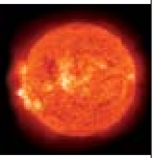


Magnetohydrodynamic simulations of the Sun

Three-dimensional simulations of the electromagnetic dynamo operating inside the Sun are now possible for researchers and their supercomputers.

Lockheed Martin Solar and Astrophysics Laboratory

Magnetic loops in the Sun's corona. The complex topology of the magnetic structures in the upper solar atmosphere facilitates reconnection of field lines, and causes eruptions.

Owing to its closeness, the Sun exerts a strong, direct influence on the Earth, and our technological society. In particular, its magnetic activity and its **wind** of charged particles interfere with our planet's space environment, to the point of impairing our satellites, or even, in the case of extreme **solar eruptions**, our power-grid. In order to be able to predict and anticipate such phenomena, the origin of these physical processes must be understood. Nowadays, it is agreed that such dynamical processes are linked to an internal **turbulent dynamo**, distributed inside the solar **convective region**, and at its base. A promising approach, to test this interpretation, consists in carrying out three-dimensional simulations of this region of the Sun on supercomputers, such as those available to CEA at its Research and Technology Computation Center (CCRT: Centre de calcul recherche et technologie), at Bruyères-le-Châtel (Essonne *département*, near Paris).

Challenges and goals for dynamic modeling of the Sun

The Sun is a large ball of hot, **ionized** gas (**plasma**), rotating over a period of about 28 days. The outermost 30% of its radius are constantly stirred by **convective** motions. These flows are turbulent and chaotic in nature and are further influenced by the Coriolis and Laplace (Lorentz) forces (see Box 2 and Box 3), resulting on a wide range of magnetic phenomena. To understand the Sun's turbulent dynamics and magnetic activity, anticipate, and shield from, its impact on Earth, a physical model of its **interior** and **atmosphere** must be devised (see Box A, *Spotlight on the Sun*). The current model for the outer, dynamic layers relies on the theory of fluid and plasma dynamics (conducting fluids), also known as magnetohydrodynamics (MHD). This theory describes the mechanical, hydrodynamic, thermodynamic and magnetic behavior of turbulent solar plasma, on the basis of nonlinear, coupled partial differential equations. Unfortunately, such system of equations does not yet possess exact (analytical) mathematical solutions that would allow full resolution of the problem of turbulence and solar activity, unless simplifying assumptions are resorted to. This difficulty has persisted for over 50 years, and represents one of the major challenges for modern astrophysics, and more specifically for astrophysical fluid dynamics. Thus in order to improve our understanding of such a complex physical system, complementary approaches have to be developed. [(1)] One may for instance, simplified the system more or less drastically such as to get analytical solutions, or programs can be developed to resolve the system as well as possible by numerical approximation. Finally, these two approaches may also be combined to study in details different aspects of the problem at hand.

Undoubtedly, the emergence of **massively parallel computers**, with ever-more impressive computing capabilities (tens of thousand-billions elementary floating-point operations per second, or teraflops), has stimulated development of high-performance **codes** to describe, as realistically as possible, solar and **stellar** magnetohydrodynamics and eventually aspects of the Sun–Earth system.

Solar magnetism is of a different nature inside our star, where **magnetic fields** are advected by the convective motions, and in its atmosphere, where the magnetic field dictates the dynamics. Consequently, **modeling** of the Sun's magnetohydrodynamics has been split into

(1) On these issues, see *Clefs CEA*, No 47, Winter 2002–2003, pp. 10–12, 18–19.

internal and *external* solar physics. Very recently, synergies have emerged, pointing to integration into a broader framework of all developments in the field of MHD simulation of the Sun. However, much remains to be done before a complete model can be arrived at.
What follows is a quick overview of the current state of multidimensional simulations, restricted to discussion of turbulent, i.e. internal, convection in the Sun. The main reason for such a choice is that the dynamics of the Sun's atmosphere owes to some extent its very existence, and variability, to its strong coupling with the internal dynamics. This is particularly true of the 22-year **cycle** in solar activity and of **sunspot** emergence (see below, "Properties and role of the magnetic field").
To investigate solar convection, two parallel, complementary numerical approaches have been pursued. The first one models locally, in Cartesian geometry, at a very-high-**resolution**, a limited portion of the Sun's surface convection. The other uses global simulation in spherical geometry at lower resolution, of the entire convective region (excluding the superficial layers). The former approach enables a better description of solar turbulence and microscopic plasma properties, to the detriment, however, of use of the appropriate geometry, and of consideration of the presence of mean global flows. The latter approach has the advantage of yielding a tentative "general" model of circulation inside the Sun, of the kind developed for climate prediction. It is the second approach that we will discuss here.

