The Rho Ophiuchi Cloud, one of the dark clouds in our Galaxy, lying in the Ophiuchus Constellation (the Serpent Bearer), 400 light-years away from the Sun, as viewed in the infrared by the Spitzer satellite. This cloud contains the nearest known instance of a cluster of solar-type stars, in the process of gestation.

NASA/JPL-Caltech/Harvard-Smithsonian CfA

I. ASTROPHYSICS AND THE EXPLORATION OF THE UNIVERSE

Just what are the Moon, the Sun, the stars? Why do they move, as time goes by? Were they always there? From such queries, there arose the great accounts of Creation, and cosmogonies. The advances achieved in terms of observational resources – from the naked eye to modern satellites, through Galileo's telescope, and giant telescopes – brought about a transformation, as regards stargazing, in astronomy, and subsequently in astrophysics. Intellectual speculation did not disappear, for all that: present-day astrophysics is grounded in a constant to-ing and fro-ing, from observation to the working out of theories to account for it, and back again. The advent of the computer brought into play a third component: numerical experimentation, involving the observation of the way computer models behave, that describe the objects in the Universe.

Looking far out into space means looking back across time. Astronomy is grounded on this point, entailed as it is by the fact that light travels at a finite velocity. This means that the more powerful our means of observation become, the "younger" the Universe they unveil to us – a primordial Universe, even.

Indeed, the Universe does not stand eternal. It does have a history, which astrophysicists are currently endeavoring to retrace in detail. According to the commonly agreed scenario – the so-called "Big Bang" scenario – the Universe has been expanding for the past 13.7 billion years. The cosmic microwave background tells us that, by the time it was 380,000 years old, the Universe was still very dense, very hot, and near homogeneous. From the minute clumps arising in this primordial "soup," gravity generated the highly hierarchical structures we find at present, with its stars herded into galaxies, these in turn coming together in galaxy clusters. These objects likewise are born, and die, altering in the process the conditions governing the birth, and thus the characteristics, of subsequent generations.

Does this mean that the scenario, henceforth, is set in stone? Most emphatically not. Much has yet to be ascertained, as regards the formation of these objects, and how their diversity arose. Moreover, such in-depth investigation may not prove exempt from big surprises, or even radical reappraisals. One only need point, for instance, to the discovery of exoplanets, detected from 1995 on, and first directly observed in November 2008. Or to the existence of so-called dark matter, suggested as early as 1933, and which has yet to be identified. More baffling still, dark energy, introduced in 1998 to account for the "recent" acceleration in the Universe's expansion. Astrophysicists are laying great expectations on a new generation of instruments, be they spaceborne (Fermi, Herschel, Planck, James Webb), or ground-based (ALMA, ELT). Not forgetting LHC, the new accelerator commissioned at CERN, since particle physics – the science of the infinitesimal – and astrophysics – the science of the infinitely large – come together, for the purposes of understanding the first moments of the Universe.

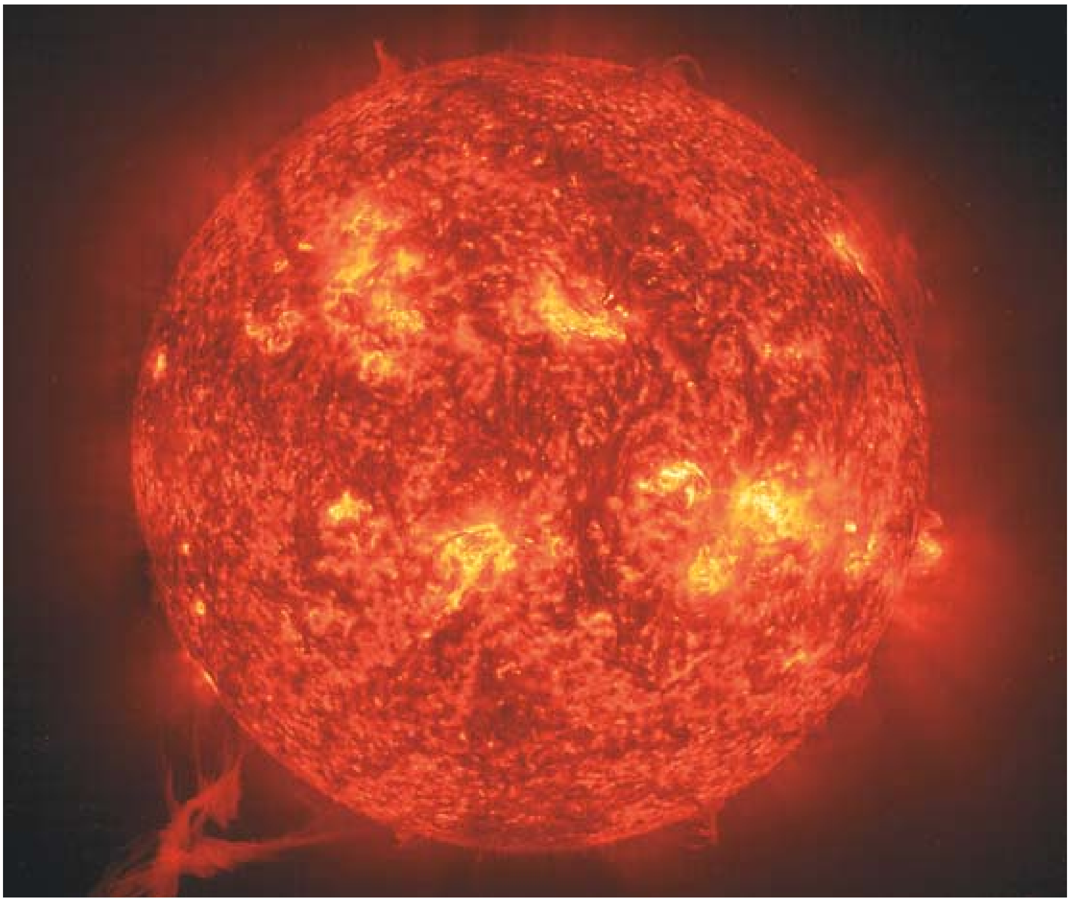
There remain, finally, the fundamental queries, as to the shape, and finite character of the Universe. Surprisingly, such essential queries may yet find an answer, well before the finer "details" in the history of the objects involved can be worked out.

Even though they appear immutable, stars are born, lead their lives, and die.
From the time of its birth, in interstellar molecular clouds, the mass of a new star determines its destiny: its lifetime, color, and final fate. In the course of their "adult" life, stars act as huge thermonuclear reactors, "burning" hydrogen to synthesize heavier chemical elements, through to iron, in the more massive stars. As rotating objects, inside which convection currents arise, and exhibiting, for the most part, an intense magnetic activity, stars lead an agitated existence. Small, and medium-sized stars end their lives as white dwarfs. Larger stars collapse, in a tremendous outburst of energy, producing supernovae, prior to transforming into neutron stars, or black holes. These explosions disseminate their outer layers. Paradoxically, it is thus at the time of dying that stars seed the interstellar space with fresh elements. Understanding the scenario of their birth, and how their mass arises, is thus one way of approaching the issue of the origin of the composition of the Universe.

Stars seed the Universe

What does the Sun tell us?

The Sun is, unquestionably, a typical star. Its nearness, however, gives to it a special status. It is considered as a stellar and dense plasma physics laboratory. Moreover, it is now also investigated as a magnetic star, interacting with the Earth.



SoHO (ESA-NASA)

Standing as the source of life on Earth, and long deified, the Sun has turned, over the past few years, into a veritable physics laboratory. Scientists are probing it to gain a better understanding of stellar evolution, but equally of the behavior of dense plasmas.

One hundred years ago, nobody knew what a **star** was. On the basis of what was known at that time: the **Sun**'s **mass**, **distance**, and composition, its internal temperature was believed by scientists to reach 15 million degrees, with a density greater than 100 times that of a solid. Such conditions were altogether unattainable on Earth. On the other hand, the **thermodynamics** of gases, and **gravity** dictated a lifetime of a few million years, against several billion years for the Earth itself! It was only with the advent of nuclear physics – which is concerned with **atomic nuclei**, their constituents, and their interactions – that the source of internal energy was discovered, that counterbalances and limits the effect of gravity.

The Sun and the atom

Very early on, this fascinating field of enquiry brought new advances in our understanding of stars. Nuclear reactions, transforming **light nuclei** into **heavier nuclei**, thus provide the missing energy source. As far as the Sun is concerned, this chiefly involves the **fusion** of four **hydrogen** nuclei (this being the simplest of all nuclei, since it comprises just one **proton**), to yield **helium** (the smallest of the remaining nuclei: 2 protons, and 2 **neutrons**). The first scientist to set out the connection between this world of infinitesimals and the infinitely large one, in 1920, was the British astrophysicist Arthur Eddington. In 1929, the British physicist Robert d'Escourt Atkinson and German physicist Friedrich Houterman published a joint paper, pointing out that, at the temperatures prevailing at the center of stars, atoms as a whole are stripped of all of their **electrons**, and thus carry a positive electric charge. There then arises a **plasma**, this being a sort of "soup," consisting of positive **ions**, and negative **free electrons**. The temperature, i.e. the agitation, prevailing within this plasma is such that two electric charges of the same sign, rather than repelling one another, as occurs in our ordinary world, may overcome the **Coulomb barrier** and interact. In the same years, Ukrainian-born physicist George Gamow showed that such interaction requires energy higher than the thermal energy. This is the reason why only a small number of protons are involved. In effect, just one reaction per cubic centimeter and per second occurs for each billion of billion of protons present inside the Sun, in the corresponding volume. Such "scarcity" accounts for the Sun's longevity. Indeed, some 10 billion years are required, for close to half of the Sun's hydrogen mass to be transformed into helium. One further, crucial lesson may be drawn from this: this interaction – the so-called *weak* interaction – calls into question the notion that the proton, and neutron are basic particles, since one transforms into the other. This calls for the involvement of a novel particle, dreamt up by Austrian physicist Wolfgang Pauli, in 1930: the **neutrino**, the mass of which has yet to be ascertained.

When the transformation of hydrogen into helium is finished, the Sun's core will contract, and its central temperature will rise. This will then become high enough to allow helium nuclei to overcome the Coulomb barrier (this being 2.5 times stronger than in the case of hydrogen), and interact in turn.

University of Colorado

George Gamow, known as he is for his contribution to the **Big Bang** theory, played a crucial part in the understanding of the nuclear reactions that occur in stars. He showed that, owing to the Coulomb repulsion, these may only occur if the relative velocities of the reactants involved are very high. Thus, the proton–proton reaction, which underlies the transformation of hydrogen into helium ($4\,p + 2\,e^- \rightarrow {}^4He + 2\,\nu_e + 27$ **MeV**), arises at 5 **keV**, rather than at 1.3 keV (corresponding to the 15 million degrees prevailing in the Sun's core). This is why such reactions are scarcer than anticipated, which accounts for the Sun's longevity.

From theory to experiment

For a long time, these results remained in the realm of the purely theoretical, since it was unfeasible to test them in the laboratory. They thus needed to be compared with actual reality, by "probing" the Sun itself. This became possible quite recently, with the launch, in 1995, of the SoHO (Solar and Heliospheric Observatory) satellite, which was placed at the first **Lagrangian point**, **L1**. This carries some 12 instruments, including GOLF (Global Oscillations at Low Frequency) and MDI (Michelson Doppler Imager), these being two **helioseismic** measurement instruments – i.e. serving to observe the propagation of acoustic **waves** within the Sun, or "sunquakes," so to speak. The data collected by these instruments, compared at CEA with **numerical models** of the Sun, corroborated predictions relating e.g. to the Maxwellian distribution[1] of particle velocities. They further made it possible to ascertain, to a precision of 1%, the probability of interaction between two protons. This value had, hitherto, been evaluated theoretically, on the basis of the neutron lifetime.

(1) Maxwellian distribution: probability law describing the distribution of velocities of particles in a classical (non degenerate) gas, governed by collision.

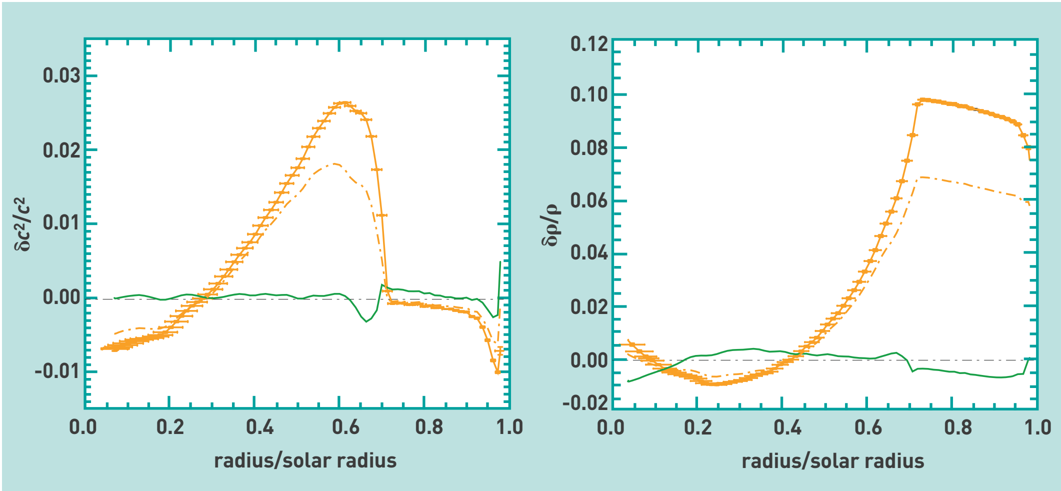


Figure 1.
To the left, radial difference between the squares of sound speed (*c*), as extracted from the acoustic modes detected by the GOLF and MDI instruments, and that obtained with a seismic model of the Sun (in green), or with a classical model, based on relative abundances, as determined from absorption lines in the photosphere (orange: two composition values are shown here). To the right, the difference obtained as regards plasma density (ρ), this varying from 150 g/cm^3 in the core to 10^{-7} g/cm^3 in the solar atmosphere.

These seismic measurements further corroborate some overarching hypotheses relating to stellar evolution. Indeed, the equations governing this evolution [**hydrostatic equilibrium**, energy transfer through radiation, or **convection**, mass conservation, evolution of abundances(2) over time…] allow the computation of the present sound speed profile within the Sun, making it possible to compare it to that extracted from the measurement of acoustic modes (see Figure 1). By introducing the findings from actual seismic measurements into such numerical models, researchers may predict the flux of neutrinos emitted by the nuclear reactions involved.(3) Now this flux is being measured by solar neutrino detection facilities set up in Japan, in Canada, in Italy, and in Russia. The remarkable agreement found between the helioseismology and neutrino detection, after 30 years' research work, highlights the complementarity of the two disciplines. The processes governing the main stages in the evolution of stars of masses comparable to that of the Sun may thus be seen to be thoroughly understood.

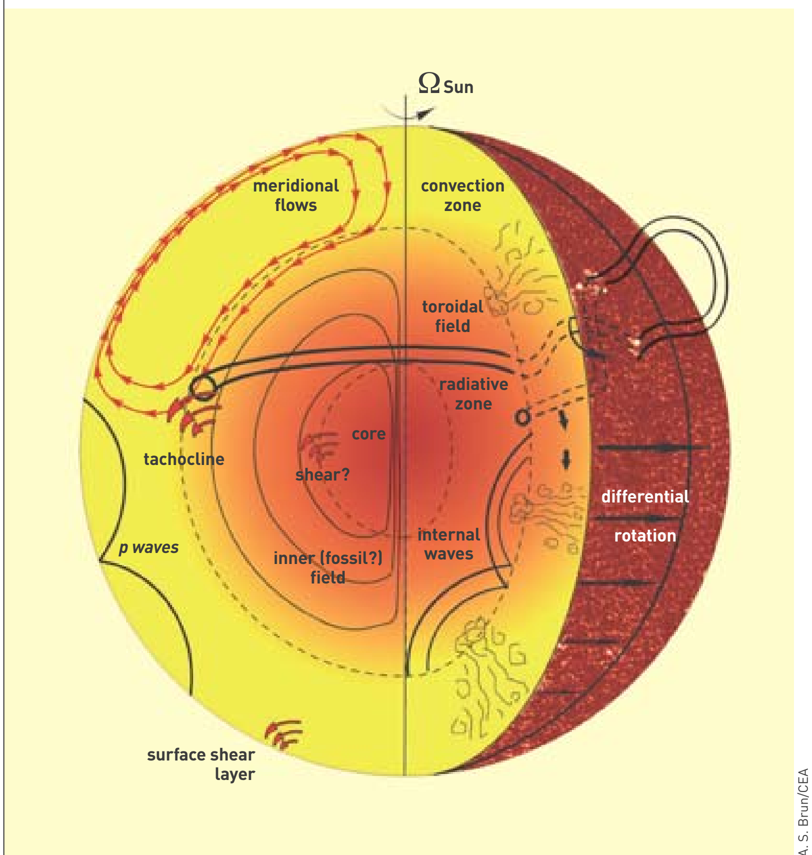


Figure 2.
A dynamic view of the solar interior, showing the two classical regions: shown in red, the radiative zone, and, in yellow, the zone where energy transport predominantly occurs through convection. Are superimposed meridional flows, acoustic waves (*p waves*) and internal waves, together with magnetic fields, involving poloidal and toroidal components.

Going beyond the classical framework

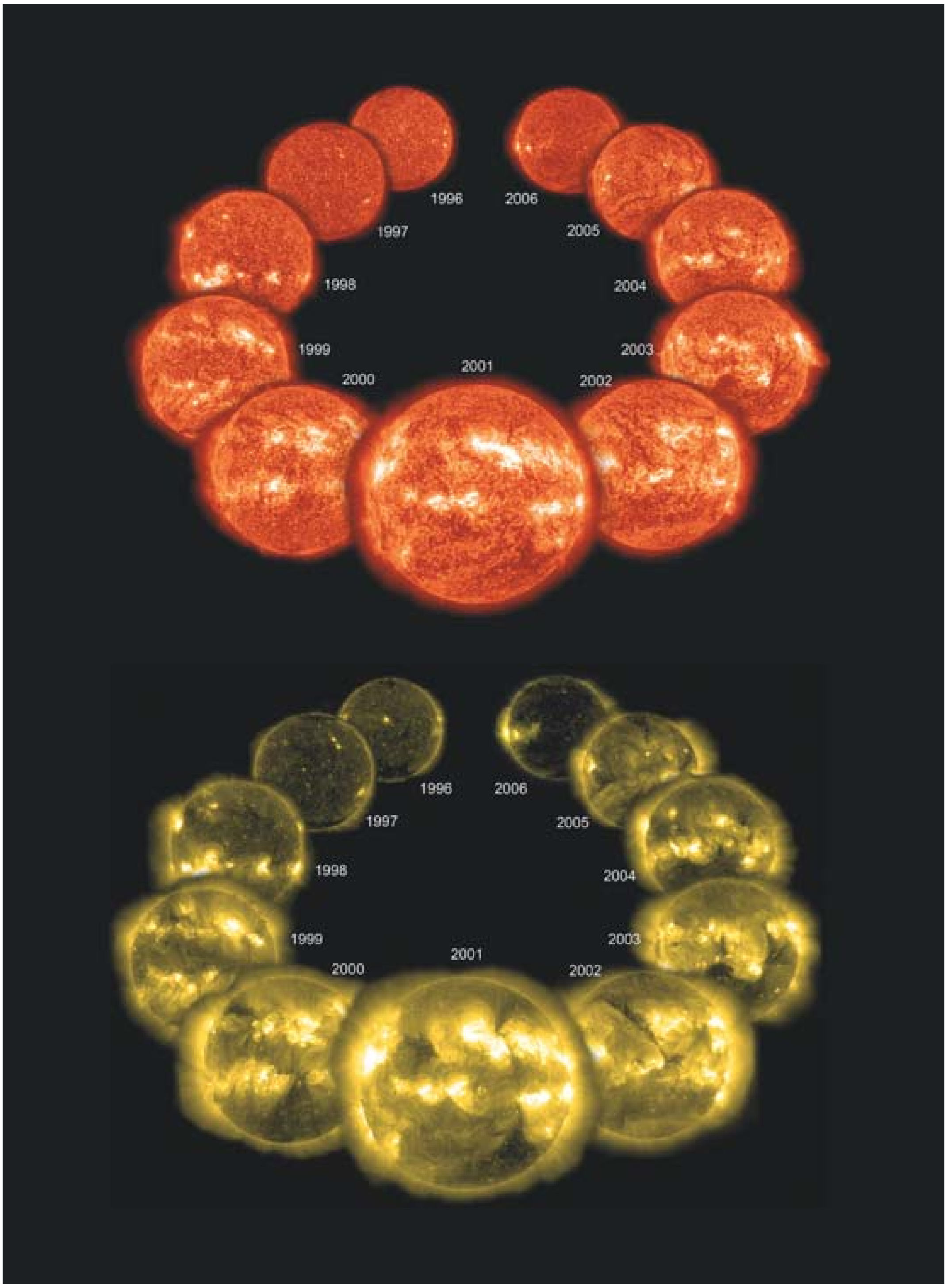
Many questions, however, do as yet remain unanswered. For instance, recent solar composition measurements lead to major discrepancies between the classical model of the Sun, and that derived from seismic observations (see Figure 1). Laboratory experiments should allow the role to be tested, of a second fundamental ingredient in stellar evolution: energy transport by way of **photons**. At the same time, such phenomena as **sunspots**, solar protuberances, currents, or flares are not amenable to description in the classical conceptual framework for stellar evolution. The origin of this **solar activity** remains something of a mystery, and it proves impossible yet to predict

(2) The relative proportions of the various elements.

(3) In effect, proton–proton (or pp) reactions; and the **CNO** (carbon–nitrogen–oxygen) **cycle**.

(4) Named after German astronomer Samuel Heinrich Schwabe (1789–1875).

(5) Named after US astronomer George Ellery Hale (1868–1938).

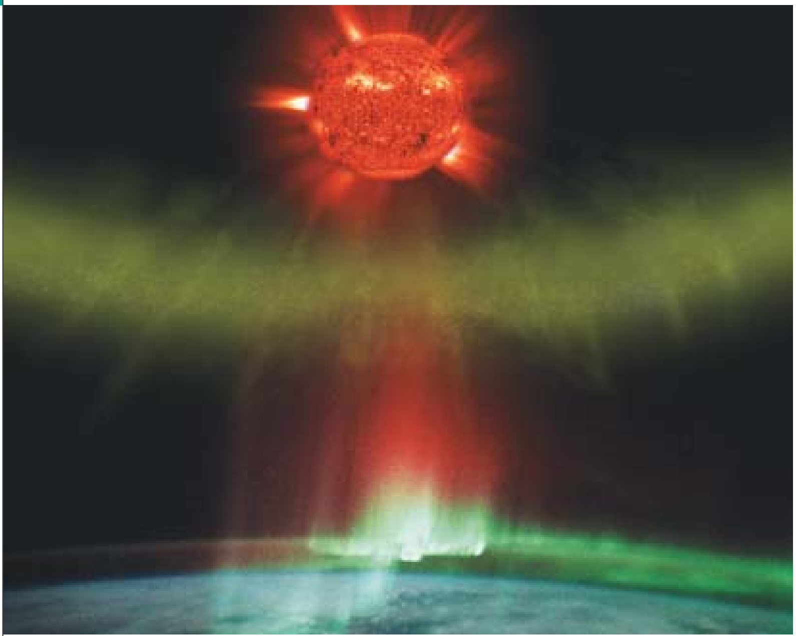


SoHO (ESA-NASA)

Figure 3.
The SoHO satellite has been observing the Sun at various altitudes in the atmosphere (top: at 60,000–80,000 K; bottom: at 2,000,000 K), across the photosphere (the Sun's visible surface) and the corona.
This makes it possible to monitor the Sun's magnetism between two minima (1996–2006).
It is apparent that variations in the magnetic field become increasingly marked as distance from the photosphere increases.

precisely the length, and amplitude of **activity cycles**. The classical equations for stellar evolution, indeed, do not take into account a number of crucial facts: stars rotate, undergo mass ejections, and, in general terms, are active (see *From the Sun to the stars*, p. 16). Such "skirting over" is indeed justified, inasmuch as rotation, or the internal **magnetic field** have but a scant incidence on the internal structure… which it is precisely the said equations' purpose to describe.

To go beyond this conceptual framework, and advance to a complete, unified view of the Sun, it will be necessary, here again, to make use of the measurements made by SoHO, observing as it is all the manifestations of Solar dynamics, be they internal, or external (see Figure 2). By looking at the iron, and helium **absorption lines** in the solar atmosphere, the satellite is exploring widely different temperatures, ranging from a few tens of thousand degrees to several million degrees, spread across the **photosphere** and the **corona** (see Figure 3). The satellite's longevity makes it possible to monitor the evolution of all such activity indices over the solar cycle. Lasting some 11 years, this so-called *Schwabe cycle*(4) has been known since Galileo. It is characterized by the migration of sunspots, from a latitude of 60° down to the equator. As the bipolar magnetic field undergoes reversal, the number of sunspots diminishes, or falls to zero; thereafter, a second cycle begins. A return to the initial polarities thus takes some 22 years: this is the *Hale cycle*.(5)



SoHO (ESA-NASA)

An aurora borealis. This phenomenon is due to the penetration, into the Earth's upper atmosphere, of a stream of particles originating in the Sun.

A highly agitated star

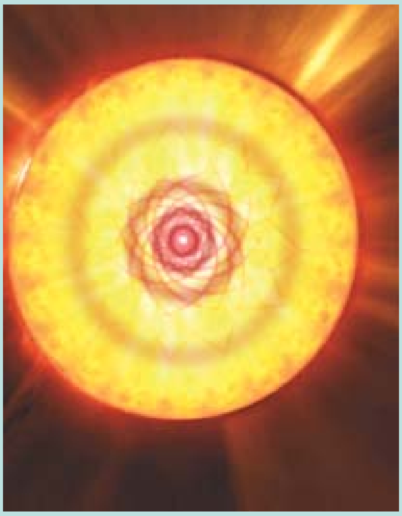
Astrophysicists at CEA are presently seeking to understand what internal source, or sources drive the Sun's activity, to achieve an improved evaluation of its variability. Indeed, the Sun, when it is very active, ejects particles, which escape from the solar corona. Such regular, or occasional – as regards the more violent phenomena – streams of particles reach the **magnetosphere** that shields our planet. However, a fraction of these particles goes round the Earth, penetrating to the upper reaches of the atmosphere over the poles, giving rise to **auroras** – northern (and southern) lights. This phenomenon induces, at times, disturbances in the atmosphere, while it also subjects pilots, or astronauts to sizeable particle fluxes. It was therefore decided to monitor such events from their formation, in the solar corona, to their arrival in the Earth's environment. Depending on particle energy, travel time takes several days.

In fact, the Hale cycle is far from regular. SoHO has clearly shown that the phenomena involved in the Sun's internal dynamics govern solar activity. An ensemble of magnetic, and mechanical processes undergo complex interactions, interfering with one another. The **dynamo**

Probing stellar interiors

Down to the latter half of the 20th century, no experimental data were available to astronomers, gathered directly from within stellar interiors. Scientists had to make do with global, or surface parameters: **star** radius, mass, **luminosity**, **electromagnetic spectrum**... The detection of solar **neutrinos**, bearing as they do information as to the **thermodynamic** conditions prevailing at the center of the **Sun**, pushed back, to some extent, these limitations. Astrophysicists, however, remained frustrated: how might one "reach into" the Sun's – and the stars' – interior, to ascertain the physical phenomena arising at every depth?

A new experimental approach, **asteroseismology**, provided an answer. This takes its cue from terrestrial seismology, which analyzes the underground propagation of acoustic **waves**, generated by earthquakes, or controlled explosions. In like manner, asteroseismology – known as **helioseismology** when applied to the Sun – investigates the propagation of acoustic, or **gravity waves** (see Figure 1) within stars, to derive from this some information as to their internal structure, and interior dynamics. Contrary to the Earth, the Sun – as indeed a host of stars of the same type – is constantly "vibrating," due to the effects of the **convective** motions arising within the outermost region. These motions, analogous to those that may be observed in water boiling in a pan heated from the bottom, remove the vast amount of energy generated by the **thermonuclear fusion** reactions at the center.

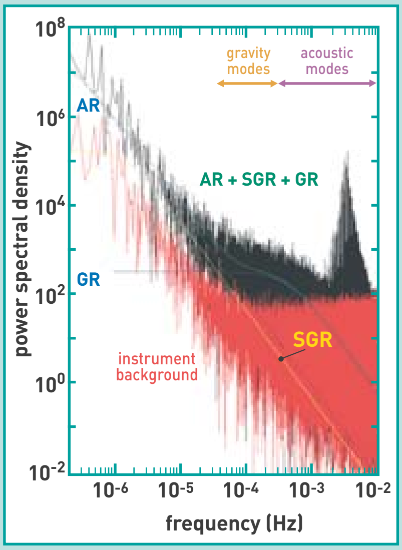


SMM/IAC

Artist's impression of the Sun's interior, showing the paths of gravity modes as they propagate through the **radiative zone**, the innermost region of the Sun (70% of the solar radius).

The Sun's music

Convection cells[1] hit the Sun's surface, setting off sound waves that subsequently propagate across the star's interior, in the same manner as strokes on a drumhead produce waves inside the instrument. The Sun thus acts as a huge resonance



R. A. García/CEA - Spécifique

Figure 1.
Power spectral density of the Sun, as obtained from the **Doppler shift** measured by GOLF (shown in black), and instrument background noise (red). For acoustic waves (with frequencies higher than $5\cdot10^{-4}$ Hz), the solar spectrum exhibits a maximum around $3\cdot10^{-3}$ Hz. The high power level found around low frequencies is due to **turbulence**, essentially associated to granular (GR), and supergranular (SGR) motions, and to the passage of active regions (AR).

(1) A convection cell corresponds to the cycling of a "bubble" of hot (less dense) material rising, then cooling down, subsequently sinking down again, there to heat up again, and rise once more.

(2) An octave corresponds to a doubling in frequency.

effect – the setting up of a magnetic field, due to the circulation of electrically charged particles – regenerates this activity, this involving the entire **convection zone**. The transition region between the **radiative zone** and the convection zone (the **tachocline**) likewise plays a major role. This, indeed, is a highly **turbulent** region, in which transverse shear motions arise. This region stores, and amplifies the **toroidal component** of the solar magnetic field. This field thus generates loops, some of which rise up to the surface, while others contribute to the regeneration of the **poloidal field**. At the same time, the equatorial region rotates faster than the poles do – the difference, of some 30%, may be observed on the Sun's surface. This differential rotation propagates through the entire thickness of the convection zone, contributing to the toroidal component of the magnetic field. The radiative zone, for its part, appears to rotate virtually in rigid fashion: it rotates as a block. Its rotational profile has been increasingly well ascertained. On the other hand, initial observations of **gravity modes** would seem to indicate that the star's nuclear core is rotating faster! This might be a leftover from the formation of the Solar System. Indeed, the young Sun was probably rotating very fast, when it uncoupled from the gaseous disk (the remnant of the initial nebula) surrounding it. During this phase, the Sun may have been highly active, and a strong magnetic field then arose in the radiative zone. Now that field diffuses very slowly: over several billion years. This fossil field, along with internal waves, generated by convection, may influence the Sun's magnetism over more extended intervals than the 11-year cycle. Such a history of the magnetic interaction between Sun and Earth, has yet to be written.

> Sylvaine Turck-Chièze
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling"
(CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

FOR FURTHER INFORMATION

Clefs CEA No. 49, Spring 2004, "The Sun and the Earth."

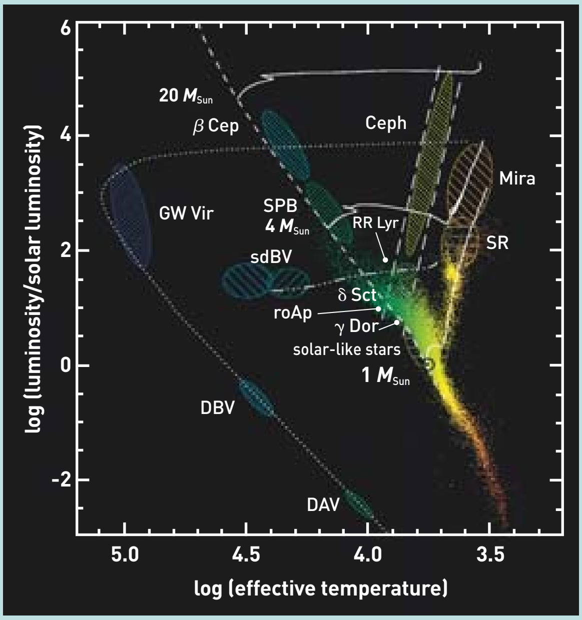
S. Turck-Chièze, R. A. García, S. Couvidat *et al.*, *Astrophysical Journal*, vol. 604, 2004, p. 455.

R. A. García, S. Turck-Chièze, S. J. Jimenez-Reyes *et al.*, *Science*, No. 316, 2007, p. 1537.

A. S. Brun and L. Jouve, in IAU Symposium 247, *Waves and Oscillations in the Solar Atmosphere: Heating and Magneto-Seismology* [Porlamar, Isla de Margarita (Venezuela), 17–22 September 2007], 2008, p. 33.

chamber (see Figure 2). In any musical instrument, the sound produced is all the lower, the larger the resonance chamber: just think of a double bass, and a violin, for instance. As the Sun spans a volume that is one million three hundred thousand times greater than that of the Earth, it will be intuitively understood that its acoustic waves will be characterized by very low frequencies. Indeed, the Sun produces soundwaves that are shifted by 17 octaves[2] relative to "middle A," which vibrates at 440 **Hz**. Solar waves have frequencies centered around 0.003 Hz, corresponding to a period of 5 minutes.
Though it has but recently arrived on the scene, helioseismology has already yielded an ample fund of knowledge, as to our star, taken globally: as to the depth of the base of the **convection zone**, surface **helium** abundance, the density profile, internal rotation profile, the diffusion of **elements**... (see *What does the Sun tell us?*, p. 10; and *Journey into the lights of the Universe*, p. 90). A current development is local seismology, which is concerned with "short"-duration dynamic phenomena, in regions close to the surface. Solar **plasma** velocity and temperature fields, below the surface, reveal, e.g., the underlying structure of **sunspots**. With the launch of the French–European CoRoT (Convection, Rotation, and planetary Transits) satellite (**CNES**, **ESA**), on 27 December 2006, asteroseismology is in full ascendancy. CoRoT has already observed hundreds of stars, of widely different **spectral types**, at various stages of their evolution. All of these data will help refine the theory of dynamic stellar evolution (see *How heavy elements arise*, p. 22).

Taken from J. Christensen-Dalsgaard and L. P. Rasmussen



- β Cep: Beta Cephei stars
- SPB: Slowly Pulsating B stars
- RR Lyr: RR Lyrae stars
- δ Sct: Delta Scuti stars
- γ Dor: Gamma Doradus stars
- roAp: rapidly oscillating Ap stars (Ap = chemically peculiar A star)
- Ceph: classical **Cepheids**
- Mira: Mira variables
- SR: **semiregular variables**
- sdBV: subdwarf variable B stars
- GW Vir: GW Virginis stars
- DBV: white dwarf variables of spectral type DB (dwarf B)
- DAV: white dwarf variables of spectral type DA (dwarf A)

Figure 2.
Hertzsprung–Russell diagram, showing the relation between stellar **effective temperature**, and **luminosity**, with the chief families of pulsating stars indicated, in the instability strips. Unbroken lines correspond to evolutionary tracks for stars of various masses, in terms of solar mass (1, 4, 20 solar masses, from bottom to top). Also indicated are **zero-age main sequence** stars (– – – –), horizontal branch stars (–···–···), and the **white dwarf** cooling sequence (·······).

