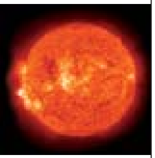
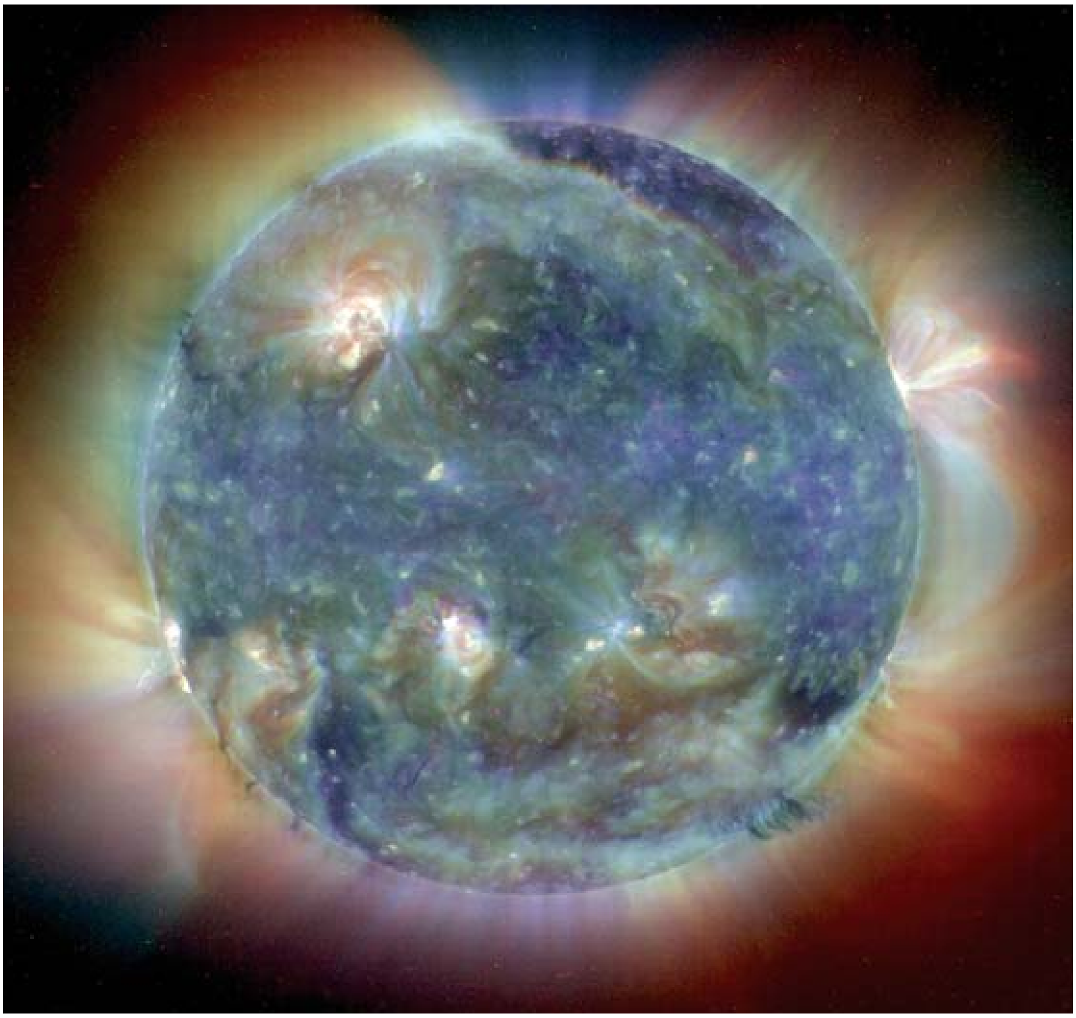


Research workers have found out more about the Sun in one hundred years than they had over two millennia. Data on the subject have accumulated over the past few years, confirming that operation of this gravitational-confinement nuclear reactor, effecting as it does the fusion of atomic nuclei, involves essentially three chains of reaction.

The **nuclear** sun



SOHO (ESA-NASA)

Composite picture of the Sun, taken at three wavelengths (171 angströms: blue; 195 Å: yellow; and 284 Å: red) in the ultraviolet, from data from the European–US SOHO satellite's EIT (*Extreme ultraviolet Imaging Telescope*) instrument.

The Sun: vital statistics	
Distance from Earth:	150 million km
Distance from galactic center:	30,000 light-years
Spectral type:	G2 V
Age:	4.6 billion years
Radius:	700,000 km
Surface temperature:	5,800 K
Mass:	$2 \cdot 10^{30}$ kg
Luminosity:	$4 \cdot 10^{33}$ erg/s
Mean energy generation:	2 erg/g per second
Mean density:	~1.4 g/cm^3
Central temperature:	15 million degrees (K)
Central density:	150 g/cm^3
Initial composition:	hydrogen 70.5%; helium 27.2%; all other elements (carbon, nitrogen, oxygen, iron and all heavy elements) 1.9%