Thermal convection — 1

This process transports thermal energy through displacement of a fluid. What is hot goes up, what is cold comes down. A common instance is that of a pan of water set on a heat source (electric heating element, gas ring...). The water heated at the bottom of the pan is lighter, and rises to the surface, where it cools, sinks back, is warmed again, rises once more, etc. Such **convective** motion tends to reduce the difference in temperature between pan bottom and surface. In the case of **stars**, convective motions serve to carry away the nuclear energy generated at the center. Positioning of the convection zones is strongly dependent on star mass, the more massive stars having central convection. When there is steep variation in density, as in convective envelopes of the solar type, the fluid's entropy[1] turns out to be the natural variable, for the characterization of convection efficiency, highly efficient convection being nearly **adiabatic** (with no heat loss). In nature, thermal-energy transport may also occur through conduction (direct contact between a hot and a cold body) or **radiation** (energy carried by **photons**). In stars of the solar type, conduction plays a negligible part, compared to radiation, which is predominant from the center up to 0.71 solar radius, and convection, which takes over from 0.71 to nearly 1 solar radius.

(1) Entropy is the physical quantity measuring the disorder in a system, as for instance energy degradation.

Global numerical simulations of turbulent solar convection

The Sun possesses a **granular** aspect, resulting from turbulent convective motions, transporting heat to the surface (see Box 1, and illustration p. 22). The large range of temporal and spatial scales for the convective region spans some six orders of magnitude for each dimension. This makes numerical simulation [1] of turbulent solar convection altogether difficult, even for today's computers. Thus, it is not currently possible to model solar granulation through the global approach discussed here. However, with the rising power of computers, the resolution used by modern hydrodynamics codes, nowadays, achieves meshing with cells 4,000 km square, for a depth of 1,000 km, thus coming closer and closer to the spatial scale of granulation.
Results from such simulations are shown in Figure 1. The convective motion (radial/vertical velocity) in a rotating sphere of gas is shown at three consecutive time frame. It is clear that descending flow lines (in blue) are narrower than the broad ascending flows (yellow–red). Cells at higher latitudes evolve over time, merge, cleave and dislocate, with the formation of new structures. At the interstice of the downflow network, cyclonic structures are apparent, rotating clockwise in the southern hemisphere, and counter-clockwise in the northern hemisphere. These structures, known as plumes, correspond to intense vorticity (rotation) tubes, and pierce through the convective zone. Closer to the

(1) On these issues, see *Clefs CEA*, No 47, Winter 2002–2003, pp. 10–12, 18–19.

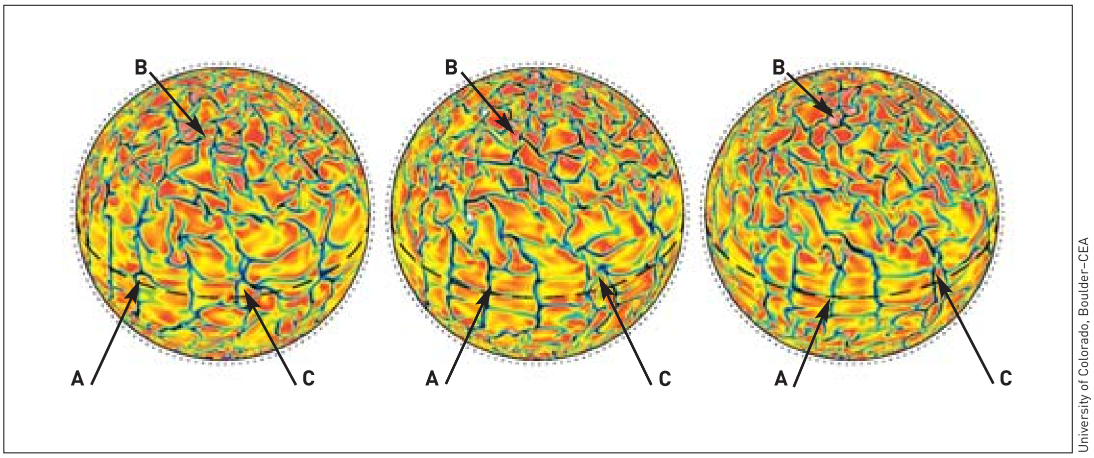
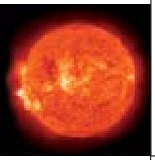


Figure 1.
Evolution over time of radial velocity in a three-dimensional global simulation of convection under the influence of rotation. Shown in blue: descending flows; in yellow–red: ascending flows. Each image is separated by 5 days from the next.
Markers A, B and C follow convective patterns of particular interest.



