Glossary

A

absorption: the process whereby the intensity of a radiation decreases as it passes through a material medium, to which it transfers all or part of its energy.

accretion: the capture of matter by a celestial object, through the effect of the **force of gravitation**.

accretion disk: the region formed owing to the capture, by an object, through **gravitation**, of matter (dust, gas), the accumulation of which may result in the emergence of more massive objects, e.g. **planets** around a **star**.

activated carbon: carbon of vegetal provenance, subjected to an activation process endowing it with a high specific surface area, and thus high **adsorption** capacity.

active galactic nuclei: black holes, of masses ranging from several million to several billion **solar masses**, emitting huge quantities of energy, owing to complex matter **accretion** processes, and **relativistic magnetohydrodynamics** processes.

adiabatic: refers to a system undergoing no exchange of heat with the outside environment.

adsorption: the retention of **molecules** on a solid surface, as a rule through a passive, nonspecific process (for instance, by electrostatic effect, in a gaseous or liquid environment). **Desorption** is the opposite process.

Alfvén waves (named after Swedish astrophysicist Hannes Alfvén)**:** magnetohydrodynamic **waves**; in a **plasma**, this takes the form of a traveling oscillation of the **ions**, and **magnetic field.**

algorithm: a theoretical method of effecting numerical calculation, implemented on a computer, by means of a programming language.

angström (Å): 1 Å = 10^{-10} meter.

angular momentum: a measure of the rotational energy of a system.

angular resolution: the smallest angular separation between two objects, characterizing, in particular, the ability of an optical system to distinguish, or reproduce details in a scene, or its image. This is expressed in **minutes of arc**, or **seconds of arc**, 1 minute of arc (arcmin) being subdivided into 60 seconds of arc (arcsec).

anisotropy: see **isotropy**.

anthropic principle: this posits that the Universe must be such that the existence of observers is possible; in particular, the constants in nature, e.g. the fine-structure constant, may only differ by very small amounts from their measured values, lest they preclude the emergence of **atomic nuclei**, **atoms**, etc., thus making the existence of observers impossible; as applied to the **cosmological constant**, the existence of **galaxies** thus entails that this constant is necessarily bounded by a value equal to 100 times the value of the energy in the constituents of the present-day Universe.

antimatter: this is made up of antiparticles, in precisely the same way as matter is made up of particles; to every particle there corresponds an antiparticle, of opposite electric charge, involving the property that, when the two come together, they annihilate: for instance, a **electron** and a positron (this being the name given to the antielectron) may annihilate, yielding two **photons**.

asteroid belt: lying between Mars and Jupiter, small objects of irregular shapes, known as **asteroids**, are found to orbit the **Sun**, at a distance of 478.72 million kilometers. It is believed there are some 1–2 million asteroids with a diameter larger than 1 km. 200 million kilometers wide, this asteroid belt is thought to be what remains of a **planet** that was unable to form, owing to Jupiter's **gravitation**.

asteroids: small celestial objects, of rocky, or metallic composition, gravitating around the **Sun**, involving sizes ranging from about 1,000 kilometers down to a fraction of a kilometer. It is thought there are at least one million asteroids with a diameter of more than 1 kilometer. Most of these follow orbits around the Sun lying between Mars, and Jupiter.

astrometry: the branch of astronomy concerned with the position, and motion of celestial objects.

atom: the basic constituent of ordinary matter, comprising a **nucleus** (made up of **neutrons**, and **protons**) around which **electrons** orbit.

aurora borealis (and australis): also known as northern (and southern) lights; a colored, luminous phenomenon generated in the ionosphere (a region of charged particles in the upper atmosphere, extending, on Earth, from 40 km to 460 km or higher) of an Earthlike **planet**. It is caused by interaction (collisions) of the **ionized** particles in the **solar wind** trapped by the planet's **magnetic field**, and the **atoms** of the upper atmosphere, close to the magnetic poles (aurora borealis in the Northern Hemisphere; aurora australis in the Southern Hemisphere).

B

barotropic equation of state: an equation of state is a relation connecting the various **thermodynamic** quantities characterizing a material (density, temperature, pressure…); it allows, in particular, pressure to be calculated as a function of density, and temperature; an equation of state is said to be barotropic if pressure is solely dependent on density.

baryogenesis: the ensemble of physical processes resulting in an **asymmetry** arising between the density of **baryons**, and the density of antibaryons; **electroweak baryogenesis:** the baryogenesis mechanism involving the specific feature of occurring at the time of the electroweak phase transition (i.e. the time, in the history of the Universe, during which particles acquired their mass).

baryon: a nonelementary particle (being a bound state of 3 quarks), the most well-known instances being the **proton**, and the **neutron**, the constituents of the **nucleus**; an antibaryon is the antiparticle of a baryon: e.g. the antiparticle of the proton is known as the antiproton, that of the neutron as the antineutron.

baryon asymmetry: the (nonzero) difference found between the density of **baryons**, and that of antibaryons, in the Universe.

baryonic acoustic oscillations: over an extended period in the history of the Universe, **baryons**, and **photons** were engaged in interaction; the outcome being oscillations, comparable to those undergone by two masses coupled by a spring; such oscillations are apparent in the distribution of matter across the Universe.

Big Bang: the Standard Model of **cosmology**, according to which the observable Universe has been expanding for some 14 billion years.

binary system: a system made up of two **stars** orbiting around their shared center of mass. Close binary systems are able to exchange matter by way of the **accretion** process.

black body: an ideal body which totally **absorbs** all radiation, at any wavelength, while itself emitting radiation that is a function solely of its temperature.

black hole: an object that is so compact it sets up a **gravitational attraction** that is so strong neither matter nor light are able to escape from it. Within the **Milky Way**, some black holes are the outcome of the collapse of a **star** of more than 10 **solar masses** (**stellar black holes**). A black hole weighing in at several million solar masses lies at the center of the Milky Way.

bolometer: a device allowing an incident flux of energy (whether carried by **photons**, or massive particles) to be measured, by way of the rise in temperature resulting from the deposition of energy.

Boltzmann constant (k_B): a fundamental constant, involved in the expression of the relation between energy and temperature, in statistical physics: $k_B = 1.38 \cdot 10^{-23}$ **J**/**K**.

brane: hypothesized objects occurring in the extra dimensions featured by forms of **spacetime** involving more than 4 dimensions; in some models, these plane objects stand as the edge of the extra dimensions.

brown dwarfs: these stand as a distinctive class of objects, having masses intermediate between those of **planets**, and of **stars**. Owing to their mass being too low, the temperature, and pressure at the core of these objects are insufficient to initiate, or sustain **thermonuclear fusion** reactions.

byte: a unit of measurement in computer science, for the quantity of data. Strictly speaking, "byte" refers to any sequence of adjacent bits, i.e. binary digits, shorter than a word. Be that as it may, "byte" (B) is nowadays universally used to mean a unit of 8 bits. Multiples include the terabyte (10^{12} B).

C

Cartesian, uniform-resolution grid: the partitioning of space into square, or cubic cells all having the same size.

Cepheid: a **bright** variable **star**, of a type found in the Cepheus Constellation. The **luminosity**, period of variation, and color of such stars are found to be correlated. Cepheids thus provide good indicators of distance, in particular for nearby **galaxies**.

Chandrasekhar limit: the maximum mass that a celestial object consisting of degenerate matter (i.e. matter formed of **nuclei**, and **electrons**: e.g. a **white dwarf**) may support, by way of electron degeneracy pressure, before succumbing to **gravitational** collapse.

Cherenkov (or Čerenkov) light (named after Russian physicist Pavel Alexeyevich Čerenkov)**:** a phenomenon, similar to a **shockwave**, yielding a flash of light, which occurs when a charged particle travels across a medium at a velocity higher than the speed of light in that medium. It is this effect that causes the blue glow in the water surrounding the core of a nuclear reactor.

chromosphere: the lower layer in the **Sun**'s atmosphere, lying in the immediate vicinity of the **photosphere**.