Table.
The Sun's main characteristics

Some 4.6 billion years ago, in the mean and far-flung outskirts of a nondescript **galaxy**, some interstellar cloud gave birth to a **star**, one among so many others, which would then go on to gain an entourage of planets, on one of which there would emerge life, and consciousness. Once that consciousness had risen to the point of differentiating between night and day, the star known as the Sun became a fount of myth-making, and a source of science. It took much longer to work out that Sun and Earth are in fact made of the same stuff, and are governed by the same physical laws. The Sun is a physical, heavenly body, and may thus be understood. And our understanding of it has leapt forward further, in one hundred years, than it had over two millennia. What are the deepest and most meaningful things we can say about it?
The Sun, crucial as it is for the destiny of humankind, is but a medium-sized star, representative of the silent majority, one out of hundreds of billions of billions of

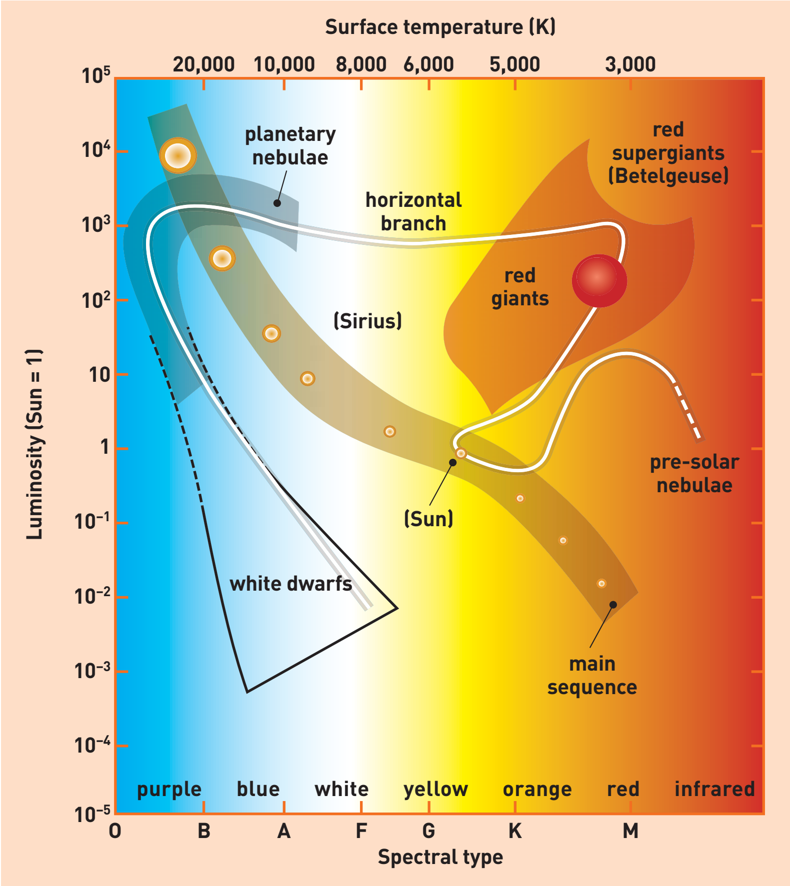


Figure 1.
The Sun is located at the very heart of the **main sequence** of the Hertzsprung–Russell diagram. Stars are classified, from hottest to coolest, on the basis of their **spectral lines**, which allow an estimate of their surface temperature. Star designations include a letter (from the sequence 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.

stars filling the observable universe. Commonplace it may be, but it is *our* star (see Table). Being so close, it has been, and goes on being, subjected to extensive investigation, both observational and theoretical, to such an extent that it is now seen as the reference star for astrophysics (see Box A, ***Spotlight on the Sun***). For the conventional astronomer, it is a type-G2 V star, in the main sequence that runs across the temperature–luminosity diagram, bringing together the stars that, like the Sun, burn **hydrogen** to form **helium** (see Figure 1).
Thus, as a heavenly body, the Sun does not stand alone; it is one of a company of stars, in a society of heavenly bodies and interstellar clouds. Over the last five billion years, our star has been plunged in a very low-density region of space, forming a bubble lying between the arm of Orion and a spur (a branching out) from the local arm of our galaxy. Our galactic environment is changing over time, as the Sun (together with its train of planets) moves through space at a rate of 54 light-years per billion years. [(1)] Moreover, it swings through an oscillation relative to the galactic plane, with a period of 66 million years.

The true Sun

The heavenly fount of daylight is a **gravitational-confinement** nuclear reactor, operating in the **fusion** mode (see Chapter II). To that extent, it is of particular interest to CEA. All of physics is required to arrive at an evolving picture of the heavenly body as a whole, from fertile core to hot **corona**. Physics of the atom, for the understanding of radiation–matter interaction; nuclear physics, to establish the Sun's energy source; particle physics, to detect messenger **neutrinos**; **plasma** physics, to investigate its deep, internal economy; numerical simulation, to make its internal structure apparent, and retrace its career, from cloudy genesis to final transformation into a *white dwarf* (see Box 2).