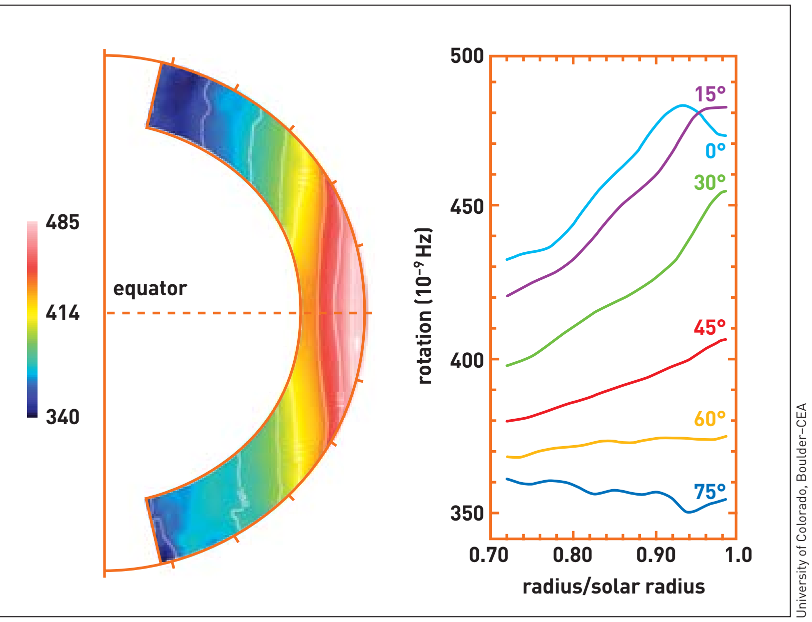


Figure 2.
Representation, in a cross section showing the meridional plane, of the differential rotation in latitude and in depth accompanying the convective patterns observed in Figure 1. Regions of fast rotation are shown in red, those of slow rotation in blue.

equator, it should be noted that convective patterns are less **isotropic** than at higher latitudes, being more aligned with the axis of rotation (north–south orientation). These structures are also stretched and sheared by a large-scale horizontal flow: the *differential rotation*.

The effects of rotation 2

Rotation, represented by the symbol Ω, occurs throughout the Universe (planets, planetary systems, **stars**, **galaxies**...). Its effect on a given element (solid object, fluid...) depends on the centrifugal force and Coriolis force. The former tends to drive any element away from the center. The latter's effect is to deflect any moving object to the right in the northern hemisphere, to the left in the southern hemisphere. The faster the system rotates, the stronger centrifugal force will predominate, to the extent of completely tearing the object apart, should its amplitude exceed the object's internal cohesion force, or forces. These internal cohesion forces would be, for instance, in a solid object, **electrostatic** forces between **atoms**, or, for a fluid mass such as a star, the **force of gravity**. The Sun rotates rather slowly (1 rotation in 28 days), compared to a dentist's drill (3,000 rpm), or even related to other stars, some of which complete a rotation in under one day. Thus, its **convective** motions are mainly influenced by the Coriolis force. The most arresting effect of this force, undoubtedly, is the setting up of cyclones in the Earth's atmosphere. A balance then prevails, between the horizontal pressure gradient and the Coriolis force: physicists speak of a *geostrophic equilibrium*. In stars, such "meteorological" phenomena also occur, however, just like on Earth, where cyclones invariably have a radius greater than about 100 km, the Coriolis acceleration only affects motions larger than a given scale, the so-called *Rossby radius*. In the Sun's **convective region**, this radius stands somewhere between 10,000 and 30,000 km, allowing a separation to be effected, of scales sensitive to the effects of rotation from scales not so sensitive. Of course, the **turbulent** character of convective motions inside stars modifies this equilibrium. For instance, the meridional circulation [(1)] that is observed in the Sun results from just such a departure from geostrophy. For more rapidly rotating stars, centrifugal force becomes a major factor, and it then tends to flatten the star at the poles, turning it from a spherical shape to an ellipsoid.