CNO cycle: also known as the **carbon–nitrogen (–oxygen) cycle**, from the name of the **elements** generated, and involved in further reactions, where they act as catalysts; or as the **Bethe cycle** – named after US physicist Hans Bethe, 1967 Nobel prizewinner. A cycle of thermonuclear reactions occurring inside **stars**, in the course of which four **hydrogen nuclei** are transformed into a **helium** nucleus, releasing energy. This cycle is believed to account for only 1.5% of the Sun's energy.

comet: a celestial object in the Solar System, comprising a nucleus consisting of ice, and rocky material, which, as it gets close to the **Sun**, heats up, ejecting an atmosphere of gas, and dust. The coma, or tail, thus formed may extend across millions of kilometers.

Compton effect: the process whereby an **electron** picks up energy as it collides with a high-energy **photon**; **inverse Compton effect:** the transfer of energy to a **photon**, as it collides with a very-high-energy **electron**.

convection zone (or region): the outermost region in the **Sun**'s interior, inside which **atoms** are not necessarily **ionized**, and within which **convection** currents arise.

corona (solar, or stellar): the outermost, transparent region in the **Sun**'s (or the **star**'s) atmosphere, extending across millions of kilometers.

cosmic microwave background: also known as the **diffuse cosmic background**, or cosmic background radiation; fossil radiation in the **microwave** region, pervading the entire Universe, and emitted at the time when the Universe became transparent to **photons**.

cosmic microwave background (CMB) spectrum: the cosmic **microwave** background (or diffuse cosmic background) is the name given to the **electromagnetic radiation** originating in an epoch when the Universe was hot, and dense, shortly after the **Big Bang**; while it did originate in a hot, dense epoch, this radiation has become diluted, and cooled down, owing to the expansion of the Universe, and now exhibits a very cold temperature, to wit 2.726 **K**; the precise measurement of the CMB's properties by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite has made it possible to set very precise constraints on the parameters for the evolution of the Universe.

cosmic rays: streams of charged particles (**protons**, **helium nuclei**, **heavy-element nuclei**) traveling across interstellar space at **relativistic** velocities.

cosmological constant: a constant introduced by Albert Einstein into his **theory of general relativity**, to obtain a stationary Universe; when the Universe was found to expand, as discovered by Edwin Hubble in 1929, Albert Einstein abandoned this idea; however, the discovery, in the late 1990s, that there is an acceleration in the expansion of the Universe brought this concept of a cosmological constant back to the fore, as its introduction into the theory of general relativity also allows a Universe undergoing accelerating expansion to be described.

cosmological horizon: this term refers to the fact that it may be impossible to communicate with distant regions of the Universe (**future horizon**, or **event horizon**), or that it never was possible to receive signals from very distant regions (**past horizon**).

cosmological principle: this posits that the Universe is **isotropic**, and homogeneous; **isotropy** refers to the fact that there is no privileged direction; homogeneity entails there are no special positions in the Universe; the Copernican principle states that the Earth holds no special position in the Universe.

cosmology: the discipline concerned with the study of the structure, and evolution of the Universe as a whole.

Coulomb barrier: the electric repulsion impeding the coming together of two charged particles (the **protons** from two **nuclei**, in particular) having same-sign charges. This barrier may be overcome if the relative velocities of the two particles are sufficiently large. Through **nuclear interaction**, which makes itself felt at very short ranges, they may then undergo a **thermonuclear fusion** reaction.

cryocooler: a device operating in closed-circuit mode, generating cold at very low temperature (at cryogenic temperature, i.e. < 120 **K** [< –150 °C]).

cylindrical-symmetry disk: an object exhibits cylindrical symmetry if it remains invariant, when rotated about an axis: the axis of symmetry.

D

dark energy: a form of energy, the nature of which is unknown, introduced to account for the acceleration which appears to characterize the expansion of the Universe, over the past several billion years. The existence of such energy is grounded, in particular, on the observation of certain **stellar** explosions: **type-Ia supernovae**.

dark matter: a major constituent of the Universe, being more than six times more abundant than ordinary, visible matter; dark matter has the specific characteristic of emitting no **radiation**, interacting solely by way of **gravity**. In order to discover its distribution across space, astronomers use, in particular, the deflection of light that is caused by dark matter (**gravitational lensing effect**).

deuterium: a "heavy" **isotope** of **hydrogen**, featuring a **nucleus** comprising one **proton**, and one **neutron**. Cosmic deuterium is understood to have been generated in the course of **primordial nucleosynthesis**, so that – since deuterium may not lastingly arise inside **stars** – the quantity present at the present time provides an essential indication as to the density of matter in the Universe.

diffuse cosmic background: see **cosmic microwave background**.

dwarf (stars): **stars** in the **main sequence**, belonging to **luminosity** class V. The **Sun**, for instance, is a **yellow dwarf**. **Red dwarfs**, on the other hand, are very-low-mass (0.08–0.3 **solar mass**) stars, with a surface temperature lower than 3,500 **K**, emitting very little light. Their central temperature is not very high, and the conversion of **hydrogen** into **helium** takes place at a very low rate. Dwarf stars are not to be confused with **white dwarfs**, or **brown dwarfs**, these latter being stages in stellar evolution.

dynamo effect: the property, exhibited by a conducting fluid, of generating a **magnetic field** through its motion, and sustaining this field, notwithstanding **Ohmic dissipation** (i.e. the release of heat, due to the resistance opposed by the conductor to the passage of an electric current).

E

effective temperature: the temperature of a **black body** (of the same radius) emitting the same total quantity of **electromagnetic radiation** as the object being investigated. This is used to arrive at an estimate of an object's temperature, when the **emissivity** curve (as a function of wavelength) is unknown.

electromagnetic (radiation, or wave): a radiation (or wave) that propagates, in a vacuum, at the speed of light, through the interaction of oscillating electric, and **magnetic fields**, and transports energy (**photons**).

electromagnetic and weak interactions: current theory states there are four interactions: the **electromagnetic interaction** (electric charges, **magnetic fields**, light…); the **weak interaction** (beta **radioactivity**, reactions inside the **Sun**, **neutrinos**, etc.); the **strong interaction** (cohesion of **nuclei**…); and the **gravitational interaction**; the electromagnetic, and weak interactions are already unified by the **Standard Model**.

electron: a negatively-charged elementary particle (lepton). One of the constituents of the **atom**, orbiting around the **nucleus**.

electron–hole pair: in a semiconductor, part of the energy deposited by a **photon** serves to strip **electrons** bound to **atoms**, in the valence band, transferring them, as **free electrons**, to the conduction band. An electron, once stripped from the atom, leaves a vacancy in that atom's electron cloud: a "hole;" a minimum amount of energy is required to generate an electron–hole pair: about 1.1 **eV** for silicon.

electronvolt (eV): unit of energy, corresponding to the energy gained by an **electron** accelerated by a potential of 1 volt, i.e. 1 eV = $1.602 \cdot 10^{-19}$ **joule**. Main multiples: the **kiloelectronvolt** (**keV**: 10^3 eV), the **megaelectronvolt** (**MeV**: 10^6 eV), and the **gigaelectronvolt** (**GeV**: 10^9 eV).

element (chemical): the ensemble of all **atoms** having the same atomic number (i.e. all atoms having **nuclei** containing precisely the same number of **protons**, irrespective of the number of **neutrons**). A distinction is made between **light elements** (**hydrogen**, **helium**, **lithium**, beryllium, boron), and **heavy elements** (the others, from carbon to uranium, as far as natural elements are concerned – though more specifically those elements of atomic number equal to or greater than 80).

emissivity: the ratio of the amount of radiation emitted by a surface, over that emitted by a **black body** at the same temperature.

energy-dispersive spectrometry: spectrometry that is carried out in the detector, bypassing the requirement to make use of an optical device, e.g. gratings, or Bragg crystals; energy is measured by counting the number of **electron–hole pairs**, scintillation **photons**, or electron–**ion** pairs, depending on whether a semiconductor, a scintillator, or a gas counter is used.

entropy: a physical quantity that is a measure of the degree of disorder exhibited by a system.

equatorial coordinate (system): **stars** are located on the celestial sphere by way of their **right ascension**, and **declination**. Right ascension (α) is the equivalent, on the celestial sphere, of longitude on Earth. This is measured in hours (h), minutes (min), and seconds (s) of time (from the vernal equinox on the celestial equator). Declination (δ) is the equivalent, on the celestial sphere, of latitude on Earth. This is measured in degrees (°), minutes ('), and seconds ('') of arc. Star positions are commonly expressed, in catalogs, in terms of **J2000** coordinates.

