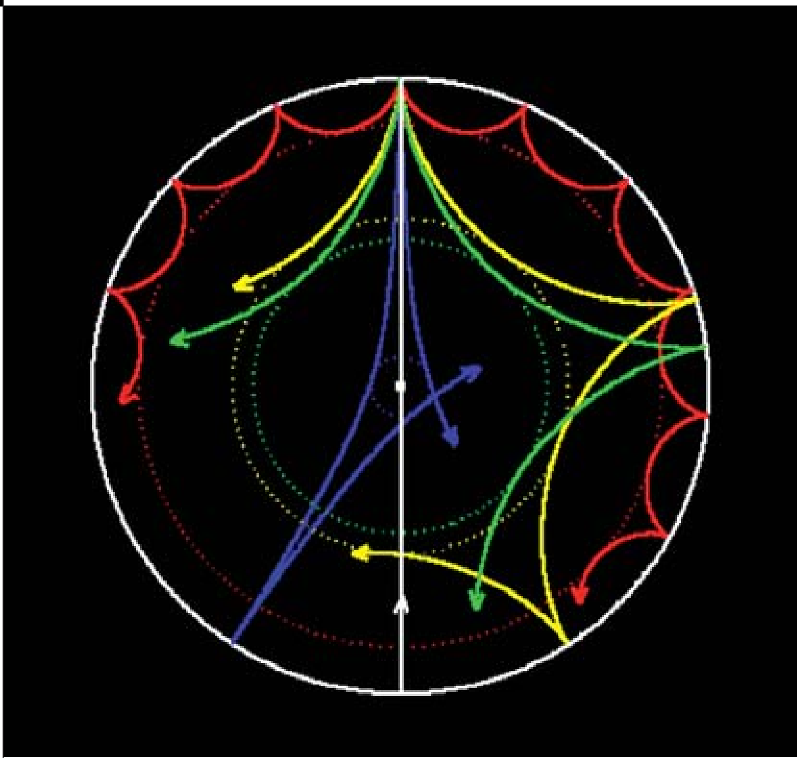


Figure 1.
Example of three oscillation modes.

their amplitude, and their damping rate, i.e. the amount of energy they lose every second, which determines their life span. The information carried by these waves also depends on their path inside the Sun. They are generated on the Sun's surface by convective motions, going on to propagate towards the star's center.
Temperature rises as the waves get closer to that center, and they become gradually refracted (i.e. their path becomes increasingly curved), up to the point where they are undergo total reflection. This reflection is due to the way sound wave velocity depends on the temperature of the medium in which the wave travels. After reflection, waves return to the surface, which they reach at a point different from their starting point, then turn back towards the center, and so on. They can thus complete "grand tours" around the Sun. This representation of the waves' propagation, however, is but an approximate one, since these waves are in fact spherical waves. The setting up of oscillation modes from such waves may be roughly understood in the following fashion: excitation of waves by convective motions being a permanent process, a wave that has completed its "tour around the Sun" and comes back to its starting point interacts with a freshly-excited wave. This interference may be constructive, or destructive. Either the incoming wave reinforces the freshly-excited wave, or they mutually destroy one another. Only oscillations of the right frequencies give rise to constructive interference, and turn into oscillation modes. Such cons-