(1) Meridional circulation: a mean flow in the form of cells contained in a meridional plane.

Understanding solar differential rotation

Observation of the Sun shows that its surface rotates at a rate that varies with latitude, from 25 days at the equator to 35 days at the poles. Models of turbulent rotating convection in spherical geometry enable investigation of the onset of such a differential rotation profile. Under the influence of rotation, convective motions exhibit a different organization, for instance by aligning with, and tilting towards, the rotation axis (see Box 2). This is particularly true of convective plumes, which are responsible for the equatorial acceleration observed in these simulations. Figure 2, displays the differential rotation as a function of depth and latitude, accompanying the convective motions shown in Figure 1. We can see that the entire equatorial band rotates more rapidly and, that the angular velocity slows down to the extent of being 30% slower at the poles. Around 45–70° latitude, rotation is constant along radial lines, as shown by the more horizontal lines in the right panel, showing radial cuts of the angular velocity at fixed latitude. This differential rotation is largely responsible for the **advection** of convective cells (to the right at the equator, to the left at higher latitudes) (cf. markers in Figure 1). The agreement between global simulations of convection and **helioseismic** observations is fair. This demonstrates that three-dimensional models of turbulent convection are on their way to becoming realistic, especially in describing the large-scale motions observed in the Sun. The angular velocity profile results from the continuous redistribution of the angular momentum [(2)] contained in the rotating turbulent convective shell. In particular, the correlations of the three velocity components (or *Reynolds stresses*) transport angular momentum from the high latitudes toward the equator, thus accelerating this part of the convective region.
One major characteristic of the solar rotation profile is that it becomes constant in the **radiative interior**. This transition between differential rotation and solid, rigid rotation occurs very swiftly in a strong shear region known as the **tachocline**. This *boundary layer* is crucial for the understanding of the solar dynamo, and it is planned to append to simulations of the convective region a stable zone to model it.

Properties and role of the magnetic field

The Sun's magnetic activity is fascinating by its diversity. The diagram of sunspot emergence, shown in Figure 3, exhibits a succession of bands migrating towards the equator and changing sign every 11 years, thus showing a pattern like butterfly wings. The direct consequence of such an observation is that the axis of the solar magnetic field must undergo reversal every 11 years, concomitant with the alternation in polarity – the well-known 22-year cycle (+/–/+) – just as a magnet that is flipped at regular intervals (see Box 3). Further, in the upper solar atmosphere (**corona**), magnetic field **loops** are constantly appearing, growing, and reconnecting, thus causing bright solar eruptions, associated however with little ejection of matter. There are also highly complex magnetic field confi-

(2) Angular momentum, or moment of momentum, is the product of mass by velocity by distance to the axis of rotation.