F

fission: the splitting of a **heavy nucleus** into two fragments, with concomitant emission of **neutrons**, radiation, and a considerable release of heat.

Fourier transform: the expansion of any given mathematical function into a sum of sine and cosine functions.

free electron: an **electron**, normally bound, at a distance, to the **nucleus** of an **atom**, which has broken from its bond with that atom.

fuel (thermonuclear): **light elements**, liable to undergo **fusion** inside a **thermonuclear** reactor (or a **star**), yielding energy.

fusion (thermonuclear): a nuclear reaction whereby small **atomic nuclei** combine at high temperature to form larger nuclei having a mass lower than the sum of the masses of the initial nuclei, the difference in mass being converted into energy in accordance with the Einsteinian mass–energy equivalence law: $E = mc^2$. This type of reaction allows the **Sun** to shine with lasting **brightness**, and stands, directly or indirectly, as the source of virtually all of the energy on Earth.

G

galaxy: the aggregation of billions, or even hundreds of billions of **stars**, bound by **gravitational attraction**, along with dust, and gas in **atomic** and **molecular** form, in variable quantities – forming the **interstellar medium** – and **dark matter**, the nature of which is as yet unknown. Galaxies exhibit a variety of shapes. **Spiral galaxies** comprise a thin **disk**, made up of a mix of gas, dust, and stars, together with a thicker central **bulge**, chiefly made up of stars. It is within the disk that spiral arms arise, in varying numbers, and more or less sharply delineated. **Elliptical galaxies**, which are gas-poor, exhibit a fairly regular elliptical shape. **Irregular galaxies**, these often being small, and not very massive, are gas-rich, and star-poor. By convention, a capital "G" is used when referring to our own Galaxy: the **Milky Way** ("the Galaxy").

galaxy cluster: such clusters comprise hundreds of **galaxies**. These galaxies, however, account for a mere 5% of the cluster's total mass, while **dark matter** accounts for 70–80%. The remainder consists of hot gas, at temperatures of up to 10–100 million degrees. This **plasma** is a strong **X-ray** emitter. These three components are bound together by **gravitational attraction**.

gamma-ray bursts: standing as the most violent phenomena in the Universe, these transient sources make their presence felt through fierce flares in the **gamma-ray** domain.

gauss: a unit serving to measure **magnetic fields**, noted G; also the name of a programming language for statistical work; named after Carl Friedrich Gauss (1777–1855), a German mathematician, astronomer, and physicist.

giant (stars): end-of-life **stars** that have exhausted the **hydrogen** in their core, and burn hydrogen in a shell around this core. Other **elements**, **heavier** than hydrogen, may also be undergoing **fusion**, in the core or in outer shells. The radius of such giants ranges from several tens of, to several hundred **solar radii**. See also **red giant**.

gravitational attraction: the property, exhibited by all the physical objects present in the Universe, of attracting each other. The **force of gravitation** is a universal force, its range being infinite.

gravitational lensing effect: the minute deflection undergone by light coming from distant **galaxies** provides information as to the distribution, and quantity of matter (galaxies, **galaxy clusters**, **dark matter**) – be it visible, or invisible – that light has passed through on its way to us. This effect is analogous to that of a lens, slightly distorting the landscape in the background.

gravity: the phenomenon whereby a massive object attracts other objects. This is due to **gravitation**, which causes two bodies to attract one another, as a function of their mass, and the inverse of the square of their distance.

gravity mode: in fluid mechanics, **gravity waves** are generated within a fluid medium (internal waves), or at the interface between two media, e.g. air, and the ocean (surface waves): such is the case of ocean waves, or tsunamis. In a **star**, gravity modes are low-frequency standing waves, the restoring force for these being provided by buoyancy.

H

halo: a vast, more or less spherical region extending around **galaxies**, holding **dark matter**, old **stars**, and gas, but no dust.

helioseismology: the discipline concerned with the study of the solar interior through analysis of the **Sun**'s natural oscillation modes. Studying the Sun's vibrations, propagating from the surface and reflected by the various internal layers, allows measurement of such parameters as the speed of sound, or rotation velocity. **Asteroseismology** is the study of seismic motions occurring in **stars** other than the Sun.

helium: chemical **element** (He), the lightest element after **hydrogen**. Its **nucleus** comprises two **protons**, and two **neutrons**, for **helium-4**, the most common **isotope** (the nucleus of **helium-3** features one single neutron). The helium present in the Universe was synthesized at the time of the **primordial nucleosynthesis**. Scarce though it is in the Earth's atmosphere, helium is abundant in **stars**, where it arises as the result of the burning of hydrogen.

hertz: a unit of frequency (**Hz**), equal to 1 cycle per second, for alternating phenomena. The chief multiples include the **megahertz** (1 **MHz** = 10^6 Hz), and the **gigahertz** (1 **GHz** = 10^9 Hz).

Hertzsprung–Russell diagram: a diagram showing, along the *x*-axis, an indicator of **effective stellar temperature** (B–V color index, **spectral type**...), and, along the *y*-axis, an indicator of total **luminosity**. Stars are found to be grouped into well defined regions (**main sequence**, **giants**, **supergiants**, **white dwarfs**), corresponding to distinctive evolutionary stages, for stars of different mass, and composition.

Higgs boson: a particle predicted by the **Standard Model of particle physics**, to account for the mass exhibited by all other particles; this is the last as yet undiscovered particle, if the Model is to stand complete; the LHC was built, in particular, for the purposes of generating this particle.

hydrogen: the simplest **atom**, comprising one **proton**, and one **electron**.

hydrostatic equilibrium: the equilibrium prevailing in a fluid when the force of **gravity** (and hence weight) exactly counterbalances the vertical pressure gradient.

I

interferometer: a device within which **electromagnetic waves** can be superposed. For astronomical purposes, the superposition modes of these waves allow the angular size of an object to be measured, to a high precision.

ion: an **atom**, or **molecule** that has lost, or gained, one or more **electrons**, and thus exhibits an electric charge (**cation**: positive ion; **anion**: negative ion).

ionization: a state of matter in which **electrons** are separated from the **nuclei**; the process whereby **ions** are produced, through collisions with **atoms** or electrons (collision ionization), or interaction with **electromagnetic radiation** (photoionization).

isotopes: forms of one and the same chemical **element**, for which the **nuclei** have the same number of **protons** (and hence of surrounding **electrons**), but different numbers of **neutrons**.

isotropic: showing identical physical properties in all directions (antonym: **anisotropic**).

J

Jeans wave: a **wave** propagating across a medium, due to self-**gravity**, and generating regions that are denser than the average for that medium.

Jeans–Toomre waves: **waves** forming when, within a disk, matter begins to aggregate through self-**gravity**. Named after the two physicists who first provided an analytical description of such structures.

joule (J): derived unit of work, of energy, and of heat in the International System of Units (SI). The joule is defined as the work done by a force of 1 newton, when the point of application is displaced 1 meter in the direction of the force; or the work done when a current of 1 ampere passes through a resistance of 1 ohm for 1 second.

K

Kaluza–Klein parity: an extra quantum number, related to the conservation of 5-dimensional momentum, introduced in theories involving **extra dimensions**; this is equal to +1 for all ordinary-matter particles, −1 for extra-dimensional copies; this KK number must be conserved by every process, and, consequently, a Kaluza–Klein particle may not decay into ordinary particles: any such decay process would involve a particle with a KK parity of −1 as its initial state, but an ensemble of particles of KK parity +1 as its final state, which is forbidden by the conservation law.

kelvin: unit of temperature (symbol **K**). The Kelvin scale features a single fixed point, this being, by convention, the thermodynamic temperature of the triple point of water (i.e. the point at which the three phases, solid, liquid, and vapor, coexist) at 273.16 K, i.e. 0.01 °C. 0 K = −273.15 °C is known as **absolute zero**, at which temperature every form of matter is frozen still.

Kelvin–Helmholtz instability: a **turbulent**, wavelike motion, which arises and develops when two fluids involving different densities, or velocities come into contact.

Kevlar: a polymer material, belonging to the class of aramid fibers, that exhibits outstanding mechanical properties (high Young's modulus, and tensile strength), and very low thermal conductivity.