> Rafael A. García
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling"
(CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

From the Sun to the stars

The **Sun** is one **star** among hundreds of billions of stars in the **Milky Way**. The number of solar-type stars (i.e. of **spectral type** G) is evaluated at 3 billion, including 1 billion stars of subtype G2 V, i.e. of precisely the same subtype as the Sun, lying along the **main sequence** of the **Hertzsprung–Russell diagram**. The surface temperature of these stars ranges from 5,700 **K** to 5,800 K. The stellar population is in fact highly diverse, each stellar spectral type having its own specific internal structure, and dynamic properties. Massive stars (i.e. stars of more than 2 **solar masses**) feature a **convective** nuclear core, and a **radiative** envelope. Solar-type stars, by contrast, feature a **turbulent** convective envelope, and a radiative interior. Finally, low-mass stars are characterized by very deep convection zones, which may even extend across the entire star (see Figure 1, on left). The outcome is a range of highly diverse dynamic behaviors, rotation regimes, and magnetic characteristics.

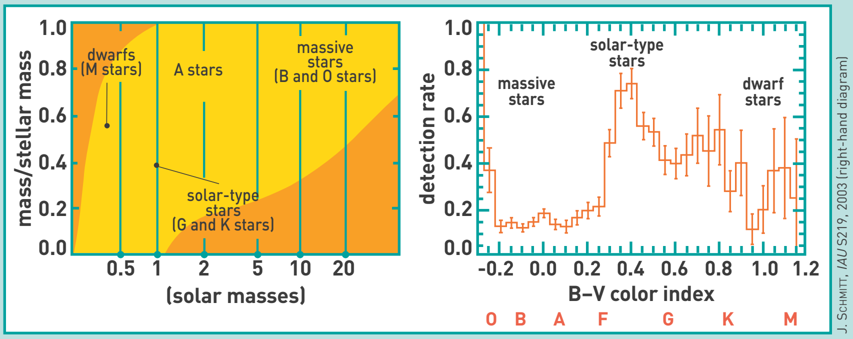


Figure 1.
On the left, spatial, and mass distribution of convection zones, as a function of stellar mass (involving convective cores for massive stars, convective envelopes for low-mass stars). The transition between surface convection and core convection occurs at about 1.3 solar masses. On the right, X-ray detection rates for stellar magnetic fields. A near absence of radiation, and hence of magnetic field, is found for A and B stars featuring a convective core. It should be noted that the direction along the *x*-axis is from dwarfs to massive stars (i.e. from M to O stars) in the diagram on the left, and – more conventionally – the other way round in the right-hand diagram.

To each star its own activity regime

From the late 1970s on, the rotation, and magnetism of several hundred stars have been investigated. It was found that stars featuring an outer convection zone – as in the Sun – are magnetically active, and exhibit, as a rule, a hot, **X-ray** emitting **corona**, providing a good indicator of activity (see Figure 1, right). The **magnetic field** of solar-type stars is often found to exhibit cyclical variations, with periods ranging from 7 to 25 years (the Sun has a half-cycle lasting 11 years). There is a correlation between rotation rate and activity, rapidly rotating stars tending to be highly active, with a mainly horizontal (**toroidal**) magnetic field. Such activity saturates at very high rates of rotation, for rotational speeds of 35 km/s, 10 km/s, and 3 km/s, respectively, for G-type stars (the Sun rotates at 2 km/s), K stars, and M stars. The **dynamo** mechanism accounts for this correlation, between rotation, and magnetic field. The latter, indeed, is dependent on the flows (mean large-scale flows, shear, turbulence) that arise in the convection zone. **Numerical simulations** carried out at CEA have highlighted the physical processes giving rise to the dynamo effect, and to these large-scale flows, together with the way these physical processes vary as a function of the stellar rotation rate (see Figure 2).

On the other hand, an overwhelming majority (90%) of massive stars exhibit neither a magnetic field, nor a hot corona. A and B stars, in particular, show very weak activity (see Figure 1, right). However, when they do feature a magnetic field, it tends to be a very intense one (several thousand **gauss**), and appears to be tilted with respect to the rotational axis. This is probably a fossil field, dating from the star's formation, since the **Ohmic diffusion** timescale, for stellar magnetic fields, is very long. The convective core, in such stars, does indeed act as a highly efficient dynamo, with the ability to generate fields of several millions gauss, as recent numerical simulations have demonstrated (see Figure 2), however such fields fail to emerge, hindered by the highly extended radiative envelope.

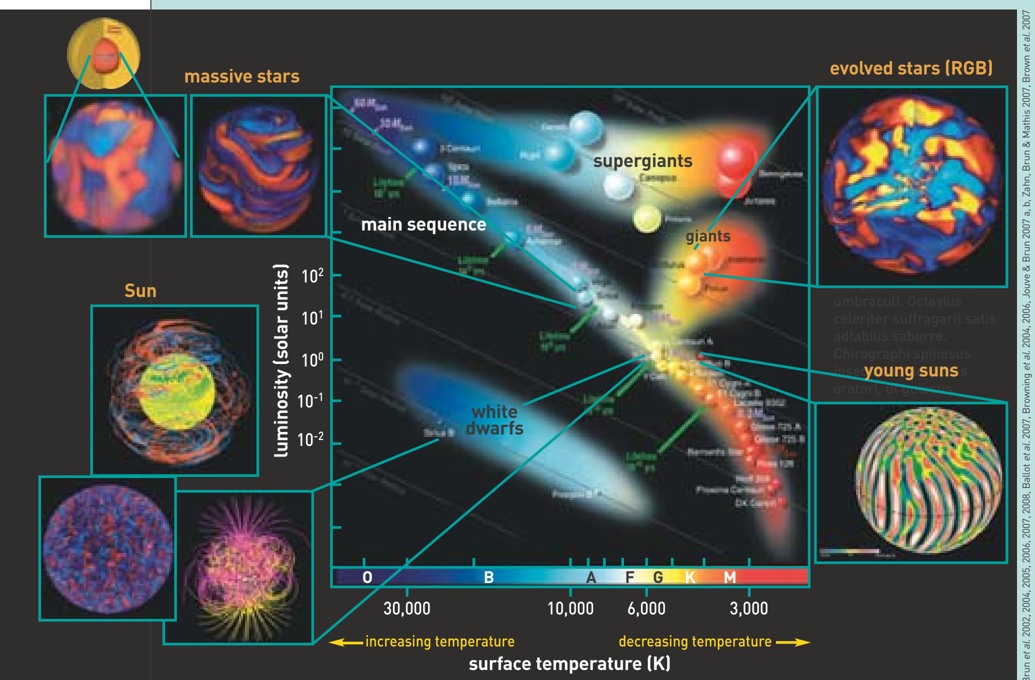
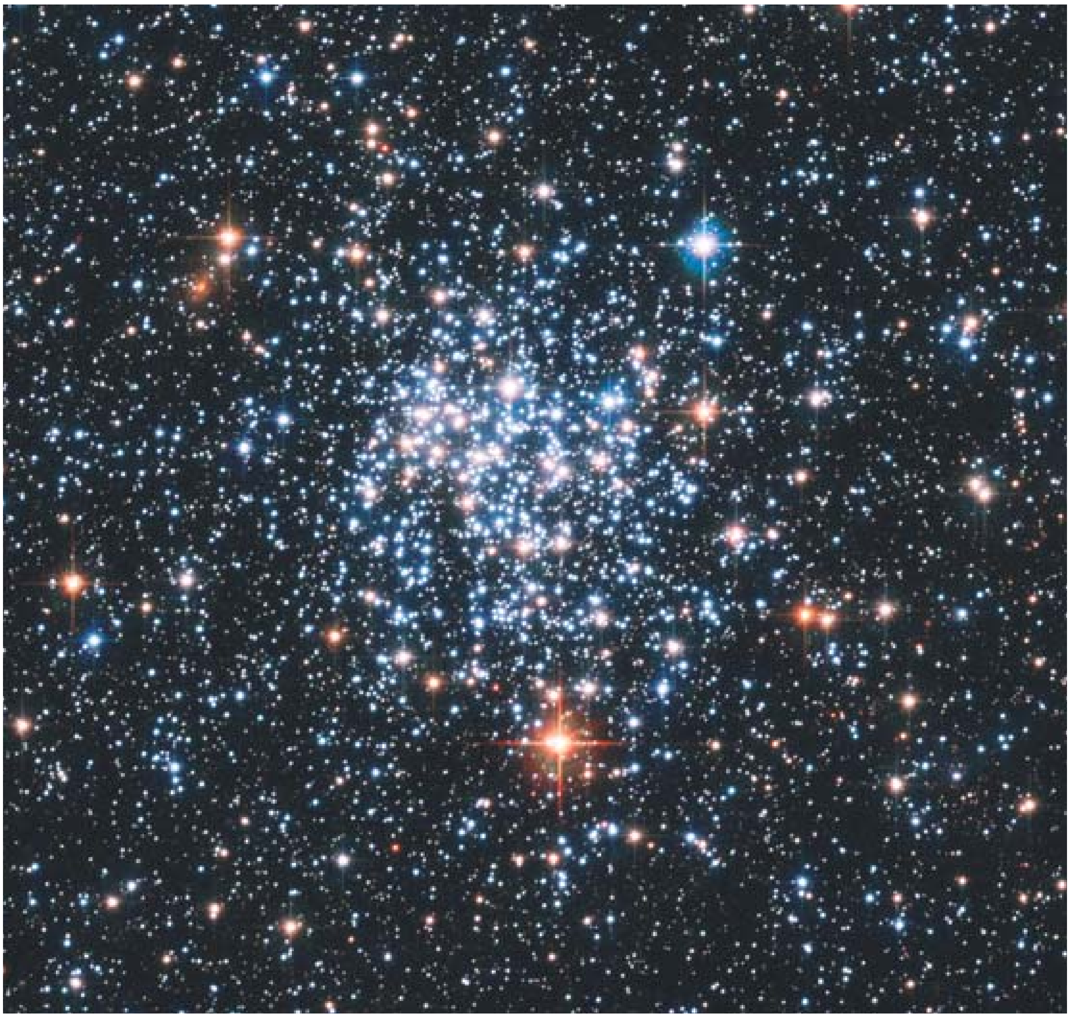


Figure 2.
3D numerical simulations of the **magnetohydrodynamics** of various star types, with their positions indicated on the Hertzsprung–Russell diagram, carried out under the aegis of the European STARS2 program (www.stars2.eu). RGB stands for "**red giant** branch."

> **Allan Sacha Brun**
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling"
(CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

A tour of stellar nurseries

The entire existence of a star is dictated by its mass. For that reason, astrophysicists are currently looking into the nascent phases of stars, seeking to ascertain what determines their masses. New observational instruments, such as the Herschel Space Observatory, are to be pressed into service for this demographic survey.



ESA-NASA

Star cluster NGC 265, in the Small Magellanic Cloud, a galaxy close to our own. Stars are not born singly, in isolation, rather they arise in groups, within a vast dust, and gas cloud. The light from star clusters is dominated, as a rule, by massive blue stars, which are highly luminous, though they have but a short lifespan. The age of a cluster may then be estimated by taking a count of its blue, yellow, and red stars.

At our scale, **stars** appear unattainable, and everlasting. And yet, they are born, go through their life, and die. Indeed, every one of the hundreds of billions of stars that make up a **galaxy** is a "mere" ball of gas – chiefly **hydrogen** – inside which **thermonuclear fusion** reactions arise, and become self-sustaining, with a concomitant release of heat, and emission of light. The larger, or more **massive** a **star** is, the more **fuel** is available to it, and consequently the **brighter** it shines, and the larger its yield of **heavy elements**, such as oxygen, carbon, or iron… and the faster it exhausts its reserves (see *How heavy elements arise*, p. 22). The more massive stars – weighing in at 10–100 **solar masses** – are very hot (10,000–30,000 **K** surface temperature), and chiefly emit in the **ultraviolet**. They appear blue to us, and disappear after a few tens of million years. At the other extreme, small stars are faintly luminous, appear red to us, and lead a quiet life. As they dissipate but very little energy into space, since their surface temperature stands no higher than 1,300 K, they may last for billions of years. The Sun, an altogether middle-of-the-road star, should last some 10 billion years. As the reader may have gathered, it is a star's mass that dictates its destiny. It determines the star's lifespan, its luminous intensity, or its ability to form heavy elements. It further dictates the star's death, e.g. in the form of a **supernova**, and thus the impact of that ending on the *galactic ecology* (through the dispersal of recyclable material into the **interstellar medium**).

Star births

A star's fate would thus appear to be sealed from the very time of its birth. And yet that episode remains poorly understood. How is the interstellar medium – a rarefied gas holding a few hundred **atoms**, and **molecules** per liter – able to give birth to such massive

Star-forming region N11B, in the Large Magellanic Cloud, as viewed by the Hubble Space Telescope. Stars are born in the dark, opaque regions of molecular clouds. This picture shows a star cluster visible in the interstellar medium, and new stars, light from which is seeping out of the reddish, and blackish clumps within the cloud.

NASA, ESA, and The Hubble Heritage Team (AURA/STScI)

objects? How do certain regions of a molecular cloud turn into veritable star "populations"? What are the main stages in star formation? Why are small stars, such as **red dwarfs** and solar-type stars, invariably more numerous than massive stars, in any given population?

A star is not, strictly speaking, born out of the interstellar medium. "Stellar nurseries" are in fact huge – some 100 **light-years** in diameter – molecular clouds, containing alcohol, ammonia, water, carbon monoxide, and, overwhelmingly, hydrogen in the molecular form (H_2). Holding as they do, on average, one thousand molecules per cubic centimeter (a thimbleful), i.e. one million molecules per liter, such clouds are much denser than the medium encompassing them.(1) This limited count of molecules per unit volume notwithstanding, the reserve of material is in fact extremely large, across such immense volumes. It is in such surroundings that thousands of stars are born, often in "**clusters**," i.e. groups of stars born in the same region, and bound by **gravitation**. Observers of the sky at night are familiar with, e.g., the Pleiades Cluster, lying in the Taurus Constellation.

A story in three stages

The transformation of a molecular cloud into a star cluster occurs in three phases. During the first, so-called "prestellar" phase, the initial cloud breaks up into clumps, as a result of **turbulent**, large-scale motions. These clumps subsequently condense, under the action of their own **gravity**. The internal pressure of the gas, however, due to thermal, turbulence, and magnetic causes, slows down such contraction, initially maintaining a degree of equilibrium. At some point, for reasons as yet little understood, that equilibrium suddenly breaks down, and each clump in the prestellar cloud swiftly collapses onto itself, as a result of its own weight. Astrophysicists do not, as yet, know whether that collapse is due to external forces, or the dissipation of internal resistances (whether arising from turbulence, or magnetism). Be that as it may, a central core, of stellar size, and density, is thus formed. This marks the beginning of the second, so-called "protostellar" phase, as this core stands as the seed, or embryo of the star that is to be. This then grows, by swallowing large amounts of matter (gas, dust) from the condensed cloud enveloping it. When all of that material is taken up, the protostellar phase come to an end. The star then enters the third phase of its birth process, the so-called "pre-main-sequence" phase, by contracting under its own weight. Its internal temperature rises, to the point where nuclear fusion reactions are initiated, turning hydrogen into **helium**. A **main-sequence** star, such as our Sun, is born (see Figure 1). While this three-phase scenario has been fairly well ascertained for medium-sized stars, the formation of stars of much lower, or much greater masses remains a matter subject to debate. Astrophysicists do not, as yet, know whether such stars are formed from individual prestellar condensations.

(1) An altogether relative higher density, since, on Earth, this would be equivalent to the vacuum that is achieved in a laboratory!

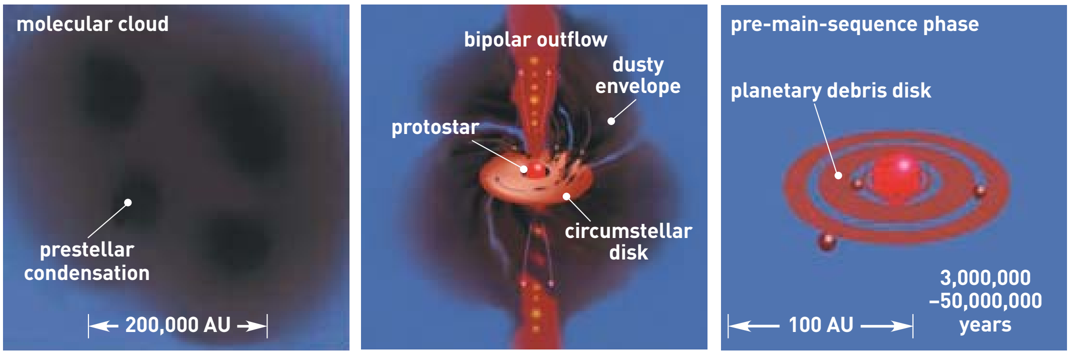


Figure 1. Theoretical considerations, and observations point to the fabrication process, for a solar-type star, involving at least three distinct phases: the prestellar phase (left); the protostellar phase (center); and the pre-main-sequence phase (right). 1 **AU** (astronomical unit) = 150 million km.

From T. Greene

Nature and nurture

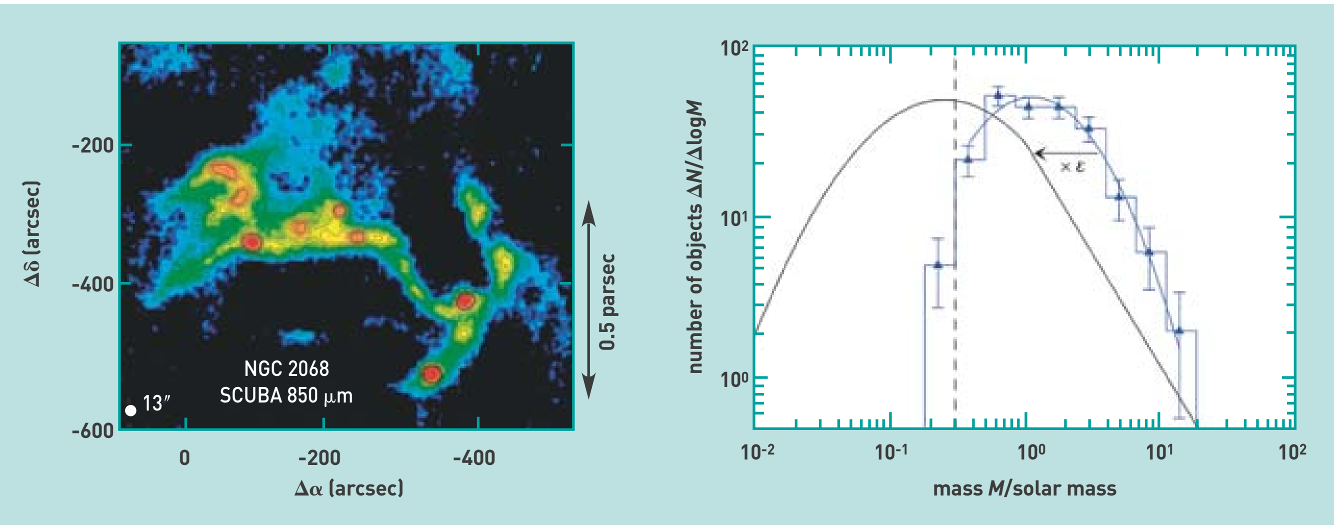
The vast majority of stars are born into large sets of siblings, i.e. clusters. Observations of young clusters show that massive stars (8 solar masses or more) are in a minority in these clusters. The same holds for very small stars (one-tenth of a solar mass, or less). The greater part of newborn stars are thus endowed with masses of the same order as that of the Sun. Is such a distribution of masses within a cluster, or "initial mass function," in astrophysical parlance, a universal one? In other words, do all stellar populations exhibit the same composition, wherever they may be found across the Universe? The question now stands.

One other major issue, concerning stars, is tantalizing scientists. When, and how does it come about that its mass is determined, for any one particular star within a cluster? To answer this, astrophysicists at CEA are carrying out a veritable demographic survey of star populations, from gestation to birth. They have suggested two **models**, based on analytical calculations, and **numerical simulations**, to account for the mass distribution, within a cluster. According to the first model, the mass of each star is already set at birth – i.e. it is "innate." Molecular clouds fragment into a number of prestellar condensations, which break free from their turbulent environment. Each condensation collapses onto itself, giving birth to one protostar. The mass of every star so formed thus depends directly on that of the prestellar condensation that bore it. In this case, the distribution of stellar masses within the population is the outcome of the cloud fragmentation process, during the prestellar phase. Stellar masses are thus determined prior to the collapse of the individual condensations (see Figure 2).

In the second model, stellar mass is acquired, and is virtually independent of that of the prestellar core, as yielded by fragmentation. Every protostar emerging in a prestellar condensation will move across the parent cloud, gradually building up its mass, by "sweeping up," and drawing in greater, or lesser amounts of the material it goes through. Now, the larger a star is, the more matter it will draw to itself, to the detriment of the smaller objects. In such conditions, objects of initially comparable – if not strictly identical – sizes will gradually differentiate. Astronomers call this process *competitive accretion*. According to this model, the distribution of individuals, ranged by mass, is determined only after the prestellar phase, i.e. subsequently to the collapse of the condensations into protostars.

Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (Univ. Washington), You-Hua Chu (Univ. Illinois Urbana-Champaign), and NASA

Nebula NGC 3603, as viewed by the Hubble Space Telescope. A cluster of young massive stars (blue) is shining bright in the ultraviolet, 20,000 light-years away from us. This cluster has broken free from the nearby dust and molecular cloud.

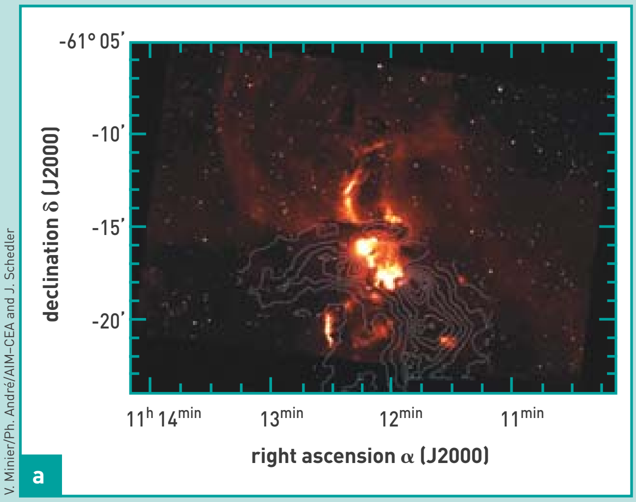


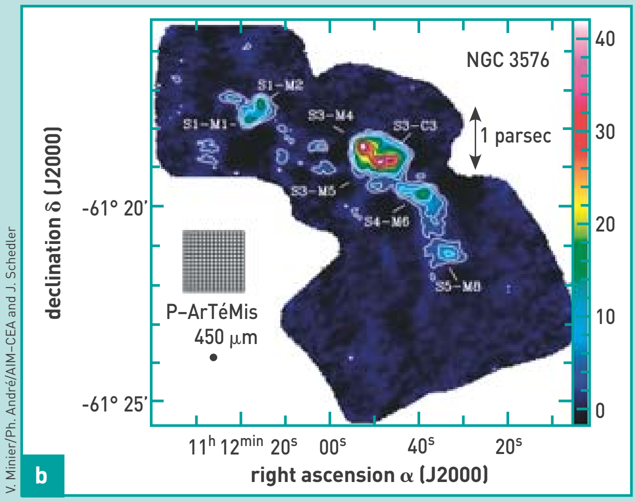
F. Motte/Ph. André/AIM-CEA

Figure 2.
Left, an image of the prestellar condensations inside NGC 2068, a star-forming region in the Orion Constellation. Observations were carried out with the SCUBA bolometer-array camera – fitted to the James Clerk Maxwell Telescope, sited in Hawaii – operating in the submillimeter wavelengths, at 850 microns. Each clump, it is thought, may give birth to one or two stars. 1 parsec (pc) = 206,265 **AU**.
Right, the number of prestellar condensations, as a function of their mass. The mass distribution, for these condensations (shown in blue), globally replicates the shape of the initial mass function, as currently estimated, for the stars in our own Galaxy (in black), offset by a factor $\varepsilon \approx 25\%$ towards larger masses. This implies that not all of the mass contained in a condensation is wholly transformed into stellar mass. This finding suggests that the masses of solar-type stars are chiefly determined by the molecular cloud fragmentation process, at the prestellar stage.

Spotlight on stellar cocoons

The approach adopted by astronomers involves finding, through observation, a sequence of objects standing as intermediate terms between the molecular cloud fragmentation stage, and a type of young star, in order to reconstruct the sequence of events in its fabrication. Scientists probe molecular clouds, looking for the icy condensations inside which stars are being born, from brown dwarfs to massive stars. These nascent stars, very cool as they are, emit energy chiefly in the infrared and submillimeter regions of the light spectrum. The cooler the condensation is, the further its color, and hence its energy, is shifted into the infrared, and submillimeter wavelengths (0.1 to 1 mm). By measuring the energy emitted by such fragments at various wavelengths, it is feasible to determine their luminosity, i.e. the power radiated by them in light form. This method is illustrated in the figures shown below, relating to a region in our Galaxy designated as NGC 3576. This is a gas reservoir, inside which stars are forming.





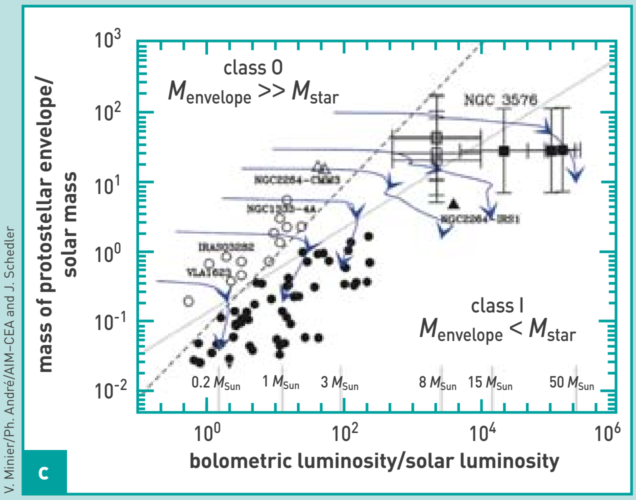


Figure.
a. The cold gas, and the cocoons enveloping stellar embryos are totally opaque regions, appearing as very dark patches in the Milky Way. Observation of the carbon monoxide (CO) emission shows these dark bands to be denser, in terms of gas (the white outlines are distribution contours for radiation emitted by CO).
b. In order to "penetrate" such prestellar condensations, astronomers carry out observations in the submillimeter infrared, at a wavelength of 450 microns for this picture, taken by the P-ArTéMis camera, fitted to the APEX telescope. The telescope takes up the light emitted by grains of dust, which only account for 1% of the total mass of the gas they inhabit. These grains absorb the luminous intensity emitted around them, reemitting it in the infrared, and, for the colder grains, in the submillimeter infrared. Measurements of their energy evidenced eight distinct clumps within NGC 3576.
c. This diagram sets out the masses of protostellar dust cocoons, and their luminosities, these determining which early stage (class 0, class I) the protostars in NGC 3576 have reached. Class I designates a stage that has evolved further than class 0. On the basis of theoretical models, the final mass of the future stars may be predicted, namely some 8–50 solar masses as regards these stars.

Observing nascent stars

In order to discriminate between these two scenarios, and to ensure the proper initial conditions are introduced into numerical simulations, the best way to proceed remains the direct observation of star populations, at the early stages. Astronomers thus look for intermediate objects, representative of all of the stages in the sequence, from molecular cloud to very young stars, for every mass type. They carry out the quantitative investigation of such populations by ascertaining such characteristics as the luminosity, temperature, mass, and density of stellar cocoons. All of which data will be fed into the astrophysicists' models (see Box). However, prestellar condensations, and the younger protostars are objects that are too cool to emit radiation at visible wavelengths, and observing them calls for instruments providing high angular resolution in the infrared, and submillimeter electromagnetic domains (see Figure 3). A number of large telescopes are eagerly awaited, over the next few years, for the purposes of expanding, and possibly revolutionizing, our knowledge, as it currently stands, as to the initial phases of stellar formation.

The Herschel Space Observatory(2) (see *Journey into the lights of the Universe*, p. 90), a scientific mission set up by ESA, will measure, for the first time, the amount of energy emitted by stellar cocoons. Herschel, placed in orbit by an Ariane 5 launcher, on 14 May 2009,

(2) See: http://www.herschel.fr.

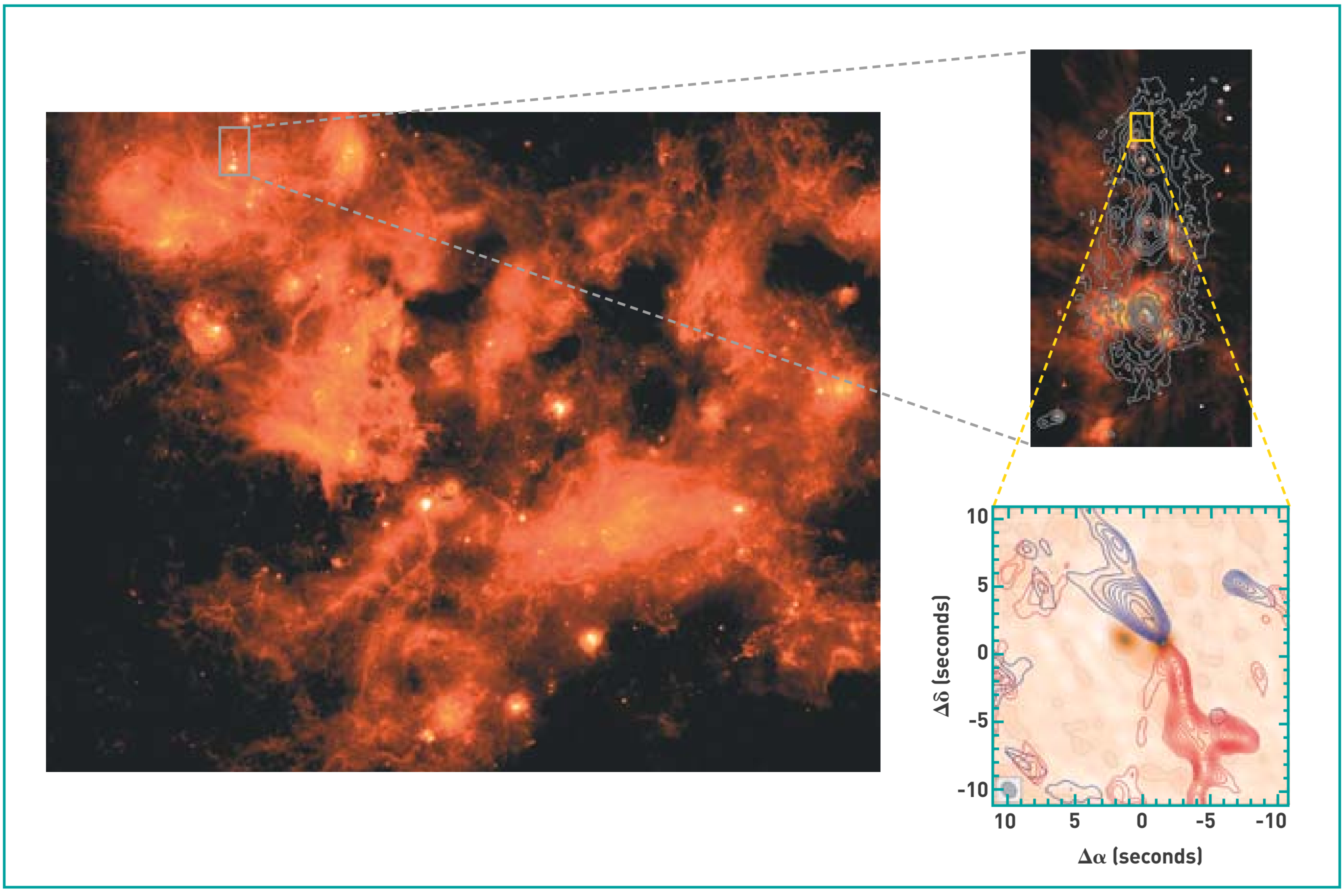


Figure 3.
Left, an infrared image of a group of molecular clouds involved in the formation of massive stars, in the Cygnus Constellation (the Swan). The infrared radiation is emitted by dust grains. Top right, a zoomed-in view of one region in the cloud, inside which protostellar condensations may be observed, by way of the radiation emitted by the very cold dust particles, at submillimeter wavelengths. Bottom right, a massive star is born within a protostellar condensation by **accreting** matter, and expelling some of it by way of molecular outflows (red, and blue contours). Such investigations call for a combination of large-area mapping, and finescale observation.

probes molecular clouds, looking for the icy condensations inside which stars are born, from **brown dwarfs** to massive stars. It is thus seeking out fragments of molecular clouds liable to undergo collapse. From measurements of their luminosity, astronomers are deriving the mass distribution of prestellar clumps. They will thus be able to construct demographic curves, plotting the distribution of prestellar condensations, and stellar embryos. By comparing these curves with those found for mature star populations in **our Galaxy**, astronomers will be able to come to a conclusion, as to the origin of stellar masses: whether these are innate (if the curves turn out to be comparable), or acquired (if the curves are different). Herschel observations cover a stellar mass range from one-hundredth to about 10 solar masses.

The APEX (Atacama Pathfinder Experiment) telescope, sited in Chile, and due to be fitted, in 2011, with the ArTéMis **bolometer**-array camera, constructed by CEA/IRFU (see *Journey into the lights of the Universe*, p. 90), will be assisting Herschel. Indeed, with the increasing size of telescopes, and thus the enhanced precision of observations, scientists are now able to probe condensations lying further out, inside which massive stars are being born.

The APEX telescope, a parabolic antenna 12 meters in diameter, sited at an elevation of 5,100 meters on the Llano de Chajnantor high plateau, in the Atacama Desert (Chile), will be receiving the ArTéMis bolometer-array camera, constructed by CEA/IRFU, in 2011. Convincing observations have already been carried out using the prototype for this camera, P-ArTéMis, at a wavelength of 450 microns. The telescope is run by a consortium, bringing together **MPIfR** (Germany), **OSO** (Sweden), and **ESO** (Europe).

> **Vincent Minier, Philippe André** and **Frédérique Motte**
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

How heavy elements arise

Most of the elements present in the Universe were formed by way of nuclear synthesis within stellar cores, and subsequently dispersed, as the stars died… going on thereafter to contribute to the formation of subsequent generations of stars. Stellar evolution thus stands as a key component in the evolution of the Universe, at every scale.

NASA and The Hubble Heritage Team (AURA/STScI)

V838 Monocerotis, a red supergiant in the Monoceros Constellation (the Unicorn), as photographed by the Hubble Space Telescope, lying about 20,000 **light-years** away. On 6 January 2002, this star produced a highly intense flash, which lit up the dust cocoon surrounding it. Understanding stellar formation – stars being the basic components of our Universe – and the stars' dynamic evolution, and how they end their lives, is one of the basic building blocks of modern astrophysics.