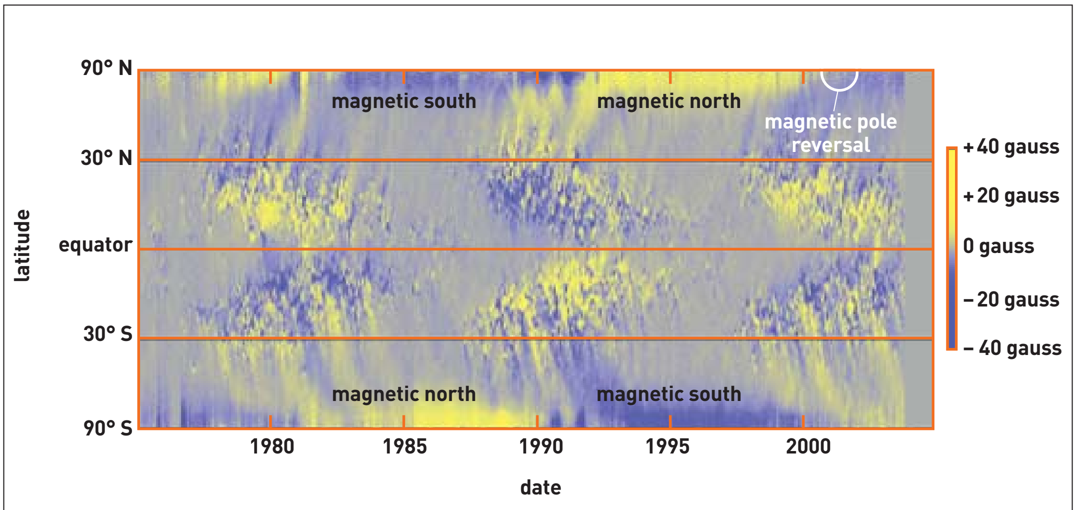
gurations, mainly linked to **active regions** bringing together a number of sunspot groups, predominantly (70%) exhibiting an S or N-shape structure, according to the hemisphere involved. In this case, eruptions are much more violent, and expel plasma into the interplanetary environment: these are **coronal mass ejections**. The regular emergence of sunspots contrasts with the unpredictability of the Sun's surface dynamics. They are linked, however, for the closer one gets to the peak in solar activity (5–7 years after the previous reversal), the greater the frequency and intensity of eruptions. These magnetic phenomena appear in the Sun because its gas is a conductor. The presence of charged particles (**electrons**, ions) in the solar plasma allows induction of a magnetic field to occur from convective motions. This dynamo effect is responsible for the magnetism observed (see Box 3). In order to understand the variety of forms exhibited by solar magnetism, it is necessary to discriminate between events that occur regularly, and those which do not. Current theory assumes that the solar dynamo is separated into a small- and a large-scale dynamo. The 22-year cycle, the polarity of leading sunspots, known as *Hale's law*, the amplification of large magnetic structures parallel to the equator are all linked to the large-scale dynamo, which is probably located and organized in the tachocline, at the base of the convective region. Irregular activity and the disordered magnetic field (eruptions, **bright spots**…), on the other hand, result from the turbulent motions present in the convective envelope.

Astrophysicists at CEA have been considering, over the past few years, the effects of the magnetic field and of the non-linear influence of Laplace forces in simulations of turbulent convection under rotation. Bringing in the magnetic field complicates the system of physical equations to be resolved, making for slower, more complex numerical codes. Thus, magnetohydrodynamic models of the Sun are getting increasingly sophisticated. Figure 4, presenting a reconstitution of the coronal magnetic field from a three-dimensional simulation of the solar convective region, shows tight loop structures, like the magnetic loops in the Sun's corona, and open **field lines**, somewhat akin to what occurs with solar **coronal holes**. The presence of a strong magnetic field, generated by the dynamo effect, changes convection, mean currents and the system's energy balance. In the example shown in Figure 4, the differential rotation accompanying "magnetized" convection has been reduced by about 30% in amplitude. The magnetic fields generated appear to be *intermittent*, and their fluctuating components preponderate, by 2 orders of magnitude, over mean global fields. The polarity of the poloidal magnetic field (going from one pole to the other) does reverse in these simulations, over too short a period however, namely 500 days. In fact, the mean toroidal (parallel to the equator) magnetic field, in the Sun, is proportionately larger than in the simulations, and reversal takes place every 11 years. Computations corroborate the current paradigm that such mean fields, and the regularity of the activity cycle,

Magnetism and the dynamo effect 3

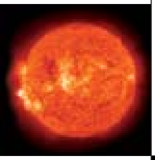
Magnetism [1] is the field, or the study of magnetic phenomena, the most common physical manifestation of which may be observed in magnets, or lodestones. Effects of the **magnetic field** are to be found in most celestial bodies and phenomena. On Earth, for instance, it is the so-called "geomagnetic" field which acts on compass needles, aligning them along the north–south axis. In the Sun, the magnetic field can have an intensity as much as 1,000 times higher, taking in turn the form of **sunspots**, **eruptions**, **prominences**, **bright points**... The magnetism of Sun and Earth is due to the **dynamo effect**. This effect refers to the property of a moving conducting fluid, namely its ability to induce a magnetic field. If it is not sustained, the magnetic field diffuses and wanes. Only some flows have the ability to amplify and sustain the magnetic field, this being the case for the **turbulent** motions prevalent in the Sun. Indeed, turbulent **convection**, in association with strong differential rotation in latitude and in depth, presents the required stretching, shearing, twisting and folding properties for dynamo action to arise and develop. The presence of magnetic fields gives rise to the Laplace force (i.e. the force exerted on currents by magnetic induction) which in turn influences the **plasma** motions through its action on charged particles. The effect of this force can be decomposed into a component linked to tension along the **magnetic field lines**, and another component linked to a magnetic pressure gradient perpendicular to the magnetic field lines. As with rotation, equilibrium states may be found between pressure gradient and magnetic field, or even with the Coriolis force, in the case of a rotating system such as the Sun. Scientists then speak of a *magnetostrophic equilibrium*. However, the large amount of turbulence prevalent in the Sun's outer layers modifies this equilibrium.