Opaque Sun, transparent Sun

The Sun presents two distinct regions, the *opaque region*, which does not readily let light through, is inaccessible to the eye and may thus only be approached through computation, and the *transparent region*, which allows

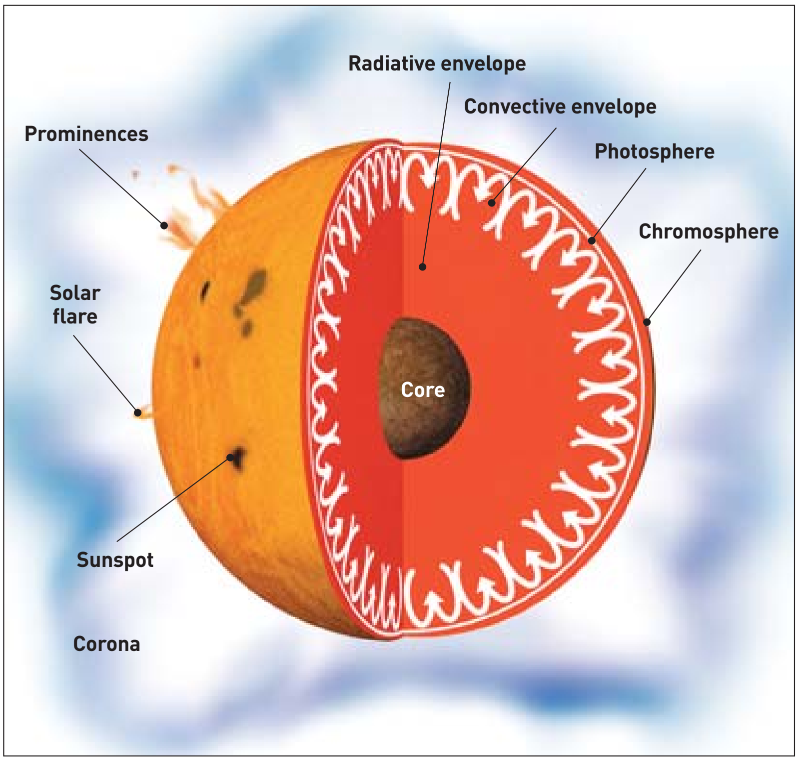
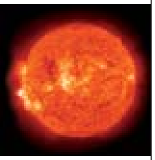


Figure 2.
Schematic representation of the main solar regions

(1) I.e. with a velocity of 16.2 m/s relative to the local environment, in a direction defined by galactic latitude and longitude $l = 53°$, $b = + 25°$. One light-year is the distance light travels in one year (at a velocity of 299,792.458 km/s in a vacuum), i.e. 9,460.53 billion kilometers, or 63,239 astronomical units (AU: the mean distance between the Earth and the Sun).



perceivable messages to traverse it.[2] The **photosphere** (etymologically: the sphere of **visible light**) marks the boundary between opaque Sun and transparent Sun. Its composition, analyzed by means of **spectroscopy** (see Box B, ***Tell-tale spectra***), bears witness to that of the Sun's, and the planets', parent-cloud, give or take a few details. This surface composition has only slightly altered since our star came into being, since it has not been affected by nuclear reactions. It thus remains that of the primitive Sun, or more accurately that of the cloud that gave birth to it. That cloud in turn reflects the composition of the galactic neighborhood, as it was 4.6 billion years ago. Bearing in mind that the Milky Way, our galaxy, is some 10 billion years old, several succeeding generations of stars arose before the Sun was born, each one bringing its contribution of complex atoms (carbon, nitrogen, oxygen … iron) by way of seeding by **supernovae**. The Sun is thus heir to the nuclear travails of its ancestors. The relative abundance

(2) Actually, with neutrinos that distinction breaks down, since for them the star is transparent through and through.