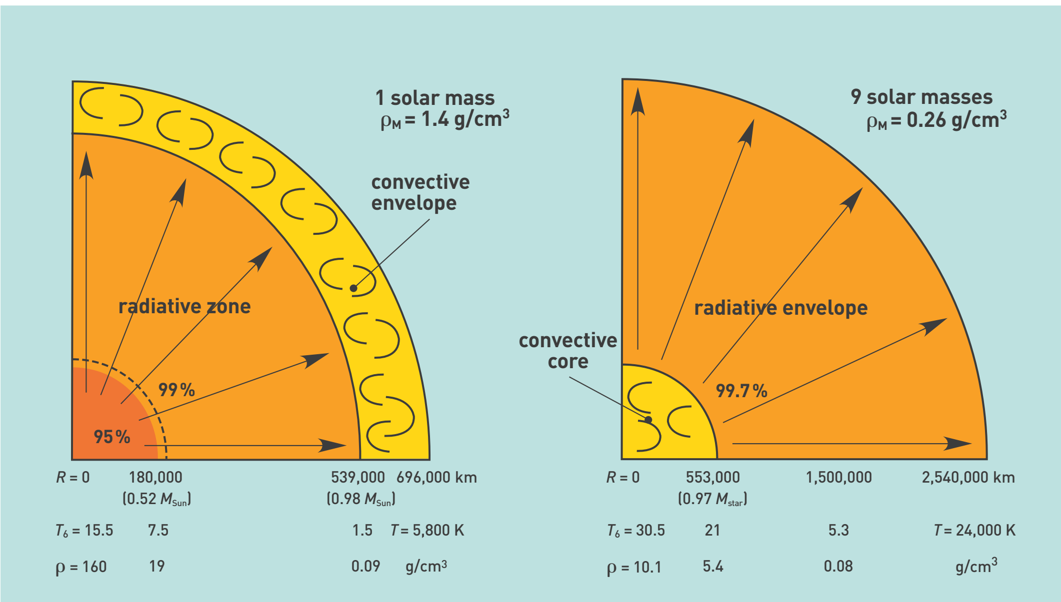
Working as true **thermonuclear** reactors, **stars** manufacture **heavy nuclei** from the **primordial elements** that were formed at the time of the **Big Bang**: **hydrogen**, **helium**, **deuterium**. When the star reaches the end of its life, these elements are seeded into its outer layers, and subsequently into the **interstellar medium**. This alters the chemical composition of **galaxies**, and consequently modifies the potential sites where subsequent generations of stars may form. In order to understand how what had initially stood – essentially – as a ball of hydrogen is able, by the end of its life, to scatter **heavy elements** across space, the sequence of that evolution must be recapped. Once a star has completed its formation phase (see *A tour of stellar nurseries*, p. 17), it enters its **main sequence** phase, this being a highly extended timespan, during which **fusion** of hydrogen yields at least 99% of the star's radiated energy. During this phase, the star's **luminosity** (i.e. its radiated power) and **effective** surface **temperature** undergo relatively little change. In stars with a mass lower than 1.3 times that of our **Sun**, the fusion of hydrogen, yielding helium, occurs by way of the interaction of **protons** (p–p reactions). In more massive stars, featuring a higher central temperature, allowing the **Coulomb barrier** to be overcome, the process occurs in accordance with the **CNO** (**carbon–nitrogen–oxygen**) **cycle**. Throughout this sequence, nuclear reactions are regulated by way of the **hydrostatic equilibrium** set up between the pressure gradient in the gas, and **gravitation**. Should the reactions run away, the star expands. On the other hand, once the **fuel** runs out, the core contracts, and its temperature rises, thus igniting further reactions, up to the point when the hydrogen that had remained intact in the uppermost layers can likewise be turned into helium. Such "shell" hydrogen burning involves a concomitant expansion of the outermost regions, these consequently becoming less strongly bound by **gravity**. At the end of this evolution, the star – which has turned into a **red giant** – loses part of its envelope.

How space is seeded by the stars

The subsequent unfolding of events, from that point on, depends on the star's initial mass. Stars of low mass (0.07–0.5 **solar mass**) end their life as **white dwarfs**, consisting of helium. Above one-half of the solar mass, by contrast, helium undergoes fusion, yielding carbon, and oxygen. The evolution speeds up, and the helium is soon burned out. Stars having less than 8 solar masses thus give birth to white dwarfs, consisting, however, of carbon, and oxygen. All white dwarfs are compact, degenerate stars, with a density of around 1 tonne per cubic centimeter. These "stellar remnants," with a mass lower, as a rule, than that of the Sun, owing to the dispersal of the outermost layers, may accumulate matter, through **accretion**. Some of these stars then reach a critical mass – the so-called **Chandrasekhar critical mass** – and explode as a thermonuclear **supernova** (see *How supernovae explode*, p. 26).
Massive stars (9–120 solar masses) undergo a different evolution. Featuring as they do a higher central temperature, fusion reactions, in such stars, may go beyond the formation of carbon, and oxygen, and involve the successive synthesis of neon, silicon, and so on through to iron, which is the most stable element. The star has by then run out of nuclear fuel, and it collapses, releasing a huge amount of energy, in the form of **photons**, and **neutrinos**. In a matter of a few minutes, it becomes one billion times brighter: such is the explosion of a gravitational supernova (see *How supernovae explode*, p. 26). The outermost layers are then ejected, enriching the interstellar medium with heavy elements. The stellar corpse that results from this is an extremely compact object, with a radius of about 10 kilometers, consisting of **neutrons**, with a density of more than 1 million tonnes per cubic centimeter, which collapses into a **stellar black hole**, should its mass be greater than three times that of the Sun.
The interstellar medium is thus constantly being enriched with heavy elements, originating in erstwhile stars (it is said to increase in metallicity), to be taken up in turn in the composition of future stars. However, while such a scenario, governed as it is by the hydrostatic equilibrium set up, and microscopic physics, does account for the main features of stellar evolution, it does not take into account dynamic processes, or the interaction of stars with their environment.

Highly agitated heavenly bodies

Indeed, stars are dynamic objects, rotating, and featuring a **magnetic field**; and various types of **waves** arise in them (see *What does the Sun tell us?*,



(adapted from André Maeder, 2009)

Figure 1.
Structures of a star having the same mass as the Sun (left), and of a star 9 times more massive (right). Radius *R*, temperature *T* (in K) or T_6 (million K), along with density ρ values are shown for the star center, and the boundaries of the radiative and convective zones. ρ_M is the star's mean density. The percentages indicate the fraction of total energy produced.

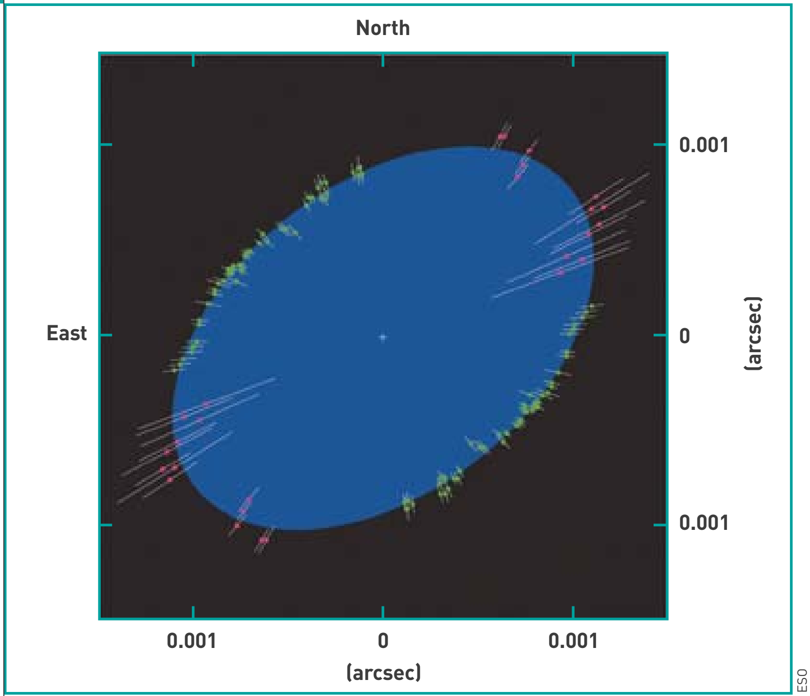


Figure 2.
Achernar, a **B-type** star, with a mass of 6.07 solar masses. It is highly flattened (oblate), owing to its very rapid rotation: at the surface, its rotational velocity is 150 times higher than that of the Sun.

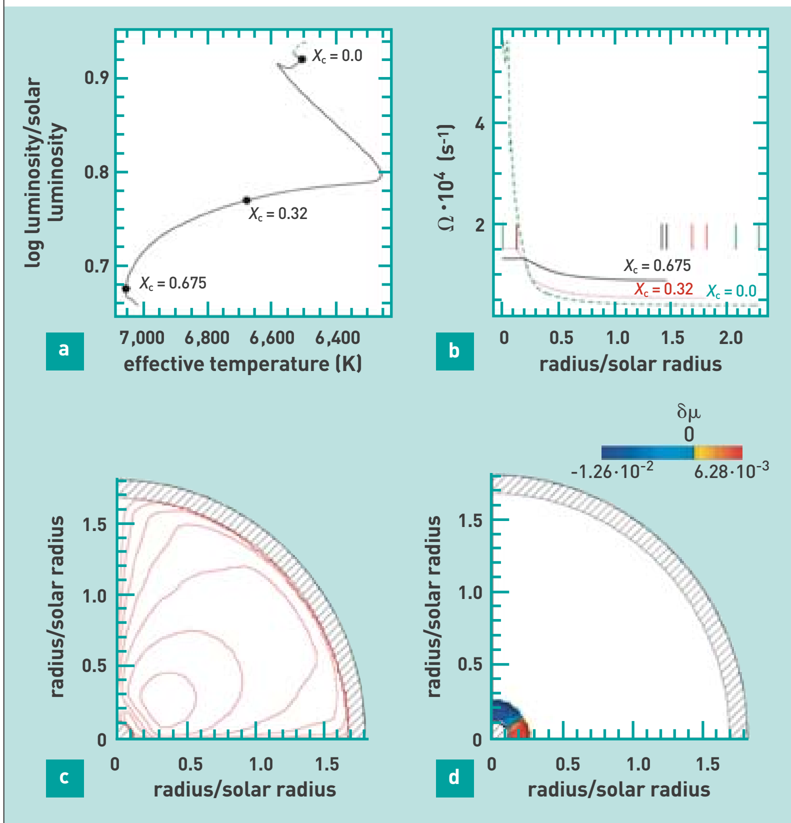


Figure 3.
Dynamic model of a rotating star, of 1.5 solar masses. At (a), evolutionary track across the **Hertzsprung–Russell diagram**; X_c stands for the hydrogen mass fraction, in the star's core. At (b), the internal rotational velocity profile, at three points in the star's lifetime. The star's radius increases as its evolution proceeds. The vertical bars show the corresponding positions of the convective zones. At (c), tangent lines for the velocity fields induced by differential rotation within the star's meridian plane, for $X_c = 0.32$. The loops are rotating in the anticlockwise direction, indicating that angular momentum is being transported outward. The hatched areas correspond to the convective zones. At (d), the chemical pollution caused by rotation, for $X_c = 0.32$. μ stands for the mean molecular weight, serving to describe the mixing of elements inside the stellar plasma. In the case of a pure, ionized-hydrogen plasma, this is equal to 1/2.

p. 10; and *From the Sun to the stars*, p. 16). Moreover, they send out into the environment **stellar winds** (driven by magnetism for solar-type stars and by radiation pressure for massive stars). During their pre-main-sequence phase, they are coupled to **accretion disks**, and they may further interact, by way of mass transfer, or through a **tidal effect**, with a companion star, should they form part of a **binary system**. Providing a description of stellar evolution that takes in all of these phenomena entails considering, at one and the same time, both microscopic and macroscopic physical phenomena, involving spatial and temporal scales several orders of magnitude apart. For instance, stellar nuclear evolution takes place over millions, or billions of years, whereas hydrodynamic processes – e.g. **convection**, or the instabilities that lead to **turbulence** – occur over timescales of the order of the month, or even less. To meet such a challenge, CEA embarked on a major drive, for the purposes of **modeling**, and **simulating** internal **magnetohydrodynamic** processes.

What is known, at present, of the mechanisms governing transfers of **angular momentum**, and mass transfers, inside stars, may be summed up as follows. Within stellar **radiative zones**, the energy generated by nuclear reactions is transported by way of photon–matter interaction. Indeed, stellar **plasma** is not highly **opaque**, and photons are **absorbed**, and reemitted millions of times, in the course of their collisions with **ionized atoms**. Within **convective zones**, hot matter wells up from the deeper layers to the uppermost regions, where it deposits its heat, before sinking down again. Such major, so-called convective general motions are due to the steep temperature gradient, and the fact that the density of matter decreases, as its temperature rises (see Figure 1). Solar-type stars feature a radiative core, and a convective envelope (in which the plasma is opaque, owing to the fact that atom ionization is only partial), whereas the reverse situation obtains in massive stars – with masses higher than 1.3 times that of the Sun – in which photons are unable to remove the energy generated around the center (see Figure 1, in *From the Sun to the stars*, p. 16).

A complex story

The mixing of the elements formed by **nucleosynthesis** occurs in the radiative zones, over very long timescales. The transport mechanisms involved fall into two main families, depending on scale: microscopic, or macroscopic. Microscopic mechanisms include gravitational settling, or separation, and forces due to radiation, acting on the motion of every particle, or atom. Magnetohydrodynamic processes, on the other hand, work at a macroscopic scale.

Thus, radiative regions undergo rotation, very rapid rotation in some cases (see Figure 2). This is neither constant, nor uniform throughout the star's evolution. In fact, each one of the star's several, distinct layers exhibits its own, specific angular velocity. This differential rotation sets up large-scale velocity fields (similar to the general circulations found in planetary atmospheres), and turbulence, associated to

shear (analogous to that found in the Earth's atmosphere, or the oceans). These transport angular momentum, and cause mixing, altering the star's structure.
At the same time, the stars have very likely trapped a so-called "fossil" magnetic field – "fossil," as it dates back to the star's formation – inside their radiative zones. This field interacts with the aforementioned processes, generating a further transport of angular momentum, such as to modify the coupling between the star's various layers. Further, due to the contrasting actions of buoyancy (pushing matter upwards), and gravity (drawing it to the center), radiative zones are also traversed by oscillatory phenomena, known as "internal gravity waves." To get a better notion of these waves – not to be confused with the gravitational waves propounded by Einstein – an apt simile would be that of the waves on the surface of the ocean. Excited by turbulent convective motions, such waves alter the angular velocity profile. The interaction set up between these various actors – which is, obviously, nonlinear – modifies the star's dynamics, and structure.
Just to make the picture an even more complex one, stars are coupled – in violent fashion, in some cases – with their environment, by way of stellar winds, accretion phenomena, or other mass transfer processes, or even tidal effects, in the case of **close binary systems**. Such couplings in turn modify the internal processes, resulting in making the star's evolution even more complex.
Modeling this dynamic evolution currently stands as the central thrust of the work carried out by stellar physicists at CEA, and their partners. They are thus developing, step by step, the theoretical tools required for the building up of new-generation models (see Figures 3, 4), along with numerical simulations of magnetohydrodynamic processes (at the timescales specific to these processes). At the same time, they are contributing both to the development, and operation of the observational instruments that provide the constraints introduced into the models (see *Journey into the lights of the Universe*, p. 90; and *Probing the Sun with GOLF–NG*, p. 130).

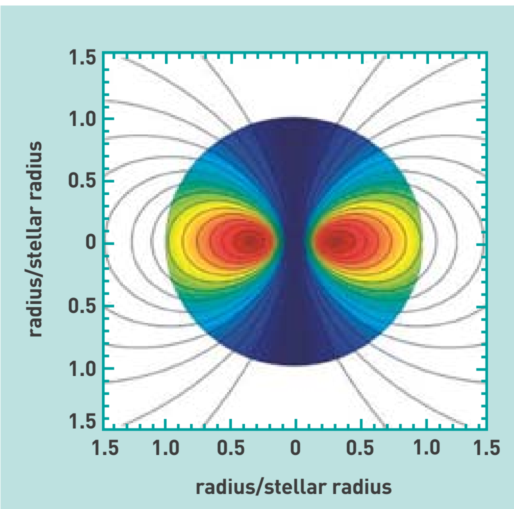
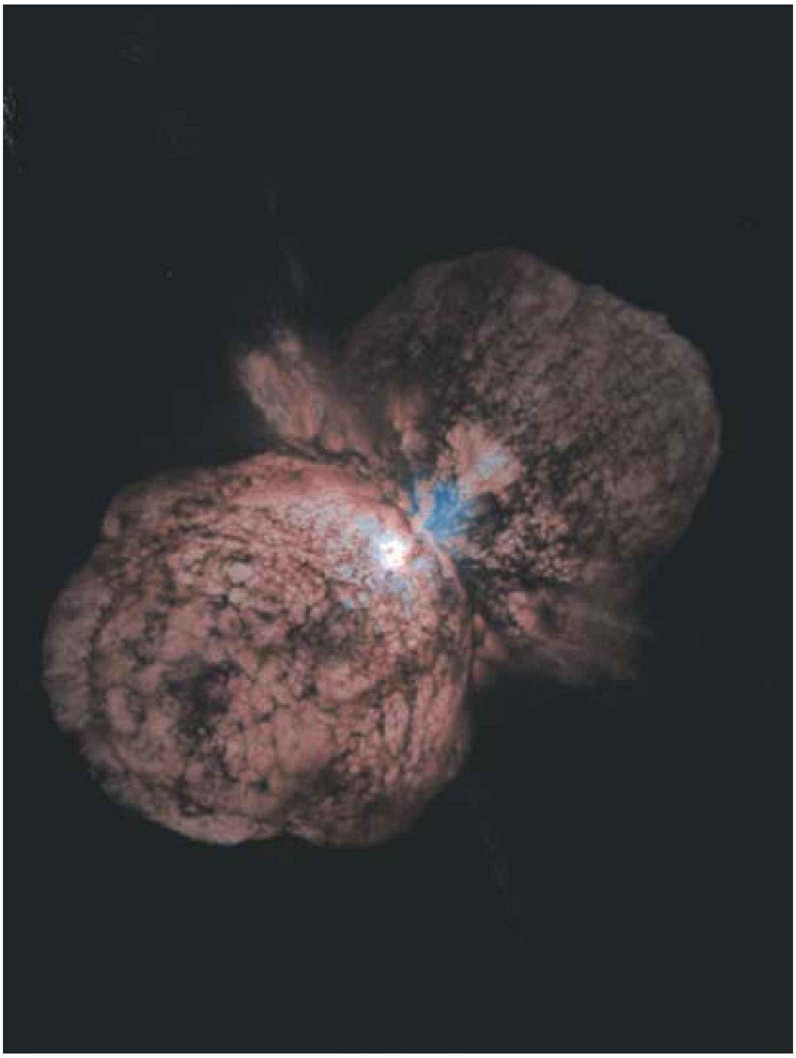


Figure 4.
The fossil magnetic field of an **A-type** star (2.37 solar masses, 3 times the **solar radius**).



Jon Morse (University of Colorado), and NASA

The star Eta Carinae, as imaged by the Hubble Space Telescope, lies some 8,000 light-years away, in the Carina (Keel) Nebula. A highly massive star – more than 100 solar masses –, it is undoubtedly very close to an incipient explosion. A small companion star is orbiting the main star, with a period of 5 years, their interaction setting off violent exchanges of gas and matter.

On the strength of this varied range of expertise, and drawing on a concurrently growing experience with large laser facilities, CEA is thus embarking on a drive to bring forward the investigation of the dynamic evolution of the only natural thermonuclear fusion reactors extant, to wit the stars.

> Stéphane Mathis
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

FOR FURTHER INFORMATION

André Maeder, *Physics, Formation and Evolution of Rotating Stars*, "Astronomy and Astrophysics Library," Springer (2009).

How supernovae explode

ESO

The Crab Nebula was discovered in 1731 by British physician and astronomer John Bevis. This is the remnant from the explosion of a supernova that was observed, in 1054, by astronomers in East Asia.

Some stars end their life in a huge explosion, propelling into the interstellar medium the matter they had synthesized over millions of years. Such phenomena, known as supernovae, are so bright that some have been visible to the naked eye. In 1054, Chinese astronomers thus observed a "guest star;" what they saw was in fact the explosion that gave birth to the Crab Nebula. Some two supernovae per century are understood to explode in our Galaxy, however automated telescopes detect several hundred such events per year, across all of the other galaxies. Cosmologists actively seek them out, since they allow distances to be measured, across the Universe. Further, they induce the formation of new stars, and stand as a major source of cosmic rays.
Stars similar to our own Sun do not explode: they end their lives by a process of slow dispersal, while a white dwarf forms at their center. Which are the stars, then, that do undergo such a tumultuous death? The supernovae observed fall into two categories: thermonuclear supernovae, and gravitational supernovae, depending on whether their progenitor was a white dwarf, or the iron core of a star having a mass at least 9 times larger than that of the Sun.
When a white dwarf is able to capture enough matter from a neighboring star to grow, and reach the Chandrasekhar critical mass (about 1.4 solar masses), the nuclear reactions at the star's center start running away. The fusion of carbon, and oxygen, yielding heavier elements, e.g. iron, then releases enough energy to blow the star apart altogether. A thermonuclear supernova is born.
By contrast, the iron synthesized in the core of a massive star is unable to release any nuclear energy, be it through fusion, or fission. Once its mass reaches the Chandrasekhar limit, the iron core collapses under its own weight, to the point where a neutron star is formed. Its diameter reduces by a factor 100 in less than one second, releasing a considerable amount of gravitational energy, chiefly in the form of neutrinos, and also photons (see Figure 1). In 1987, ground-based observatories captured neutrinos originating in gravitational supernova SN 1987A, thus corroborating the theoretical understanding achieved, for this phenomenon.

Creative instability

Some questions, however did remain unanswered. How could the successive shells of carbon, oxygen, helium, and hydrogen, surrounding the iron core, be ejected sufficiently rapidly, before the mass of the central neutron star was able to reach the critical threshold for the formation of a black hole (about 3 solar masses)? Indeed, such a black hole would swiftly swallow up the entire star, precluding any spectacular explosion. In 1985, US physicists Hans Bethe and James Wilson suggested a delayed explosion scenario, whereby neutrinos deposit sufficient energy into the envelope to ensure its ejection. Numerical simulations appeared to run counter to this scenario, right up to the point, in 2003, when the beneficial effects were discovered, of a new hydrodynamic instability. This develops less than 200 kilometers from the neutron star's center, during the few tenths of seconds following its birth. Theoretical investigations, carried out at CEA/IRFU/SAp, have elucidated its mechanism, in terms of the interaction between acoustic waves and vortical motions (see Figure 2). The turbulent motions induced by this instability are able to slow down the envelope's infalling motion towards the neutron star, thus exposing it for a longer interval to the neutrino flux. This effect would seem to be the key to an explosion being successfully achieved.
This instability proves decisive, with regard to both the explosion mechanism and the fate of the residual neutron star. As found in numerical simulations, it is responsible for the asymmetrical character of the explosion. This asymmetry is able to propel the neutron star across space, at velocities that may exceed 1,000 kilometers per second, which stands in good agreement with observations.
Future investigations should allow a better understanding to be gained of the diverse character of supernova explosions, in particular as regards their connection with gamma-ray bursts.

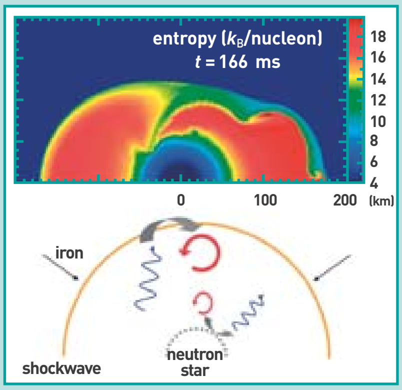


Figure 2.
Numerical simulation of the instability – as defined by entropy, expressed in terms of k_B per nucleon – which distorts the shockwave, in asymmetrical fashion (in collaboration with MPA, Garching [Germany]). Its mechanism is based on the interaction between acoustic waves (blue arrows), and vortices (red arrows), setting up an unstable feedback cycle.

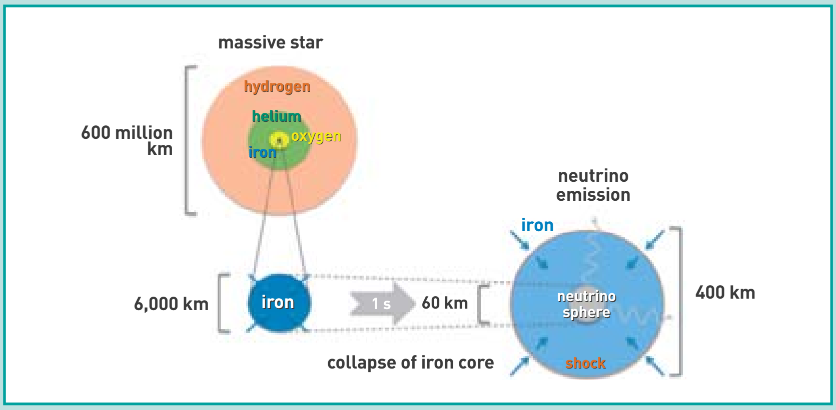


Figure 1.
Schematic of a gravitational supernova. The collapse of the iron core is slowed down by a standing shockwave, about 200 kilometers from the center.

> **Thierry Foglizzo**
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

Supernova remnants

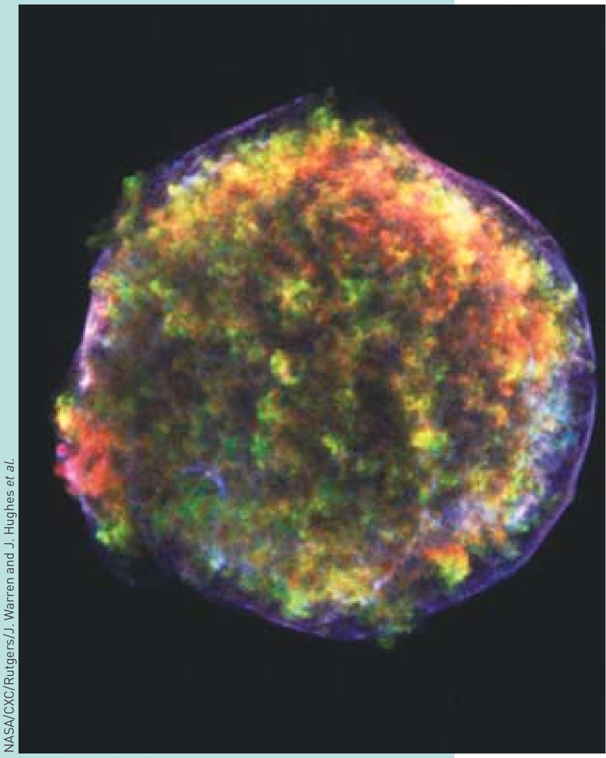
The explosion of a supernova releases a huge amount of energy (around 10^{44} J), only a small fraction of this arising in the form of visible light. When the explosion occurs, a supernova is as bright as an entire galaxy, however its visible light declines fairly swiftly thereafter, and vanishes after a few years. Within the Milky Way, the most recent observations of supernovae date back to the late 16th, and early 17th centuries. Even though outstanding instruments are now available to astronomers, whether on the ground, or out in space, no new supernova has yet been observed, inside our Galaxy! Now, on average, 2 or 3 explosions are known to occur every century, in a spiral galaxy such as our own. Some 10 supernovae or so must therefore have exploded, over the past 400 years; this, however, presumably occurred in regions that are obscured to us.

The heavy elements synthesized during the final phase of the star's existence are dispersed by the explosion, and enrich the interstellar, and intergalactic medium. The remnants of the wrecked star persist for several thousand years in space, and the X-rays emitted by it provide valuable evidence as to the nature of such explosions, and the physics involved.

A supernova remnant is a complex structure. Stellar matter, ejected as it is at very high velocity (some 10,000 km/s) by the explosion, impacts the surrounding interstellar medium, and, acting as would a piston, forces it back. In an initial phase, lasting less than one thousand years, two opposing shock fronts fashion the structure. On the one hand, the shockwave from the explosion, propagating outward into the surrounding medium; and, on the other hand, the reverse shock, due to the deceleration of stellar debris by the interstellar medium, traveling inward, within the ejected matter. Subsequently, the interstellar medium becomes dominant, with the freshly synthesized matter ceasing to prevail. Compressed as they are, and heated to tens of millions of degrees by the shockwaves, the stellar debris, and the surrounding medium become powerful X-ray emitters. This is what makes it possible to detect them. As the Earth's atmosphere acts as a shield against such radiation, ground-based observations are not feasible: the instruments have to be placed in orbit. The European XMM–Newton satellite (see *Journey into the lights of the Universe*, p. 90), and the US Chandra satellite have garnered a wealth of new findings in this area.

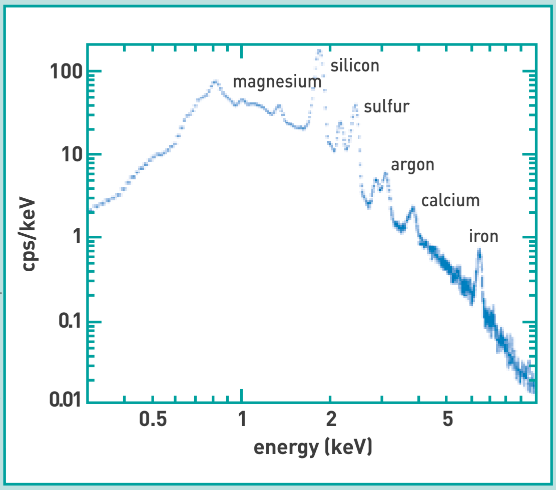
Highly instructive radiations

The two telescopes were pointed, in particular, at the supernova that had been observed in 1572 by Danish astronomer Tycho Brahe (known as Tycho's Supernova). Figure 1 shows the X-ray image of the remnant of that supernova, taken 432 years after the explosion. Its overall spectrum (see Figure 2) shows the presence of highly ionized heavy elements, e.g. silicon, sulfur, argon, iron. Spectral composition allows a distinction to be made, e.g., between thermonuclear, and gravitational explosions (see *How supernovae explode*, p. 26). The elements' spatial distribution within the ejecta provides a fresh insight into layer mixing processes, inside the supernova, or as to explosion asymmetry. The X-ray emission further yields evidence as to such physical processes as hydrodynamic instabilities, developing at the interface between the ejected matter, and the surrounding medium. 3–D numerical simulations are then compared with the findings from observations. X-ray instruments, nowadays, have the ability to carry out spatially resolved spectroscopy (allowing imagery to be produced in narrow energy bands, e.g. emission lines; and spectroscopy across regions of restricted spatial extension), which has opened up the investigation of so-called "noncollisional" shockwave physics. This has brought about, in particular, a better understanding of cosmic ray acceleration by supernova remnants (see *Elucidating the cosmic ray acceleration mechanism*, p. 50).



NASA/CXC/Rutgers/J. Warren and J. Hughes *et al.*

Figure 1.
An X-ray image of Tycho's Supernova Remnant, as viewed by the Chandra satellite, more than 400 years after the explosion. The ejected matter (shown in red, or green, depending on its chemical composition) appears clumpy, owing to hydrodynamic instabilities. The shockwave propagating through the surrounding interstellar medium is indicated by a narrow filament of synchrotron emission (blue), generated by electrons accelerated to velocities close to the speed of light.



XMM-Newton (ESA) and CEA/SAp

Figure 2.
X-ray spectrum of Tycho's Supernova Remnant, as obtained by one of the cameras mounted on the XMM–Newton satellite, more than 400 years after the explosion. This exhibits intense emission lines, due to heavy elements synthesized just before the explosion, and during it. These elements, heated as they are to tens of millions of degrees by the shockwave traveling across the ejected matter, are highly ionized. Investigation of these lines yields evidence as to the nature of the supernova involved (thermonuclear explosion, or gravitational collapse).

> **Anne Decourchelle** and **Jean Ballet**
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling"
(CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

High-energy objects – sources for astonishment

Stellar "corpses" – poorly visible, extremely dense objects – may become powerful sources of radiation, should they be associated to a companion star. With the new observational resources now becoming available, the zoo of such high-energy objects is forever expanding.

S. Chaty/ESA

Artist's impression of a high-mass binary system, comprising a neutron star orbiting a supergiant star. The neutron star accretes matter from the dense, inhomogeneous stellar wind, ejected by the supergiant. The investigation of high-energy objects allows not only solid-state matter physics issues to be addressed, but equally the physics of very-high-temperature plasmas. Such objects are ideal, for the purposes of understanding accretion–ejection phenomena, and, in some instances, stellar winds from massive stars.

When they reach the end of their evolution, some **stars** turn into extremely compact objects: **white dwarfs**, **neutron stars**, or **stellar black holes**. These three types of celestial bodies differ in terms of their density. A white dwarf typically contains one **solar mass**, within a sphere some 6,000 km in radius. A neutron star holds a similar mass inside a sphere having a radius of 15 km only. Finally, a black hole weighing in at 10 solar masses would involve a "radius" of 30 km (corresponding to the **event horizon**). These "dead" stars emit but little radiation, when they stand in isolation, making them poorly visible, or even altogether invisible to us. On the other hand, these objects may become extremely **bright**, should they stand as one component in a **binary system**, in other words if they are bound by **gravity** to a companion star, the matter from which they are able to draw to themselves. Such a system is referred to as a "cataclysmic variable," when the compact object is a white dwarf, or as an "X-ray binary" when the object involved is a neutron star, or a black hole. The present paper is concerned with X-ray binaries.

Powerful emitters

The infall of matter turns part of the **gravitational** potential energy into radiated energy. Owing to the extremely high density of the object involved, matter is brought to very high temperatures (about 10 million degrees), and emits **X-ray radiation**. This is what gave their name to such systems. When the companion is a **massive star** (with a mass greater than 10 solar masses or so), it generates an intense **stellar wind**, which is intercepted by the compact object, and directly **accreted** by it. Such objects are not very bright, and may even be buried in the stellar wind. If, on the other hand, the companion star is typically less massive than the Sun, the compact object strips matter away from its outside layers. Owing to the conservation of **angular momentum**, such matter, originating as it does in a rotating star, in a binary system, may not fall directly onto the compact object. An **accretion disk** thus arises: matter spirals in, gradually coming closer to the compact object, at the same time heating up… and emitting an abundant flux of X-rays. Moreover, a corona of relativistic electrons surrounds the central object, emitting X-rays, and gamma rays by inverse Compton effect (see Figure 1). For the purposes of characterizing such high-energy objects, and their environments, astronomers therefore make use of X-ray, and gamma-ray telescopes, as e.g. XMM–Newton, and INTEGRAL – to which instruments CEA/IRFU made a substantial contribution (see *Journey into the lights of the Universe*, p. 90) – but equally radio-wave and infrared/visible radiation sensors.

The discovery of microquasars

Going beyond the image of a black hole accreting matter from a companion star, astrophysicists at CEA/IRFU showed, in the 1990s, that such objects could give rise to massive plasma ejections, in the form of apparently superluminal jets (i.e. with velocities apparently higher than the speed of light) (see Figure 1). Such bodies were dubbed microquasars, by analogy with quasars, which are active galactic nuclei holding at their center a supermassive black hole (with a mass ranging from several million to several billion solar masses). This finding revolutionized investigations in this area. Indeed, it may be the case that universal physical mechanisms are at work, in both populations of black holes. Now, physical phenomena, within microquasars, arise over restricted timescales (from a millisecond to a year). This finally makes it possible to investigate – albeit indirectly – phenomena similar to those that arise within active galactic nuclei… over timespans so long, however, as to be inaccessible, at the human scale. Various properties of the accretion stream were identified at this point, and it became apparent that the disk was strongly coupled with the relativistic jets, by way of a corona of hot electrons feeding into these jets (see Figure 1). Further, the presence of ionized matter within the accretion disk results in the emergence of lines from such substances as iron. Gravitational effects induced by the compact object alter the emission profile, for matter in the rotating disk. In coming years, with the X-Ray Evolving Universe Spectroscopy Mission's International X-ray Observatory (XEUS/IXO), and other instruments, such emission lines will provide astronomers with information as to black hole rotational velocities, one of the three fundamental parameters of such objects, along with mass, and electric charge.