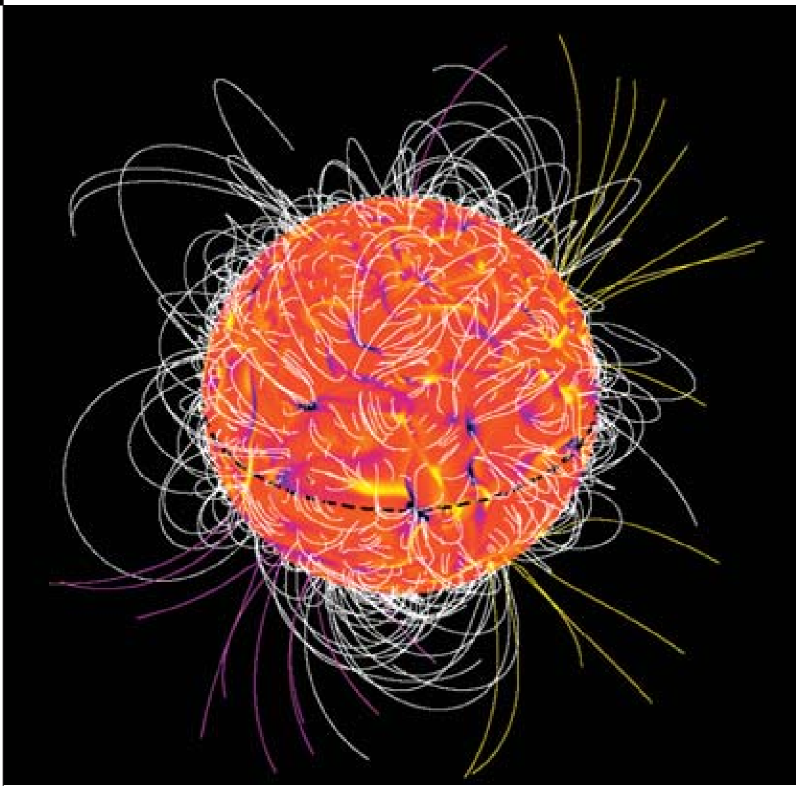
(1) Magnetism: from *magnes*, i.e. stone of Magnesia, or magnet, natural magnets being originally found in that Greek city.



D. Hathaway/NASA-Marshall Space Flight Center

Figure 3.
Butterfly diagram of sunspot emergence as a function of latitude and time over the past three decades. This makes apparent the equatorial drift of sunspots over a cycle, then the polarity reversal, the entire pattern following a complete 22-year cycle.





A. S. Brun/CEA

Figure 4.
Reconstruction of the coronal magnetic field from a three-dimensional turbulent dynamo simulation, carried out at CEA, concerning the Sun's convective region. White lines correspond to closed field lines, yellow and purple lines to open field lines. The background image represents the radial component of the magnetic field at 0.95 solar radius.

cannot be generated in a turbulent convective region, but most likely in a stable shear zone, such as the tachocline.
The next stage will consist on computing MHD models of the Sun with a tachocline and, in the medium term, a more realistic atmosphere. In coming years, it will become feasible to compute in real time a "meteorological" model of the Sun, and thus to control more effectively the dangers linked to Earth–Sun interactions. In the meantime, current models allow waypoints to be set for future developments, and make it possible to interpret the large quantity of observational data available.