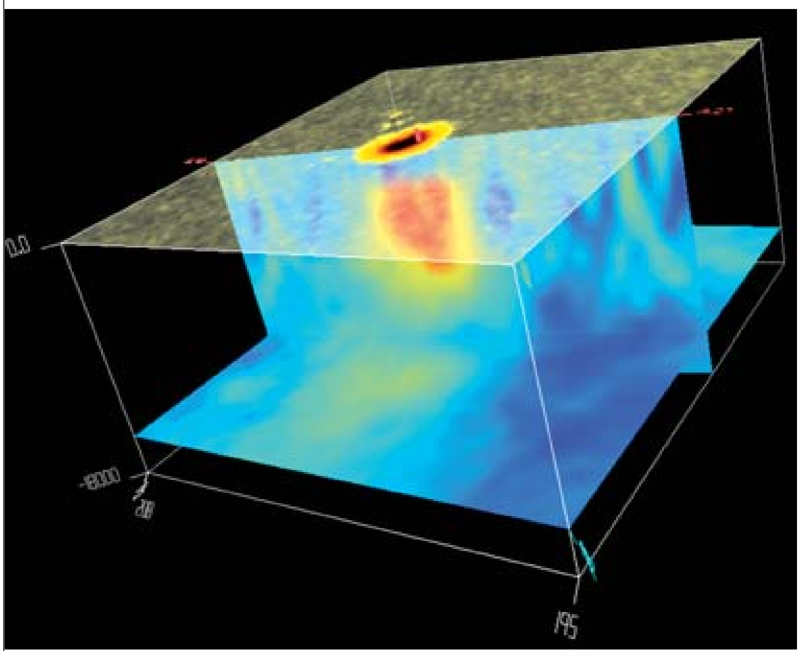




ESA

Propagation of acoustic waves. Some waves, of a more tangential kind, remain near the surface and a reflected at many points on the sphere. Others, with a more radial orientation, reach the Sun's center.

tructive interference ensures a "decent" life span for these modes, as opposed to the other waves, which are destined to vanish swiftly. These modes are trapped inside a cavity delimited, on the outside, by the Sun's surface and, on the inside, by a sphere centered on the Sun's center, having a radius equal to the distance at which the mode undergoes reflection (*lower turning point*).



MDI Stanford University-SOHO (ESA-NASA)

Figure 2.
Speed of sound profile under a sunspot, obtained by the MDI instrument. The regions where the speed of sound is higher are shown in red, those where it is lower in blue.

If each mode can be characterized by its degree *l* and order *n*, then several thousand have been detected, with due precision, on the Sun's surface. The relevance of that number is that, since each mode propagates along a different "itinerary" inside the Sun, the greater the number of oscillations researchers may access, the more complete a cover of the solar interior they can achieve. Due to the absence of certain modes, some regions of the Sun remain inaccessible. For a given degree *l*, the greater a mode's radial order *n*, the deeper it penetrates into the Sun before it is reflected (its lower turning point is closer to the core). Likewise, for a given *n*, the smaller *l* is, the closer the lower turning point is to the Sun's center (see Box).

From waves to internal structure

The method most commonly used to recover the Sun's internal structure, from a sufficient number of observed modes, is the so-called *inverse-problem* method. Physicists set about this in the following fashion: they have access, for instance, to a number of oscillation-mode frequencies (observational findings), and equally to a computer-generated solar model, adequately representative of the actual Sun. With the help of this solar model, they predict the frequencies for the oscillation modes observed. There is a relation linking the discrepancies between observed and predicted frequencies, and the discrepancies between sound speeds in the model and inside the Sun, and between densities inside the Sun and in the model. Mathematical techniques then allow them to find the inverse for that relation, and thus to recover the actual speed of sound and density profiles inside our star. By making a further assumption as to the relation pertaining between pressure, density and temperature (equation of state), the Sun's temperature profile is then derived. Observation of oscillation modes further allows access to the Sun's rotation profile. As of now, it is still not feasible to recover solar structure for the innermost 7% of the radius (15% of mass), or rotation for the innermost 20% (nuclear core).
The past decade has seen the rise of a branch of helioseismology concerned with local solar structure. Using oscillation modes (so-called *global* oscillations) can only yield information that is averaged over longitude, and, quite often, averaged over latitude also. *Local helioseismology*, by contrast to that *global helioseismology*, is based on observation of local wave propagation. It enables investigation of localized structures such as **sunspots** (see Figure 2). These two branches of seismology are complementary, rather than incompatible or contrary.