The discovery of a number of correlations (regarding flux in various energy bands, quasiperiodic oscillation frequencies, spectral characteristics, etc.) further showed that these jets of matter may emit in the X-ray, and gamma ray regions, i.e. way outside their conventional radio-wave domain. In a matter of a few years, relativistic jets were thus identified as powerful, multiwavelength emitters. The direct observation of an X-ray emission arising from the interaction of such jets with the interstellar medium corroborated this (see Figure 2). This, indeed, provided unambiguous evidence that these jets contain very-high-energy (> TeV) particles. Emission up to the gamma ray region is a possibility: observatories such as Fermi, or HESS may then be able to detect this (see *Journey into the lights of the Universe*, p. 90).

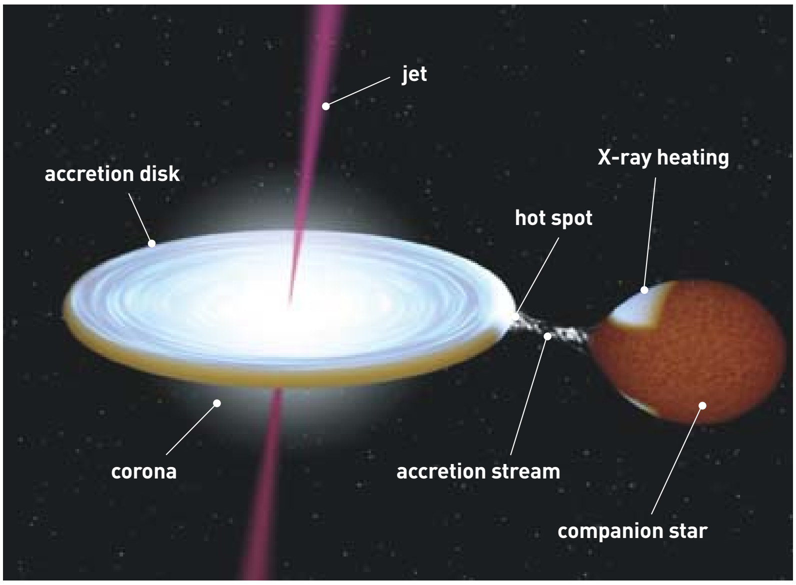


Figure 1.
Artist's impression of a microquasar. Matter stripped from the companion star falls into the black hole through a spiraling motion. A disk forms around the dense object, and jets of matter arise.

"Intermediate" microquasars?

A new conundrum has emerged, over the past few years. The powerful observatories now available, e.g. XMM–Newton, detected very large X-ray sources, in many galaxies close to the Milky Way. Now these objects would seem to be far too luminous to be assimilated to X-ray binary systems. This suggested the notion that these might be black holes with masses intermediate between those of microquasars, and active galactic nuclei, i.e. masses ranging from a few hundred to several thousand solar masses. However, current theories are hard pressed, when it comes to accounting for the formation of such intermediate mass black holes. Multiwavelength observations will shed new light on these bodies. Either they will bring evidence as to the existence of a new class of exotic objects, or a number of currently accepted theories, regarding accretion disks, will have to be revised.

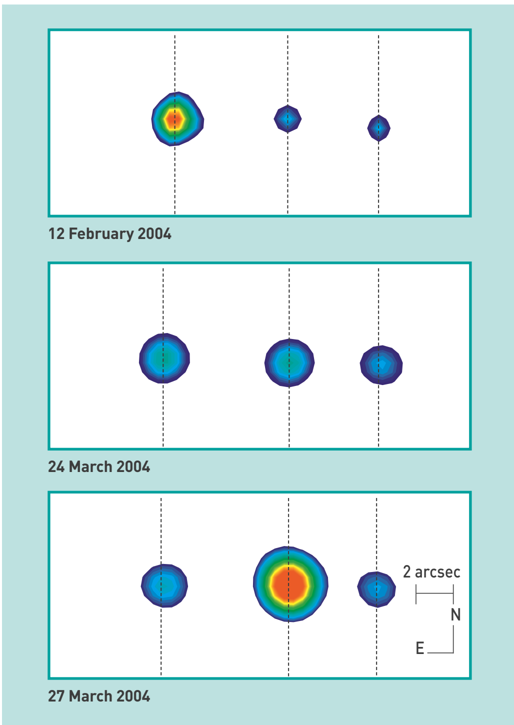


Figure 2.
An image of the X-ray emission around microquasar H 1743–322. On either side of the central source, two moving X-ray sources may be seen, due to the interaction between relativistic plasma bubbles, and the interstellar medium.

Figure 3.
Left, a buried object, with the neutron star orbiting close to the supergiant, constantly remaining inside the stellar wind.
Right, a "fast transient," where the neutron star, following an eccentric orbit, enters the stellar wind at regular intervals.

Baffling sources

Within the Milky Way itself, the INTEGRAL observatory also discovered, in January 2003, a novel type of X-ray source. These sources are concentrated in the galactic plane, chiefly in the direction of the spiral arms. An intensive observation program was then launched, and the XMM–Newton, Chandra, and Swift observatories provided precise positions for some 30 of the sources identified by INTEGRAL. Spectral information indicates that many of these sources exhibit strong intrinsic **absorption**, which is unusual for high-energy objects. This came as a first surprise; others were to follow…

Aside from these X-ray observations, astrophysicists at CEA/IRFU embarked on a multiwavelength program, to unravel the nature of these sources. This investigation brings together, for a sample of such objects, precise **astrometry**, and **visible-light**, and **infrared** (both **near-**, and **mid-infrared**) **photometry** and **spectroscopy**. This is where the second surprise came in: most of these objects turn out to be high-mass binaries, involving **supergiant** stars – highly evolved stars, which have exited the **main sequence** – whereas, prior to the launch of INTEGRAL, most of the known high-mass binary systems held Be stars – main-sequence stars featuring an early **spectral type**, rotating so rapidly that they set up an equatorial disk of matter around them.

Going from surprise to surprise

These new high-energy objects appear to be intrinsically obscured, i.e. they directly absorb some of their own radiation. Source IGR J16318–4848 stands as an extreme instance: this is a neutron star, orbiting a supergiant of an extremely rare spectral type, noted sgB[e], owing to the presence of "forbidden" emission lines.(1) Observations in the mid-infrared showed that these objects appear to be obscured owing to the presence of absorbent material (dust, and/or cold gas), surrounding the binary system as a whole. The neutron star is thus orbiting within a cocoon of cold gas, formed by the stellar wind from the supergiant.

Finally, a third characteristic marked out an even more unusual subpopulation, among these objects. Indeed, some of these sources exhibit very swift surges in activity, lasting about one hour, occurring in apparently haphazard manner. Such bodies have been designated "supergiant fast X-ray transients." The prototype for these sources is IGR J17544–2619. As the sample of sources investigated expands, it is becoming apparent that the differences arising between buried objects, and fast transients are chiefly due to the orbital characteristics involved (see Figure 3). Indeed, buried-object sources are akin to conventional high-mass binary systems, comprising one supergiant, together with a neutron star keeping to a very close orbit, at 2 or 3 stellar radii only. Accretion of matter – from the stellar wind – thus occurs constantly, and the X-ray emission is persistent. "Fast transients" are systems in which the neutron star is located at some distance from its companion, on a circular, or eccentric orbit. It is when the compact object passes through the stellar wind, which is inhomogeneous and clumpy, that fast activity surges occur. When the object swings away from the supergiant, on the other hand, little or no X-ray emission occurs.

To sum up, it would seem that there exists, in nature, a continuum of such high-mass binary systems, involving emission characteristics depending on the closeness obtained between the compact object, and its companion, and the nature of the orbit. It is the interaction between the two components in the system that governs the properties of these high-energy objects.

> **Sylvain Chaty, Stéphane Corbel** and **Jérôme Rodriguez**
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling"
(CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

(1) Spectral lines emitted by an **atom** that deexcites according to a mode of very low probability.

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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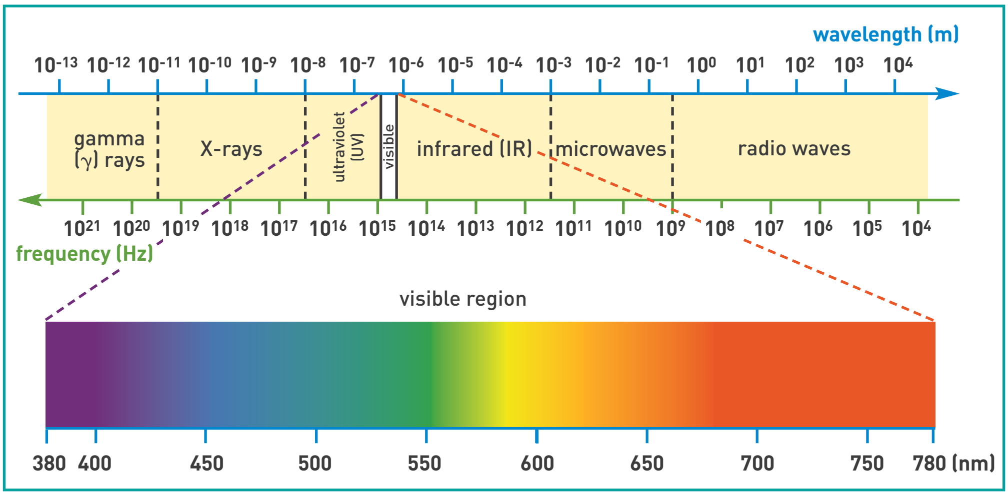


Figure 1.
The electromagnetic spectrum. Electromagnetic waves are grouped into families, of differing frequencies and wavelengths.

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.

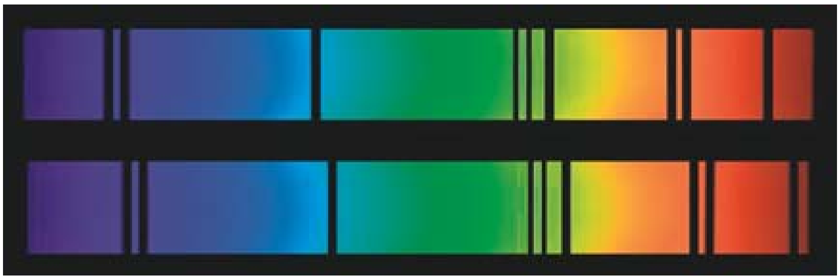


Figure 2.
Spectrum of a light source, exhibiting no shift of spectral lines (top), and featuring a redshift (bottom).

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' spatiotemporal 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.

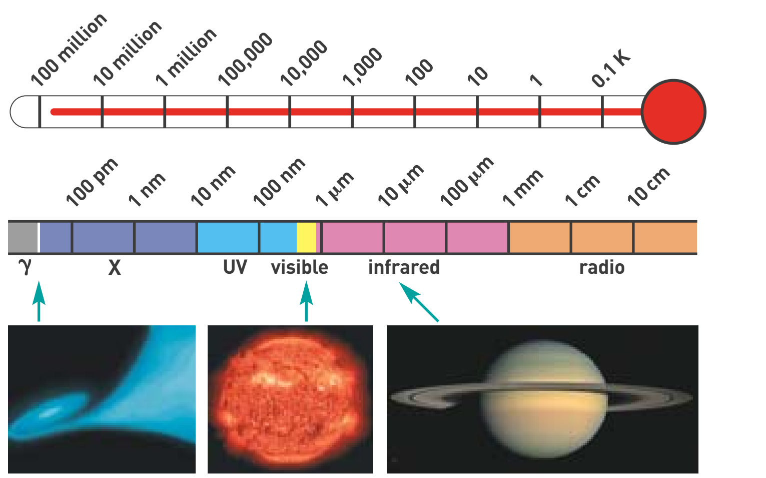
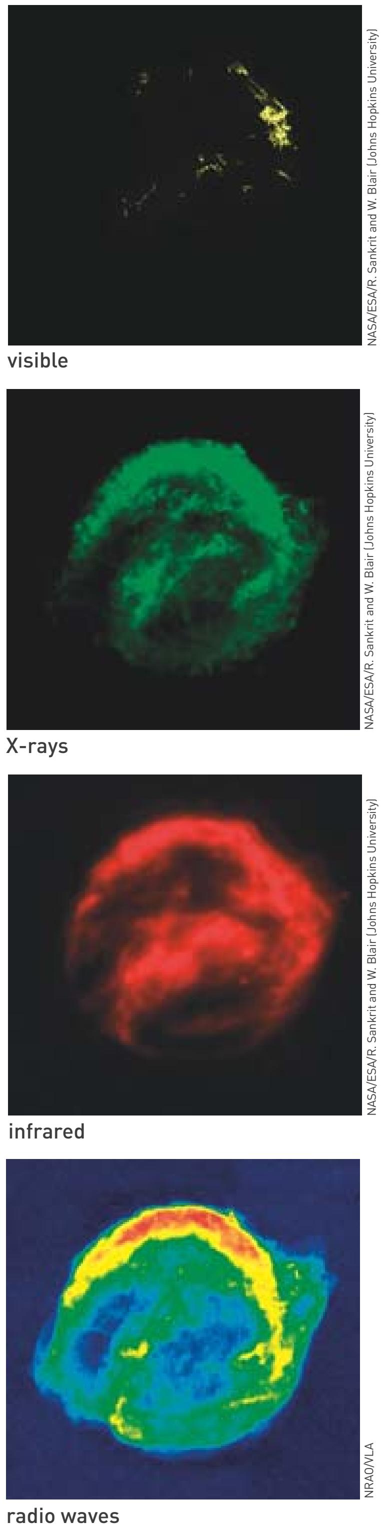


Figure 3.
The distribution of radiation yields information as to the temperature of a celestial body, and its characteristics. In two major segments of the electromagnetic spectrum, infrared on the one hand, X-rays and gamma rays on the other, advances in spaceborne detection are making it possible, 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.

Exploration of the Solar System has made it clear to us, and the discovery of exoplanets has further confirmed it: the Earth is just one planet, amongst others. All of these planets were born inside a gas and dust nebula, surrounding a young star. Once the central star has completed its initial contraction, a complex process is initiated, involving the condensation of the nebula's constituents, to form grains, and subsequently larger bodies: planetesimals, further going on to form planetary embryos. At large distances from the star, these embryos ultimately draw in, and accumulate a large mass of gas, thus turning into gas giants. Such firstborns – Jupiter in our planetary system – govern, thereafter, the dance of inner planetesimals. Through accretion, and collisions, these end up forming terrestrial planets, such as the Earth. Nothing is set forever, however, since protoplanets may migrate within the disk, along a variety of paths. Why, and how such migration comes to an end is an issue that is currently being actively investigated, to gain an adequate understanding of the formation of stable planetary systems.

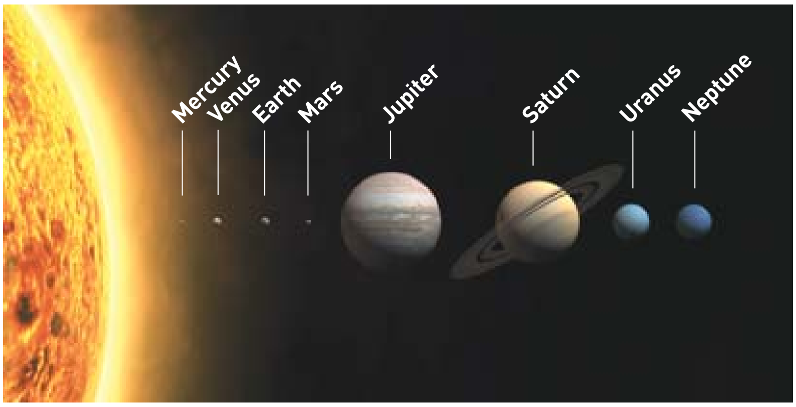
Planets: a **dance** of small **bodies, swirling** around up to the finale of their **birth**

How our world was born

The exploration of the Solar System, the discovery of extrasolar planets, new ideas, and powerful numerical simulations have made it possible to gain a better understanding of the way planets are formed. It became apparent, at this point, that the outcome might have been altogether different, given the extent to which the final form of a planetary system is dependent on initial conditions.

NASA/JPL/Space Science Institute

Jupiter, as viewed by the Cassini probe. Jupiter determined the entire history of the Solar System. It played a part at the time when Saturn was formed, assisted in the formation of the other giant planets, and indeed even in the formation of the terrestrial planets. In particular, it stood at "just the right place" to promote the emergence of our Earth.



International Astronomical Union

The exploration of the Solar System, carried out in conjunction with a vigorous research effort, and the use of novel Earth-based observation techniques, stimulated the emergence of a new, essentially multidisciplinary science: planetology. Comparative investigation of the planets is an excellent way of gaining an improved knowledge of the Earth itself -spars.

The century that has just drawn to a close will stand in history as the century of the exploration of the Solar System. Men set foot on the satellite of our Earth, and brought back moonstones, to be analyzed in our laboratories. Robots explored Mars, studied its surface, measured the winds over it, and found an absence of life there. Automatic probes landed on Venus, others penetrated its clouds, and revealed the details of its surface. Halley's **Comet**, along with a number of other comets, **asteroids**, Jupiter, Saturn, Uranus, Neptune, and these bodies' environments, were visited by manmade machines. The salient moments of this exploration were the Apollo missions to the Moon, in the late 1960s; the Viking mission to Mars, in the 1970s; and, most crucially, the Voyager mission, which reached the outer confines of the Solar System during the 1980s. The outset of the 21st century is synchronous with a return to Mars, and the worlds of Saturn, with the Cassini–Huygens mission, including an active contribution from CEA research scientists, these indeed collaborating in the construction of one of the probe's infrared sensors.

The vast wealth of data collected over the past few decades – a collection that is currently ongoing – brought about an upheaval in scientific thinking. Sophisticated **numerical simulations** allowed a number of **models** to be tested, and new avenues of investigation to be opened up. Astrophysicists then came to realize that the Earth is one planet amongst others, amenable to investigation by way of comparing it with its neighbors. They came to understand that the Solar System is far more prolific than had been anticipated, be it in terms of the variety of bodies occurring in it, or the diversity of physical phenomena arising within it. The recent discovery of extrasolar **planets**, together with the observation of **star**-forming sites brought in its train a significant leap forward, as regards our understanding of our own origins.

A cloud collapses

The history of our planetary system began some 4.55 billion years ago. At some place within our **Galaxy**, a cloud of interstellar gas collapsed under its own weight, giving birth to a star – the **Sun** – itself surrounded by a gaseous nebula that soon flattened out, forming a disk. Chemical reactions being highly sensitive to temperature, chemical composition depended on distance from the Sun: temperatures ranging from more than 2,000 **K** close to the star, to a few tens of degrees above **absolute zero** at the confines of the Solar System. Refractory compounds (aluminum oxides, calcium oxides, titanium oxides, magnesium silicates, sodium and potassium feldspars, iron oxides), along with many other minerals, thus arose close to the Sun, whereas water ice, or carbon dioxide, methane or ammonia ices formed at the periphery. How was the transition to be achieved, however, from gaseous disk around a protostar, to the array of planets we now find? In the 1980s, astronomers conceived of a succession of stages, such as would unfailingly result in a single, unique final state, involving terrestrial planets close to the center, and giant planets at the periphery. All planetary systems would therefore resemble our own. The detection of extrasolar planets, along with the development of theoretical models, and the very exploration of the Solar System itself brought about the realization, some 20 years further on, that the planetary system formation process, around a star, is in fact much more complex, and may yield a wide variety of final situations.


NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA)

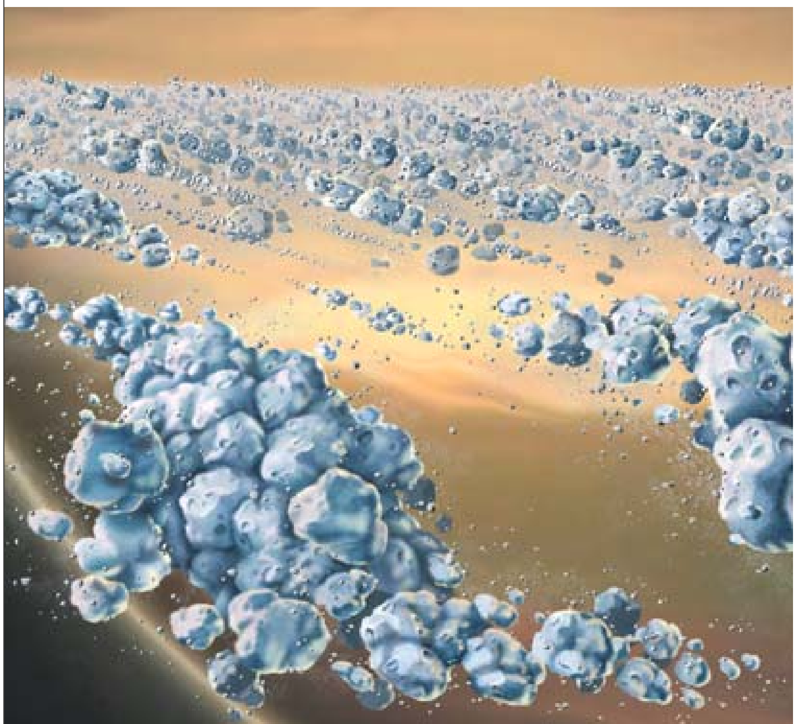
The Carina (Keel) Nebula. Through the observation of star-forming sites, astrophysicists are able to conceive how the transition might occur, from interstellar cloud to protostellar nebula, and subsequently through to a sun surrounded by a dust, and gas disk.

Once the Sun had finished contracting, an abrupt cooling occurred, over a relatively short interval, at the astronomical scale. Indeed, a star that draws its energy from the **thermonuclear reactions** arising within it proves far less **luminous** than a protostar in the process of collapsing. A major part of the gas cloud then solidified into grains, with sizes ranging from a few **microns** to several millimeters. Over a few tens of million years, the gaseous nebula thus turned into a disk of dust grains, with chemical composition depending on their distance from the Sun. As cooling continued, various metals, and ices condensed. Refractory compounds of calcium, aluminum, magnesium, and titanium become solid below 2,000 K. Magnesium silicates, sodium and potassium feldspars, iron oxides solidify around 1,000 K. Around 300 degrees above absolute zero, water vapor turns to ice, while, at a temperature of a few tens of degrees, grains of solid methane appear. This is why only refractory compounds, and some other minerals solidified in the vicinity of the Sun. At the Solar System's periphery, on the other hand, water, carbon dioxide, methane, or ammonia ices became dominant, in grain composition. The variations in density, and composition found for the present Solar System are thus the outcome of the temperature conditions that prevailed within the protoplanetary disk.

From "grains" to planets

The formation of bodies such as planets, or their satellites from so minute grains of matter did, however, long remain baffling. Direct growth of small grains, to yield large planets, by way of successive aggregations, would require timescales longer than the age of the Universe. The solution of that puzzle only emerged in the 1970s, when simulations showed that, in a relatively undisturbed disk of dust grains, local **gravitational** instabilities inevitably arise. Bodies a few hundred meters across are then formed, by collapse. Should, by contrast, the primitive nebula be agitated by strong **turbulent** motions, condensations will arise at the center of the vortices. These likewise involve sizes of a few hundred meters. To sum up, in either case, bodies a few hectometers across emerge, known as *planetesimals*. The disk of dust grains is thus superseded by a disk of planetesimals.

By the sheer interplay of the collisions arising between them, these planetesimals then aggregate into bodies some 500 to one thousand kilometers across, which may be seen as planetary embryos. Here again, collisions play a crucial part in the final outcome. Should the relative velocity of the two bodies involved be low, they tend to merge. Should, on the other hand, the encounter occur at high velocity, they will fragment. If matter is to accumulate gradually, and give birth to planets, relatively "gentle" collisions are required. This can only occur if the orbits followed by the planetesimals are almost identical, or even – ideally – if they stand as concentric ellipses. Should that be the case, however, a body will only be able to take up such matter as lies in its immediate vicinity. The **accretion** process thus fairly swiftly comes to a halt. If an object is to accumulate more matter, it must "sweep" across a broader region of the system, hence follow an eccentric orbit. This, however, leads to a contradiction. Indeed, collisions between such a body, and other planetesimals then occur at very high relative velocities… resulting in the breakup of the bodies involved. In other words, starting from a disk of planetesimals, it is a process relatively readily imagined, that results in a system comprising a hundred or so small planets, however it is far more improbable that a few large planets will be obtained, such as the eight bodies that make up our own system.



NASA/JPL/University of Colorado

Detail view of a model of the rings of Saturn, showing how they take the form of a very thin disk of icy dust, and pebbles, similar to planetesimals, the forebears of present-day planets. Placed into orbit around Saturn in 2004, the Cassini probe daily sends back unique data, allowing research scientists to develop cutting-edge models, for the purposes of simulating a number of important mechanisms.

Terrestrial planets and gas giants

The process whereby planets with a radius of several thousand kilometers can form, from embryos about the size of France, proved to be amenable to investigation, and understanding only by way of numerical simulation. A planetary embryo, owing to its mass, disturbs the motion of the diffuse material lying in its vicinity, ultimately drawing in large quantities of matter. The greater the accretion, the wider the embryo's sphere of influence extends. It would appear that, in our own planetary system as elsewhere, a few embryos, initially slightly larger than the others, were thus able to "take over," taking up all of the matter lying in their neighborhood. Gradually, all of the matter available was drawn closer to these "dominants." At the same time, even as the bodies orbiting the Sun became fewer, the further the probabilities of collision – and hence of fragmentation – would diminish. Everything then concurred to ensure the survival of these few objects. The final collisions determined the direction of the axis of rotation, and initial period of rotation, for each planet. Such is, currently, the virtually universally accepted mechanism, seen as accounting for the formation of terrestrial planets, i.e. planets such as Mercury, Venus, Mars, and the Earth.

The emergence of giant planets, such as Jupiter,

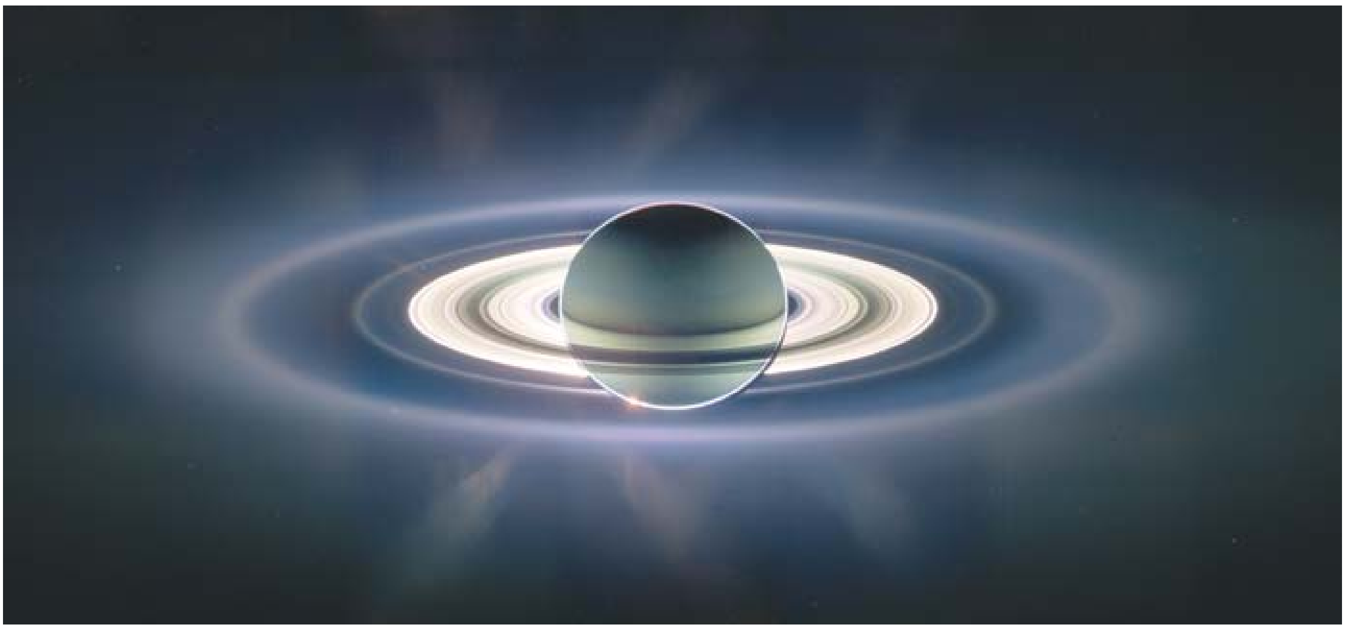
DR

The Allende meteorite. On the basis of the evidence accumulated within meteorites, and sophisticated numerical simulations, scientists came to the understanding that the transition from a continuous disk of matter to a disk of planets took several tens of million years – a very short time, at the astronomical scale.

Saturn, Uranus, and Neptune took longer to be understood. In the 1970s, astronomers considered that such objects would form, as stars did, by way of a local collapse of the gas cloud. This scenario is dismissed, nowadays, since, for that to occur, the disk of the primitive nebula would have to be unstable, and at least ten times more massive than the Sun, which is scarcely realistic. Moreover, the gas giants found in our own planetary system exhibit compositions that are markedly different from those of the Sun, and of the primitive nebula. It became apparent, in more recent years, that a scenario of the accumulation of planetesimals type, such as specifically applies for terrestrial planets, is likewise to be excluded. The formation of giants by this route would, indeed, require too much time. It would appear, ultimately, that a number of solid cores, formed by way of an accumulation of planetesimals, drew in to themselves the gas present at large distances from the protosun, each giving birth to one giant planet.

Such a scenario unfolds over a number of stages. Initially, planetesimals come together to form a solid, dense core, surrounded by a gaseous atmosphere, of low mass. Once that core has captured virtually all of the solid bodies lying within its gravitational sphere of influence, the protoplanet keeps on growing, by capturing all of the gas in its vicinity. Through a runaway "snowballing effect," this capture process accelerates, and the planet undergoes very rapid growth. Such captures then heat up the whole body, even as the temperature of the nebula around the protoplanet falls off, with increasing distances from the center. This accounts for the densities, decreasing with distance, of the satellites (these solidifying subsequently) presently orbiting the giant planets. Ultimately, as it has collected all of the gas available in its own environment, the new planet stands isolated in space; it completes its contraction, and thereafter slowly cools down, to reach its present state.

According to scenarios of this type, the formation of the giant planets proved far speedier than that of the terrestrial planets. The models developed by various teams show that the solid core, resulting from the accumulation of smaller particles, took less than one million years to form, subsequent to the collapse that gave birth to the Sun, and that accretion of a massive **hydrogen**, and **helium** gaseous envelope took less than 10 million years. Jupiter would appear to have been the first planet to form in the Solar System, and its emergence fashioned what happened subsequently. Its growth occurred at an amazing pace. Once the proto-Jupiter reached a size comparable to that of the Earth, it took less than one thousand years to capture one half of its ultimate mass (which stands at some 300 Earth masses)! The heat released was so intense, at that point, that it was almost as **bright** as a star. The planet swiftly became massive enough to evacuate all of the gas remaining near it. Indeed, it "drew back" the gas **molecules** occurring between itself, and the Sun (which



NASA/JPL/Space Science Institute

Saturn and its rings, seen backlit by the Sun. The planet was imaged by the Cassini probe, as it was masking the Sun. The Earth may be seen at the top, left. You are in this picture!


NASA/JPL/Space Science Institute

Hyperion, one of the satellites of Saturn, measuring about 340 km in diameter. It is riddled with craters, evidence that satellites, and planets in the Solar System were subjected to an intense bombardment by asteroids.

molecules were orbiting faster than itself), thus causing that matter to infall onto the star. By contrast, the gas lying outward from its path being slower than itself, the planet accelerated it, thus propelling it to the periphery. The planet thus cleared a swathe across the circumsolar gas disk, cutting off the supply of raw material. The gas does tend, of course, to seep back into such a gap, however numerical simulations show that, with Jupiter lying 750 million kilometers from the Sun (as is the case at present), it ultimately pushes the gas back. At the same time, the faster a giant protoplanet forms, the larger it will ultimately be, as large quantities of gas are still available in the planetary system. If Jupiter is larger than Saturn, Uranus, and Neptune, it is simply because it formed several million years earlier.

The importance of Jupiter

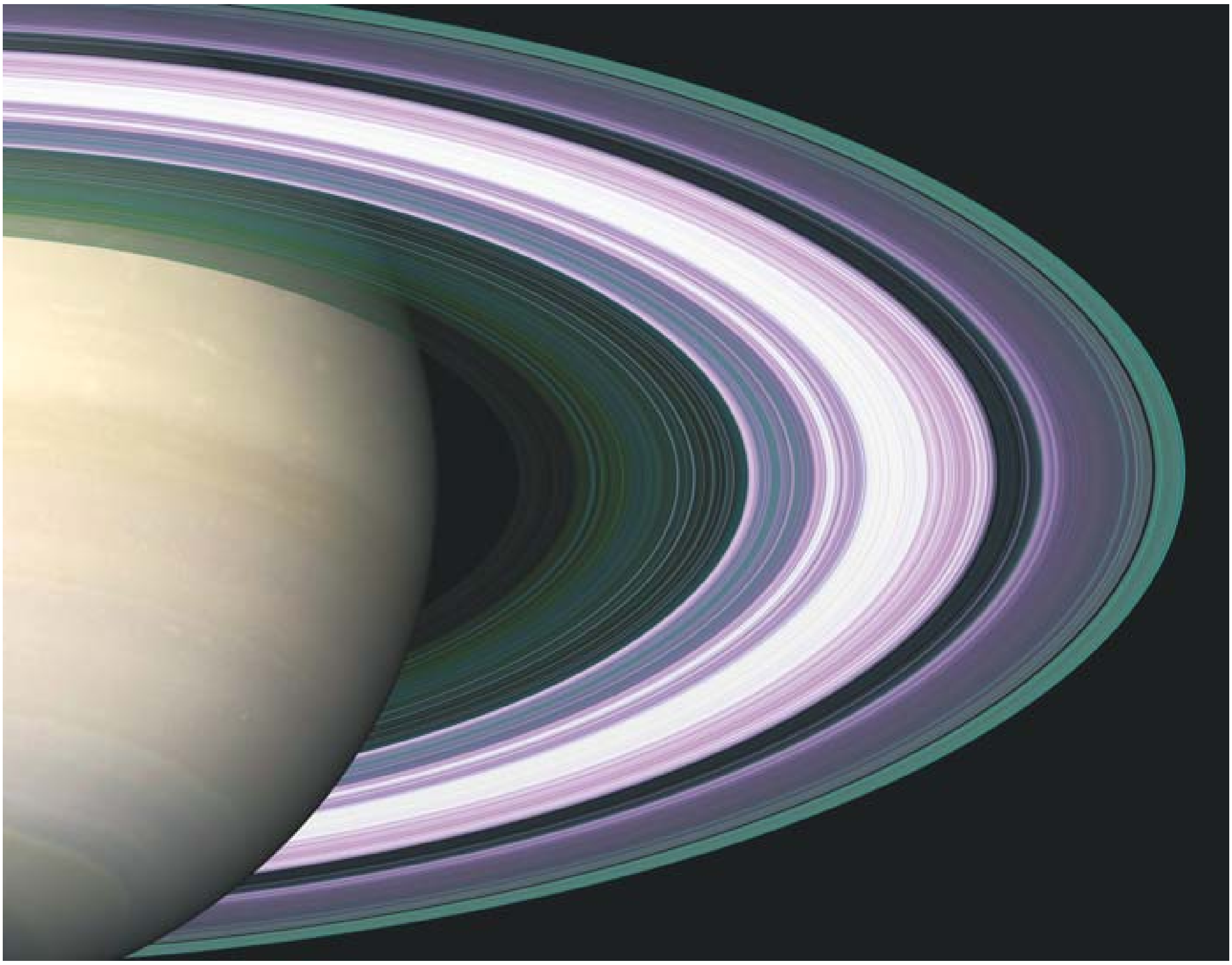
By promoting gas condensation in the outer regions, and evicting planetesimals to the confines of the disk, through its gravitational action, the young Jupiter provided raw materials for the formation of the other giant planets. Owing to that role played by Jupiter, in collecting materials, Saturn could thus form more promptly. Had Jupiter not been there, Uranus and Neptune would probably never have reached their present sizes. Indeed, at large distances from the central star, in regions of low density, the growth of a body proves so protracted that the gas disk is dissipated well before a large planet can form, leaving behind it a mere "stunted" body. The emergence of this second generation of giant planets, within our planetary system, might in fact have had a devastating effect. Indeed, had two of these planets formed too close to one another, they could have set up so strong an interaction as to be catapulted into highly eccentric, inclined orbits, leaving a trail of perturbations throughout the system. The Earth could have been expelled from its position, by the close passage of such a giant. This is probably what occurred around stars that feature a planetary escort following eccentric, inclined orbits, whereas all of the planets in the Solar System follow near-circular orbits, lying in the solar equatorial plane.