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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

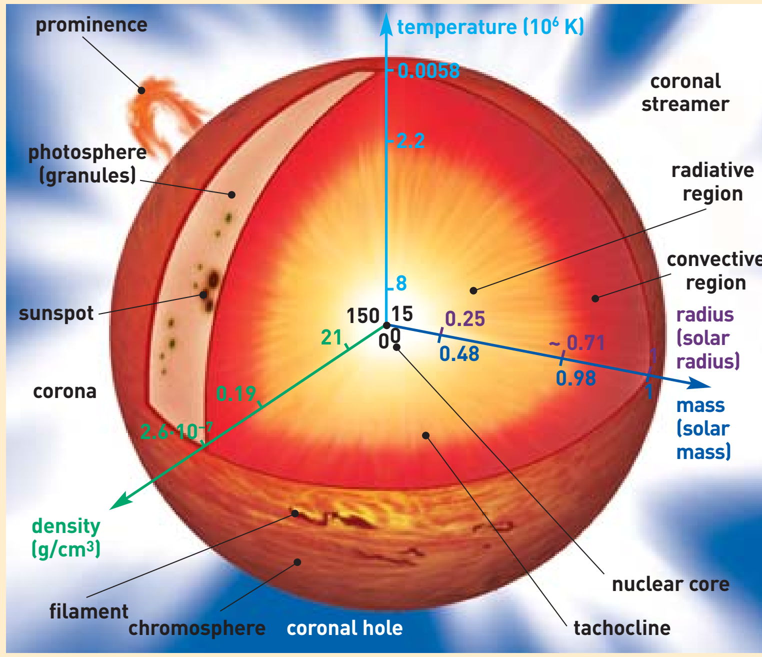
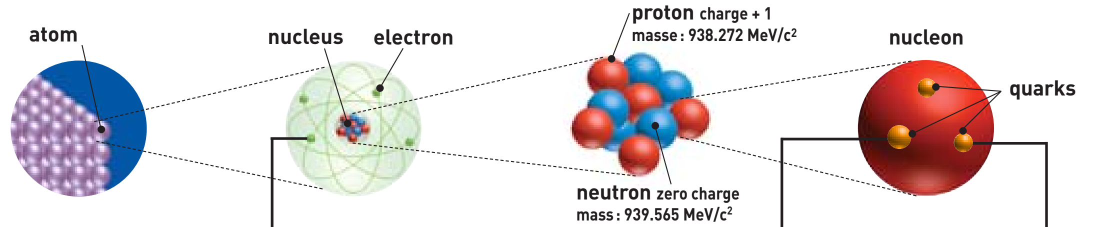


Figure.

(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.

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
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.

C (next)

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.

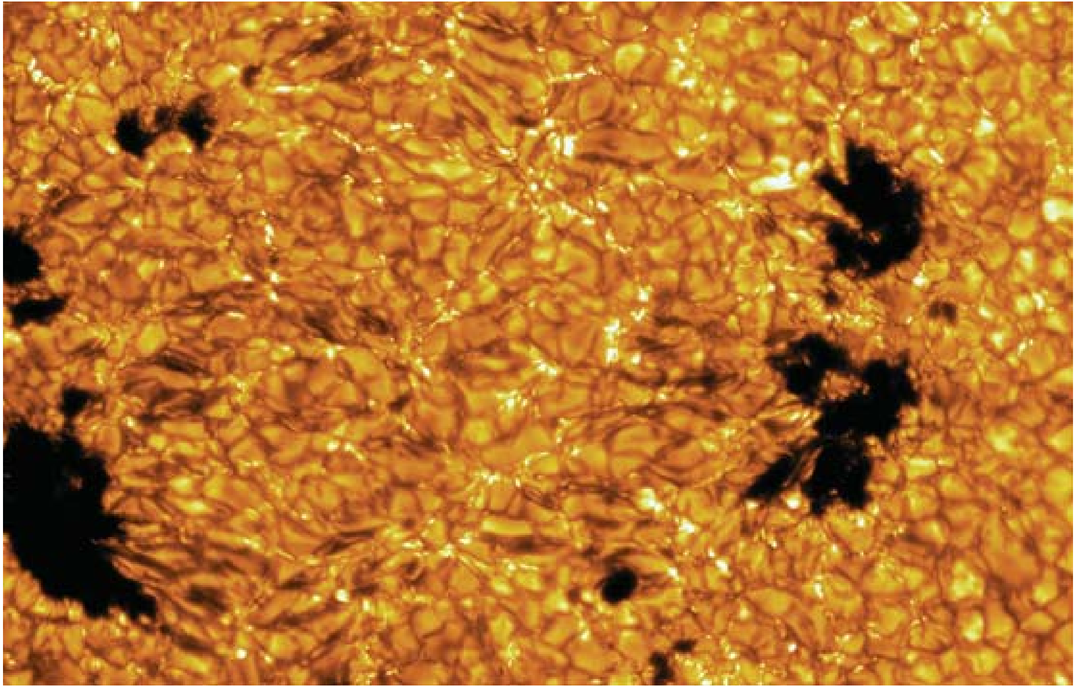
The graviton, the vector for gravitational interaction, has not so far been observed.