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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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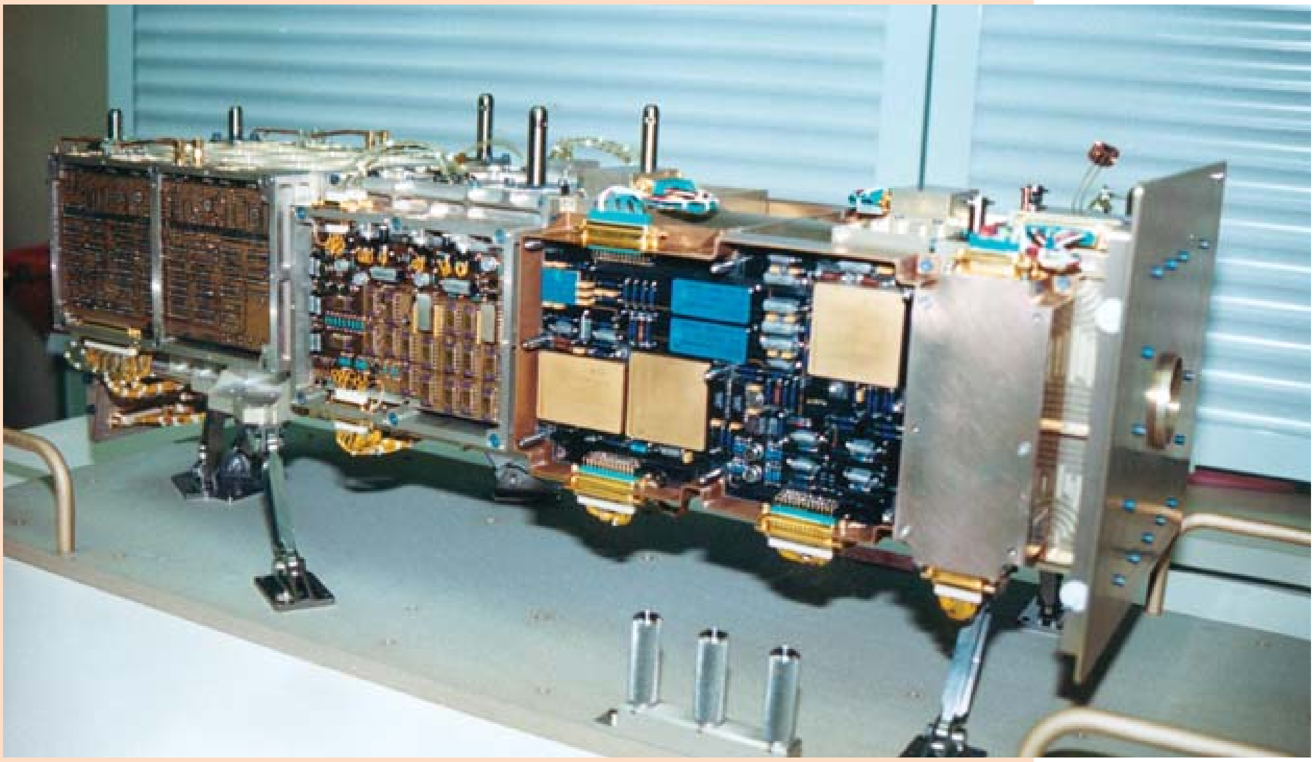


Institut d'astrophysique spatiale

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.

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

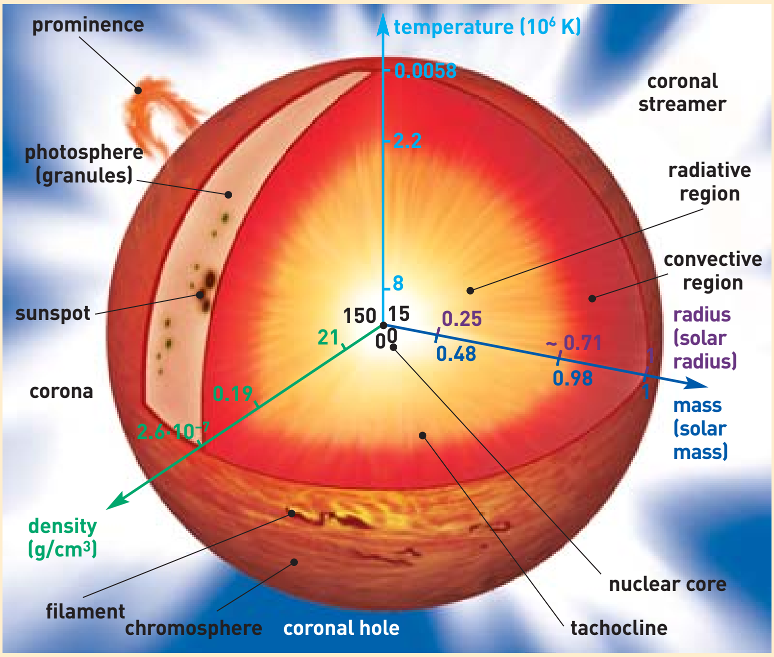


Figure.