Solar nuclear reactions

1

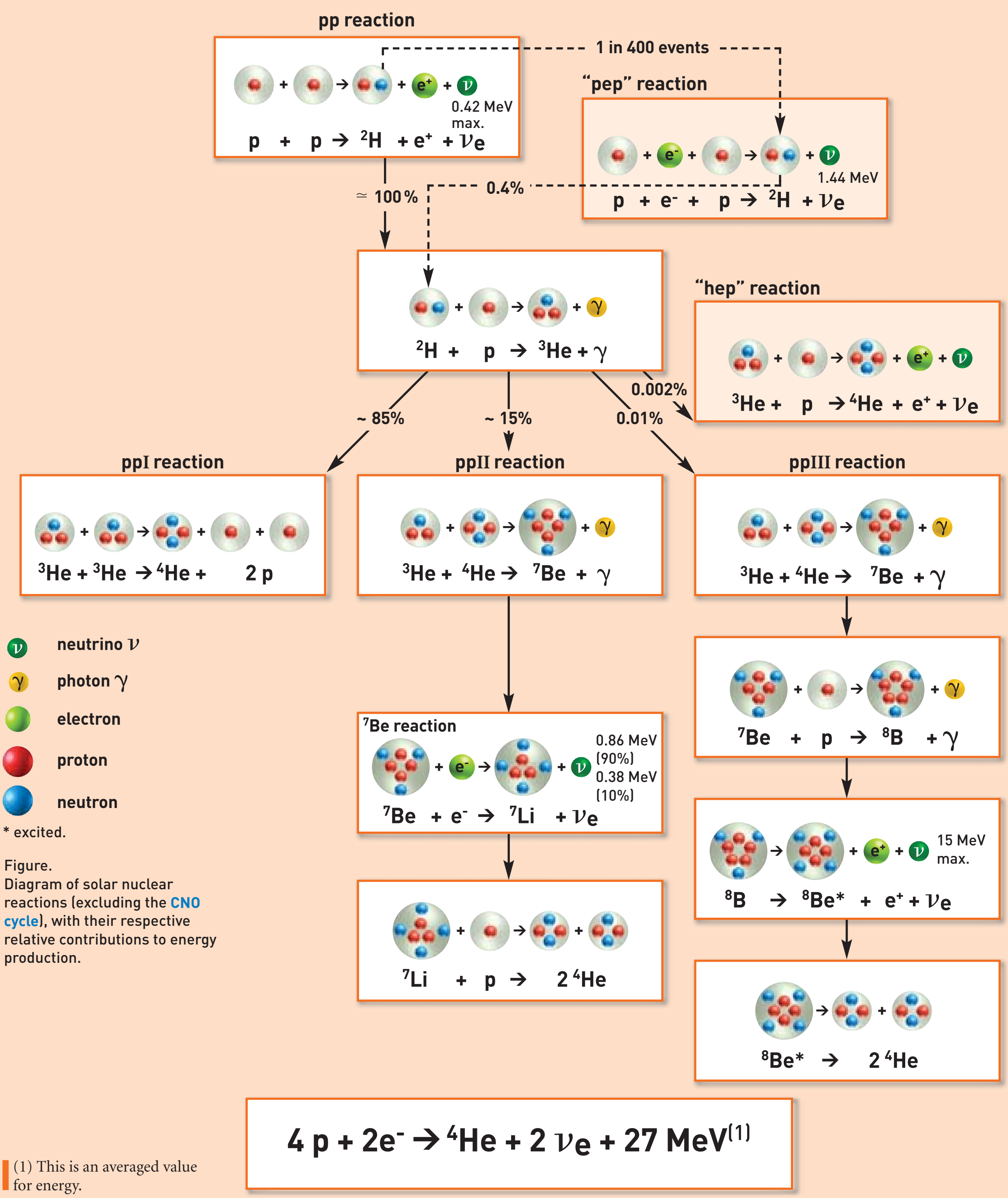


Figure.
Diagram of solar nuclear reactions (excluding the **CNO cycle**), with their respective relative contributions to energy production.

(1) This is an averaged value for energy.

of various elements, arrived at by combining investigations of the photosphere and of meteorites, shows an overwhelming dominance of **hydrogen**, the first element, arising out of the **big bang** (see Table).

E = *mc*² – and the Sun shines!

What nuclear reactions are there, for the relevant temperature and density conditions (15 million degrees, 150 g/cm³), liable to set in train a reaction of hydrogen with itself? That burning conundrum was only solved in the twentieth century, once quantum mechanics had varied the dictates of conventional, classical physics. The **tunnel effect**, allowed for, and indeed made unavoidable, by the wave character of quantum entities, is an absolute requisite, if one is to account for the fact that the Sun shines, as is relativity ($E = mc^2$). The Sun is a **relativistic**, quantum-mechanical heavenly body.

In 1939, German-born physicist Hans Bethe described, in an epoch-making paper, two mechanisms of **thermonuclear fusion**, through which main-sequence stars such as the Sun generate energy commensurate with their observed luminosity. These two mechanisms are referred to as the proton–proton chain (pp chain) (see Box 1) and the **CNO cycle** (carbon–nitrogen–oxygen cycle). In both kinds of reaction, the basic energy source is provided by the fusion of four **protons** (hydrogen nuclei), yielding a helium **nucleus**. However, the mere coming together of four protons, in pairs for instance, is not enough, since these form an unstable entity. Further, in the same time, and twice in succession, a proton transforms into a **neutron**. Nuclear physicists, however, realize – having observed this thousands of times – that, whenever a proton changes into a neutron, a neutrino is released. From which they conclude directly that the Sun needs must be an abundant source of neutrinos.

Over the years, ever more precise laboratory measurements (requiring proton and nucleus accelerators) of the nuclear-fusion reactions involved in sophisticated theoretical models have led to the inference that the Sun shines, essentially, by way of the pp chain, rather than the CNO cycle. (3)

The Sun's **core** is a stable, self-regulating reactor. Its energy is generated by nuclear conversion of hydrogen into helium. The four protons having a mass greater than that of the helium nucleus by some 0.7%, this mass shortfall is accounted for by radiated energy. This is how the Sun shines.

(3) Current calculations show 98.5% of the Sun's luminosity is of pp-chain origin.

On this picture of spiral galaxy NGC 2997, the star marked out holds a position corresponding to that occupied by the Sun in the Milky Way – a galaxy of similar type.

1 (next)

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.

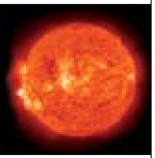
The deuterium nucleus captures a proton, yielding a helium 3 nucleus and a gamma photon. Two helium 3 nuclei react to produce one helium 4 nucleus, releasing two protons, thus available to initiate a new chain. In some 85% of instances, such is the end of the **ppI chain**. This chain is prolific in 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*).