In effect, Jupiter determined the evolution of the entire planetary system, by way of the interplay of resonances set up between planetesimals. Had it been closer to the Sun, or further out, or placed in an elliptical orbit, Jupiter would have disturbed the accretion of such bodies, precluding the formation of terrestrial planets.

A consensual scenario

To sum up the story of our origins, most scientists nowadays agree on the following scenario. First of all, giant planets formed in the outer reaches of the protosolar nebula, by way of the capture of hydrogen, and helium gas around a massive core, this being the result of an accumulation of solid planetesimals. Subsequently, the terrestrial planets emerged, through the accretion of planetesimals, in the inner regions of the nebula. All of this took barely a few tens of million years, i.e. a very short timespan, at the astronomical scale. The planetesimals that had not been used up in planetary formation then interacted with the planets, and an **asteroid belt**, far more massive than that currently extant, arose between Mars (the last terrestrial planet), and Jupiter (the first giant planet), along with a host of bodies expelled beyond Neptune. Once all of these perturbations had run their course, a period of relative quiescence prevailed, for some 600 million years. The investigation of craters found on moons in the Solar System shows, however, that an intense bombardment took place, about 800 million years after the planets had formed. What happened? It would appear that the giant planets initially stood some 2–3 times closer to the Sun than they do at present. The **gravitational interactions** arising between them resulted in their swinging away from the Sun, and migrating to the outer regions. The arrival of the giant planets at the confines of the Solar System caused tremendous chaos, and a host of asteroids pervaded the entire planetary system, bombarding planets, and moons for 10 million years or so. The rate of bombardment, at that time, stood some 20,000 times higher than its present value. The Earth would be impacted by a 1-kilometer object every 20 years! It is at that point that the asteroid belt, and the **Kuiper Belt** were formed, that Jupiter captured its Trojan asteroids,(1) and that the giant planets acquired their irre-

(1) Trojan asteroids: asteroids sharing the orbit of Jupiter around the Sun, and clustered around two points of stable gravitational equilibrium. They are distributed into two groups, one leading by 60°, the other one trailing Jupiter by 60°.



gular satellites. From then on, everything was in its place. Some 800 million years after its birth, the Solar System stood close to its present state, and had stabilized. Since that time, evolution has occurred quite slowly. To sum up, many chance contingencies had to come together, for our planetary system to become what it presently is, and for us to stand there, commentating on its origin. Had the gas distribution been ever so slightly different, across the disk surrounding the protosun, the final outcome would have been altogether unrecognizable.

What we have learnt from Saturn

Does this mean we now know all there is to know about our own past history? Most emphatically not. Spectacular recent advances notwithstanding, many points still need unraveling. The time needed for certain stages, and the timescales for a number of phenomena are still subject to debate. The cloud fragmentation process is still poorly understood. The adhesion holding together particle aggregates yet proves something of a mystery. As was mentioned above, scientists are now turning their gaze to Saturn, with the Cassini probe. The rings of this giant planet have indeed frequently been seen as a "laboratory," inasmuch as they would be characteristic of the gas and dust disk that surrounded the Sun, prior to planetary formation (see *The rings of Saturn: a magnificent research laboratory*, p. 40).

Far from being uniform, the rings in fact consist of thousands of ringlets, with sharp, perfectly distinct edges. They further contain arcs of material, first discovered around Neptune in 1984 by the present author. All of which strongly suggests the existence of confinement mechanisms, this being a major subject of investigation, in many areas of physics. Collisions between particles, gravitational interactions between thin rings and small satellites, and resonance phenomena result in exchanges of energy, and **angular momentum** taking place, such that the rings, and satellites mutually repel one another. In this manner, two small satellites, known as "shepherd moons," are able to confine a small ring. Astronomers are currently wondering whether mechanisms of this type, arising between the first planetary embryos to form, and smaller particles, might have played a major part in the formation of the terrestrial planets. While Jupiter unquestionably determined the very existence of the Earth, it is Saturn, another gas giant, which may now tell us more as to the formation of our own planet.

> André Brahic
Paris-VII University
Joint Research Unit "Astrophysics Instrumentation Modeling"
(CEA–Paris-VII University–CNRS)
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)

The rings of Saturn, viewed in **radio-wave radiation**. The similarities between these rings, and protoplanetary disks are being put to use by scientists, who are able to observe directly processes that made planetary formation possible.

The rings of Saturn: a magnificent research laboratory


NASA/JPL/Space Science Institute

High-resolution images obtained by the Cassini probe have revealed the astonishing shapes of Pan (right), and Atlas (left), two moons embedded in the rings of Saturn. The ridges they exhibit give them a flying-saucer-like appearance. They have formed through a recent accumulation of dust from the rings.

The rings of Saturn, standing as bright as the planet itself, have fascinated humans for centuries. Galileo was the first to note them, in 1610, using the telescope that had enabled him, the previous year, to observe the craters on the Moon, and the satellites of Jupiter. Owing to the instrument's poor optical quality, he could see some sort of luminous spots, appearing on either side of the planet. It was Dutch physicist and astronomer Christiaan Huygens who, in 1655, understood that Saturn was girded by rings. Nowadays, after the amazement, the time has come for investigation. The Cassini mission – in which CEA is heavily involved, with access to two of the instruments fitted to the probe: the Imaging Science Subsystem (ISS) cameras, and the Composite Infrared Spectrometer (CIRS) – regularly scans the rings, from a variety of angles, over timescales of a few hours, several months, or several years, to monitor seasonal effects. The CIRS instrument measures, in particular, the temperature of the rings, which consist entirely of frozen material, and analyzes precisely the composition of their constituent particles (see *Journey into the lights of the Universe*, p. 90).

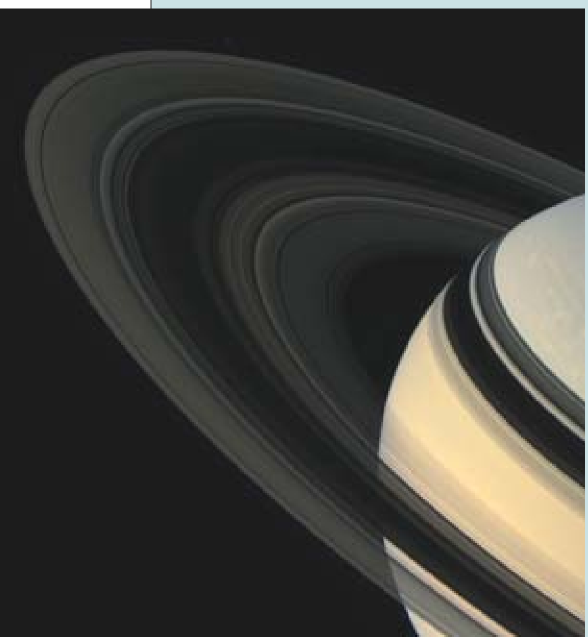
More than 300,000 km in diameter, and some 10 meters thick (except for the odd location), while weighing, overall, no more than a satellite 400 km in diameter, consisting as they do of myriads of blocks of ice about 1 meter thick, the rings stand as a world apart – a world that is undergoing ceaseless evolution, constantly distorted by the action of nearby satellites, and across the surface of which spiral waves ripple. They also stand as one of the most highly evolved structures in the Universe, if at any rate evolution is to be measured by the yardstick of the number of revolutions – this being known as "dynamic time." From the time of their formation – which indeed still stands as an open issue – the rings may have effected hundreds of billions of revolutions, while our Galaxy has completed but a few tens of revolutions... Indeed, the rings revolve in about 10 hours, as against some 200 million years for our Galaxy (as measured at the Sun's position). In the course of these countless revolutions, the most intricate patterns have had all the time they needed to develop, like some vast piece of gravitational counterpoint, at planetary scale.

Aside from being an object of interest in their own right, the rings are of interest to scientists owing to their similarity with other disks, of greater size (see *Planetary cocoons*, p. 41). Indeed, in like manner to accretion disks around stars, or black holes, or as with protoplanetary disks, the rings' evolution is dictated by viscous spreading. As is the case for spiral galaxies, or accretion disks, the flattening the rings have undergone is the outcome of energy dissipating processes. They are gravitationally unstable, which again makes them akin to spiral galaxies. Finally, the regions close to their outer boundaries give rise to accretion processes that suggest the processes arising in the protoplanetary disks, within which planets form.

Observing nascent planets

Saturn's rings do nevertheless exhibit specific characteristics, setting them apart from all other astrophysical disks. For instance, they largely lie within a particular region around Saturn, known as the planet's Roche limit. This has delayed accretion processes, owing to tidal effects. One fortunate result of such a delay is that astronomers are now able to conduct, at first hand, visual investigations of the manner in which matter comes together to form satellites, as a "miniature" version of planetary formation.

By coupling observation and numerical simulations, the teams working at CEA investigated, in particular, the way matter structures itself, and accretes at the outer boundaries of the rings, and, taking their cue from models of planetary formation, they were able to account for the shape of the small moons Pan, and Atlas (about 30 km in radius), both lying inside the A ring.[1] This further made it possible to show how spiral structures form around the F ring, due to collisional processes, suggestive of circumstellar disks. Finally, CIRS observations have evidenced the presence of gravitational structures which are to be identified with Jeans–Toomre waves – these being, here again, encountered at the outset of planetary formation.


NASA/JPL/Space Science Institute

The dark side of the rings. In this view, Saturn's rings are seen against the Sun. In this, highly unusual, observational geometry, dense rings stand out as very dark (the B ring in particular), while the less dense rings exhibit a faint twinkle (C and A rings). The shadow cast onto the planet is quite visible.

(1) From center to periphery, Saturn's rings are identified as follows: D, C, B, A, F, G, and E. The inner series (D–A) includes the dense, bright rings, visible from the Earth. The outer series (F–E), discovered during the closing decades of the 20th century by the Pioneer and Voyager probes, covers rings that are much less dense.

> Sébastien Charnoz
and **Cécile Ferrari**
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

Planetary cocoons

Young stars are surrounded by a gas and dust disk, within which planets form. Astrophysicists are seeking out, and exploring such "protoplanetary" disks, to gain an understanding of planetary formation. Observation of the more tenuous disks surrounding old stars in turn allows indirect evidence to be obtained, of the presence of exoplanets.

ESO

Artist's impression of a flared protoplanetary disk.

Since 1995, when the first such object was discovered, the search for extrasolar planets has proved highly fruitful. To date, astronomers have totted up more than 350 such planets on their scoreboards. "Exoplanets" – as indeed the **planets** in the Solar System – very likely formed in the gas and dust disks surrounding young **stars**. These disks play a twin role, in current planetary formation scenarios: they provide the matter planets are made of, and also influence their orbits. It is thus crucial to gain a good knowledge of such disks (in terms of size, geometry, mass, density…), if a better understanding is to be achieved, of how planets emerge.

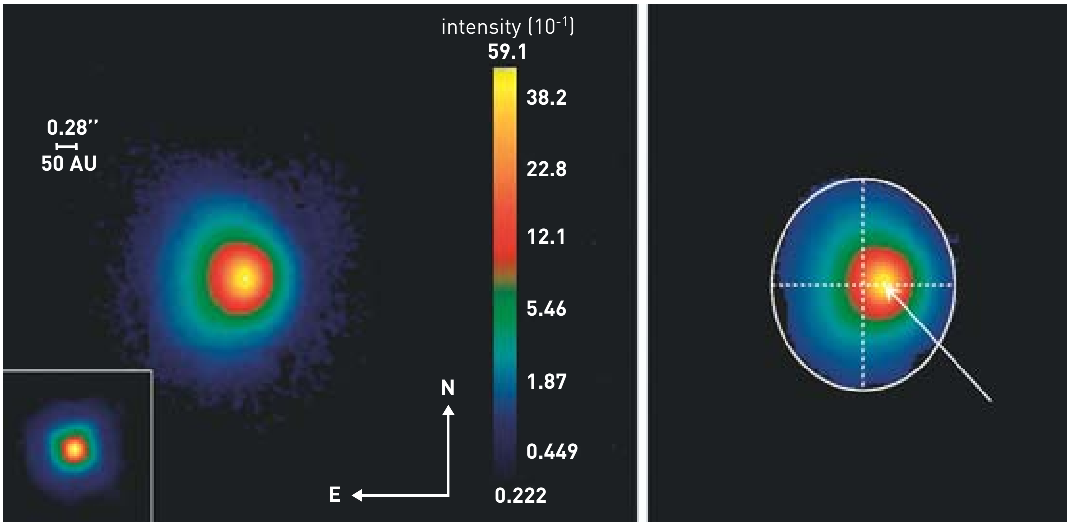
An unexpected geometry

Observing disks is no straightforward matter. The presence of a disk around a particular star is initially inferred from the light emitted by the star–disk system. Indeed, dust particles **absorb** the star's light (chiefly **visible light**), heat up, and reemit that energy in the form of **infrared radiation**. To the observer, a star–disk couple thus manifests itself by excess infrared emissions, compared to a star by itself. Imaging a disk is a far more difficult affair, and very few disks have been **spatially resolved**, and mapped. One of the few such disks is the one around star HD 97048, lying in the Chamaeleon Constellation (the Chameleon, in the Southern Hemisphere), at a distance of 600 **light-years** from the Earth. With a mass two and a half times larger than that of the **Sun**, and 40 times more **luminous**, HD 97048 is still a very young star: a mere 3 million years, i.e. less than one-thousandth the age of the Sun. It was observed in 2006, using the VISIR (VLT Imager and Spectrometer for the mid-Infrared) infrared instrument, fitted to the Very Large Telescope (VLT), and constructed by CEA/IRFU for **ESO** (see *Journey into the lights of the Universe*, p. 90).

VISIR evidenced the existence of a disk, reaching out from the star for more than 370 times the average distance between the Sun and the Earth, i.e. 370 **astronomical units** (**AU**). The images revealed a highly peculiar morphology: the disk is not flat, rather it is flared regularly outward (see Figure 1). At the periphery, i.e. at 370 AU from the central star, the disk reaches a thickness of 360 AU. This was the first time such a structure, predicted as it was by some **models**, was directly evidenced around such a massive star. This type of geometry may only be accounted for if the disk still contains large quantities of gas, with a mass estimated at 10 times that of Jupiter, i.e. some $1.9 \cdot 10^{28}$ kg. The large amounts of dust the disk holds – more than 50 Earth masses, i.e. close to $3 \cdot 10^{26}$ kg – is further evidence of its young age. In all likelihood, astronomers are viewing, in this instance, a disk similar to the **primordial** nebula that surrounded the Sun, from which the planets in our planetary system – and hence the Earth – were born.

Planetary migrations

Well before the first extrasolar planet had been detected, theorists were well aware that planets, as they formed within disks, would prove highly mobile, in



CEA/SAp

Figure 1.
At left, a false-color image (colors vary from blue to yellow, depending on intensity) of the infrared emission, at a wavelength of 8.6 **µm**, from the matter surrounding star HD 97048. This emission is much more spread out than that coming from a diskless star, as shown inset, bottom left. At right, the center of the infrared emission perimeter (which is elliptical in shape) is markedly offset, with respect to the star's position (arrowed), indicating that this structure is an inclined disk.

other words that their orbital radius might vary considerably, owing to **tidal effects** arising with the disk. They further knew that such tidal effects tended to draw the planets, as they were forming, close to the central star, thus causing them to follow a spiral path. Such considerations, however, had reached but a fairly restricted public, so it came as a tremendous surprise when it was found that 51 Peg b, the first extrasolar planet to be discovered, takes 4.23 days to complete its orbit, with a radius of a mere 0.052 AU around its central star! For comparison's sake, Mercury, the planet lying closest to the Sun, completes its orbit in 88 days, at 0.39 AU from the Sun. Since that time, the theorists' investigations of tidal interactions between protoplanetary disks and nascent planets have come to the fore, in planetary formation scenarios. Indeed, no viable mechanism exits, such as would allow the *in-situ* formation of giant planets, so close to their stars. The astrophysical community is agreed, therefore, that such objects form much further out from the central star, in regions of the disk that are sufficiently cool to allow condensation of water ice, and are subsequently drawn into the vicinity of their star by tidal effect. This process is known as *planetary migration*. This is a crucial mechanism, as regards the formation of planetary systems: a thoroughgoing understanding of this mechanism is thus essential.

A variety of paths

Since 1995, planetary migration theories have made great strides. Initially restricted to analytical studies as they were, these investigations greatly benefited from the rise of computing resources sufficiently powerful to yield finescale predictions of disk response, in the course of the many orbits a protoplanet describes. Currently, a number of distinct planetary migration

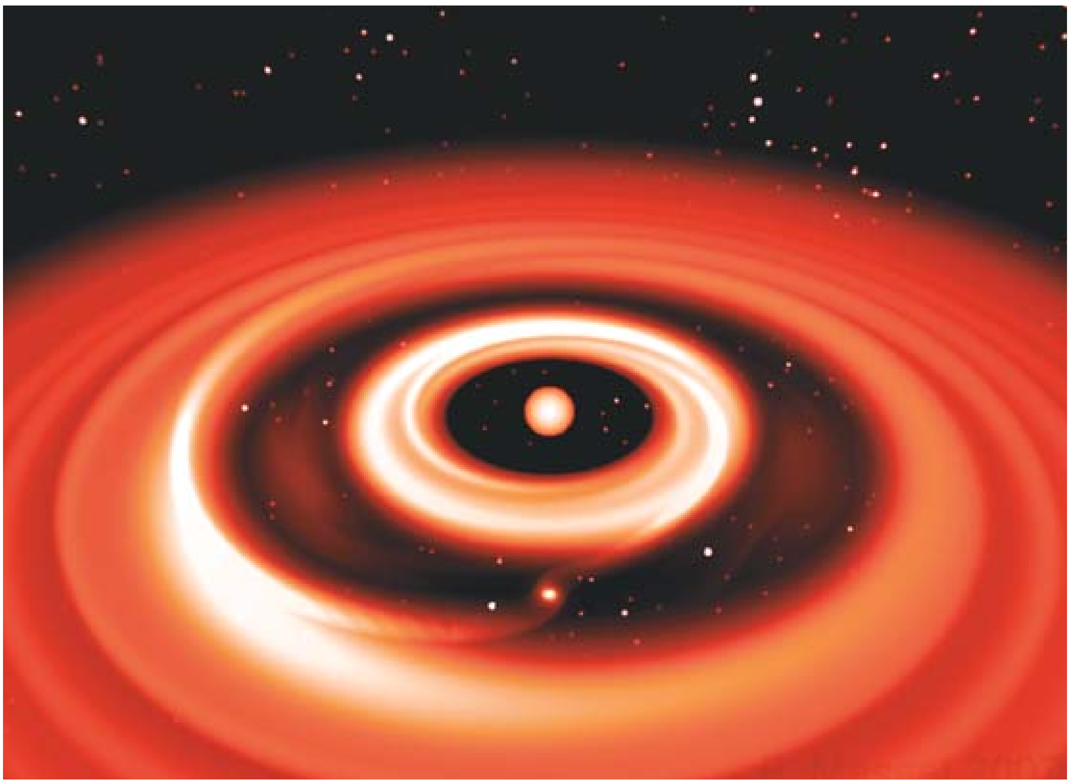


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Figure 2.
The result of a **simulation** of the interaction between a giant protoplanet (one Jupiter mass), and a protoplanetary disk. A gap (the dark annulus, through which stars in the background may be seen) has been emptied, within the disk, by the planet. The planet is further exciting, across the disk, a spiral wake, by tidal effect. It is the force exerted by this wake that causes the planet to migrate.

modes have been identified, within a disk. *Type-I migration* covers the rapid drift, towards the center, of low-mass planets – typically, of Earth-mass size. Giant planets, by contrast, empty their orbits, around which they form a gap by tidal effect (see Figure 2). The outcome is *type-II migration*, this being much slower. **Turbulent** protoplanetary disks bring about quite different forms of migration: fluctuations in density, due to turbulence, tend to drive a random walk in the semimajor axis(1) of low-mass planets. This is referred to as "*stochastic*," or "*diffusive*" *migration*. Investigation of this type of migration is of particular importance, since astrophysicists expect protoplanetary disks will prove turbulent over a large fraction of their radius. Further, more exotic migration modes exist, e.g. "*runaway*" (or *type-III*) *migration*, for "subgiant" planets; or outward "*pair*" *migration*, involving giant planets in resonance(2) with one another. At CEA, the Astrophysics Service/IRFU, strongly involved as it is in planetary migration studies, has contributed a number of first-rate discoveries. One crucial issue remains, however: what is it that brings planetary migration to an end? To which one further query may be added: Why is it the planets in our own Solar System do not appear to have so migrated?

Highly useful debris

The disk around young stars tends to disappear over a timescale of some 10 million years. Indeed, a fraction of the disk matter ends up in the planets, while another fraction is "blown away" by radiation pressure from the star, while a third spirals down to the central star. This implies that mature stars should be bereft of any disk, and that only light emitted by the star should be observed. And yet, when, in 1984, the first US infrared satellite, IRAS (Infrared Astronomical Satellite), carried out observations of such stars as Vega, or β Pictoris, for calibration purposes, it detected an excess of infrared light. How was such a phenomenon to be accounted for? Could there be some dust still remaining around these stars? Indeed, this turned out to be the case, as visible-spectrum observations of star β Pictoris soon confirmed, revealing as they did the presence of a resolved disk around the star.(3)

How might this observation be reconciled with theories predicting an absence of dust? The quantities of dust involved are very small, far lower than those contained in protoplanetary disks. Indeed, these are no primary dust particles: they were "stored" in such heavenly bodies as **comets**, or **asteroids**, and subsequently regenerated as the comets evaporated when passing close to their star, or in the course of collisions between asteroids. In fact, such phenomena arise within the Solar System, the dust thus yielded being the cause of "zodiacal" light.(4)

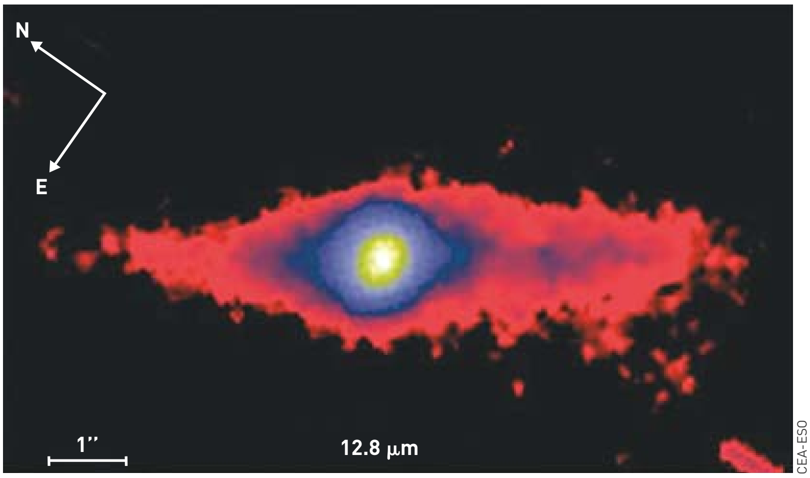


Figure 3.
An image of the debris disk around star β Pictoris, as observed by the VISIR instrument, fitted to VLT. The disk's asymmetry is particularly worthy of note.

These "debris" disks are of interest to astronomers, since a planet may "carve out" gaps in such a disk – gaps that prove markedly easier to observe than the planet itself. In 1994, CEA's Astrophysics Service obtained the first images of the central regions in the disk around β Pictoris. These revealed a morphology such as to hint at the presence of a planet within the system (see Figure 3). Recently, a team from the **Astrophysics Laboratory** at the **Grenoble Observatory for the Sciences of the Universe** showed that at least one planet lies inside that disk. While they are no cocoon, within which exoplanets may form, "debris" disks do at any rate provide a valuable aid, to assist in locating such planets.

The investigation of disks, relatively tenuous structures as they are, is predicated on the telescope's resolving power, i.e. on the fineness of the details amenable to observation. Now, this resolution is directly dependent on mirror diameter. Indeed, owing to the phenomenon of light diffraction, the image of a point object, viewed through a telescope, is not a point, but a spot: the diffraction spot. The larger the telescope's diameter, the smaller that spot will be. The image of a star, as viewed through the European Extremely Large Telescope (E–ELT: see *ELT/METIS, a 42-meter giant*, p. 110) – a European 42-meter-diameter telescope, due to come on stream in 2018 – will thus occupy an area 25 times smaller than in images yielded by VLT. E–ELT will thus prove an outstanding instrument, for the purposes of disk investigations!

(1) Semimajor axis: the (imaginary) segment joining the center of an ellipse to its edge, passing through one of the foci.

(2) A resonance occurs when two objects, orbiting a third one, involve periods of revolution standing in a ratio that is a simple integer fraction (e.g. 2/3, in the case of Neptune, and Pluto, in their orbits around the Sun).

(3) That visible light originates in the star itself, being simply scattered by the dust particles, by contrast with the infrared light, which is actually emitted by these very particles.

(4) Zodiacal light: a faint glow, which may be observed in the night sky, extending, along the ecliptic, from the vicinity of the Sun, soon after sunset, or shortly before sunrise.

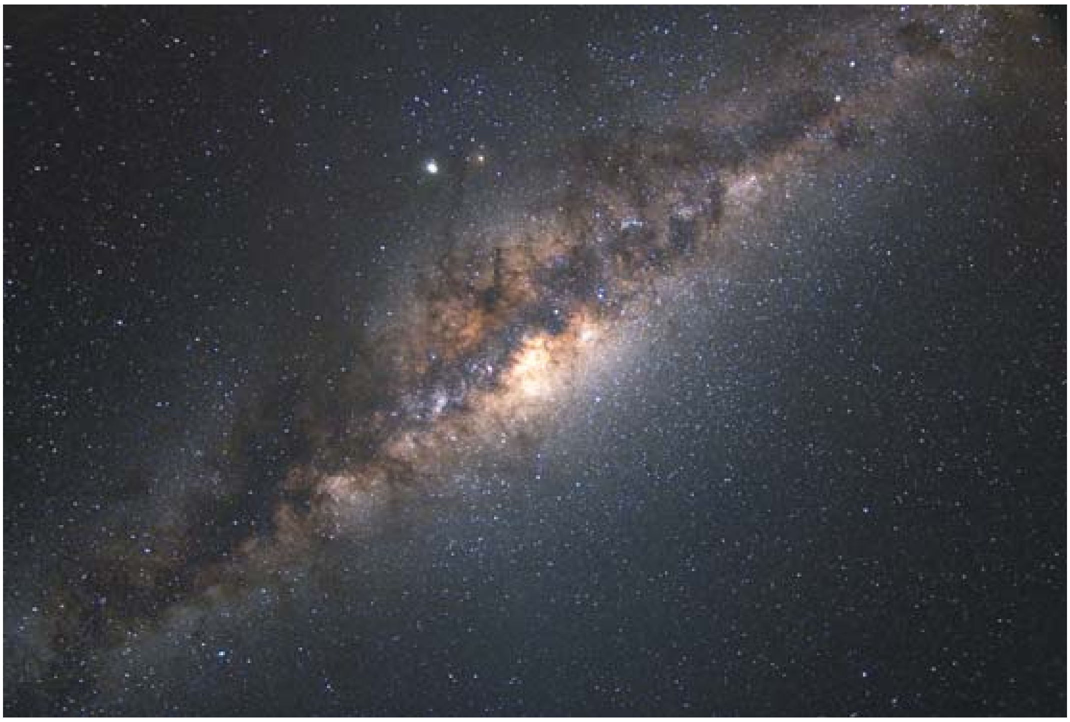
> **Pierre-Olivier Lagage, Frédéric Masset** and **Éric Pantin**
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

Our Galaxy, the Milky Way, exhibits the shape of a well-delineated, grand-design spiral galaxy. This rotating disk, consisting as it does of gas, and more than 200 billion stars, is indeed traversed, very slowly, by ripples, within which the youngest, most luminous stars are concentrated, marking out the visible shape of the spiral arms. At the center, a spherical bulge, at the core of which a supermassive black hole lies concealed. The entire structure is enveloped by a halo of dark matter. Not all of the galaxies in the Universe conform to such an ordered plan. Some galaxies, known as elliptical galaxies, take on a more spherical shape, and chiefly consist of old stars, following chaotic paths. How did these two populations form? In order to reconstruct the evolution of galaxies, astrophysicists seek out the oldest objects in the Universe. Involving spontaneous evolution, for spiral galaxies, and successive collisions as regards elliptical galaxies, various scenarios emerge. Numerous paradoxes, and puzzles remain, however: the history of galaxies has yet to be written.

Galaxies: a richly **paradoxical evolution**

The active life of galaxies

In like manner to all spiral galaxies, our own Milky Way never sleeps: new stars are born across it, even at the present time. While they are indeed far from accounting for the totality of galactic mass, stars do stand as the chief galactic "engines."



Serge Brunier

Humans have always been fascinated by the stars, and heavenly phenomena. Our own Galaxy, the Milky Way, is a disk holding more than 200 billion stars. The Universe contains hundreds of billions of other galaxies, where stars are born, at varying rates.

Observers of the sky of night are familiar with the **Milky Way**, that luminous lane stretching across the heavenly canopy. This is how our own Galaxy appears to us, since it is a disk, seen from within. Astronomers, nowadays, have found out much more about its actual shape. Its stellar component(1) extends across a diameter of some 100,000 **light-years**. The most up-to-date measurements locate the Solar System 26,000 light-years away from the Galaxy's center, at which point it is about 2,500 light-years

(1) The visible fraction, comprising the stars.

NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

NASA/JPL-Caltech/S. Willner (Harvard-Smithsonian CfA)

Figure 1.
At left, an image, taken in visible light by the Hubble Space Telescope, of spiral galaxy M81, lying 12 million light-years from the Milky Way. The diffuse star disk shows up yellow, the spiral arms holding young stars are blue. At right, these arms reveal, in the infrared image taken by the Spitzer Space Telescope, active star-forming regions (clouds). The stars themselves, emitting little in the infrared as they do, have effectively disappeared from the picture, except in the central region, where star density is high.

thick. It is a **spiral galaxy**: in other words the stars and gas it is made of are not evenly distributed across the disk, rather they form a number of spiral arms, curving about the center (see Figure 1). In actual fact, this appearance is deceptive. Indeed, these arms are transient patterns, materializing, within the disk, the propagation of compression regions, due to the differential rotation of **stars**, and gas around the galactic center.(2) These density **waves** sweep across our Galaxy, as waves ripple across the ocean. At peak density – the "crest" of the wave – the gas turns into stars, thus giving rise to the visible pattern, which makes our Galaxy a "spiral" galaxy.

The galactic "menagerie" falls into three main categories: **elliptical galaxies**; spiral galaxies; and irregular, or dwarf galaxies. These various morphologies reflect fundamental differences in the history of these galaxies. For instance, most of the stars making up the population in elliptical galaxies appeared about 10 billion years ago, whereas, in spiral galaxies, star formation is presently ongoing. Thus, the Milky Way contains, at one and the same time, **star clusters** of an age comparable to that of the Universe, and other clusters that are yet maturing. The Galaxy's core is of particular interest, with regard to star formation. Indeed, owing to the interplay of **gravitation**, and galactic dynamics, this is where vast quantities of gas come together with tremendous compression forces, and a supermassive **black hole**, the combination giving birth to the most active region in the Milky Way, which is often taken as a model for the purposes of investigating distant active galaxies (see *A mysterious black hole*, p. 48).

Stars...

What, in fact, is there to be found, in a galaxy? Stars, obviously, first and foremost. A trained observer can make out some 4,000 with the naked eye, however our Galaxy holds some 200 billion stars. The mass of each star determines most of its characteristics: **luminosity**, color, lifetime… (see *A tour of stellar nurseries*, p. 17).

For instance, the presence of blue stars – these being therefore **massive stars**, with short lifetimes – in a given region is evidence of recent star formation, as in the Pleiades cluster, well known to amateur astronomers.

The stars in our Galaxy were classified, historically, into two populations, each being characterized in terms of age, chemical composition, and trajectory. *Population I* includes stars that go along with the disk's rotation, particularly young, **heavy element**-rich objects. It is these stars that have an impact on the physics of the **interstellar medium**. *Population II* brings together old stars, containing little by way of heavy elements, often grouped into **globular clusters**, distributed within the **halo**, and following chaotic paths. These stand as the remnants of the first wave of star formation in the Galaxy, at the time when it was just a ball of gas in the process of contracting. By contrast, *population I* is made up of stars that formed after the disk had emerged.

... and everything else

Stars form, by far, the most important component of a galaxy, in terms of radiated power, however they are not the sole component. Such highly compact concentrations of matter indeed lie at great distances from one another. The interstellar medium thus takes up, overwhelmingly, most of the volume in the Galaxy.

interstellar medium phase	density (cm^{-3})	temperature (K)	volume fraction (%)
hot intercloud medium	0.003	1 million	50
warm neutral medium	0.5	8,000	30
warm ionized medium	0.1	8,000	25
cold neutral medium	50	80	1
molecular clouds	> 200	10	0.05
HII regions	1–100.000	10.000	> 0.05

Table.
The various phases of the interstellar medium, with their characteristic properties. Interstellar clouds in HII regions chiefly consist of hydrogen, most of the atoms being ionized by ultraviolet radiation from stars of spectral types O and B, whereas clouds in HI regions consist of neutral atomic hydrogen.

(2) By way of example, as measured at the position of the Sun (26,000 light-years from the center), the disk's rotational velocity stands at some 200 km per second. Our own Solar System circles around the Galaxy in 250 million years.