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.



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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.

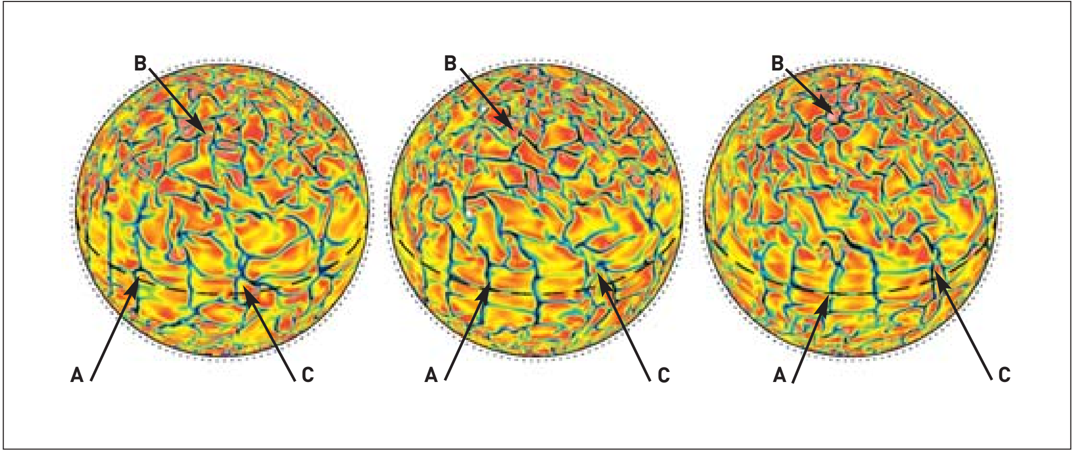

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Figure 1.
Evolution over time of radial velocity in a three-dimensional global simulation of convection under the influence of rotation. Shown in blue: descending flows; in yellow–red: ascending flows. Each image is separated by 5 days from the next. Markers A, B and C follow convective patterns of particular interest.

The effects of rotation

Rotation, represented by the symbol Ω, occurs throughout the Universe (planets, planetary systems, **stars**, **galaxies**...). Its effect on a given element (solid object, fluid...) depends on the centrifugal force and Coriolis force. The former tends to drive any element away from the center. The latter's effect is to deflect any moving object to the right in the northern hemisphere, to the left in the southern hemisphere. The faster the system rotates, the stronger centrifugal force will predominate, to the extent of completely tearing the object apart, should its amplitude exceed the object's internal cohesion force, or forces. These internal cohesion forces would be, for instance, in a solid object, **electrostatic** forces between **atoms**, or, for a fluid mass such as a star, the **force of gravity**. The Sun rotates rather slowly (1 rotation in 28 days), compared to a dentist's drill (3,000 rpm), or even related to other stars, some of which complete a rotation in under one day. Thus, its **convective** motions are mainly influenced by the Coriolis force. The most arresting effect of this force, undoubtedly, is the setting up of cyclones in the Earth's atmosphere. A balance then prevails, between the horizontal pressure gradient and the Coriolis force: physicists speak of a *geostrophic equilibrium*. In stars, such "meteorological" phenomena also occur, however, just like on Earth, where cyclones invariably have a radius greater than about 100 km, the Coriolis acceleration only affects motions larger than a given scale, the so-called *Rossby radius*. In the Sun's **convective region**, this radius stands somewhere between 10,000 and 30,000 km, allowing a separation to be effected, of scales sensitive to the effects of rotation from scales not so sensitive. Of course, the **turbulent** character of convective motions inside stars modifies this equilibrium. For instance, the meridional circulation [1] that is observed in the Sun results from just such a departure from geostrophy. For more rapidly rotating stars, centrifugal force becomes a major factor, and it then tends to flatten the star at the poles, turning it from a spherical shape to an ellipsoid.

(1) Meridional circulation: a mean flow in the form of cells contained in a meridional plane.