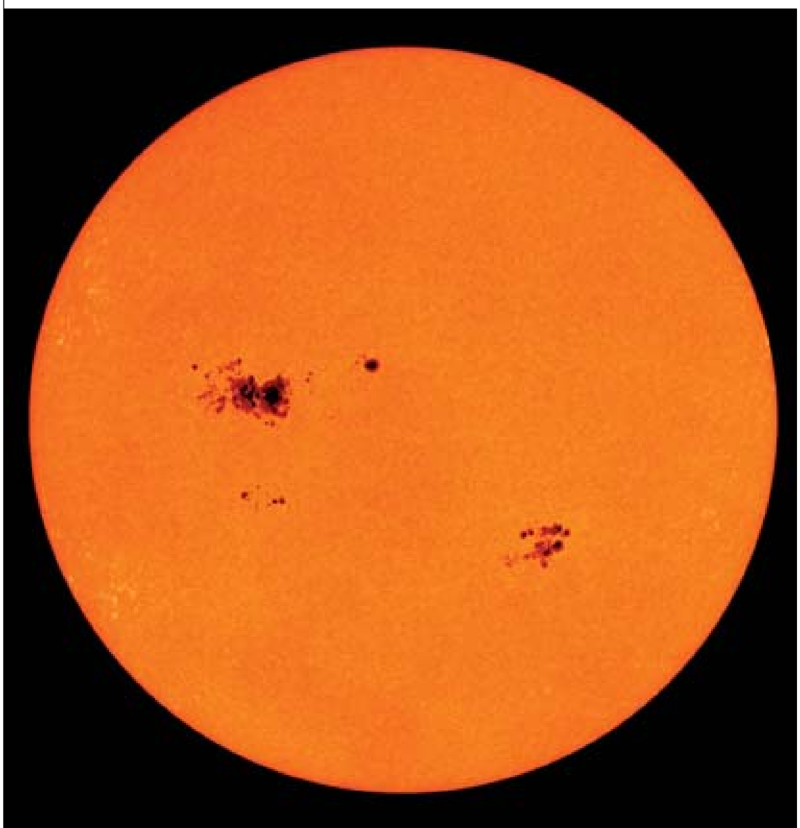
The energy generated in the guise of gamma rays goes to keeping the solar furnace hot, thus precluding it from collapsing, and to making it shine. This energy, in the guise of photons, filters through to the surface. It is scattered, absorbed, re-emitted by ions and electrons. The neutrinos alone pass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



The fundamental nuclear equation for its operation may be set out as: $4\ p \rightarrow He + 2\ e^+ + 2\ \nu_e$ [(4)]
The Sun is burning – in the nuclear sense of that word – the primordial hydrogen issued from the big bang. An ancient **fuel**, but an effective one, since 1 gram hydrogen yields $6.6 \cdot 10^{13}$ **ergs**, making it a fuel millions of times more energetic than petroleum (where its chemical combustion generates 2.6 times more energy than for the latter).

The coming together of forces inside the Sun

To come back to the inner workings of heavenly bodies, fundamental astrophysics *par excellence*. The four fundamental forces (**gravitational**, **electromagnetic**, **strong**, and **weak**; see Box C, ***Elementary particles and fundamental interactions***) come together inside the Sun, and work in harmony. Strong and weak nuclear interactions bring about thermonuclear fusion, yielding energy. Weak interaction – or, more accurately, slow interaction – is what lies behind our star's prolonged lifetime. Electromagnetic interaction moderates nuclear reactions, by setting up an **electrostatic** potential barrier between electrically-charged particles. That same interaction is responsible for the solar substance's lack of transparency. Were it not for such near-opaqueness, the Sun would instantly void itself of all of its energy. [(5)] As for gravitation, it is responsible for the Sun remaining within certain bounds. Every elementary volume, at any depth, is drawn to the center by the attraction of matter to matter, and repelled outward by the thermal-pressure gradient. Thus does nature bring about one of its most beautiful processes: **hydrostatic equilibrium**.
Hydrogen, in the guise of a proton, given the prevalent temperature, has no option available but to react with its fellow protons, overcoming by means of its velocity (kinetic energy) the electric repulsion arising between itself and like particles. The issue of their union, however, may only survive if, during that brief contact, one proton transforms into a neutron, releasing a neutrino. Such is the birth of **deuterium**, which is the crucial link in the chain of reactions (see Box 1).



SOHO (ESA-NASA)

Sunspots observed on 22 September 2000 by the SOHO satellite's MDI instrument.

(4) It should be noted that, in the guise of **positrons** (e^+), the Sun thus produces **antimatter**.

(5) The value obtaining for opacity (a coefficient measuring the impediment set up by solar matter to **photons** passing through, at varying depths) depends on a number of processes, operating concurrently: scattering of protons by **free electrons**, and interaction with bound electrons.

In praise of solar suppleness

Our star has been quietly shining forth, with a near-even light, for 4.6 billion years. The Sun thus is a lasting, self-regulating nuclear power-house. Why doesn't it explode? If a nuclear reaction begins to run away inside the Sun, the latter, being a perfect gas, expands slightly as a result of the rising temperature. As it expands, it cools down, and the nuclear reaction is moderated. Conversely, should a nuclear reaction run down, the core will slightly contract, and the reaction picks up again. Thus does the Sun owe its long life, in part, to its gassy suppleness. A viable, healthy star is a supple, gaseous star, and a shining star, with a hot interior. However, if the Sun is shining, this means it is burning off, and if it burns off, it will die. The Sun is mortal, it could be said, were it not for the danger of abusing anthropomorphic categories. Actually, the Sun is not to die: it has to undergo a change in state, a rearrangement. Be that as it may, its future is already spelled out (see Box 2). The energy generated by nuclear reactions is equal to the Sun's luminosity ($4 \cdot 10^{33}$ erg/s, i.e. $4 \cdot 10^{26}$ watts). The Sun shines because it is hot. However, it shines over a long time span, since it is drawing on a lasting energy source: nuclear energy.