Kuiper Belt: a vast region in the Solar System, containing large numbers of **asteroids**, and **comet** nuclei, thought to extend, within the **ecliptic** (i.e. the plane containing the Earth's orbit around the **Sun**), outward of the orbit of Neptune, out to 500 **astronomical units** away from the Sun.

L

Lagrangian (nature): refers to a method used for the physical description of a fluid, involving tracking its motion over time; by contrast, Eulerian methods describe the flow of a fluid past a fixed point; the evolution of the velocity of a boat navigating along a river involves Lagrangian data, whereas the evolution of the flow rate of that selfsame river across a weir involves Eulerian data.

Lagrangian points: named after Italian-born French mathematician and astronomer Joseph-Louis Lagrange (1736–1813), who mathematically deduced that a pair of heavenly bodies undergoing **gravitational** interaction will have, in its vicinity, five equilibrium (neutral) points, known as its Lagrangian points (L1–L5). At these points, the gravitational forces from two objects (the two heavenly bodies), combined with the centrifugal force, are able to hold in equilibrium a third object keeping to the same orbital plane, provided that its mass be very small, compared to the masses of the two main objects. Many satellites have thus been positioned at **Lagrangian point L1**, lying between the **Sun** and the Earth, 1.5 million kilometers from the Earth. **Lagrangian point L2**, likewise located 1.5 million kilometers away from the Earth, is in a symmetrically opposite position to L1, relative to the Earth.

leakage current: a current arising in a detector, due to an outside electric field being applied to it, in the absence of any light source, whether **X-ray** or **gamma-ray**, in the case considered.

leptogenesis: a **baryogenesis** mechanism, whereby a **lepton asymmetry** arises, and is subsequently partly converted into a **baryon asymmetry** by sphalerons.

lepton asymmetry: the (nonzero) difference found between the density of **leptons**, and that of antileptons, in the Universe.

light-year: the distance traveled by light in one year (at a velocity of 299,792.458 km/s in vacuum), i.e. 9,460.53 billion kilometers, or 63,239 **astronomical units**.

Lorentz force (electromagnetic force): one of the four fundamental forces of physics, along with the force of gravitation, and the weak, and strong interactions; the electromagnetic force induces all of the **electric, and magnetic interactions** that are found to occur.

luminosity (of a star, or a galaxy): a measure of the power radiated, in the form of light, by a **star**, or a **galaxy**, i.e. of the energy it emits, as a function of time. This is expressed in **watts** (**W**). **Bolometric luminosity** corresponds to the luminosity measured across the entire **electromagnetic spectrum**. Stars are classified according to their luminosity (luminosity classes I–VII). **Supergiants** (class I) are the **brightest**, followed by bright, and normal **giants** (classes II, and III), subgiants (IV), **dwarfs**, or **main-sequence** stars (V), subdwarfs (VI), and **white dwarfs** (VII).

luminous arcs: the image of a point source, when distorted by **gravitational lensing**, often appears as luminous arcs, resulting from the deflection of light from that source by the lens's mass.

M

magnetic field: a force field generated by electric currents. Magnetic field strength is expressed in **teslas**, or **gauss** (1 G = 10^{-4} T). The **toroidal component** of a typical magnetic field is aligned in like manner to the parallels at the surface of the **star**, or **planet**. The **poloidal component** of that field, going from pole to pole, is thus aligned as the meridians.

magnetohydrodynamics (MHD): a theory, analogous to the hydrodynamics governing electrically neutral fluids, which allows the large-scale behavior of conducting fluids – liquid metals, **plasma** – to be studied.

magnetosphere: the region in space within which a **planet**'s **magnetic field** predominates over the **solar wind**, shielding that planet from the **ionized** particles making up the solar wind. As regards the Earth, this extends beyond the ionosphere, from about 1,000 kilometers above the Earth's surface, out to the magnetopause, which forms the boundary with interplanetary space.

magnitude: a scale of **brightness** for astrophysical objects. **Stars** visible to the naked eye have magnitudes ranging, as a rule, from 0 to 6.

magnitude scale: the distances of far-off objects are calculated by way of the **luminosity** of the objects observed; astronomers make use of their **magnitude**, this being graded on an inverse logarithmic scale of luminosity.

main sequence: the region in the **Hertzsprung–Russell diagram** inside which lie all the **stars** that use, for their source of energy, the **fusion** of **hydrogen**, yielding **helium**: one of these is the **Sun**, in its present state. Stars of a given chemical composition take up a position, depending on their mass, along a line known as the **zero-age main sequence** (ZAMS).

megohm: a unit of electrical resistance, equal to 1 million **ohms**.

meteorite: a fragment from an **asteroid**, or a **comet**, of varying size, of stony, or metallic composition, traveling across space, and liable to land on the surface of a celestial body.

micro-: a prefix (symbol **μ**) representing one millionth (10^{-6}). 1 **micrometer** (**μm**), or **micron** = 10^{-6} meter.

microquasars: **binary systems** in which a compact object (a **neutron star**, or a **black hole**), **accreting** matter from its companion star by way of an **accretion disk**, causes the ejection of jets of matter at velocities close to the speed of light.

Milky Way: the name given to our own Galaxy, this being a vast rotating **disk**, comprising slightly more than 200 billion **stars**. It is a **spiral galaxy**.

minimal dark matter models: models recently put forward, in the field of particle physics, to account for the nature of **dark matter**, without framing it in a way that would entail the full complexity of theories such as **supersymmetry**, or **extra dimensions**.

modeling: the working out of a simplified representation (a **model**) for a system, or a process, for the purposes of simulating it, which is then drawn up in a computation software (often referred to as a **code**), in the form of mathematical expressions. Mesh **cell** size, across space, and time, yields the model's **resolution**.

modified Newtonian dynamics (MOND) theory: this is a theory put forward by Israeli research scientist Mordehai Milgrom, in the 1980s, when he suggested modifying **Newton's second law** (amply corroborated to date though it is, by every astronomical observation), to account for the rotation curves found for **galaxies**, without resorting to the introduction of **dark matter**.

molecule: a group of **atoms**, held together by chemical bonds.

moment equation: an equation obtained by averaging, over angles, the **radiative** transfer equation.

multiplexing: a technique involving making two or more information streams pass through one and the same communication channel; this makes it possible to share a unique resource between a number of users. Two main multiplexing techniques are in use: time-division multiplexing, and frequency-division multiplexing (also known as wavelength-division multiplexing, this coming down to the same thing).

muon: the name given to two positively, and negatively charged elementary particles, within the **Standard Model**. They have a mass 207 times larger than that of the **electron** (for which reason they are also referred to as heavy electrons) (105.66 **MeV**), and their spin is 1/2. Muons, as electrons, belong to the same family of fermions, to wit the leptons. Muons are noted as μ^-, or μ^+, depending on their electric charge.

N

nano-: a prefix (symbol **n**) representing one billionth (10^{-9}); 1 **nanometer** (**nm**) = 10^{-9} meter.

natural radioactivity: radioactivity that is due to sources not produced by human agency (radon, **cosmic rays**).

nebula: a huge cloud of dust particles, and gas, lying out in space.

neutralino: a new particle, proposed in the context of **supersymmetry**, consisting of a mix of supersymmetric partners of the **photon**, the **Z weak boson**, and the **neutral Higgs bosons**; it has a zero electric charge, and a predicted mass of some 100 **gigaelectronvolts**; it is the most heavily investigated candidate **dark-matter** particle.

neutrino: an elementary particle having a very low mass (long assumed to be zero mass). Neutrinos are emitted in **thermonuclear reactions** within **stars**, and in large numbers when gravitational collapse occurs, in a **supernova**. They are extremely difficult to observe, owing to their interacting very little with matter.

neutron: an electrically neutral particle, 1,839 times heavier than an **electron**. Neutrons and **protons** are the constituents of **atomic nuclei**.

neutron star: an object consisting chiefly of **neutrons**, the end result of the final collapse of **stars** far more massive than the **Sun**. Neutron stars have a radius of 10–15 km, and a density of 10^{14} g/cm^3. **Pulsars** are rapidly rotating magnetic neutron stars.