(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.

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.

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.

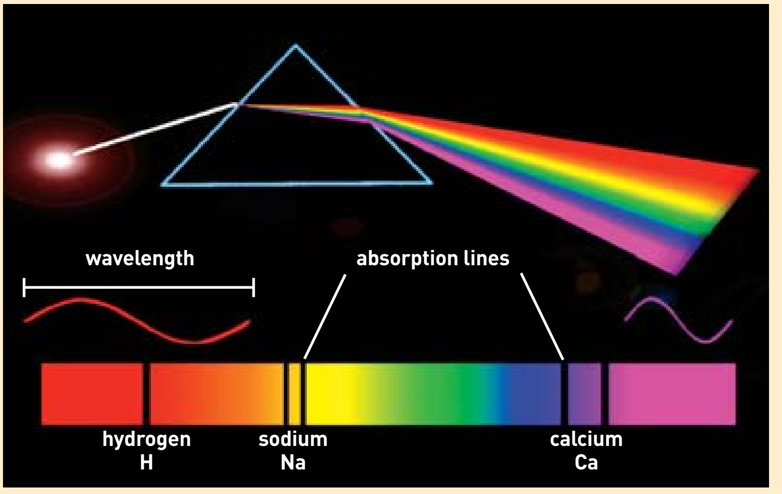


Figure a.

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.

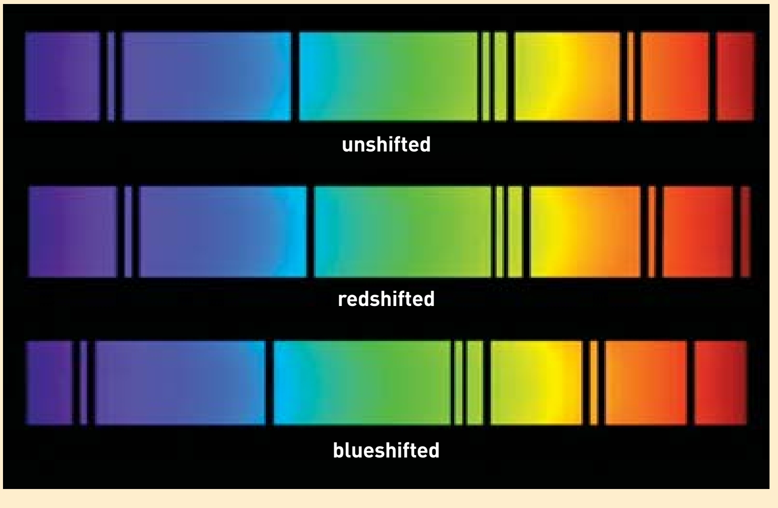
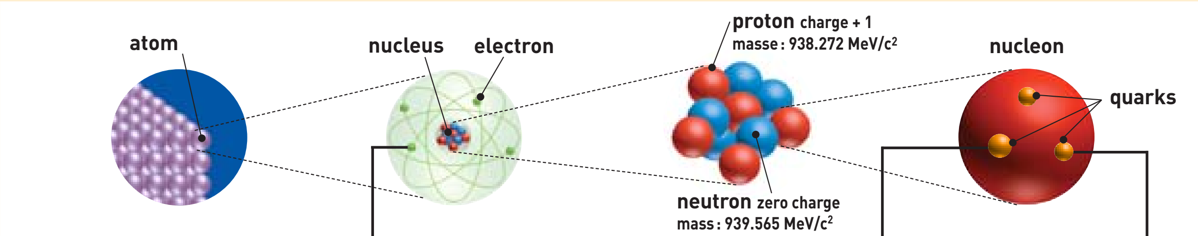


Figure b.

(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.

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
Most of these particles were around just after the Big Bang. Presently only to be found in cosmic rays, and around accelerators.	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
	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±, Z⁰** (W+, W-, Z0) 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.