The Sun's nuclear engineering

The Sun's structure is sensitive to the **opacity** of matter at varying depths, for when this alters the star readjusts its parameters in such a way as to enable effective migration of the energy generated in the core of the nuclear reactor, precluding its remaining blocked at any point within the star (see Figure 2). In the **radiative region**, closest to the core, the gas is highly **ionized**. Energy transport in that region is basically governed by scattering of **photons** on **electrons**.
In the boiling outer region, the so-called **convective region**, atoms retain some of their electrons, owing to the lower temperature. Neutral atoms now appear. Many atomic processes are at work here, and the high level of opacity greatly impedes the photons' travel. High temperature gradients arise, setting up gigantic **convection** currents. The solar envelope's achieved equilibrium is convective, rather than radiative. This is the region where **sunspots** and other surface electromagnetic phenomena develop.

The Sun's future 2

H. Bond/R. Ciardullo/Hubble Space Telescope/NASA

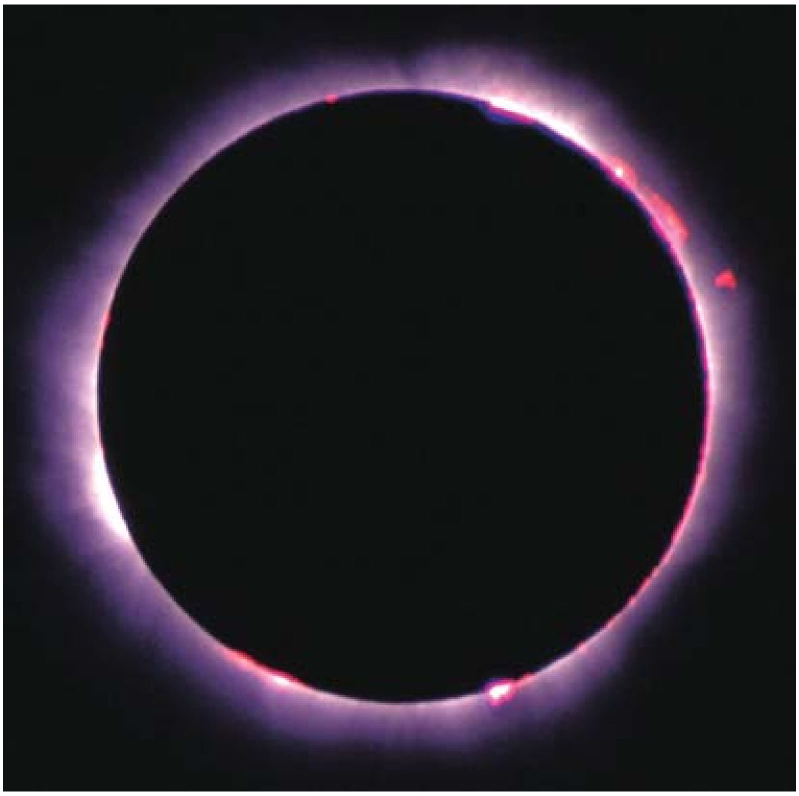
The Sun will inescapably end its life in the form of a white dwarf, such as the one shown (bright spot, center) in this photograph of the NGC 2440 nebula.

During the greater part of the nuclear life of the star that lights our days, hydrogen is turned into helium in the core of the stellar reactor. Helium then undergoes fusion, yielding carbon, and oxygen. Around the core, nuclear fusion continues in two thin layers, where helium yields carbon and oxygen, and hydrogen yields helium.
Now aged some 4.6 billion years, the Sun holds sufficient hydrogen within its core to sustain its life for a further equivalent period. Once it has exhausted all its hydrogen, it will begin burning the helium that will have accumulated in its core. It will turn into a *red giant*, [1] remaining 500 million years in that state. Its energy production will increase 3,000-fold. Its diameter, multiplied by a factor of 50, will extend to as much as 3 times the present Earth–Sun distance. Our planet will not be engulfed by its star, however, since the Sun will disperse half of its mass, in the form of a huge wind. Finally, in some 7 billion years, the Sun will eject its outer layers, and there will only remain a small, solid star, known as a *white dwarf*, [2] which will slowly cool down over several billion years, merging into blackness.

(1) Red giant: a bright star, featuring however a low surface temperature (below 5,000 K), of great size, having reached one of the final stages of its evolution, once it has turned its hydrogen and helium into heavy elements.

(2) White dwarf: a faint star, with a surface temperature in the 2,500–20,000 K range. A white dwarf is a cool, stable star, kept in equilibrium by the repulsion between its electrons, and which, having exhausted its nuclear fuel, is contracting. Such a star, with a mass around that of the Sun for a radius 100 times smaller, attains a density that is one million times greater. In such extreme density conditions, the pressure precluding total collapse is solely due to the electrons, which, owing to the Pauli exclusion principle, may not coexist with the same velocity in any single location. Quantum mechanics thereby achieves one of its most beautiful astrophysical implementations.

In effect, the Sun only radiates whatever its poor transparency allows. The rate of nuclear reactions adjusts so that, in any second, the energy lost (radiated away) is replenished by "fresh" energy. To burn off, however, in the most general sense, is to turn fuel into ashes, and light (energy). In this case, the fuel is hydrogen, and the ashes helium. When the Sun's core will have turned to ashes, it will undergo a transfiguration, a change in structure, that will threaten the innermost planets (see Box 2), further seeing its envelope dissipated, to become a sheer dwarf star, now compact and solid. A hot wind will blow over the Earth, searing off its surface. Originating as they did in the stars, the atoms of the Earth, and of its dead beings, will be returned to the heavens, and the stars.