Newton's laws: the set of laws that stand as the foundations of mechanics, set out by Isaac Newton at the end of the 17th century. Newton's first law, also known as the law of inertia (first formulated by Galileo), states that the **center of mass** of a solid body that is subjected to a sum of forces equal to zero either continues in a state of rest, or in a uniform motion in a straight line. Newton's second law states that the sum of the forces acting on a point object is equal to the product of the mass of that object by its acceleration vector. Finally, the third law states that, when a solid body S_1 exerts a force on a second solid body S_2, then body S_2 exerts on body S_1 an equal and opposite reacting force. Complementing these three laws of dynamics with his law of universal gravitation, Newton was able to show that the motions of the **planets** around the **Sun** conform to elliptical paths.

northern (and southern) lights: see **aurora borealis (and australis)**.

nucleons: the constituent particles of the **atomic nucleus**, bound together by way of the **strong nuclear interaction**, which ensures their cohesion. **Protons**, and **neutrons** are nucleons.

nucleosynthesis: the ensemble of physical processes resulting in the formation of **atomic nuclei**. See also **primordial nucleosynthesis**.

nucleus (atomic): the essential constituent of an **atom**, bearing a positive charge and comprising **protons**, and **neutrons** (except in the case of **hydrogen**), to which **electrons** are bound at a distance.

numerical simulation: the mimicking, by way of computation, of the functioning of a system, once it has been described by a **model**, or an ensemble of models.

O

opacity: the capacity, exhibited by matter, to **absorb radiation**.

Ostrogradski's theorem: this has the import that modifying **general relativity**, while precluding that this entail an instability of the Universe, is a highly tricky business; only one type of theories, known as "scalar–tensor" theories, complies with this criterion.

P

parsec (pc): a unit of length, defined as the distance at which 1 **astronomical unit** (**AU**) – this being equal to the **distance between the Earth, and the Sun**, i.e. about 150 million kilometers – subtends an angle of 1 second of arc. 1 pc = 206,265 AU = 3.26 **light-years**.

passive radiator: a wholly passive cooler, making use of **radiative** exchanges (heat exchanges by way of radiation, using a sink kept at a colder temperature).

photolithography: a technological process that makes it possible to fabricate **pixels** across the surface of a semiconductor substrate.

photometry: the measurement of the intensity of a light source.

photon: the quantum (i.e. an indivisible quantity) of energy of an **electromagnetic radiation**. An elementary particle, having zero mass and no electric charge, associated to such radiation.

photosphere (solar): the visible surface of the **Sun**, standing as the boundary between the opaque underlying region, and the transparent peripheral regions.

photovoltaic: an effect allowing the direct conversion of light into electricity, by way of the generation, and transport of electric charges in a semiconductor material, featuring one region that exhibits an excess of **electrons**, while another one exhibits an electron deficit.

pixel: a unit of area serving to define the basis for a digital image. So named as an abbreviation of the phrase "picture element."

planet: a celestial body that is not of itself luminous, and orbits around a **star**.

planetesimals: small rocky objects, occurring in the primordial Solar System, which aggregated to form **planets**, their moons, and **asteroids**.

plasma: a gas brought to such a temperature that **atoms** are **ionized**. Plasma properties are determined by the electromagnetic forces prevailing between its constituents (**ions**, and **electrons**), resulting in various types of behavior. Seen on Earth as the fourth state of matter, this stands, around the Universe, as its main state.

Poisson equation: an equation describing the properties of the **gravitational** field, and **gravitational forces**, on the basis of a mass distribution across space.

polarimetry: the science concerned with the measurement of the **polarization** of light.

polarization: in **electromagnetism**, the polarization state of a **wave** is characterized by the way the **electric field** (and **magnetic field**) varies across the wave's polarization plane, this being a plane perpendicular to the wave's direction of propagation. The figure traced out by the electric field vector may then be: a straight line segment, in the linear polarization case; an ellipse, in the case of elliptical polarization; or a circle, in the case of circular polarization.

polarized: having an electric-field vector which, as it describes an electromagnetic vibration, remains in a definite plane.

polyethylene: one of the simplest polymers (an inert plastic material), belonging to the class of polyolefins.

primordial: relating to the very dense, very hot, and very short (a few minutes) phase in cosmic evolution during which the **lightest elements** in the Universe (**deuterium**, **helium**), were generated.

primordial nucleosynthesis: the synthesis of **deuterium**, **helium-3**, **helium-4**, and **lithium-7 nuclei** over an interval of three minutes, as the temperature of the primordial Universe dropped from 10 billion to 1 billion degrees.

principle of least action and Lagrangian: in optics, light rays comply with Fermat's principle (least-time principle), whereby they minimize the optical path taken between any two points; particle theories comply with a similar scheme; in this case, particle motions (or variations in the fields associated to these particles) correspond to an extremum for the action of the particles involved, this being precisely equal to the (mathematical) integral of the Lagrangian of the system.

proton: a particle – a constituent of the **atomic nucleus** (**nucleon**) – bearing a positive electric charge, equal to that of the **electron**, and of opposite sign. A proton is 1,836 times heavier than an electron.

protostellar disk: a gas disk arising from the collapse of a diffuse cloud, at the center of which a **star** is forming; the outer regions of the protostellar disk may give birth to **planets**.

pulsar (abbreviation of "pulsating radio source"): a very rapidly rotating **neutron star**, emitting a strong beam of **electromagnetic radiation** along its magnetic axis.

Q

quantum: relating to the theory developed on the basis of Planck's quantum principle – whereby any manifestation of energy can only be expressed in terms of discrete (discontinuous) values, known as quanta (i.e. indivisible quantities) – and Heisenberg's uncertainty principle, whereby it is not possible to measure precisely, at one and the same time, both the position, and velocity of a particle.

quantum efficiency: the detection efficiency, as determined by the ratio of the number of **photons** detected, over the number of incident photons. A perfectly efficient detector would exhibit a quantum efficiency of 100%.

quasars: highly **luminous**, compact, energetic objects, lying at the center of certain **galaxies**. Very distant quasars bear witness to the first ages of the Universe.

R

radiation: energy emitted in the form of **electromagnetic waves**, or a flow of particles.

radiative (zone, or region): a region close to the **Sun**'s core, within which the gas is highly **ionized**, and energy transport occurs by way of **photon** scattering.

radio interferometry: a measurement method making use of the interferences arising between a number of mutually coherent **waves**; interferometry is used in astronomy (both optical, and radioastronomy) to achieve a **resolution** equivalent to that of a mirror (or of a radiotelescope) having a diameter equal to the baseline separating the instruments being combined; this makes it possible to obtain high-resolution instruments, using an ensemble of small telescopes, which prove less expensive to construct than a single large telescope.

red giant: a large, **bright star**, involving however a low surface temperature (less than 5,000 **K**), that has reached one of the final stages in its evolution, subsequent to the transformation of the **hydrogen**, and **helium** in its core into **heavy elements**. See also **giant (stars)**.

relativistic: relating to phenomena involving velocities close to the speed of light. Matter is said to be relativistic when its velocity comes close to the speed of light.

resonant spectrometer: this type of instrument was invented for the purposes of investigating velocity displacements in the superficial layers of the solar atmosphere. When applied to **lines** that are well known in the laboratory (sodium, potassium, iron, nickel), it affords the advantage of yielding **atomic** precisions.

Reynolds number (named after British engineer and physicist Osborne Reynolds)**:** a dimensionless number, used in fluid mechanics.

ridgelet transform: this allows the optimum analysis of line singularities occurring in an image.

Roche limit: the outer limit of the region around Saturn (or any other **planet**) within which any **gravitational** aggregation is impossible, owing to **tidal effects**. Saturn's Roche limit extends out to about 140,000 km (~2.5 Saturn radii). Édouard Roche (1820–83) was a French astronomer.

***R*-parity:** an extra quantum number, introduced in **supersymmetry theory**. This is equal to +1 for all ordinary-matter particles, –1 for supersymmetric partners. This number must be conserved by every process. Consequently, a supersymmetric particle may not decay into ordinary particles: any such decay process would involve a particle with an *R*-parity of –1 as its initial state, but an ensemble of particles of *R*-parity +1 as its final state, which is forbidden by the conservation law.