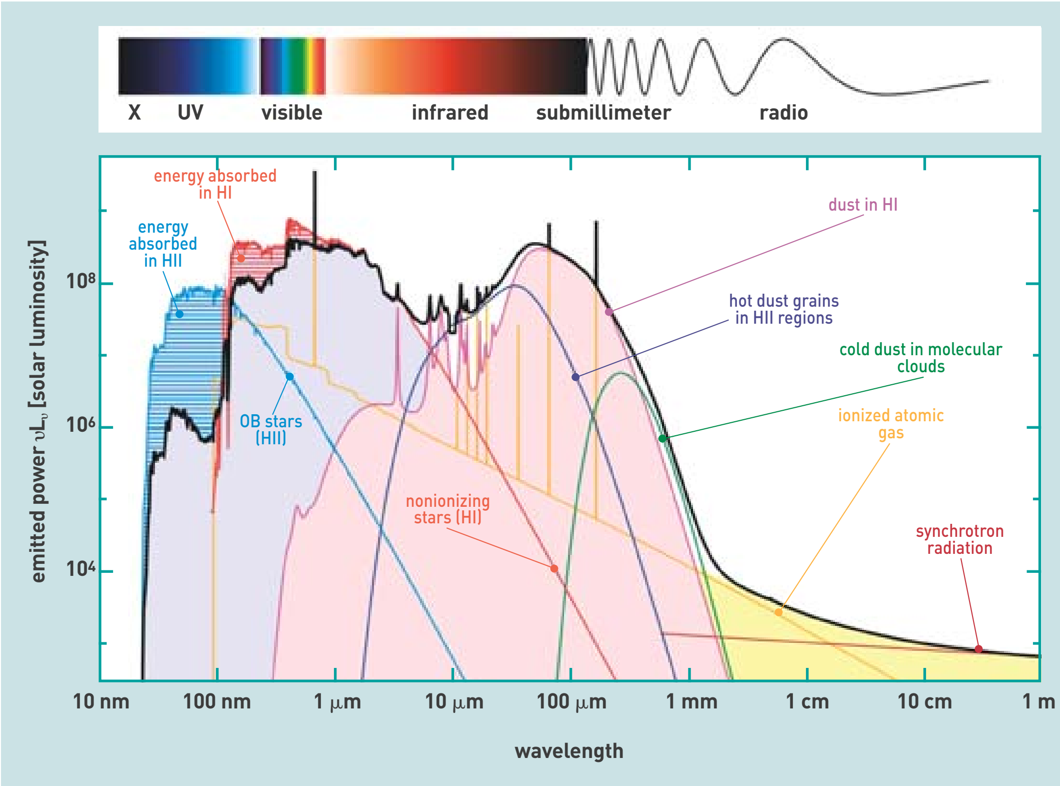


Figure 2.
Electromagnetic spectrum from a galaxy (shown in black), this resulting from emissions from the more massive stars (blue); from gas in regions ionized by these stars (yellow), and dust mingled with this gas (purple); from other stars (red), and interstellar dust heated by their radiation (mauve); from dust in the denser clouds (green), and radiation from charged particles in the **magnetic field** (dark red). Hatched areas show the emission fraction that is absorbed *in situ*, yielding interstellar emissions. Every pattern (emission lines, or bands, breaks in the continuum) in this spectrum carries information as to galactic physics.

And yet, with an average density of just one **atom** in every 3 cubic centimeters, it only amounts to 3% of the stellar mass.(3) It consists of neutral, or **ionized** atoms, **molecules**, and solid particles a few tenths of **microns** across, or even less: dust grains. In effect, far from being homogeneous, the interstellar medium features various regions, involving diverse densities, and temperatures (see Table). Its low mass notwithstanding, the interstellar medium plays a crucial role in the Galaxy's energy balance, since it **absorbs** about one third of stellar radiated power, reemitting it at longer – and therefore less energetic – wavelengths. In some, so-called "starburst" galaxies, the fraction so reemitted may reach 99%.

(3) Such a density ranks as an extreme vacuum, compared to our atmosphere, which contains 10^{22} atoms per cubic centimeter.

The interaction arising between stellar radiation, and the interstellar medium, which is a highly complex phenomenon, bears a great wealth of information (see Figure 2). By way of galactic spectra, astrophysicists are able to ascertain remotely the composition, and physical state of various regions in a galaxy. The shape of the **continuous emission** from the grains thus yields evidence as to their abundance, and the intensity of the stellar radiation they are subjected to, while **emission lines** from atoms, and molecules indicate the composition of the gas phase, along with its density, and temperature.

Finally, this inventory would hardly be complete, if mention was not made of one component, which is not as yet understood: **dark matter**. This probably accounts for 70% of the total mass, however it emits no **electromagnetic radiation**, and only makes itself felt by **gravity**. Historically, indeed, it was only evidenced indirectly, owing to its effect on the rotation of galaxies. Its presence in no way affects the microphysics of the interstellar medium. On the other hand, it is crucial, if an understanding is to be achieved of galactic formation, and dynamics (see *The formation of galaxies: a story of paradoxes*, p. 56; and *The morphogenesis of galaxies*, p. 60).

Stars as galactic engines

Just as stars do, and indeed chiefly owing to their influence, galaxies undergo an evolution, over timescales of a few tens of million years. Each of the stages in the stars' life has an impact on the galaxy (see Figure 3). Stars are born within dense molecular clouds, through **gravitational** collapse, and fragmen-

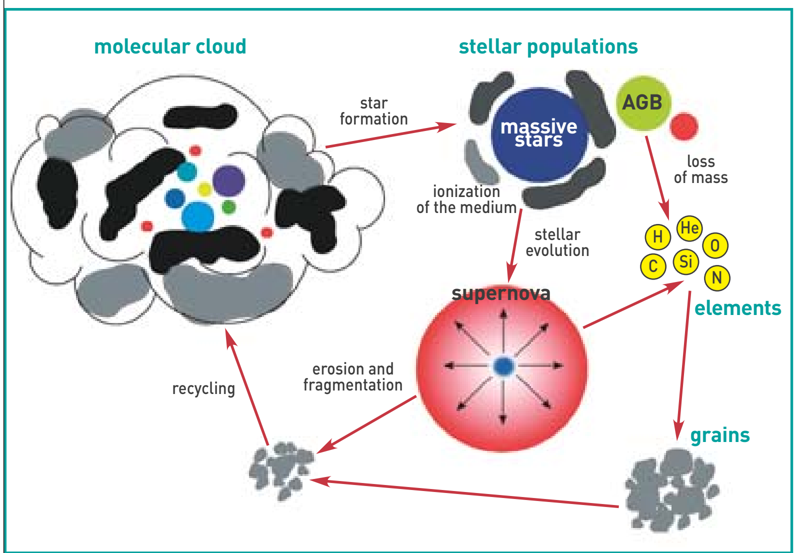


Figure 3.
The stellar evolution cycle, and its impact on galactic composition. Star formation, and stellar evolution make a contribution in terms of a modification, not just of the galaxies' chemical composition, but equally of their energy content. The AGB (Asymptotic Giant Branch) population corresponds to low-mass stars, in their **giant** phase.

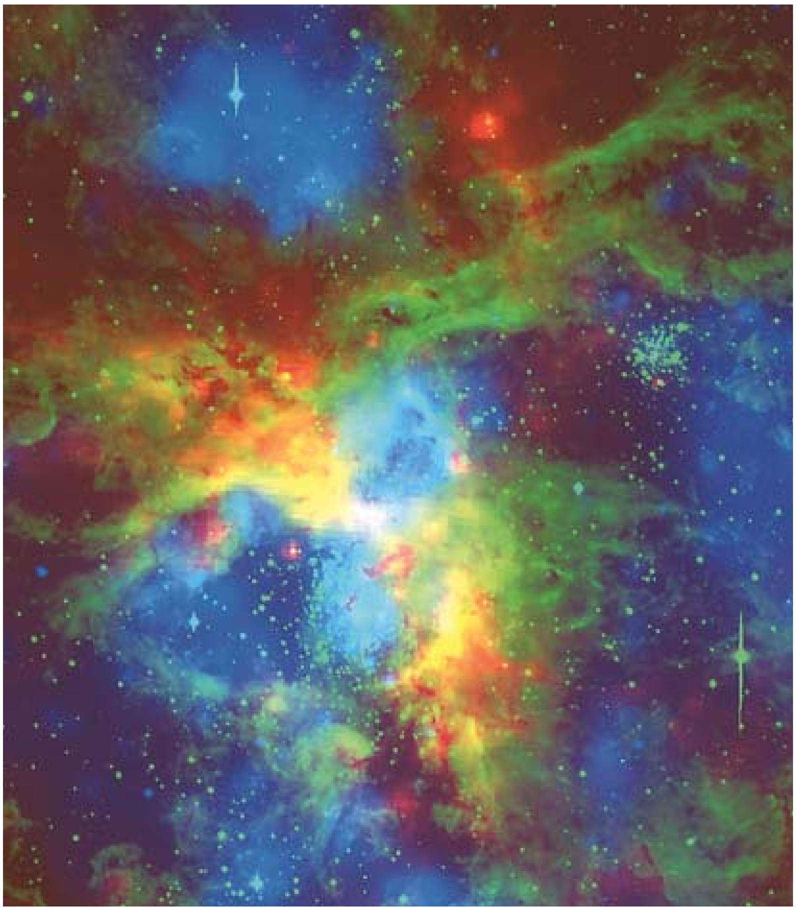
tation (see *A tour of stellar nurseries*, p. 17). Molecules accumulate at the surface of dust grains. Star formation thus contributes to the emergence of the more complex compounds arising in the interstellar medium. Conversely, these compounds play a part in star formation. The physical conditions specific to these regions – low temperature, high density – give rise to a distinctive spectral emission: this features a large number of molecular lines, and radiation that is continuous at long wavelengths (in the **infrared**, and **submillimeter** radiation), to which the interstellar medium proves relatively transparent. It should be noted that cold molecular **hydrogen**, which emits practically no detectable radiation, forms, overwhelmingly, the largest fraction of the mass being considered here. Observations are thus necessarily targeted at constituents (dust particles, molecules) that occur as traces, in order to yield extrapolations to overall properties.

Subsequently, during the second stage in their life, massive stars inject energy into the galaxy. For several million years, these objects expel but little matter, however they do fashion, quite dramatically, the medium around them. Stellar radiation causes molecular dissociation, atom ionization, and the **sublimation** of ices that had accumulated at grain surfaces. Such regions rank along the most luminous, and most spectacular in galaxies, owing to the fascinating shapes generated by the interaction of radiation, and the **stellar wind** with the surrounding medium (see Figure 4). Observation of these regions is thus fairly easy, and the measurement of the quantity of stellar energy being injected, e.g. by way of hydrogen recombination radiation, is used to quantify the rate of star formation. Such measurements, however, are not free from uncertainties, as chemical composition of galaxies does influence stellar luminosity, and the interstellar medium's **opacity**. This injection of vast quantities of energy into the interstellar medium regulates galactic evolution. Without it, the star formation process would be deprived of one of its chief restraining factors, and most galaxies would presently be found to hold populations of old stars, as their gas reserves would have been exhausted within a few million years.

A fecund death

The explosive end of life that is the fate of massive stars results in far-reaching alterations of the interstellar medium. Such an explosion, known as a **supernova**, disperses virtually all of the heavy elements that had been manufactured by the star, along with the entire series of elements heavier than iron, which form subsequent to the explosion (see *How supernovae explode*, p. 26). Observing extragalactic supernovae as they have done for some years now, astrophysicists are beginning to gain a better understanding of the distribution of the chemical elements thus returned to the interstellar medium. They are thus able, conversely, to "read," from a galaxy's chemical composition, the effects of star formation, over its lifetime. Supernova explosions further generate shockwaves that sweep across the interstellar medium over thousands of light-years. Such shockwaves have far-reaching effects: they inject energy, which the interstellar medium will have to evacuate, if the star formation process is to be initiated. They also break up dust grains, which alters their emissions. Finally, supernovae stand as one of the chief sites of **cosmic ray** generation, and acceleration, cosmic rays being **atomic nuclei** which travel over distances that are, in some cases, larger than the galaxies themselves, and which, by depositing some of their energy in molecular clouds, delay their collapse (see *Elucidating the cosmic ray acceleration mechanism*, p. 50).

The death of less massive stars likewise plays its part in the galactic cycle. Such deaths are characterized by the existence of phases during which the various stellar layers, enriched in carbon, silicon, and oxygen, are slowly expelled into the interstellar medium. Temperature gradually declines, reaching a level that is suitable for many chemical reactions, and the formation of interstellar dust. Such "envelope" stars stand as the chief sites of interstellar dust formation.



R. Indebetouw *et al.*, *Astrophysical Journal*, vol. 694, issue 1, 2009, pp. 84-106

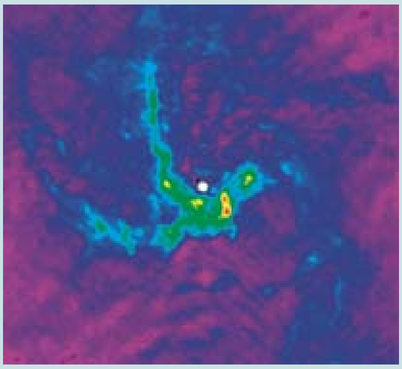
Figure 4.
The 30 Doradus region, in the Large Magellanic Cloud. This is a region very rich in massive stars, concentrated in clusters (center of the picture), which have a far-reaching impact on the surrounding medium. The blue component represents the **soft X-ray** emission from diffuse, very hot, ionized gas. The green component corresponds to the **visible light** emitted by stars, and the denser regions in the nebula. The red component shows the **infrared** emission from dust particles.

> **Marc Sauvage**[1] and **Frédéric Galliano**[2]
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA[1]–Paris-VII University– CNRS[2])
CEA Saclay Center (Orme des Merisiers)

A mysterious black hole

NASA/CXC/MIT/F. K. Baganoff *et al.*

The center of our Galaxy, as viewed by Chandra, NASA's dedicated satellite for observation in the X-radiation domain. At the core, a giant black hole lies concealed.



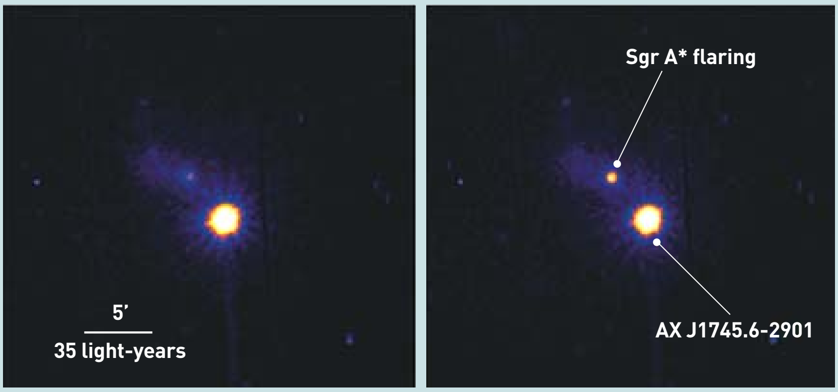
NSF/VLA/F. Yusef-Zadeh (NWU)

Figure 1.
Radio-wave image of the center of our Galaxy, showing the spiral nebula, and compact source Sgr A* (the white spot, at the center of the picture).

An extraordinary object is lurking at the core of the Milky Way, in the direction of the Sagittarius Constellation.[1] This complex, violent region, hidden from view by interstellar matter, may nevertheless be observed in the radio wave, infrared, X-ray, and gamma ray domains. Using telescopes working at these frequencies, astronomers have detected there a supermassive black hole, weighing about 4 million solar masses. Starting from 1992, infrared observations, carried out over a period of some 15 years, of a handful of stars, lying at the very center of the Galaxy, and describing very rapid elliptical orbits around the same point, conclusively demonstrated the presence of such a black hole. Such motions may indeed only be accounted for by the attraction of a mass several million times larger than that of the Sun… concentrated within a radius smaller than 100 times the distance between the Sun and the Earth, i.e. measuring less than 15 billion kilometers. No system that compact could withstand gravitational collapse: this therefore must be a giant black hole. Its horizon radius[2] is estimated at a mere 17 solar radii. Owing to its gravitational power, this object dominates the dynamics of matter, within a radius of several light-years, and is able, in particular, to capture part of the stellar wind from stars in that region. Infalling towards the black hole, such matter follows a spiral path, forming an accretion disk. It is brought to very high temperatures, emitting electromagnetic waves at various frequencies, before vanishing into the hole. Thus it was that, in 1974, radio-wave observations (which had been ongoing since 1950) discovered, in that location, a compact, bright, variable emission source, lying at the center of a diffuse spiral nebula (see Figure 1). Dubbed Sagittarius A* (Sgr A*), this source is located precisely at the focus of the orbits of the stars that have been observed in the infrared, and is thus seen, nowadays, as the counterpart of the central black hole.

(1) The dynamic, and symmetry center of our Galaxy lies in the celestial Southern Hemisphere, at some 26,000 light-years from the Earth.

(2) Horizon radius: the event horizon is a spherical surface, around a black hole's central singularity. Nothing that crosses to the inside of this surface may escape from it – not even light.



G. Trap/CEA

Figure 2.
The galactic center, as viewed by the XMM–Newton telescope in April 2007 (with the EPIC PN camera, X-radiation at 2–10 keV), before (left), and during (right) an X-ray flare from Sgr A*. The location of radio source Sgr A* is pinpointed, evidencing that the X-ray flare is indeed associated with the black hole – rather than with other objects, e.g. source AX J1745.6–2901.

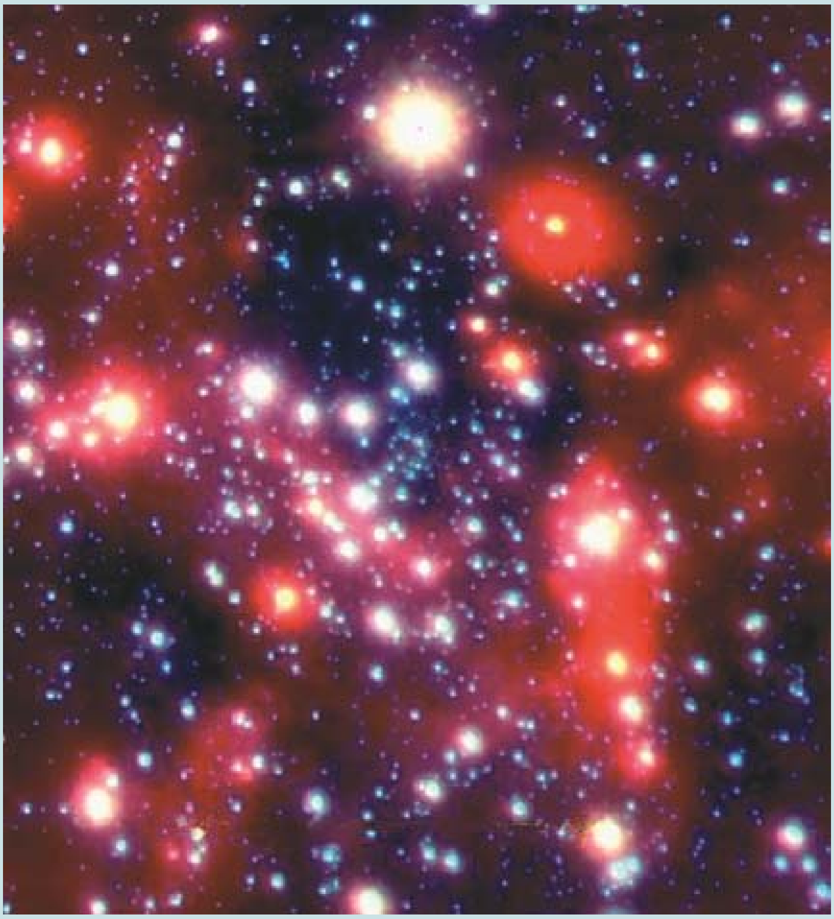
A shortfall in emissions

Despite its remarkable radio brightness, the total power emitted by this object is much lower than predicted. For that reason, high-energy astronomers have been searching, over the past three decades, for its counterpart in the X-ray, and gamma-ray domains, looking that is for the energetic radiation emitted by the inner, hot regions of the accretion flow, bearing the hallmarks of the relativistic effects ascribable to the black hole. In 1999, NASA's Chandra X-ray Observatory finally detected a persistent, faint X-ray emission. One billion times less intense than predicted, this signal shows that matter is not being accreted at the rate anticipated. Be that as it may, the most spectacular discovery, in the past few years, was the detection, in 2000 and in the following years, of violent X-ray flares, in the course of which luminosity increases up to 150-fold, over a few hours.

Teams at CEA's Astrophysics Service/IRFU, and at APC have investigated a number of Sgr A* flares, by making simultaneous measurements of X-ray emissions (using ESA's XMM–Newton space observatory), infrared emissions (with ESO's VLT telescope, in Chile), and gamma emissions (with the IBIS telescope, on board ESA's INTEGRAL space observatory) (see *Journey into the lights of the Universe*, p. 90). The last campaign observed, in X-radiation, and in the near infrared, the second-brightest flare known for Sgr A* (see Figure 2). The absence of any gamma signal, on that occasion, shows that the gamma-ray emission from the galactic center, recently discovered by INTEGRAL (see Figure 3), is not directly related to such flares. This does reveal, nonetheless, the presence of a powerful cosmic particle accelerator, the relationship of which to the central black hole has yet to be ascertained.

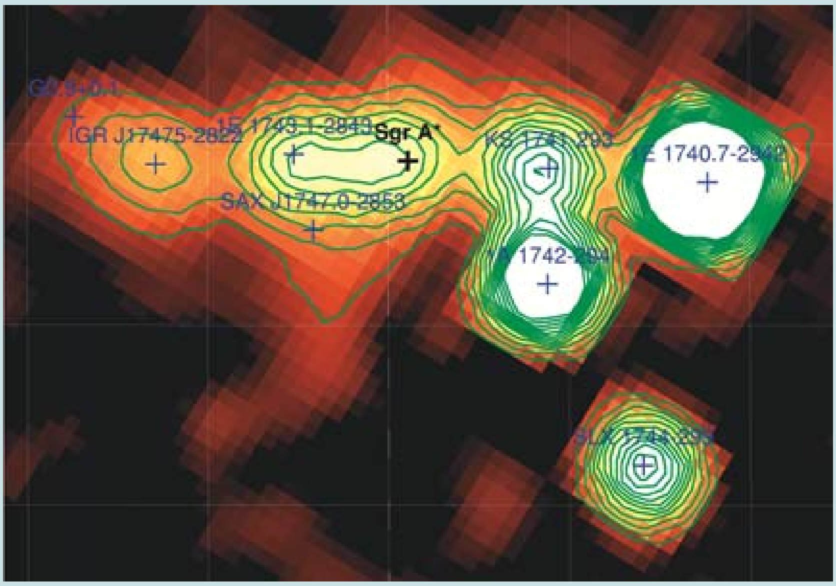
We will have to wait for the coming on stream of new-generation X- and gamma-ray space telescopes, before further knowledge may accrue (see *SIMBOL-X, pioneering formation flying*, p. 108).

> Andrea Goldwurm
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astroparticle and Cosmology" (CNRS–Paris-VII University–CEA)
CEA Saclay Center (Orme des Merisiers)



ESO

Image of the galactic center, taken by the NACO infrared camera, mounted at the focus of the Yepun telescope, part of ESO's Very Large Telescope (VLT), sited on the Cerro Paranal mountain, in Chile. This shows the more luminous stars in the region, feeding, through their powerful stellar winds, the central black hole.

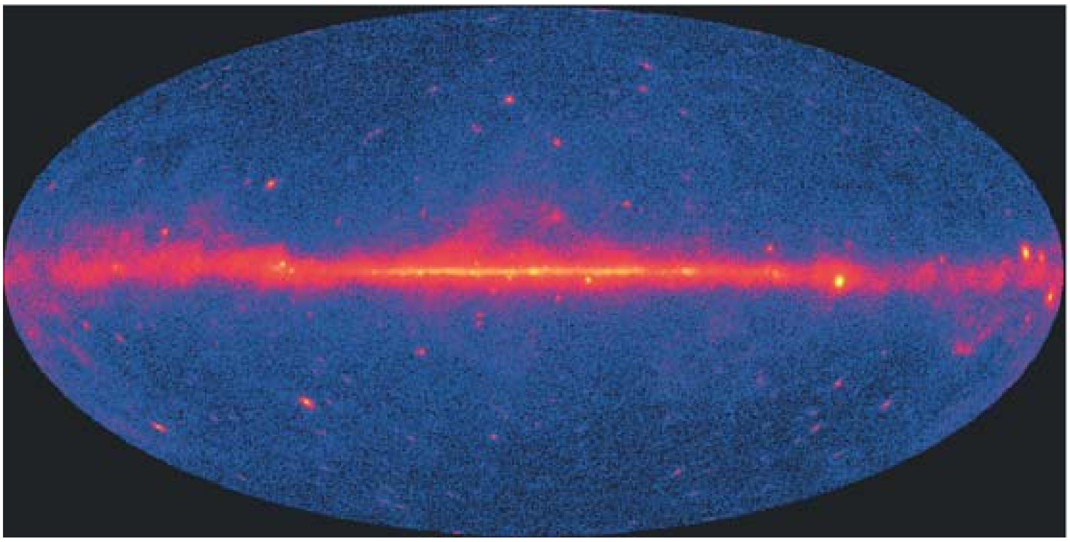


G. Bélanger/CEA

Figure 3.
Image (with intensity contours) of the central region of our Galaxy, as recorded by the IBIS telescope, mounted on INTEGRAL (20–40 keV gamma-rays). The position of Sgr A* is indicated, showing that the gamma-ray source at the center may well be related to the supermassive black hole. The other gamma ray sources visible in this image are, for the most part, associated to known X-ray binary systems, including microquasar 1E 1740.7–2942.

Elucidating the cosmic ray acceleration mechanism

Galaxies are pervaded by a flux of electrically charged particles, traveling at velocities comparable to the speed of light: cosmic rays. The process whereby cosmic ray acceleration occurs still holds many mysteries, however it is generally agreed that the requisite energy does originate in supernovae.



Fermi/LAT (NASA) and CEA/IRFU/SAp

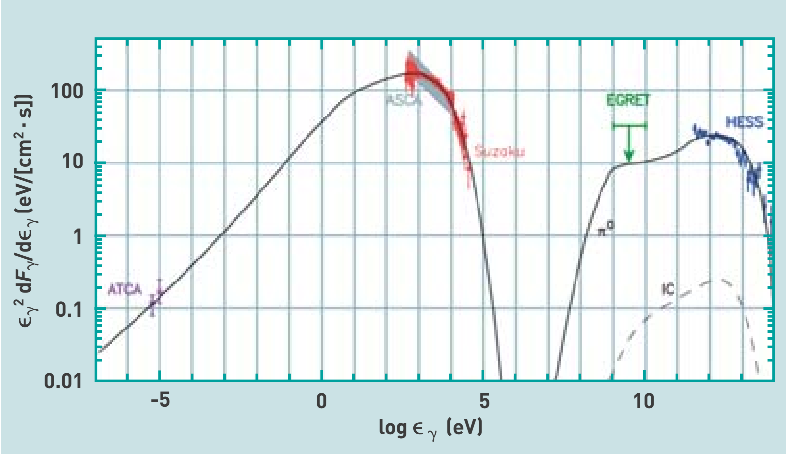
Map of the gamma-ray heavens, obtained by the Fermi Space Telescope. Aside from point sources, most of the emission is due, overwhelmingly, to the cosmic-ray irradiation of the interstellar medium. Nuclear collisions with the gas yield, amongst other particles, neutral pions,(1) and subsequently gamma photons. The structure observed is chiefly that of the interstellar medium, with a high concentration in the galactic plane, and around the galactic center.

Cosmic rays were so named at the time of their discovery, at the beginning of the 20th century. They were described as "rays," as they share with **X-rays**, and **gamma (γ) rays** – two contemporary discoveries – the property of **ionizing** matter. And they were dubbed "cosmic," owing to their extra-terrestrial provenance. In fact, this is something of a misnomer: this is no **electromagnetic radiation**, rather these rays are a stream of **relativistic** – and thus highly energetic – charged particles. They chiefly comprise **protons**, further including however a fraction of heavier constituents, and a few percent **electrons**.
At CEA, the Astrophysics Service/IRFU made a name for itself, in the 1980s, with the investigation of the detailed composition of cosmic rays; as a result, cosmic rays are now known to be of interstellar provenance, with a lifetime, within our **Galaxy**, of some 20 million years. Their energy spectrum regularly extends through to $3 \cdot 10^{15}$ **eV**. Pervading as they do the entire Galaxy, cosmic rays ensure the continued ionization of a fraction of the gas right into the core of **molecular** clouds. These electrically charged particles are deflected by the galactic **magnetic field**, and thus yield no information as to their provenance. On the other hand, the X- and gamma **photons** they emit do propagate in a straight line, enabling astronomers to locate the sources of cosmic rays.

A tennis racket

Considering the total energy, and lifetime of cosmic rays, considerable power is required, to sustain the present level of cosmic rays: this amounts to about 10% of the chief source of energy for the **interstellar medium**, namely **supernovae**. That is the locus, therefore – in all due logic – where their origin is to be sought. In fact, it is not the explosion itself that accelerates the particles, rather this is due to the resulting shockwave (see *Supernova remnants*, p. 27). The theory accounting for this phenomenon was formalized in the late 1970s. This is based on the existence of magnetic **turbulence**, arising in the ionized gas, which scatters the cosmic rays. Owing to their velocity, these readily pass through the shock-wave, which propagates at a few thousand kilometers per second only (about 1% of the speed of light). By scattering on either side of the shockwave, the particles pick up mean energy, in like manner to a tennis ball rebounding on an advancing racket, since the gas does not have the same velocity on either side. Indeed, a shock may be assimilated to a discontinuity in velocity. This process is self-amplifying – since the accelerated particles excite in turn the magnetic turbulence upstream of the shockwave – and takes up a major fraction of the kinetic energy available.
Some difficulties do remain, however, as regards accounting for the way energies higher than 10^{15} eV are achieved in a supernova remnant. Acceleration is all the more effective, the faster the shockwave travels, and the stronger the magnetic turbulence. On the other hand, the more energy a particle picks up, the greater the required acceleration time becomes. Now, even in the most favorable circumstances (with the turbulent magnetic field equaling the strength of the ordered field), the supernova remnant would have spent itself before particles could reach 10^{15} eV.

(1) Neutral pion: a particle which, together with the charged pions, π^+, π^-, plays a major role in the cohesion of **atomic nuclei**. With a mass slightly lower than that of the charged pions (134.97 MeV/c^2), and a much shorter lifetime ($8.4 \cdot 10^{-17}$ s), π^0 decays, in 98.79% of cases, into two gamma photons, or, failing this, into one gamma photon and one electron–positron pair.



(taken from E. G. Berezhko and H. J. Völk, *Astronomy and Astrophysics* 492, 2008, p. 695)

Figure 2.
Spectrum from supernova remnant RX J1713.7–3946, across the entire electromagnetic domain. Measurement points (colored) are located in the radio-wave, X-, and gamma radiation regions. The first hump (from radio waves to X-radiation) corresponds to the synchrotron emission from accelerated electrons. The second hump (gamma radiation) results from the **inverse Compton emission** from electrons (IC), and decay of pions[1] yielded by nuclear interactions between interstellar gas, and accelerated protons (π^0). EGRET was the forerunner to Fermi. The superimposed model (full line) gives pride of place to the gamma emission from protons, however it is equally feasible to construct a model where the gamma emission from electrons predominates (dashed line).

Inexplicable energy

Where might the key to this puzzle lie? Most **massive stars** undergo group explosions, this taking place in an environment that is profoundly altered, owing to the **stellar winds** from all of these stars, and the initial explosions. The shockwave develops in a highly rarified medium, and, even if the acceleration mechanism operates, the associated emission remains weak. Astronomers are therefore showing an interest in isolated supernovae, which arise in a denser, simpler medium, and thus lend themselves better to observation. Remnants from historical supernovae, as e.g. SN 1006 (see Figure 1), are particularly suitable for **modeling** purposes, as their age is known precisely, and their velocity remains high.
The prime observable quantity is the **synchrotron emission** from accelerated electrons spiraling in the magnetic field. Electrons admittedly only account for a few percent of cosmic rays, however they do provide a tracer for the acceleration mechanism. Highly energetic (10^{13} eV) electrons emit X-radiation, while the remainder (at about 10^9 eV) emit **radio waves** (see Figure 2). In the early 2000s, X-ray observatories showed that this emission is concentrated within a very thin shell, just where the shockwave stands, whereas these particles should exist, along with the gas, further in. Electrons thus lose their energy (through synchrotron radiation) very swiftly at the rear of the shockwave. This means that the magnetic field is very high, indeed exceeding predictions by a factor of more than 10. Cosmic rays are thus able to excite magnetic turbulence to well beyond the level of the ordered field. This unexpected amplification of the magnetic field accounts for the way some particles are able to reach an energy of $3{\cdot}10^{15}$ eV.

Pending issues

Astrophysicists are thus beginning to get a good hold on the cosmic ray acceleration mechanism, the more so since observation of a number of supernova remnants, including SN 1006, in 2008, in the gamma ray domain with the HESS instrument (see *Journey into the lights of the Universe*, p. 90) has yielded new data (see Figure 3). A number of issues do nevertheless remain standing. First of all, do accelerated protons in fact occur, as opposed to electrons only? The nature of the gamma emission detected by HESS remains ambiguous (see Figure 2). Second, how efficient is this process? What fraction of the available kinetic energy does actually get transferred to cosmic rays? For that query to be answered, protons will have to be detected, as they are the dominant component, and the gas density will need to be measured. The gamma ray flux will then give an idea of the quantity of accelerated protons.
Finally, one concluding query: to what extent is acceleration dependent on the direction of the magnetic field? In SN 1006, the synchrotron emission is not uniform, rather it is concentrated into two crescent-shaped areas (see Figure 1). This pattern undoubtedly results from the direction of the magnetic field, prior to the explosion. The very faint X-ray emission at the center of SN 1006 indicates that the crescents should rather be seen as caps, located at the magnetic poles, and that acceleration operates when the shockwave propagates along magnetic field lines. Now, statistical studies carried out in the radio-wave region tend to show that emission rather takes place within an equatorial belt. And, just to make matters simpler still, there are theories that account for both situations!

Concurrent advances

The theory of diffusive shock acceleration is making advances, concurrently with observations. **Models**, taking on board both the generation of turbulence by cosmic rays, and feedback from this on the shockwave's structure, are being developed. Astrophysicists at CEA/IRFU are incorporating these into a global supernova remnant model. They are presently seeking to carry out more in-depth investigations in the X-ray domain, and, under the aegis of an extensive program

XMM-Newton (ESA) and CEA/IRFU/SAp

Figure 1.
X-ray image of the remnant of the 1006 supernova (about the size of the Moon), taken using the XMM-Newton observatory. Red corresponds to the thermal emission from oxygen (0.5–0.8 **keV**), green and blue to slightly more energetic emissions (0.8–2 keV, and 2–4.5 keV, respectively). The synchrotron emission from accelerated electrons appears white.