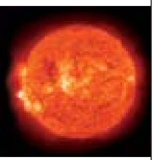


L. Duriez/ Lille-I University Astronomy Laboratory

Total solar eclipse of 11 August 1999, photographed in the Oise département (France, north of Paris). Such an eclipse is a privileged moment for the observation of the solar corona.

A slow softening of radiation

For the time being, however, we bask in its tender light. Originating from nuclear reactions as an emission of **gamma rays**, solar energy filters through the Sun's core with difficulty, making protracted progress. The photons are scattered by the (free) electrons in the environment, shedding at every encounter a portion of their energy. As they travel on and filter through to the surface, the photons' energy alters, and they change register, going from gamma radiation to **X-radiation**, then on to **ultraviolet** radiation, and ultimately **visible radiation**. After a time span that is measured in hundreds of thousands of years, the original radiation from the center, consisting as it did in lethal gamma rays, emerges from the photosphere in the form of beneficial light, soothing to the eye. It then only takes *8 minutes* for it to hit the retina.



The internal structure: exquisite precision mechanics

The Sun is wholly gaseous, and its atoms, from center to photosphere, are bereft of their electrons. The solar **plasma**'s internal structure is determined by the conditions of conservation of mass, momentum and energy, and the energy transport mode, conditions that may be summed up in four equations (see Box 3).
Constructing a model of the Sun thus involves determining pressure, temperature, chemical composition (and many other parameters, such as rate of energy generation, the rate of production of neutrinos with various energies…) for any depth and at every instant. A solar model needs must – at the very least! – yield the apparent parameters observed for the Sun (luminosity, radius, temperature) for an age of 4.6 billion years. It should also, however, take into account the flux of neutrinos sent out by the Sun, and the speed of sound – again at any depth – this being a key parameter to account for the physical oscillations our star is subject to. The outcome of this work is truly a piece of intricate, precision solar mechanics (see *Static and dynamic views of the solar interior*).
The Sun, once it has thus been perfectly defined, now becomes a laboratory where the most exotic and sophisticated of physics may be tested – as, for instance, the hypothetical existence of a form of dark matter, made up of extremely elusive particles (**WIMPs**) which, owing to their large mass, would have accumulated at the center of the heavenly body.
The solar model covers the Sun through every layer of its extant form, and throughout its very evolution. It is thus possible to plot, for every period in its history, radial profiles of temperature, density and chemical makeup. Chemical composition changes over time in the region undergoing consumption (see Box 2).

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**.

Neutrino shortfall: Sun exonerated

DR

Bruno Pontecorvo, who first suggested the hypothesis of neutrino oscillation.

The flux of solar neutrinos reaching the Earth is one of the most precise diagnostics to monitor the proper nuclear operation of our star. However, Earth-based detectors manifestly showed that electron neutrinos arrive from the Sun in smaller numbers than predicted (see *Solar neutrinos: a puzzle finally solved*). After a long-drawn-out trial, the verdict was finally arrived at. The guilty party behind such an alarming shortfall is not the Sun, but the very neutrino itself. The theoretical model of the Sun has been absolved from all suspicion, thanks to **helioseismology**, which allowed constraints to be set for its central temperature and thus, ultimately, for the numbers of neutrinos emitted (see *Static and dynamic views of the solar interior*).
Such was the conclusion of an episode initiated in 1949 by US chemist Raymond Davis Jr., who first suggested using chlorine as a solar neutrino detector, a device he was actually to set up at a later date. Italian-born physicist Bruno Pontecorvo then pointed out that solar neutrinos could be of potential interest to particle physicists, going on to lay the foundations of the modern theory of neutrino oscillation between various forms. US astrophysicist John Bahcall and his coworkers developed ever more detailed solar models. It is however a model arrived at by CEA's Saclay center that has gained general acceptance.
The neutrino saga mobilized an entire community of chemists, astronomers, engineers and computer scientists, notably at CEA, who made a critical contribution to the refinement of nuclear physics, astrophysics, and detectors. To such an extent that solar neutrinos served as a precision testbed not only for stellar evolution, but equally for weak interaction theory. [6]

The solar model has held

Over the past few years, our understanding of the Sun's interior has made spectacular advances. By looking into sunquakes (for the Sun is subject to tremors, as indeed its light is), it was possible to work out the speed of sound at varying depths, to an accuracy of 1‰. The same approach allowed important properties of the convective envelope to be arrived at (depth, rotation, helium content at its base). Measurement of neutrino fluxes induced from boron disintegration, achieved by combining data from the SNO (Sudbury Neutrino Observatory), in Canada, and Super-Kamiokande, in Japan, has yielded an estimate for the Sun's central temperature with an accuracy close to 1%. Helioseismology has clearly demonstrated that the solar-neutrino problem may not be ascribed to some error as to the temperature profile for our star. There is some satisfaction to be drawn from the fact that, ultimately, none of the basic hypotheses formulated in modern solar models have been faulted – and that is something to reassure the research workers who have taken on the mantle from the pioneers (to the ranks of which should also be added William Fowler), as to their ability to achieve an ever-deeper understanding of the Sun, and the Stars.
"Sun arise! Atoms are dancing." (Jalal al-Din Rumi)

> **Michel Cassé**
Physical Sciences Division
CEA Saclay Center

(6) An historical overview may be found at the following website: www.sns.ias.edu/~jnb/