S

scalar field: particles, and fields are the two aspects of the **relativistic** form of the wave–particle duality in **quantum** mechanics; particles are classified according to their spin (1/2 for the **electron**, 1 for the **photon**); scalar fields are the **waves** associated to particles of spin 0.

semiregular variable (star): a **giant**, or **supergiant star** of intermediate **spectral type**, exhibiting a marked periodicity in its **luminosity** variations, accompanied however, or interspersed in some cases, by a variety of irregularities.

shock: a discontinuity arising in terms of density, as generated e.g. by an airplane going through the sound barrier.

solar cycle: a periodic variation observed in **solar activity**. The most clearly defined cycle lasts around 11 years. This activity manifests itself by the rise in the emergence of **sunspots**.

solar granulation effect: the **Sun**'s surface, kept as it is at a temperature of some 5,800 degrees, is highly **turbulent**, exhibiting a granular aspect, corresponding to **convection** cells, about as large as the area of France.

solar wind: a stream of charged, energetic particles, chiefly **protons**, and **electrons**, forming a **plasma**, issuing from the **solar corona** at velocities of several hundred kilometers per second.

spacetime: a concept arising as a result of Einstein's **theory of special relativity**, and suggested by Einstein to supplant the concepts of space, and time. The relation between space measurements, and the time measurements is given in terms of a constant, the value of which is independent of the observer: the speed of light in vacuum.

spectral type: this serves to classify **stars** by temperature, from hotter to cooler (O B A F G K M S R N H). Each spectral type is further refined by appending to it a digit, from 0 to 10 (e.g. an A5 star is slightly hotter than an A6 star). The **luminosity class** is often further appended. Thus, the **Sun** is a G2 V star, i.e. a G2, **main-sequence** star.

Standard Model of particle physics: the theory that describes the **strong**, **weak**, and **electromagnetic interactions**, together with all of the elementary particles that make up matter.

star: a gaseous sphere, consisting, overwhelmingly, of **hydrogen**, and **helium**, standing in equilibrium under the effect of its own weight, and the pressure of the gas. **Thermonuclear fusion** reactions occur in the star's central region. **Massive stars** (10–100 **solar masses**) are very hot (10,000–30,000 **K** surface temperature). They shine **brightly**, chiefly in the **ultraviolet**, and appear to be of a blue color to our eyes. **Small stars** shine faintly, are red in color, and lead a quiet life. They are relatively cool (1,300 K surface temperature).

star cluster: a group of **stars**, born out of the same **molecular** cloud, which remain bound by **gravitation**. These stars are thus all of identical age, and chemical composition. A distinction is made between **open clusters**, these being groups comprising from a few tens of stars, to several thousand stars, forming in the molecular clouds lying in the galactic plane; and **globular clusters**, exhibiting a spherical structure, comprising from several tens of thousand to several million stars.

stellar wind: an intense stream of particles that is emitted by **stars** throughout their evolution. Some massive stars eject matter at rates that may reach one hundred-thousandth **solar mass** annually, at velocities of several thousand kilometers per second.

stochastic signal: a signal that varies randomly over time. This arises in many domains: in physics, in electronics, in chemistry, and even in music. **Convective** bubbles, hitting a **star**'s surface, stochastically excite **waves**, which then propagate across the star.

string theory: an attempt to unify the laws of **general relativity**, and of **quantum** mechanics; for that purpose, particles are no longer to be seen as pointlike, rather they are turned into microscopic strings.

sublimation: the process whereby a substance passes directly from the solid to the vapor state.

Sun: an average **star**, of **spectral type** G2 V, lying at the core of the **main sequence** in the **Hertzsprung–Russell diagram**. The Sun is 4.6 billion years **old**. It has a **radius** of 700,000 km, a **mass** of about $2 \cdot 10^{30}$ kg, and a **surface temperature** of up to 5,770 **K**. Its **luminosity** stands at $3.8 \cdot 10^{26}$ **watts**. The **distance between the Earth, and the Sun** stands at around 150 million km, i.e. 1 **astronomical unit** (**AU**).

Sunyaev–Zeldovich (SZ) effect: the scattering of **photons** from the **cosmic microwave background** over the hot **electrons** in the gas inside **galaxy clusters**. Photons thereby pick up energy.

supergiant (stars): stars of masses ranging from 10 to 70 **solar masses**, exhibiting **luminosities** ranging from 30,000 to several million times the **solar luminosity**, and sizes of 30–500, or even more than 1,000 **solar radii**.

supernova: a **stellar** explosion in which the star's **luminosity** in the **visible** spectrum increases considerably, this phenomenon occurring at the end of the evolution of some stars. **Type-Ia supernovae** stand as the disintegration of a small, compact star – a **white dwarf** – that has become unstable owing to the buildup of matter stripped from a companion star, the white dwarf's mass having reached, at that point, the **Chandrasekhar critical mass** (1.44 **solar masses**). **Type-II supernovae**, by contrast, mark the explosion of a massive star (at least 8 solar masses). A substantial fraction of the star is ejected, the remainder forming a **neutron star**, or a **black hole**.

supersymmetry theory: a theory propounded in the 1980s, in particle physics, to account, in particular, for the mass predicted for the **Higgs boson**. This suggests that the ingredients in the **Standard Model** be duplicated: every ordinary-matter particle would have a supersymmetric partner, endowed with the same properties, but much heavier. Such superpartners may be generated in high-energy physical processes, such as, in particular, the collisions planned at LHC.

synchrotron (radiation, or emission): electromagnetic radiation emitted by electrically-charged particles traveling at **relativistic** velocities in a **magnetic field**, spiraling along field lines.

T

tachocline: a region, lying at the base of the **solar convection zone**, marking the transition between the differential rotation prevailing in the convection zone, and the rigid rotation, as a block, of the **radiative core**; the word itself comes from the Greek *takhos*, meaning "speed," and *klinein*, meaning "make slope, slant:" the term thus refers to a slope in velocity, i.e. shear: this boundary layer plays a major role in the large-scale organization of the Sun's **magnetic field**.

theory of general relativity: as set out by Albert Einstein (and David Hilbert) in 1915, general relativity brings together **special relativity**, as formulated in 1905 by Albert Einstein, and the theory of gravity. General relativity is based on the equivalence principle, which states that it is impossible, for an observer, to detect a difference between the effects of a **gravitational** field he would be subjected to, and an accelerated motion imparted to him. The illustration commonly given of this is that of an observer inside an elevator, who is unable to determine whether the elevator is subjected to a force of **gravity**, or is moving with an accelerated motion. General relativity is used to describe the evolution of the Universe.

thermodynamics: the branch of physics concerned with describing energy transfers in matter.

tidal effects: the **tidal force** arises owing to inhomogeneity in the **gravitational** field of an object. It distorts objects lying in the vicinity of that main object. In some cases, the forces generated may cause the disruption of small objects.

time step: the basic step in a **numerical simulation** having the purpose of computing the evolution of a system over time; starting from an initial state, the program computes the state of the system after a relatively short interval, the "time step," and reiterates the procedure for the following "time step."

turbulence: a flow mode in fluids, in which, onto the mean motion, a random agitation motion is superposed.

V

Van der Waals force: a low-intensity **electric interaction** force, arising between **atoms**, or **molecules**.

viscosity: a measure of the ability of a fluid to flow.

Vlasov–Poisson equation: an equation combining the equations of hydrodynamics, governing the evolution of a fluid, and the **Poisson equation**, which describes **gravitation**; the Vlasov–Poisson equation describes the evolution of a fluid subjected to its own **gravity**.

W

wave: the propagation mode for a periodic oscillatory phenomenon. A wave is characterized by its frequency, and the distance separating two consecutive peak values in the cycle, this being known as the **wavelength**.

wavelet transform: in like manner to the **Fourier transform**, this maps an input space (spacetime) to another space (frequency space).

weakly interacting massive particle (WIMP): a heavy particle undergoing **weak interactions**; thus, the term may refer to any particle sensitive to the weak force, and characterized by a very large mass, of around 100 **gigaelectronvolts**.

white dwarf: a small, faintly **luminous star**, having a surface temperature close to 20,000 **K**. A white dwarf is a hot, stable star, held in equilibrium by the repulsion arising between its **electrons**, once it has condensed, after having exhausted its **thermonuclear fuel**. Such an object, with a mass about equal to that of the **Sun**, for a radius that is 100 times smaller, reaches a density 1 million times greater than the Sun's.