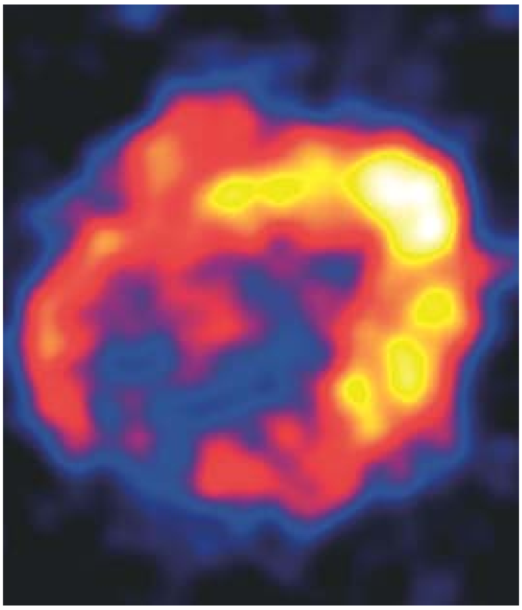

HESS and CEA/IRFU/SAp collaboration

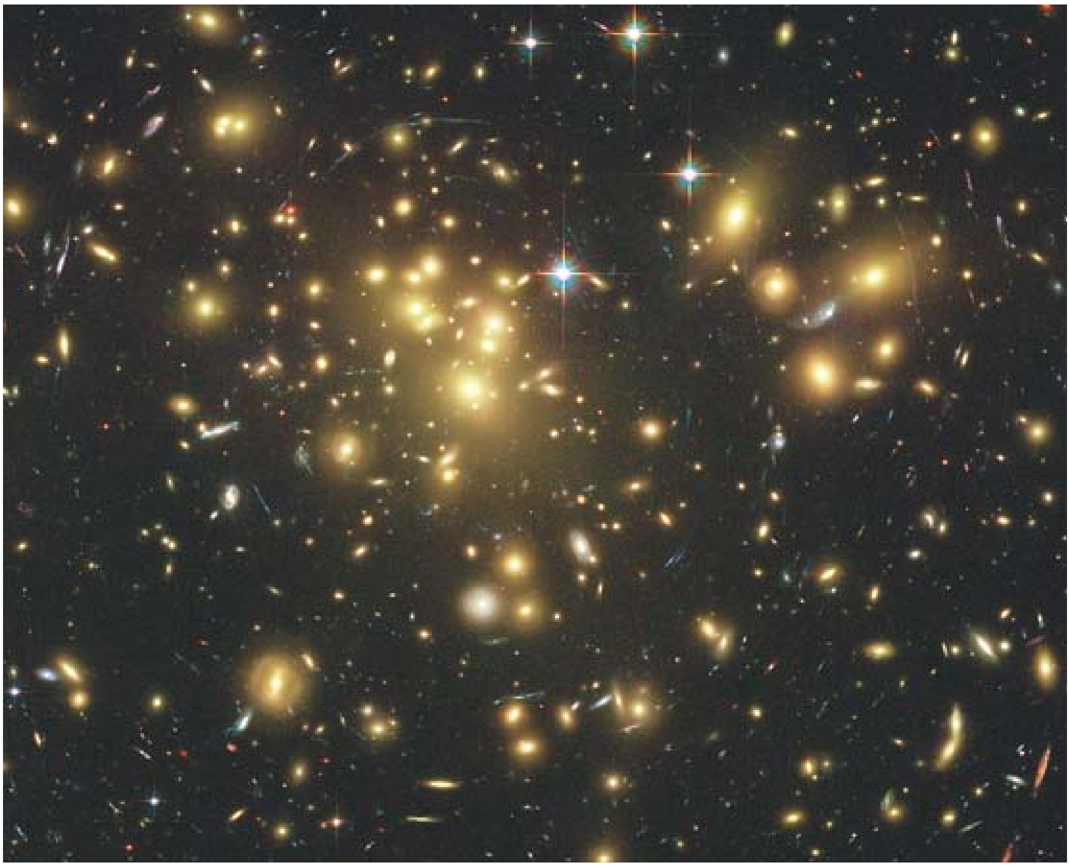
Figure 3.
Supernova remnant RX J1713.7–3946, as viewed by the HESS instrument, in the very-high-energy (TeV) gamma-ray range. The emission peaks observed are due to the structure of the interstellar gas.

concerning SN 1006, they are preparing to probe this supernova remnant, making use of the XMM–Newton observatory, the sensitivity of which should yield answers as to feedback, and the direction of the magnetic field (see *Journey into the lights of the Universe*, p. 90). The issues relating to protons, and efficiency chiefly involve gamma ray astronomy. While **spatial resolution** does remain limited, in this domain, on the other hand the energy range should expand considerably. Indeed, the HESS 2 instruments (due to come into operation early in 2010), and the Fermi observatory (launched in 2008) will cover, between them, the 100 **MeV**–10 **TeV** gamma band, allowing discrimination of the electron, and proton components.

> **Jean Ballet, Anne Decourchelle** and **Isabelle Grenier**
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

Seeking out the great ancestors

At what point did the first galaxies begin to shine, in the history of the Universe? In what manner did they differ from present-time galaxies? The quest for the oldest objects in the Universe is seeking out the answers to such questions.


NASA, ESA, L. Bradley (JHU), R. Bouwens (UCSC), H. Ford (JHU), and G. Illingworth (UCSC)

Galaxy cluster Abell 1689, within which a very distant galaxy, with a redshift of about 7.6, has probably been found. Investigation of the first galaxies is an active research topic, which proves extremely fascinating.

In the very distant past, the Universe was very dense, and very hot. The **cosmic microwave background** radiation stands as evidence that, 380,000 years after the **Big Bang**, the Universe still consisted of a homogeneous **plasma** (see *The grand thermal history of the Universe*, p. 62). It is apparent that, at that point in time, there were no **stars**, or **galaxies**. Deviations from such homogeneity – as measured by two US satellites: the Cosmic Background Explorer (COBE), and subsequently the Wilkinson Microwave Anisotropy Probe (WMAP); and, in the coming years, by the Planck satellite, launched in 2009 (see *Journey into the lights of the Universe*, p. 90) – barely exceeded one part in 100,000. And yet, such minute fluctuations are of the greatest interest to **cosmologists**. Indeed, they provided the seeds from which there arose the stars, galaxies, and **clusters** that, 13 billion years later, stand out across the intergalactic space.

In order to gain an understanding of how galaxies first formed, the oldest objects in the Universe must be identified, or, at any rate, their fossil light has to be collected. This search relies on the fact that the Universe is expanding. Since all objects are receding from one another, **photons** emitted by a given source, and received by an observer undergo a **spectral shift**, known as **redshift**, this being noted z (see Focus A, ***Probing the Universe across the entire light spectrum***, p. 31). The photons' **frequency** – and thus their energy – decreases, somewhat as the siren of an ambulance moving away from us sounds lower-pitched. Now, all objects, even the oldest ones, are (were) made of the selfsame **elements**, for which the **emission**, and **absorption wavelengths**, or frequencies have been precisely measured in the laboratory. By matching against these reference values the wavelengths, or frequencies occurring in the **spectrum** of a cosmological source, physicists are thus able to estimate its distance, and hence the time when its light was emitted. The ratio of the wavelengths observed, over the intrinsic wavelengths is precisely equal to the ratio of the global scale of the present-day Universe, over the scale of the Universe at the time when that light was emitted. Conventionally, this parameter is taken as being equal to "one plus redshift," thus: $1 + z$. Zero redshift ($z = 0$) corresponds to the present time, and characterizes light coming from nearby objects, whereas high z values relate to the distant Universe.

Identifying very distant objects

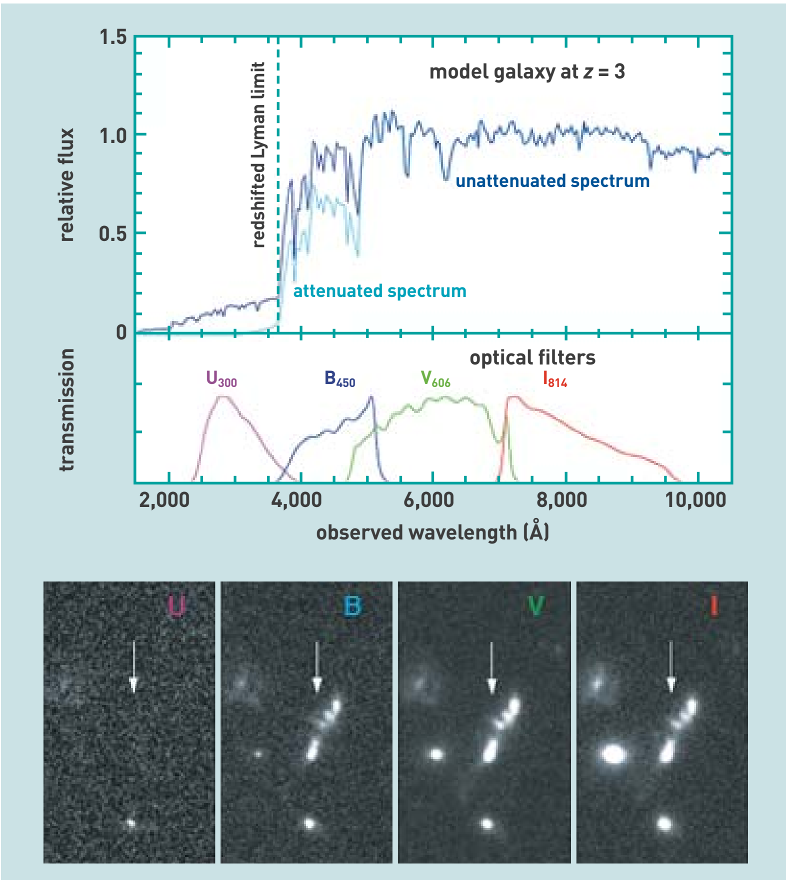
The cosmic microwave background (or diffuse cosmic background), emitted as it was by a Universe that was 380,000 years old, exhibits a z value slightly higher than 1,000. For most of the stars, and galaxies surveyed, z ranges from 0 to 3. The latter value corresponds to an age of the Universe of around 2.2 billion years. Cosmologists believe that "normal" galaxies, such as the **spiral galaxies**, comparable to our own **Milky Way**, or very massive **elliptical galaxies** (e.g. M87, in the Virgo Cluster), formed after that time. The "first galaxies," on the other hand, would involve a redshift higher than 3. Unfortunately, it becomes very difficult, with existing instruments, to locate, and study galaxies lying beyond that limit. The largest telescopes have to be pointed at one and the same region over extended periods.[1] This does yield images that are, admittedly, very "deep," however they show so many galaxies that it proves hard to discriminate such galaxies as are faint because they are distant, from those that are weak emitters simply because they are small. The most distant galaxies ascertained, to date, have a redshift of around 7, corresponding to a Universe less than 1 billion years old.

In order to discover the most distant objects, astrophysicists make use of the Lyman break technique, which has been widely adopted since the mid-1990s. This relies on the fact that galactic (and intergalactic) **hydrogen absorbs** photons of wavelengths shorter than 912 **Å**, corresponding to the **extreme ultraviolet**. This "Lyman limit" corresponds to the energy required to strip its **electron** from a hydrogen **atom**. Consequently, very little light – or even no light at all – emitted at wavelengths shorter than 912 Å may reach us from distant galaxies. This gives rise to a highly distinctive discontinuity (or break), allowing distant galaxies to be identified by their anomalous color. In astronomical parlance, the term "color" is used, as a rule, when referring to the ratio of the fluxes, or **luminosities** observed, using different bandpass filters ("color index") (see Figure 1). Now the redshift featured by very distant sources means that limit is offset to longer wavelengths.[2] For

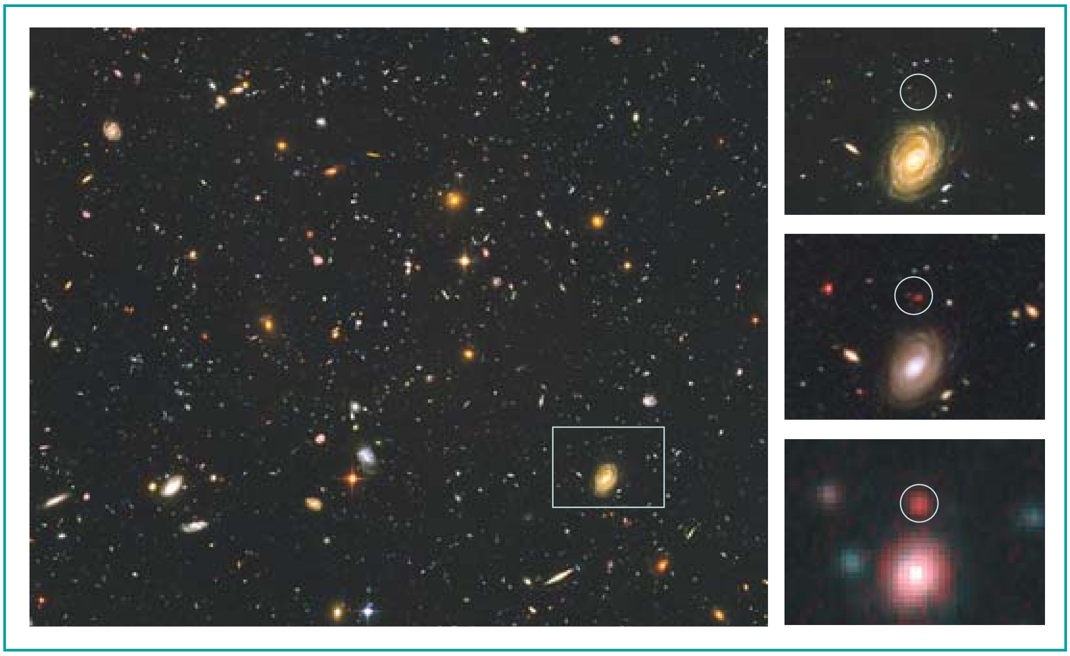
(1) The Hubble Ultra-Deep Field, a small region in the sky measuring about 3×3 **arcmin**^{2}, was thus observed over an interval of some 400 hours, by means of **NASA–ESA**'s Hubble Space Telescope, using four filters at different wavelengths, from 4,000 Å to 9,000 Å.

(2) This makes it possible to observe it from the ground, whereas the Earth's atmosphere blocks out wavelengths around 1,000 Å.

Figure 1.
An illustration of the Lyman break technique, using images obtained with the four filters fitted to the Hubble Space Telescope. The photographs below show an actual galaxy, at $z = 3$, selected by this technique.

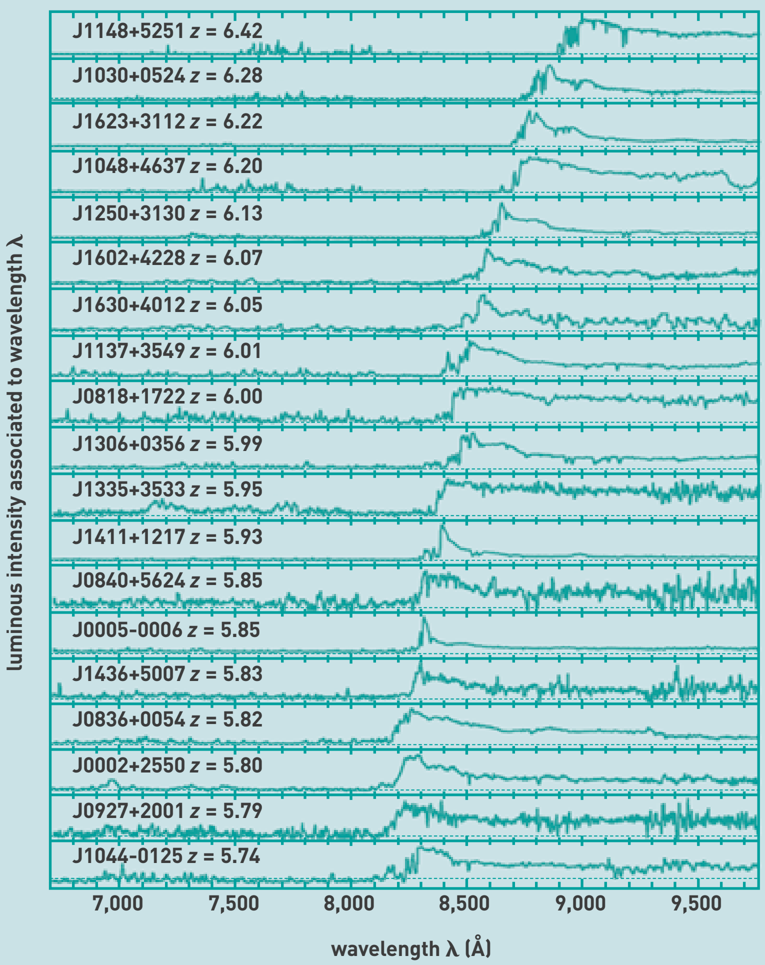


(M. Dickinson, in *The Hubble Deep Field: Proceedings of the Space Telescope Science Institute*, May 1997, STScI, eds. M. Livio, S. M. Fall and P. Madau)



NASA, ESA/JPL-Caltech/B. Mobasher (STScI/ESA)

The Hubble Ultra-Deep Field, showing numerous objects, amongst which scientists must separate out distant galaxies, from small galaxies.



[Fan Xiaohui *et al.*, *The Astronomical Journal*, 132, 2006, pp. 117–136]

Figure 2.
Spectra from very-high-redshift **quasars**, ranking as some of the most luminous known high-redshift sources. These objects were selected as their nature had been clearly confirmed by their Lyman break, and related spectroscopy. The break, at such redshifts, occurs around 1,216 Å, owing to the Lyman-alpha forest phenomenon.

instance, if z is equal to 3, the break is observed at around 3,600 Å, corresponding to **ultraviolet radiation**. Very distant galaxies (involving z values greater than 3) exhibit a break at **visible** wavelengths. As redshift increases, a further phenomenon, tending to shift the break to longer wavelengths, is superimposed: this is the part played by Lyman-alpha forest clouds,(3) which absorb radiation emitted at wavelengths in the 912–1,216 Å range (see Figure 2). The most distant galaxy known, with a redshift of 6.96, exhibits a break around 10,000 Å, this now lying in the **near infrared**.(4)

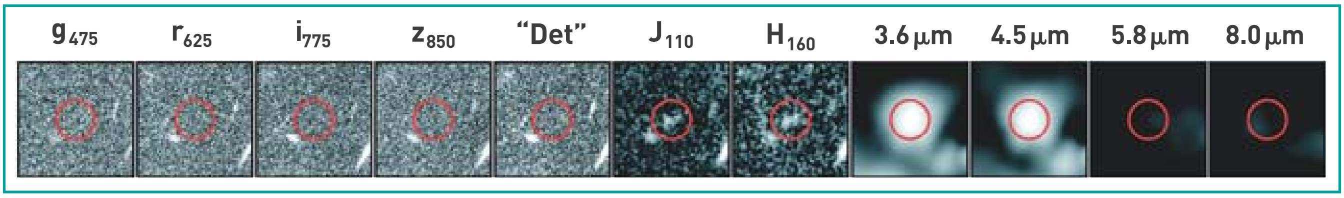
The race is on for the first galaxies

Currently, astronomers have identified several thousand galaxies exhibiting a redshift of around 3, several hundred more galaxies involving z values close to 6, but only a handful of galaxies having a redshift higher than 6.5. And these are only “candidate galaxies:” a number of other object types could exhibit colors similar to those due to Lyman breaks at high redshift. For instance, **M dwarfs**, or **brown dwarfs** exhibit a similar kind of break, at wavelengths in the visible region, and even in the **near infrared**. Further, galaxies involving a lower redshift, but which are very old, or highly dust-reddened may be confused, owing to their color, with high-z galaxies.

It follows that the Lyman break is not sufficient, of and by itself, for the purposes of identifying, unfailingly, distant objects. It has to be complemented by spectroscopic investigations, if distances are to be determined unambiguously. This process, which is

(3) Lyman-alpha forest clouds: these are gas clouds, absorbing a fraction of the light emitted by distant galaxies, and quasars, this resulting in the generation, in the spectra of these objects, of a multiplicity of absorption lines.

(4) Other techniques have proved effective, such as, e.g., looking for redshifted Lyman-alpha emissions at 1,216 Å; and, in some instances, very distant galaxies have been discovered by way of the **gamma bursts** detected in their high-energy emissions.



(L. Bradley *et al.*, *The Astrophysical Journal* 678, 2008, pp. 647–654)

Figure 3.
Probably ranking as the most distant object known, this Lyman-break galaxy is believed by scientists to have a redshift of about 7.6. Discovered in the field of galaxy cluster Abell 1689, this galaxy appears with a luminosity that is amplified by the **gravitational lensing effect** due to the cluster. Multicolor images show this galaxy is only detected at wavelengths longer than 1.1 **μm**, remaining invisible at shorter wavelengths. g, r, i, z are four filters in the visible region, ranging from blue to red, close to infrared. As for filters J, H, they let through infrared light only. "Det" corresponds to an image combining several colors.

relatively straightforward for galaxies with a redshift close to 3, becomes very protracted, and in many cases unfeasible, beyond $z = 6$. Furthermore, it becomes increasingly difficult to investigate the properties of such very distant galaxies. Some scientists have claimed to have discovered galaxies up to $z = 7.5$, which does seem quite plausible, albeit impossible to corroborate, as of yet, by means of spectroscopy (see Figure 3). Even bolder claims refer to galaxies exhibiting redshifts of 10, or even 12; such discoveries however do remain disputed.

A mysterious ionization

While the quest for the most distant galaxies is indeed a most fascinating pursuit, astronomers are not solely motivated by the desire to push back the confines of the known Universe. They aim, further, to find the answers to a number of fundamental scientific issues. For instance, observation of the cosmic microwave background has shown that hydrogen, throughout the Universe, was re**ionized** at an epoch corresponding to a redshift of about 11. In other words, hydrogen remained chiefly neutral, from $z = 1{,}000$ to $z = 11$; and predominantly ionized, from $z = 11$ to the present time ($z = 0$). Most atoms, in order to become ionized, require energy to be provided to them, to strip them of their electrons. This energy, it is believed, was supplied by the ultraviolet radiation emitted by the first objects to be formed. Photons of wavelengths shorter than 912 Å are indispensable for that process. There only remains the issue of finding the sources for such ultraviolet radiation. Such photons could originate in stars in the process of formation, or in the **accretion** of matter around the first supermassive **black holes**. For these concepts to be corroborated, the demonstration would have to be adduced, that sufficient numbers of very-high-redshift sources exist, to reionize the Universe. Now, astronomers are still far removed from achieving such a goal. Even at lower redshifts, around 6, not enough galaxies have as yet been detected. An intensive research effort is currently ongoing, to address this puzzle. The more widely held theories suggest countless small galaxies may abound, that have not yet been discovered, such as to provide the required amount of ultraviolet radiation.

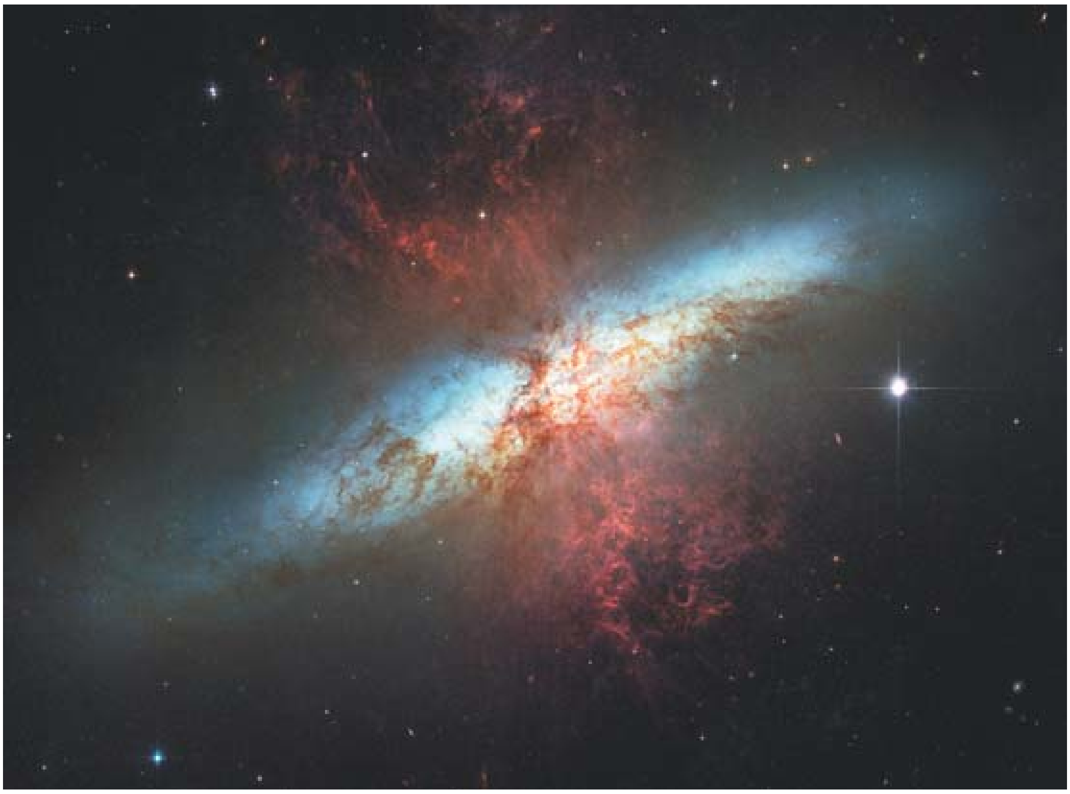
Stars and dust

The research effort, concerning distant galaxies, is currently seeking to unravel yet another puzzle, which is equally fascinating: that posed by *population-III* stars. Historically, astronomers brought together the metal-rich stars, found in the spiral arms of the Milky Way, as forming *population I*, while the older, more metal-poor stars, found in the galactic **bulge**, formed *population II* (see *The active life of galaxies*, p. 44). However, according to some theories, when gaseous matter was first turned into stars, a very different type of star was formed. In the absence of metals (i.e. **elements heavier** than hydrogen, or **helium**), only very massive stars could form: to wit, of several hundred **solar masses**. The spectrum of such objects would necessarily feature very intense helium **emission lines**. Now, in spite of ceaseless endeavors, nothing like this has been observed to date. The manufacture, and dissemination of heavy elements probably occurred, therefore, very early on in the history of the Universe. Discovering *population-III* stars does remain, nevertheless, a major goal. This would make it possible to understand, and study the Universe, at a time when most of the gas stood in its primordial state, immediately after the first chemical elements (hydrogen, helium) had been formed, in the course of the Big Bang. Astrophysicists have pinned great expectations on the launch of the James Webb Space Telescope, in the coming decade (see *JWST: looking back on a past 13 billion years old*, p. 102). They hope they will then be able to discover what kinds of objects reionized the Universe, and demonstrate the existence of *population-III* stars.
Finally, most of the detection techniques used to date, relying as they do on ultraviolet radiation, are only applicable to objects the emission from which does not have to go through cosmic dust, which absorbs, and extinguishes photons of this type. Quite recently, astrophysicists at CEA have identified giant star-forming galaxies at very high z values, higher than 4 in some cases, by detecting the **continuum emission** from dust. Many objects of this type could exist, even if they involve lower star formation rates than the extreme galaxies so far discovered. The Herschel Space Observatory, launched in May 2009 (see *Journey into the lights of the Universe*, p. 90), and, subsequently, the commissioning of the Atacama Large Millimeter/Submillimeter Array (ALMA), sited in Chile, will open up new avenues for research, as regards the identification, and study of the first, dust-obscured galaxies.

> Emanuele Daddi
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

The formation of galaxies: a story of paradoxes

Current observational resources make it possible to go ever further back into the past history of the Universe. Over the past few years, astrophysicists have been striving to piece together the scenario of galaxy evolution, from the time when the first galaxies were formed. Which does hold a few surprises in store...



NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

Messier 82, also known as the Cigar Galaxy, is the closest galaxy (at 13 million **light-years**) to exhibit a "starburst." It lies in the direction of Ursa Major. This is a spiral galaxy, seen edge-on, in which stellar explosions (supernovae) are so powerful, and so numerous that they are expelling interstellar gas from the galaxy. The red hue of the gas filaments is an artificial color, serving to visualize **ionized** gas.

The tip of a pencil, held at arm's length, masks but a tiny fraction of the heaven's canopy. And yet, recent deep images of the sky have detected so many **galaxies**, that close to 2,000 such objects could be "packed" behind that one pencil tip! Referred to the sky as a whole, such observations point to the Universe holding at least 120 billion galaxies. Galaxies thus stand, to the Universe, as **stars** do to galaxies, since the **Milky Way** contains 230 billion stars. Light from the most distant galaxies has taken nearly 13 billion years, i.e. 95% of the age of the Universe,(1) to reach observers. Scientists are thus viewing galaxies, today, as they stood at various past times. By combining all of the information so provided, they endeavor to draw up a kind of "identikit" picture of the typical galaxy, at various points in history, thus piecing together the scenario of galaxy formation.

For that purpose, they need to observe the sky across the entire gamut – across all **wavelengths**, or "colors" – of the **electromagnetic spectrum**, since every **cosmological** process emits radiation in a specific region of the spectrum.(2) High-energy radiation (**X-** and **gamma radiation**) thus originates in the hotter, and consequently more energetic events, such as gas heating up as it infalls onto a supermassive **black hole**, stellar explosions… Low-energy radiation, e.g. **infrared**, or **radio waves**, evidences dust cocoons (within which stars are born), interstellar gas, or **supernova** remnants. Stars, once formed, radiate most of their light in the **visible**, or **ultraviolet** regions (see Focus A, ***Probing the Universe across the entire light spectrum***, p. 31). Thus, depending on the color in which a given galaxy is observed, its shape, its morphology, its composition vary. Over the past few years, such multicolor observations have brought about a revolution in our knowledge of the evolution of galaxies (see Box)… and have brought up new queries, verging at times on the paradoxical.

(1) In astronomical parlance, the age of the Universe refers to the time elapsed since the **Big Bang**, this being estimated at 13.7 billion years. The actual age of the Universe remains beyond reach, since current theories do not allow the Universe to be investigated further back than the Big Bang.

(2) If a full understanding of the history of galaxies is to be achieved, their environment must also be taken into account. Indeed, most galaxies (some 90%) are concentrated into groups of a few units, while the remainder (nearly 10%) come in clusters of over several hundred galaxies. Further, theoretical **models** suggest that, extending between the galaxies themselves, gas bridges arise, forming invisible filaments, so to speak (so far invisible; however, they may prove observable at some later date), feeding into them.

Two contrasting scenarios

Over the course of the history of astrophysics, two scenarios have been considered, to account for the formation of galaxies: the *bottom–up*, and *top–down* scenarios. According to the former scenario, the first galaxies were "dwarf" galaxies, yielding, by way of successive mergers, ever larger, more massive conglomerations. In such a scenario, massive galaxies, such as the Milky Way, are the outcome of the mergers of a hundred or so such galactic entities. The top–down scenario, by contrast, assumes that the large structures in the Universe form first, subsequently fragmenting. Galaxies would thus stand as clumps from some **primordial** super-structure, this having turned into a **galaxy cluster** by the present time. The discovery of galaxies in the process of merging, together with that of the primordial seeds of galaxies, appearing in the **cosmic microwave background**, contributed to the widespread acceptance of the bottom–up scenario. In this context, the formation of a galaxy is a continuing, ongoing process, since it is the outcome of a succession of mergers, this being known as the hierarchical formation of galaxies.

Just over ten years ago, however, the investigation of star formation within galaxies did cause some serious consternation. Indeed, astrophysicists found that, rather than appearing last, the more massive galaxies had, on the contrary, formed all of their stars quite early on in the history of the Universe, whereas the less massive galaxies exhibit formation that is ongoing even at the present time. This property exhibited by galaxies, running contrary to what might have been anticipated according to the bottom–up scenario, stands as one of the great puzzles facing astrophysicists.

The evolution of galaxies: the mechanisms involved

A number of mechanisms are involved, in the course of the evolutionary history of **galaxies**.

Star *formation*. In this mechanism, the interstellar gas forms clumps, inside which **molecules** arise, this in turn cooling the gas down. This gas then collapses, down to densities sufficiently high for stars to form. In astronomical parlance, such regions, within galaxies, are referred to as giant molecular clouds (GMCs).

The formation, and growth of supermassive ***black holes***, lying at the center of galaxies. The investigation of stellar motions, at the center of the **Milky Way**, shows that stars are subjected to the attraction of an invisible, highly concentrated mass: a supermassive black hole, of nearly 4 million **solar masses**. Astronomers know, nowadays, that virtually all galaxies hold just such a black hole, which may have a mass of up to several billion solar masses.

Morphological evolution, as characterized by the changes in shape a galaxy may undergo, during its history. The term morphology is used, as a rule, to refer to the shape of the galaxy's star complement, since its gas is less readily observed.

The "genealogical," or merging tree tracks, as for humans, the sequence from the forebears (lower-mass galaxies), through their descendants, arising from the mergers of these small galaxies, down to the present-day massive galaxy.

Accretion *of intergalactic gas*. Contrary to manifest observation, galaxies are not entities standing in isolation. It may occur that two galaxies cross each other's path, and merge (or merely alter their shapes, without merging); however, mass growth, in galaxies, is also the outcome of their ability to take up, or draw in the matter surrounding them.

Debra Meloy Elmegreen (Vassar College) *et al.*, NASA, ESA, and The Hubble Heritage Team (STScI)

Two spiral galaxies merging, seen head-on. In a few billion years, the large spiral galaxy on the left (NGC 2207) will have engulfed its close neighbor (IC 2163), and the traces of this event will become difficult to detect, in the future galaxy.

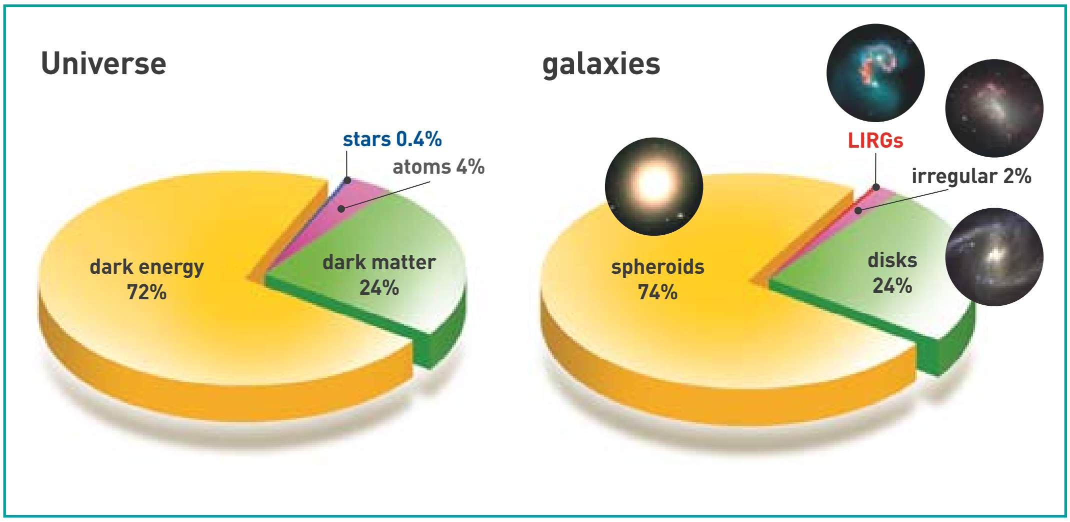


Figure 1.
Compared distribution of energy-bearing components in the Universe (at left), and of galaxies into morphological types (right). The parallel is striking, however nothing warrants, at the present time, seeing anything else than a coincidence in this.

Dark energy, the "red component" and other puzzles

It would appear, presently, that some 72% of the energy content of the Universe is of an as yet unknown nature (see Figure 1). This **dark energy** is accelerating the expansion of the Universe, and prevents the formation of new galaxy clusters. At a smaller scale, within galaxies, it is found that, in nearly 74% (by mass) of galaxies, some mechanism has blocked the generation of new stars. Such **elliptical galaxies**, or galactic bulges, appear with a red color, as their stars are old, and cool. While the issue of dark energy has become one of the major challenges in astrophysics, such is also the case as regards seeking the mechanism that has caused the premature death of the red galaxies.