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

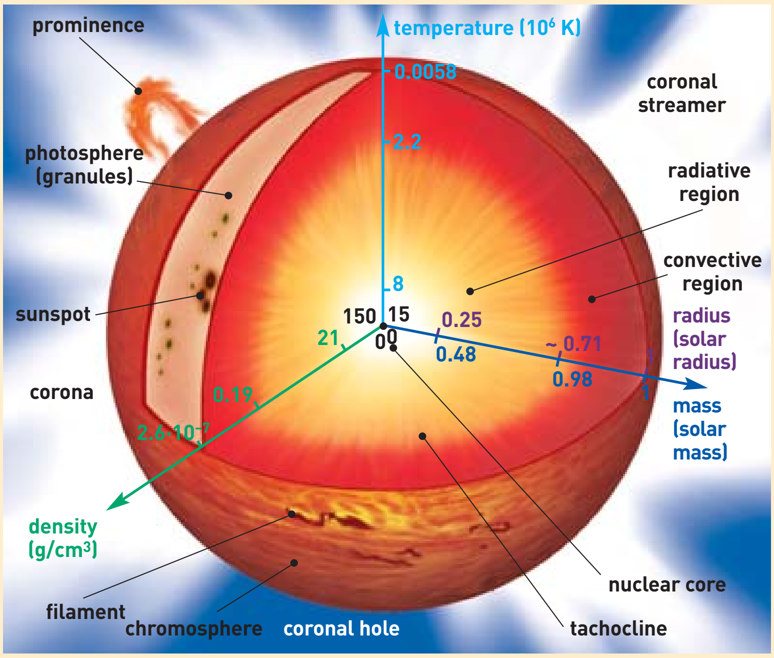


Figure.

(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.

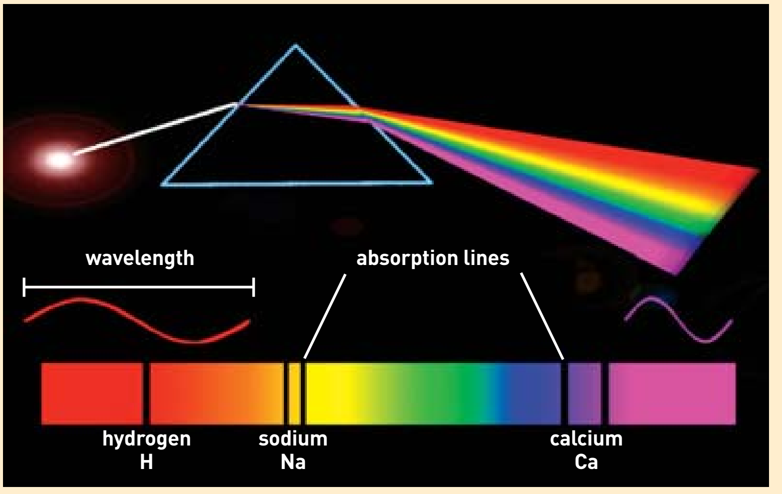


Figure a.

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.

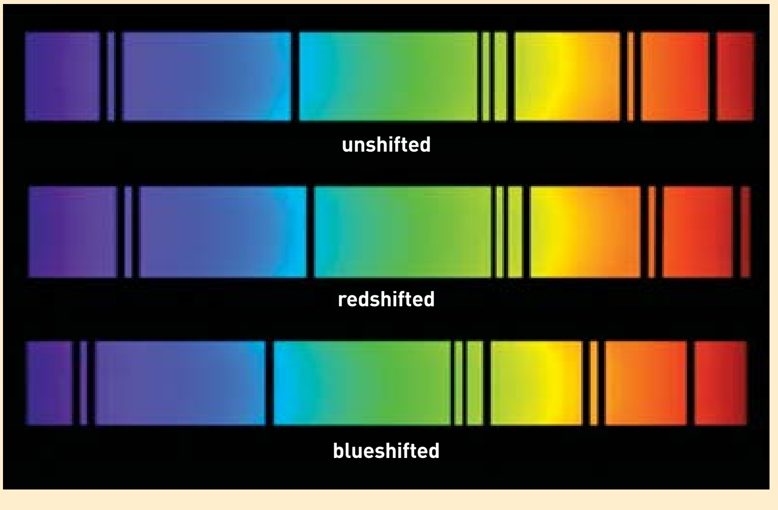
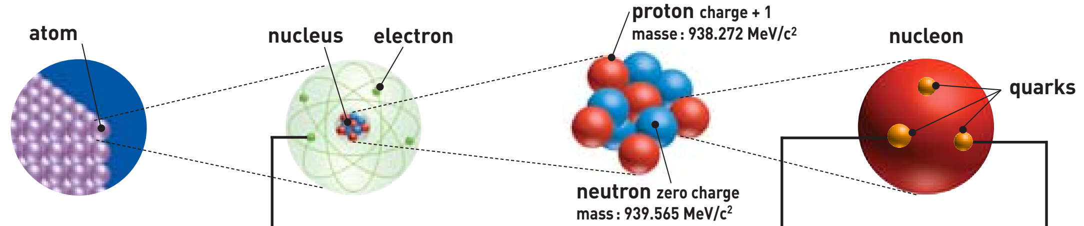


Figure b.

(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 $\nu\mu$, 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±, 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.