Z

Z and W bosons: just as the **photon** is the mediating particle for the **electric force**, the Z and W bosons are the mediating particles for the **weak forces**, i.e. the forces causing beta **radioactivity**; by contrast with the photon, these are very heavy particles (about 100 **gigaelectronvolts**, i.e. 100 times the weight of a **proton**), this accounting for the fact that the weak force proves far less strong than the electric force.

FOCUS A

Probing the Universe across the entire light spectrum

Light is an **electromagnetic wave**, which may be characterized by its **wavelength**, or its **frequency**. The various types of radiation are distributed across the **electromagnetic spectrum**, according to their wavelengths, from the shorter (gamma rays) to the longer wavelengths (radio waves), through visible light (see Figure 1). Light may equally be described in terms of a massless particle, the **photon**, having an energy that is proportional to its frequency.

NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University)

ESO

The three "Pillars of Creation" in the Eagle Nebula, as viewed by the Hubble Space Telescope in visible light (left), and in the infrared (right). Infrared radiation makes it possible to see through clouds.

Types of radiation

Radio-wave radiation (**radio waves**) covers the frequency domain below 1 **GHz**, corresponding to wavelengths longer than 30 cm. The **microwave** region extends over the 30 cm (1 GHz)–1 mm (300 GHz) range. Wavelengths for **infrared** (**IR**) **radiation** range from 780 **nm** to 1 mm. This region is further subdivided into **near IR** (780 nm–2.5 **μm**), **mid-IR** (2.5–27 μm), **far IR** (27–100 μm), and **submillimeter IR** (100 μm–1 mm). Infrared is often related to heat, since, at ambient temperature, objects spontaneously emit this type of light radiation. **Visible light** covers that part of the electromagnetic spectrum to which the human eye is receptive. This region covers a wavelength segment extending from 380 nm (purple) to 780 nm (red). Wavelengths for **ultraviolet** (**UV**) **radiation** fall in the range from 380 nm to 10 nm. **X-rays** are high-frequency electromagnetic waves, with wavelengths ranging from a few fractions of a nanometer (0.01 nm) to 10 nm. A distinction is made between **soft X-rays** (at longer wavelengths), and **hard X-rays** (short wavelengths). The energies involved, for the photons associated to X-rays, range from 100 **eV** to 100 **keV**. **Gamma** (**γ**) **rays** come in at even shorter wavelengths, of less than 0.01 nm, and the corresponding photons have high energies, higher than 100 keV.

Our eyes can see but a tiny fraction of the full light emitted by celestial bodies. Making use of the entire wavelength range has opened up windows onto the Universe, allowing new objects to be detected, or showing already known objects under a new light. This ability to scan the skies at every wavelength is heavily indebted to the placing into orbit of dedicated satellites, for the observation of celestial objects, making it possible to be freed of **absorption** by the atmosphere. Nowadays, all wavelength regions are permanently being exploited, with correlations being drawn between the various regions, in order better to narrow down the physical mechanisms involved, for the objects observed.

Moreover, instrumental optics has likewise undergone a revolution, with the construction of giant telescopes, having the ability to collect the extremely weak light originating in the most distant objects.

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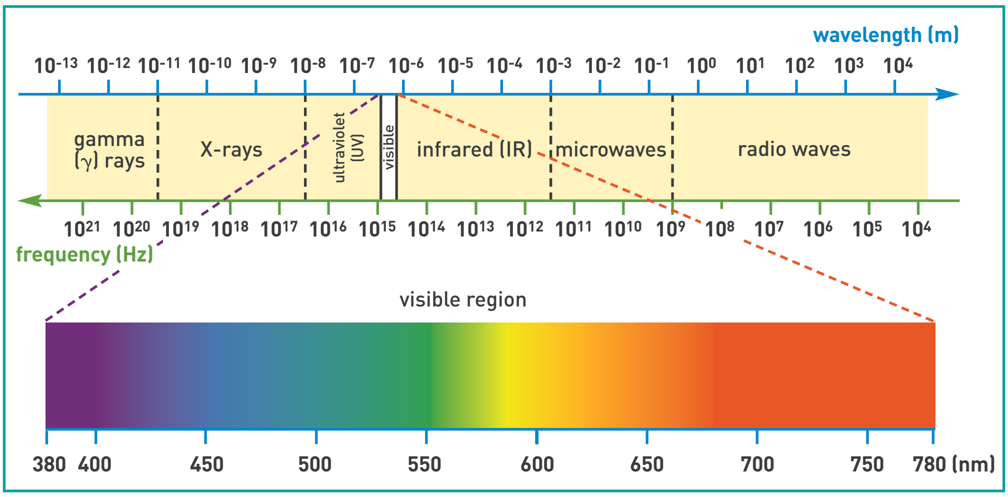


Figure 1.
The electromagnetic spectrum. Electromagnetic waves are grouped into families, of differing frequencies and wavelengths.

FOCUS A

Page 31 cont'd
These new telescopes further stand out through the use of innovative techniques, and technologies, ensuring that the quality of astronomical imagery has leapt forward: active optics (the ability to adjust, in real time, the shape of the mirror surface), and adaptive optics (correcting for alterations in the image due to the atmosphere, by altering the shape of the mirror).

Highly informative spectra

Any matter at a temperature higher than **absolute zero** (0 **K**, i.e. –273 °C) emits electromagnetic waves, making up thermal radiation. Of itself, temperature determines the quantity of power emitted by any one body, this being proportional to the fourth power of temperature. Thus, a body at an absolute temperature of 600 K (i.e. about 320 °C) radiates a quantity of light power that is sixteen times larger than that from a body at ambient temperature (300 K, i.e. close to 27 °C). All wavelengths are present in thermal radiation, in unequal amounts however. Again, it is temperature that determines the **spectrum** of the radiation thus emitted, i.e. the distribution of energy across the various wavelengths present. The emission maximum occurs for a wavelength that is inversely proportional to temperature. In other words, any given body emits the greater part of its light at a wavelength that is all the longer, the cooler the body is. Our chief source of light, the **Sun**, exhibits a power maximum, in its emission, in yellow visible light, at a wavelength of around 0.5 μm. This corresponds to a temperature of 5,770 K. At the same time, any given body exhibits the ability to emit light at highly specific wavelengths. Indeed, an **atom** may not emit, or absorb any arbitrary quantity of energy. Its energy may only vary by definite, discrete steps, these depending on the way its **electron** cloud is configured. When energy is absorbed, or emitted, the electron distribution in the atom is modified. Light is emitted when an electron undergoes a transition from a high energy level to a lower energy level; absorption of light corresponds to the transition of an electron from a lower energy level to a higher one. The ensemble of such transitions, manifesting themselves in the form of as many **lines** in the spectrum, is characteristic for any given atom, and stands as its identifier. Such **emission lines** are also found for **molecules**, these being sets of atoms that are bound together, only the range of wavelengths involved being affected. When light passes through a gas, the latter may absorb such light as has a wavelength matching its own lines. This results in an **absorption spectrum**, i.e. an ensemble of dark lines on a luminous background, forming a kind of barcode, so to speak, making it possible to obtain information as to the light source, and absorbent gas. Thus, the Sun's spectrum takes the form of a continuous spectrum, ranging over the entire gamut of the colors of the rainbow, over which are superimposed absorption lines characteristic of the atoms present in the Sun's atmosphere.
While a source's spectrum makes it possible to determine its temperature, and composition, it further allows many other important parameters to be measured. Thus, a **magnetic field** splits a given spectral line into a number of close, distinct lines (**Zeeman effect**). This offset in wavelength is used to measure the intensity of the magnetic field, for some astronomical objects. A light source's spectrum is also affected by the source's relative motion, with respect to the observer, according to the selfsame principle that leads to the sound made by a vehicle that is approaching an observer being found to be higher pitched, while that sound is lower pitched when the vehicle is moving away. The apparent variation in frequency (this being all the higher, the shorter the wavelength) is proportional to the relative velocity of the observer, and source. The frequency increases as the light source approaches the observer (**blueshift**), and decreases as the source draws away (**redshift**). To put it in more quantitative terms, the **spectral shift *z*** is equal to the relative variation found, between the wavelength observed, λ_{obs}, and that anticipated in the rest frame, λ_0. This takes the form: $z = \lambda_{obs}/\lambda_0 - 1$. If z is positive, the shift found is a redshift, a blueshift if z is negative. This effect was independently discovered by French physicist Hippolyte Armand Fizeau (1819–96), and Austrian physicist Christian Doppler (1803–53). It is used, in particular, for the purposes of ascertaining the velocity of **stellar** motions. This physical phenomenon, known, broadly, as the **Doppler effect**, is termed the **Doppler–Fizeau effect**, when applied to light waves.
Finally, the spectral lines of distant objects are found to be systematically shifted to longer wavelengths (i.e. to the red, for the visible spectrum). This redshift may be measured easily, since atomic spectral lines can be identified, and their characteristics are well known, through measurements in the laboratory (see Figure 2). This phenomenon has been interpreted as evidence of the *global expansion of the Universe*, affecting cosmological scales.

redshift	age of the Universe, at the time of the light emission (billion years)
0	13.7
0.5	8.7 (63.5%)
1	6.0 (43.8%)
2	3.4 (25%)
3	2.2 (16%)
5	1.2 (8.7%)
7	0.8 (5.8%)
10	0.5 (3.6%)

Table.
Some representative values of the age of the Universe, at the time of emission, as a function of the redshift for the source observed.

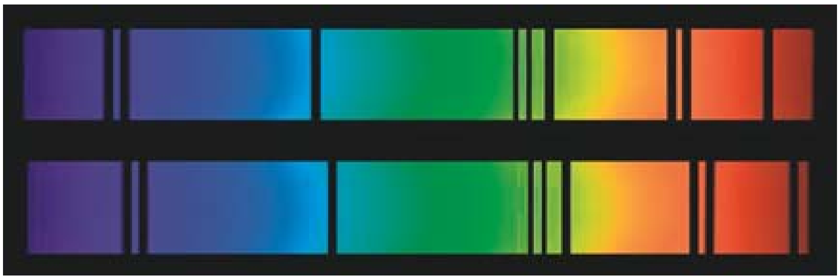


Figure 2.
Spectrum of a light source, exhibiting no shift of spectral lines (top), and featuring a redshift (bottom).

This arises from the fact that, once a radiation is emitted, it reaches us after a time lapse, during which space has stretched. This is why the radiation's wavelength is found to be dilated. It should be noted that cosmological expansion modifies the spectrum of distant sources through a purely **gravitational** effect, which has no bearing on the source's relative motion with respect to the observer (causing the Doppler effect). The redshift found for light from distant sources indicates these sources' spatio-temporal distance, making it possible to range them in terms of increasing distance (see Table).

The lights of the Universe

In their quest to gain an understanding of the Universe by way of observation, astrophysicists make use of the entire electromagnetic spectrum, from radio waves through to gamma rays, each region of the spectrum yielding specific information (see Figure 3).

Microwave radiation, at very long wavelengths, is not readily blocked by matter. It emerges quite freely from the cold, dark clouds inside which stars are formed. This radiation is ideal, for the purposes of penetrating the secrets of such clouds, and observing the initial stages of stellar development. When stars are born, they are enveloped in dust, and may only be seen by way of their *infrared radiation*. Grouped as they are in the sky in the form of **clusters**, young stars appear in *visible light*. The energy source that ensures a star may shine **brightly**, and lastingly, is provided by the nuclear reactions arising within the star, throughout its lifetime. A star may not live forever, and it experiences a convulsive end of life, in the course of which its extremely hot, very dense core ultimately becomes apparent. This then shines with an intense *ultraviolet light*. Very hot objects, at temperatures higher than 10,000 K, preferentially emit ultraviolet radiation. Objects at temperatures higher than 1 million degrees are X-ray emitters. The spectacular death undergone by stars spreads a searing wind, which may be viewed by way of *X-rays*. Some dead stars leave behind a very dense core, out in space. In some, yet more extreme cases, the stellar core turns into a more exotic object, a **black hole**, with a mass that may be as large as 10 **solar masses** or so. The black hole itself emits no light, however matter, as it infalls into it, may be brought to very high temperatures. This matter then emits high-energy radiation, in the form of *X-rays*, and *gamma rays*.

Bringing together the entire electromagnetic spectrum is thus essential, if an understanding is to be gained of the structure of the Universe, and its evolution, each type of radiation manifesting a different aspect.

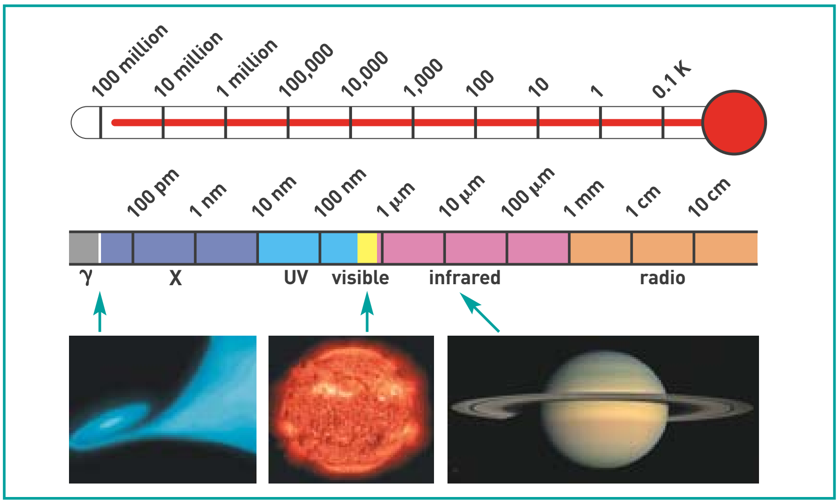
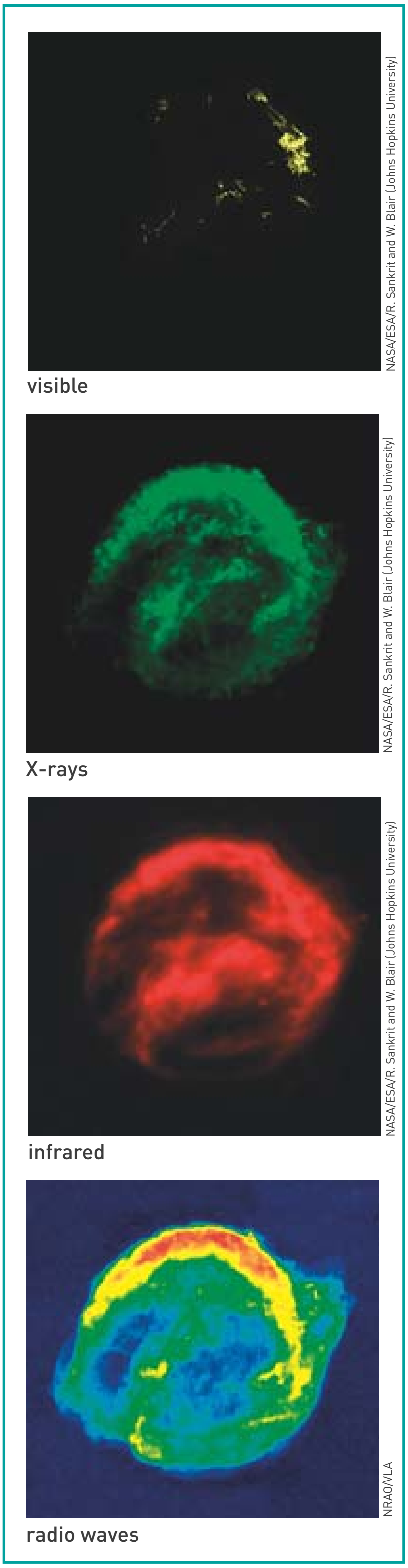


Figure 3.
The distribution of radiation yields information as to the temperature of a celestial body, and its characteristics. In two major segments of the electromagnetic spectrum, infrared on the one hand, X-rays and gamma rays on the other, advances in spaceborne detection are making it possible, by way of ever finer measurements, to access crucial information on the first stars, and **galaxies**.



Remnant of Kepler's **Supernova** (SN 1604), the explosion of which, visible to the naked eye as it was, was observed in 1604 by German astronomer Johannes Kepler. This bubble of gas nowadays emits very little visible light. It is bright in terms of X-radiation, infrared, and radio waves.