One further puzzle: of the 4% of baryonic matter(3) – in other words: of **atoms** – that contribute to the energy content of the Universe, just one tenth (i.e. 0.4% of total matter) is found in stars. Star formation, within galaxies, has thus proved to be a remarkably inefficient process. Why is it that most baryonic matter (90%) has remained in gas form? Why is that gas, which is supposed to be drawn by the attraction of galaxies, not infalling into spheroids (see *The morphogenesis of galaxies*, p. 60), thus contributing to the birth of new stars?

Dark matter and galaxy formation

A galaxy, taken as a whole, is a structure consisting of gas, stars, and a **halo** of **dark matter**. Dark matter produces the opposite effect to that of dark energy. It speeds up the formation of structures across the Universe. It may be thought of as a bowl, inside which a soup of baryonic matter is kept hot. Dark matter, of itself, emits no radiation, however it does contribute to the growth of structures through the effects of its **gravitational** force.

Without dark matter, there would be no accounting for how galaxies arise, since the quantities of standard matter are insufficient to give an account of galaxy formation. Even at the present time, nearly 24% of this matter, contained in galactic **disks**, is continuing to give birth to new stars. Such regions stand out through their blue color, indicating the presence of young, **massive** – and hot – **stars**, by contrast to elliptical galaxies, consisting as these do solely of old, cool stars.

The distribution of matter within galaxies, into a blue component (disks: 24%), and a red component (spheroids: 74%), puts one in mind of that found, at a larger scale, across the Universe, between dark matter (24%), and dark energy (72%) (see Figure 1). This is but a quantitative analogy, or similarity, involving no physical relation, however it does stand as a reminder that, at either scale, the Universe does appear to be predominantly subject to forces that work against new star formation.

A blaze of stars

A minority of galaxies exhibit a morphology that is less clear-cut than the others: **irregular galaxies**. The Magellanic Clouds, lying quite close to the Milky Way, are good instances of this group. One further component may be found, that is even more of a minority, but which proves of singular interest to astrophysicists: the "luminous infrared galaxies," or LIRGs. Whereas the overwhelming majority of galaxies, in the local Universe, generate stars at a rate of a few suns per year, or even less, LIRGs undergo "starbursts," generating several tens, or even hundreds of **solar masses** annually.

It took observations of the sky in the **far infrared** to discover these starbursts, which had remained invisible up to that point. Indeed, massive stars do not have a long enough lifetime to emerge from the giant **molecular** cloud that gave birth to them, and their visible, and ultraviolet light is **absorbed** by dust in the cloud. This dust, as it is heated up, radiates in turn in the far infrared.(4) The US Infrared Astronomical Satellite (IRAS: launched in 1983, featuring a 57-cm diameter mirror) was thus able to discover the LIRGs, a disco-

(3) Baryonic matter: the word "baryon" comes from the Greek *barys*, meaning "heavy." In theory, this term covers heavy particles, chiefly **protons**, and **neutrons**, however it is also used, in **cosmology**, to refer to standard matter – comprising protons, and neutrons (the constituents of **atomic nuclei**), but equally **electrons** – hence to atoms as a whole.
This is as opposed to "nonbaryonic matter," this being the chief (hypothesized) constituent of dark matter. Nonbaryonic particles have yet to be discovered. They are assumed to be sensitive solely to **gravitational interaction**, which would account for their not being subject to the same physics as baryonic particles, thus radiating no light.

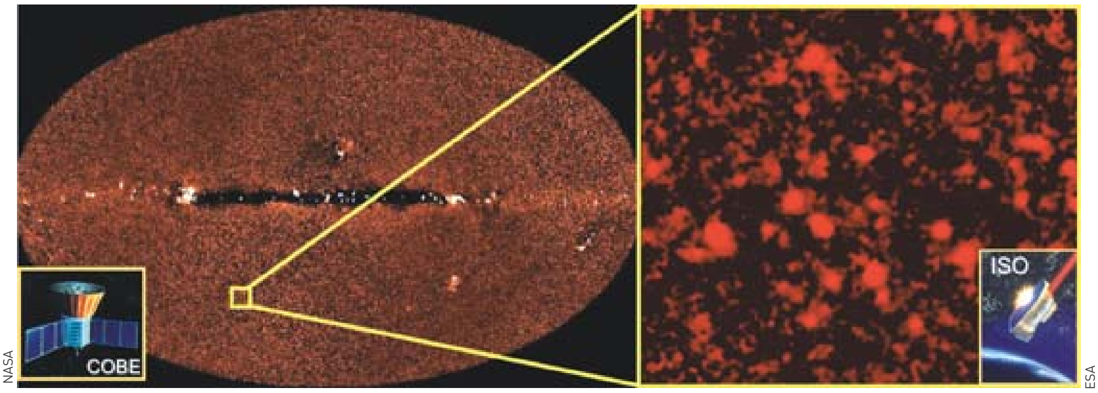


Figure 2.
The diffuse infrared background, as measured by NASA's COBE satellite (at left), and the resolution of this background into individual galaxies, by ESA's ISO satellite (right).

very that would doubtless have remained something of an anecdote, had it not been for the placing into orbit, by **ESA**, of the Infrared Space Observatory (ISO: 1995; 60-cm mirror), embarking the ISOCAM camera, constructed under CEA project leadership.
In the late 1990s, a French team at the Space Astrophysics Institute (**Institut d'astrophysique spatiale**, at Orsay, near Paris) discovered, by way of the US Cosmic Background Explorer (COBE) satellite, the existence of a background of light in the far infrared, distinct from the cosmic microwave background. This was doubtless the outcome of the buildup of light radiated by dust, heated by massive stars, over the entire history of the Universe. Almost simultaneously, a team at CEA was able to identify the individual galaxies that had yielded this diffuse background, using the ISOCAM camera. Astrophysicists had thus made the discovery that LIRGs, standing as they do as an anecdote in the local Universe, in fact played a major part in the past (see Figure 2). This finding was recently corroborated by **NASA**'s Spitzer satellite (2004; 85-cm mirror), and scientists have now ascertained that, in past times, galaxies underwent star formation at stupendous rates, which could reach a thousand solar masses or so annually.

Yet another contradiction

By combining such observations with those yielded by measuring the distances of galaxies, by way of their **redshift** (see *Seeking out the great ancestors*, p. 52), it became feasible to go back over time, and look back at the history of star formation within galaxies (see Figure 3). Infrared data show that, after rising throughout the first quarter of the age of the Universe,(1) the annual star formation rate, thereafter, underwent an abrupt decline. This measurement chimes in perfectly with the proportion of stars born at various points in time, as obtained by measuring the total mass of stars found in galaxies from various epochs. These two ways of addressing one and the same phenomenon suggest that the fraction of stars formed, as time went on, has remained practically equal to the fraction of the age of the Universe. Now, it was shown, at the same time, that the part played by LIRGs was predominant, during the greater part of the history of the Universe – this reflecting the fact that all present-time galaxies

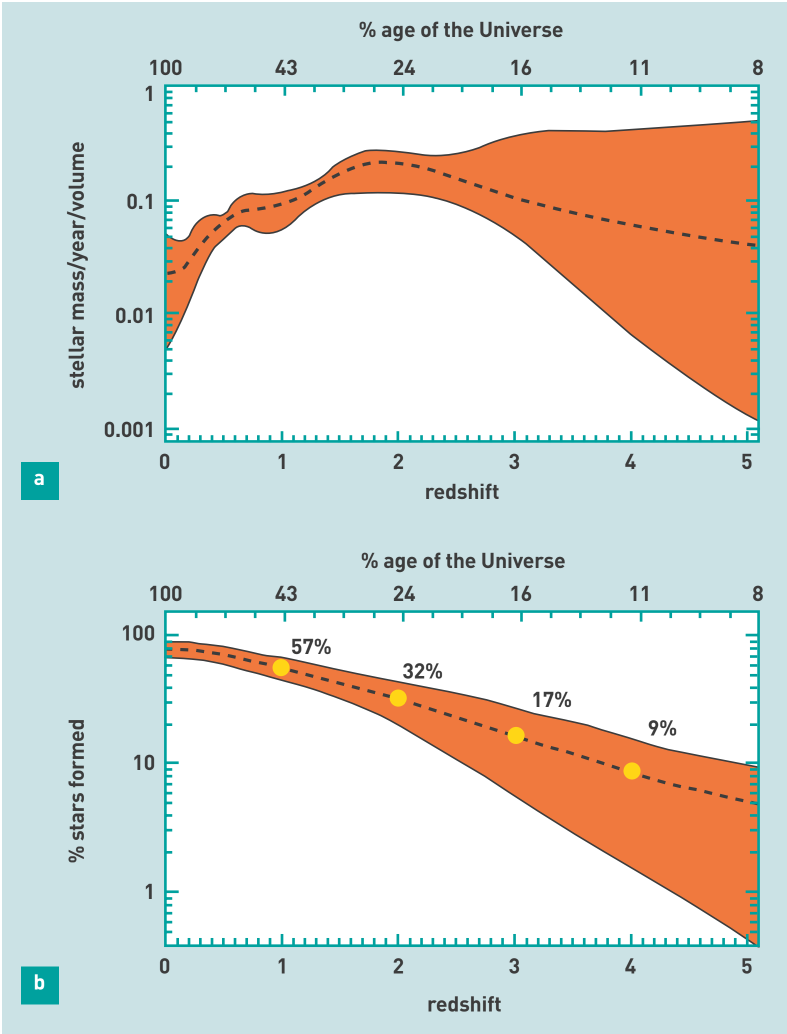
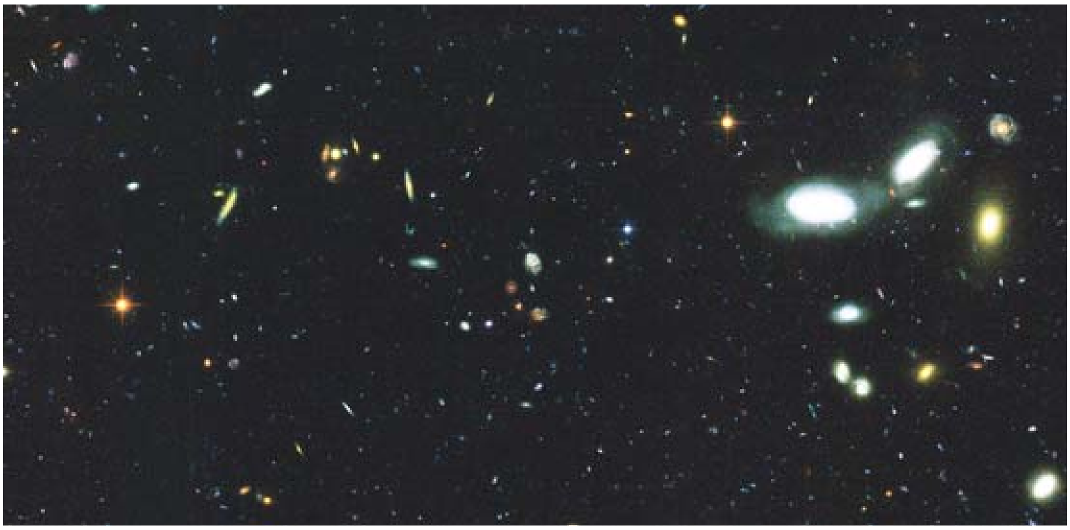


Figure 3.
The topmost curve plots the intensity of star formation in the Universe, over time.
This is measured in terms of the stellar mass (in solar mass units) formed, per year, in a given volume (in the present case, inside "boxes" of 3 million light-years per side). This intensity peaked when the Universe reached about 30% of its present age (top *x*-axis). The bottom figure plots the proportion of stars born over time, in the Universe (referred to the present quantity of stars). This quantity may be computed either from the graph at top here, or from direct observations, by adding up the mass of stars contained in distant galaxies across the Universe. The two methods yield the same result.

(4) At the same time, a star having a mass 10 times larger than that of the **Sun** emits 10,000 times more radiation, and ends its life 10,000 times sooner. This is why the measurement of galactic star formation activity relies on measurement of the quantities of massive stars found in galaxies, since the lifetime of such stars is so short (a few tens of million years) that, when astronomers do see some of these stars, they know they were born a short time ago.

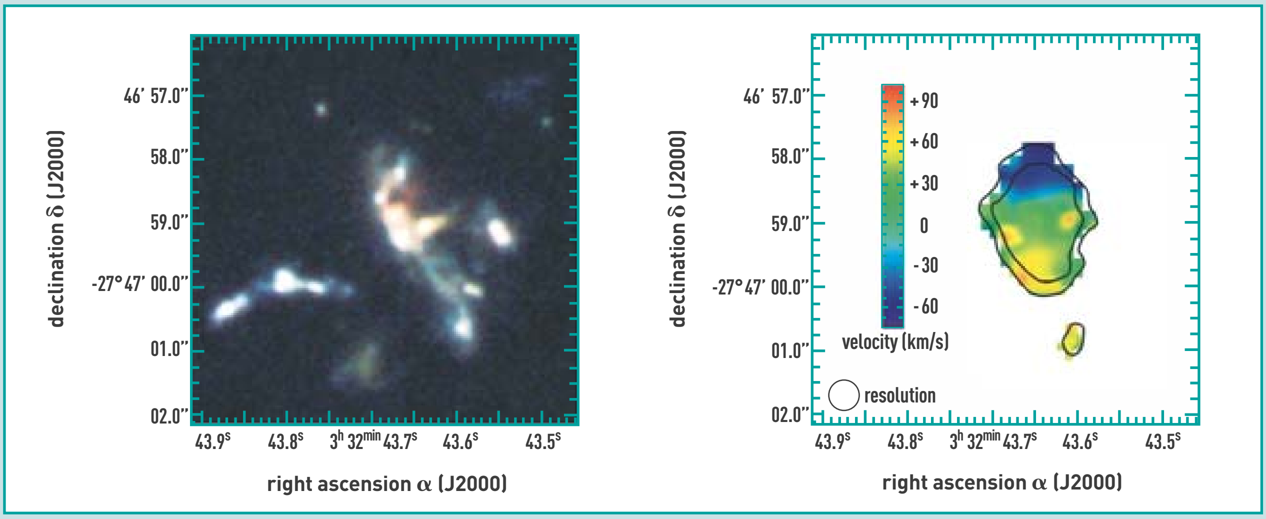


NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

Figure 4.
Deep image of the sky, taken with the ACS camera, on board the Hubble Space Telescope, in the Southern Hemisphere (in a region targeted by the Great Observatories Origins Deep Surveys [GOODS]). Covering as it does an "area" equal to one tenth of that of the Moon (or of the Sun), the image shows a whole range of galaxy shapes.

The morphogenesis of galaxies

Galaxies, in the present-day Universe, fall into two main morphological types. *Spiral* galaxies are disks of stars, and interstellar gas, rotating around a small central bulge. Gravity acts gradually to form the spiral arms. By contrast, *elliptical* galaxies feature no rotating disk. They take on a spheroidal shape, within which disordered stellar motions counterbalance gravity, precluding the emergence of internal structures.
These two types of galaxy are the outcome of two distinct formation processes. To gain an understanding of these mechanisms, astronomers collect the light from distant – and thus old – galaxies, by means of large instruments, both ground-based and spaceborne, in particular the Very Large Telescope (VLT), sited in Chile, and the Hubble Space Telescope. They have thus found that the morphology of galaxies underwent a marked evolution, in the course of their formation. At a time when they were some two or three times younger than is the case at present, spiral galaxies exhibited far more irregular shapes. They did, of course, comprise a rotating disk, however this was far less homogeneous, and would feature no central bulge. In many cases, indeed, the disk appears to be fragmented into a number of large condensations of gas, and stars. Such "protospiral galaxies" – i.e. primordial galaxies, destined to form spiral galaxies – are huge rotating disks that have accreted large numbers of smaller galaxies, and large quantities of intergalactic gas. Their mass is so great they have become gravitationally unstable, the forces of gravity overcoming the forces of pressure, and inertia. This instability results in fragmentation. Each fragment contains very dense gas, involved in a very high rate of star formation: several tens of solar masses per year. Subsequently, the inner components of these fragments migrate to the center of the galaxy, forming a small, spherical bulge. The remainder of the material is redistributed into a disk, this now proving gravitationally stable, and gradually taking on the spiral shape that is observed at present (see Figure 1).



F. Bournaud/CEA/NASA/ESO

Figure 1.
A galaxy from the young Universe (UDF 6462, $z = 1.57$), as observed by the Hubble Space Telescope (left). Spectroscopy carried out at the Very Large Telescope (ESO) yielded its velocity field (right). The regions coming towards us are shown in blue, those receding from us in yellow/orange. In spite of its highly irregular shape, this galaxy is a spiral galaxy to be, snapped in the midst of its phase of disk, and central bulge assembly.

have undergone, in the past, a phase where they were generating stars at a very considerable rate. These two findings may be seen as contradictory, since LIRGs undergo starbursts, whereas, on average, the Universe does appear to produce stars in continuous fashion, with no major surge.
In order to understand what may have happened, it proves necessary to look at things in another way, by returning to the visible view of the sky, and consider the morphological evolution of galaxies (see *The morphogenesis of galaxies*, p. 60). Deep images, taken by the Hubble Space Telescope, have made it possible, not only to detect distant galaxies, but equally to investigate the shape, and morphology of such galaxies, over extended timescales (see Figure 4). While LIRGs observed in the nearby Universe all exhibit highly "perturbed" morphologies – an indication of galactic mergers –, distant LIRGs are found to look more like the Milky Way: they appear as well delineated "grand design" spiral galaxies. Astrophysicists have discovered, quite recently, that the part played by galaxy mergers, through the history of the Universe, was not as important as had been initially believed. While the more extreme starburst galaxies are probably the outcome of merger episodes, galactic activity does not prove highly sensitive, for the most part, to such phenomena. Another mechanism, not as yet ascertained, would appear to play a leading role. Two candidates are currently being looked into. Largely overlooked in the past, these may turn out to be major players in the cosmological history of galaxies, whether it be as regards igniting star formation, or extinguishing it. These possible mechanisms are the **accretion** of intergalactic gas, in the form of filaments, and the formation of supermassive black holes, at the center of galaxies. The next generation of instruments needs must be awaited, before we can learn more about this.

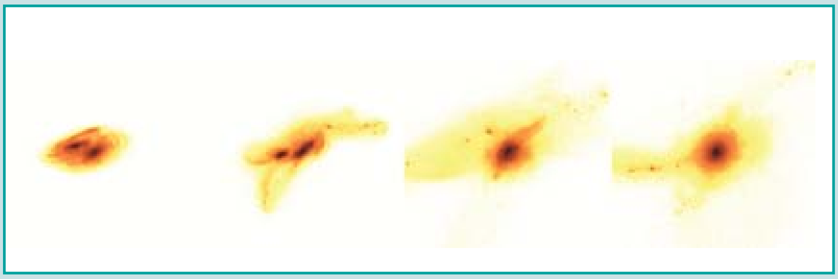
> David Elbaz
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

Fertile shocks

A spiral galaxy thus forms, essentially, through internal evolution: this stems from the instability, and fragmentation of a primordial, gas-rich disk. By contrast, an elliptical galaxy does not acquire its shape solely by way of the internal evolution of a system. A more tumultuous process is required, to disrupt the organization of rotating disks, and turn them into spheroids. This involves galaxy collisions, and mergers. When two galaxies, of similar masses – spiral galaxies as a rule – collide, they expel a fraction of their own mass, owing to **tidal forces**; however, most of their mass merges into a single galaxy. This process is known as "violent relaxation," since gravitational forces vary quite rapidly (compared to the orbital period of each of the stars involved). The outcome is disorganization, both in terms of morphology (the disk), and kinematics, so that the resulting galaxy spontaneously acquires the properties of an elliptical galaxy. **Numerical simulations** have shown that the merger of two galaxies does yield an object that is in every way comparable to actual elliptical galaxies (see Figure 2).
The large-scale properties of the Universe, and the properties of **dark matter** govern the frequency involved by either process, in particular the rate of galactic collisions. Accounting for the proportions of spiral, and elliptical galaxies in our present-day Universe thus remains as one of the major challenges that cosmological structure formation **models** have to meet.


ESO
An elliptical galaxy (NGC 1316).


ESO
A spiral galaxy (NGC 6118).


F. Bournaud/CEA/CCRT
Figure 2.
Numerical simulation of a collision between two spiral galaxies. The two galaxies merge, their disks are disrupted, and the outcome is an elliptical-type galaxy.

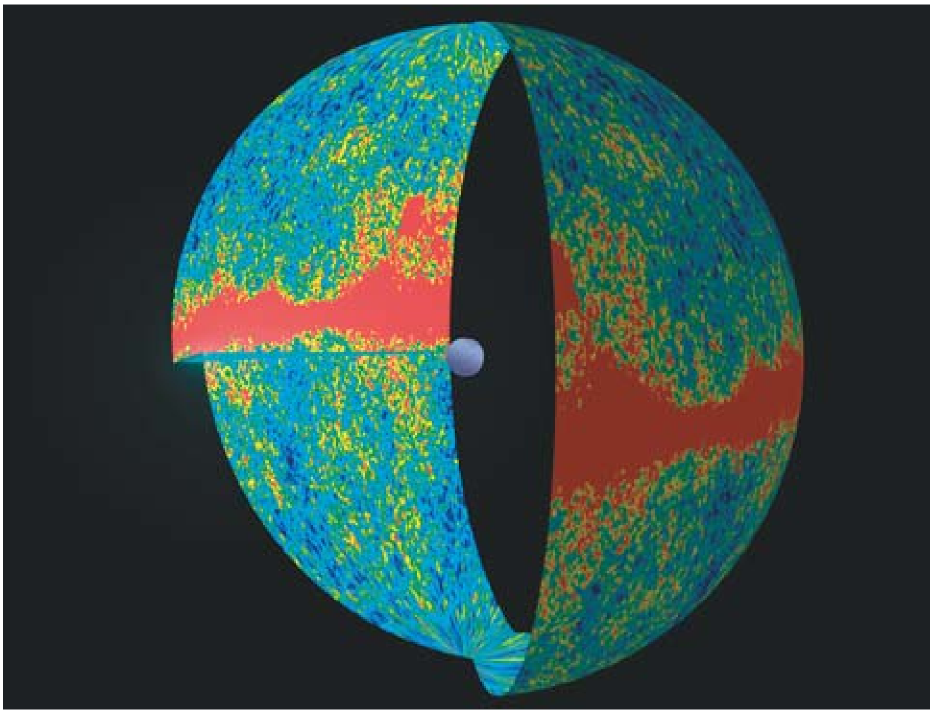
> Frédéric Bournaud
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling"
(CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

A gigantic spider's web. This is what the Universe looks like, at the present time. Standing essentially empty, and cold, the Universe contains a population of galaxies, concentrated along filaments, at the intersections of which are found the largest known objects: clusters of galaxies. How did such a well-defined structure emerge? The fossil radiation, dating back to the first ages of the Universe, indicates, by contrast, a hot, dense "soup," homogeneous in all directions. Minute local variations in density are understood to have given birth to the objects that emerged thereafter, chiefly through the action of gravity, this being slowed down by the Universe's expansion. The engine of that evolution is the force of gravity, this causing the much-debated dark matter – which remains a puzzle – to collapse into huge filamentary structures, into which "ordinary" matter in turn is entrained. Surprisingly, while so many issues remain open, those concerning the shape, and the finite character of the Universe could find an answer quite soon.

The **Universe**, a **homogeneous "soup"** that has turned into a **hierarchical structure**

The grand thermal history of the Universe

The discovery of the cosmic microwave background gave rise to a new discipline: modern observational cosmology. From the time the COBE satellite was launched, observational data have finally been available, to corroborate theoretical models of the evolution of the Universe. Cosmologists are currently planning numerous experiments, to refine their scenario.



C. Carreau/ESA

Artist's impression of the observations, made by the Planck satellite, of the diffuse cosmic background, the fossil microwave radiation that pervades the entire Universe. In this picture, the Earth is positioned at the center of the sphere of the heavens. The satellite, during every one of its revolutions, observes (depicts) across the celestial sphere the map of the cosmic microwave background.

At the present time, astronomers observe a rarified, cold Universe that is transparent to light. Chiefly consisting of vast, empty expanses, it contains, on average, just a few **atoms** per cubic meter. In regions shielded from the radiation of bright objects, radiation temperature is no higher than 2.763 **K**, i.e. about –270 °C. Finally, the Universe is expanding: in all directions, distant **galaxies** are receding from one another.

This had not always been the case. An imaginary observer, going back across time, would see the Universe contract, becoming denser, more "compact." Physicists know that, when matter is compressed, its temperature rises. The same holds for the Universe: 13 billion years ago, the density of the Universe was such that its temperature equaled the surface temperature of the **Sun**. In such conditions, matter no longer occurs in the form of atoms, rather it takes the form of **plasma**, i.e. a kind of "soup" of **photons**, **nuclei**, and **electrons** involving no atoms. A "soup" that is very bright, to be sure, since it is very hot – as hot as the Sun – but altogether **opaque**. Indeed, photons are frequently scattering over the **free electrons** in a plasma, and are thus unable to travel across it.

As time went on, the Universe thus expanded, and cooled down. At a given point in time, temperature had so far declined that photons ceased to have sufficient energy to **ionize** atoms. At that point, electrons recombined with nuclei, forming atoms. **Cosmologists** refer to this event as *recombination*. Somewhat abruptly, the Universe became transparent to photons. Since that time, photons have been traveling in a straight line, forming the diffuse cosmic **microwave** background (CMB), also known as fossil radiation. Thus observing the diffuse cosmic background, around 100 **GHz**, yields a snapshot of the **primordial** Universe, as it stood when it was 380,000 years old, at the time of "electron–photon decoupling" (see Figure 1).

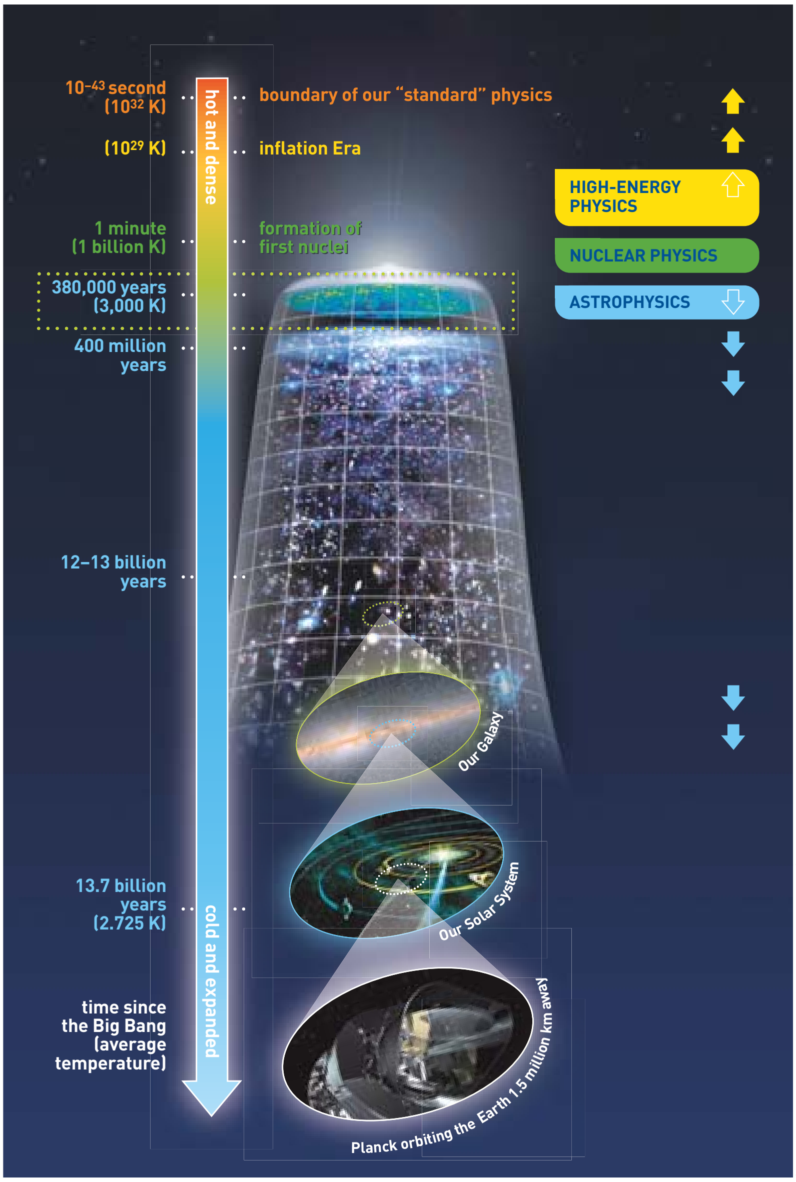


Figure 1.
This figure sums up, in a single diagram, what is known, by physicists, of the thermal history of the Universe.

A "snapshot" that has much to tell us

At first sight, when looking at this picture, the sky seems to be uniformly bright: this is what US physicists Arno A. Penzias and Robert W. Wilson(1) discovered, in 1965, using radio antennas – this being what cosmologists now refer to as the CMB "monopole" (see Figure 2a). The primordial Universe was thus highly homogeneous. A more careful scrutiny, after removing the average brightness of the map of the sky, yields a map dominated by a hot spot, and a cold spot (the CMB "dipole component"), along with small structures, corresponding to radiation from "hot" (about 20 K!) dust particles in the **Milky Way** (see Figure 2b). The dipole component, which is due to the Earth's motion, yields no information as to the primordial Universe. Once that dipole component had been removed, and after 4 years' measurement operations, the Cosmic Background Explorer (COBE) satellite was able to show up minute variations in brightness in the primordial CMB(2) (see Figure 2c). The central red strip corresponds to the emission from dust particles in the galactic plane, these completely saturating the picture. More recently, the Wilkinson Microwave Anisotropy Probe (WMAP) further refined this map of the sky, yielding a picture from which the galactic component has been removed, the colors corresponding to variations in apparent temperature of some 50 **μK** – whereas average temperature stands at 2.763 K (see Figure 2d).

The extraordinary homogeneity, in terms of brightness, featured by the COBE map thus highlights the fact that the Universe was extremely homogeneous, in terms of temperature, and thus of pressure, at the time of decoupling. The minute details appearing in the WMAP map are local variations in apparent temperature, and thus in pressure, arising in the plasma at that point in time. Ever so minute though they may have been, these variations gave birth to the major structures of the Universe: galaxies, **galaxy clusters**, and filaments.

(1) US physicists Arno A. Penzias and Robert W. Wilson were awarded the Nobel Prize in Physics, in 1978, for this discovery.

(2) US physicists John C. Mather and George F. Smoot were awarded the Nobel Prize in Physics, in 2006, for this discovery.

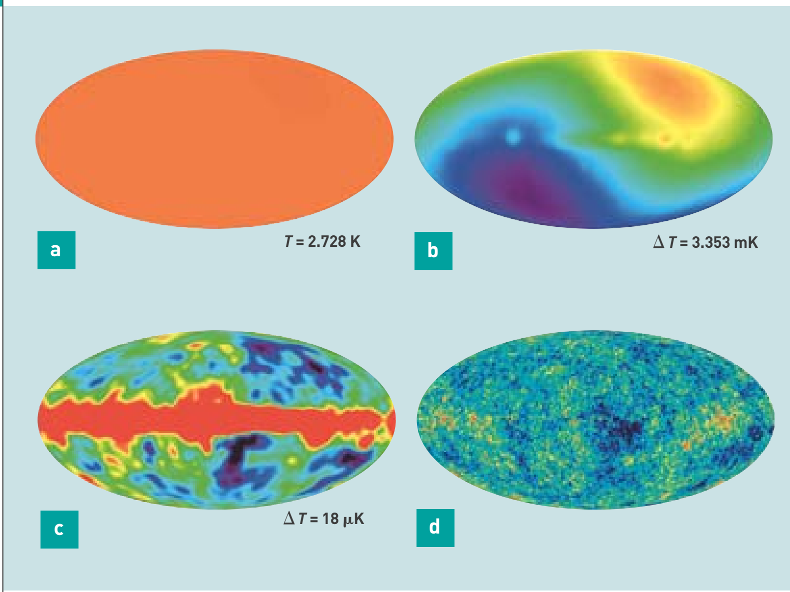


Figure 2.
Maps of the sky, showing the structures appearing in the cosmic microwave background at various levels of detail.

Modeling the primordial Universe

No-one can adduce witnesses as to the history of the Universe, in primordial epochs. Hence, cosmologists resort to **models**. They devise a scenario which, while complying with the laws of physics, as they are found to exist on Earth, reproduces, as far as feasible, all of the available observations of the primordial Universe, as of the recent Universe. **Primordial nucleosynthesis** tells us, for instance, that the Universe experienced a temperature higher than 10^{10} K, and has been expanding ever since. Now, cosmologists have the ability to measure precisely variations in density, and pressure, arising in the plasma at the time of decoupling. They assume, at that point, that, in the very primordial Universe, **quantum**-physical mechanisms spontaneously generated random, if minute, fluctuations in density, in the primordial plasma. Applying the laws of fluid mechanics, they computed the evolution of such density fluctuations, when subjected to the main forces then prevailing: **gravity**, and pressure forces, chiefly originating, at that time, in the photon gas. The CMB snapshot finally makes it possible to compare these models with actual reality, for that time.

The birth of the first objects

Subsequent to decoupling, the photons forming the CMB ceased to interact with atoms, thus lifting the pressure forces that had been exerted by the photon gas. Gravity remained as the sole force, tending to accentuate overdensities, being moderated only by the overall dilution of the fluid of matter, owing to the expansion of the Universe. Computations show that, once a clump of matter reaches a density 4.6 times greater than that of the fluid, it ceases to dilute along with the expansion of the Universe, instead collapsing onto itself, yielding an astrophysical object: a **halo** of matter. Such halos, the mass of which is dominated by their **dark matter** component, go on to give birth to the **bright** astrophysical objects that arise thereafter: **stars**, subsequently dwarf galaxies; these, by merging with one another (along with their respective halos), then go on to form galaxies, and clusters of galaxies.
To sum up, the CMB thus makes it possible to observe the seeds of the large structures of the Universe. That is not all, however! At millimeter wavelengths, the CMB monopole forms a bright screen, illuminating all astrophysical objects. Should a CMB photon pass through a galaxy cluster, it traverses a hot plasma, at a temperature of several tens of million degrees, across distances of up to one million **light-years**. It then has a probability of about 1/10,000 of scattering over an electron from the hot gas, by way of the **Compton effect**, thus picking up energy. This is the Sunyaev–Zeldovich effect.(3) For that effect to be detected, the sky must be observed with enhanced **angular resolution**, at a number of frequencies. In the direction of a cluster, at frequencies lower than 220 GHz, the map of the sky shows a cold spot, corresponding to the **absorption** of CMB photons. On the other hand, at higher frequencies, it exhibits a hot spot, due to the Sunyaev–Zeldovich effect. This makes it possible to discriminate a galaxy cluster, from the primordial inhomogeneities in the CMB.

The great quest

The Particle Physics Service at CEA/IRFU consequently became involved with the OLIMPO stratospheric balloon experiments (see Figure 3), and – together with the Astrophysics Service at IRFU – with the Planck satellite(4) (see *Journey into the lights of the Universe*, p. 90). These experiments will yield two complementary catalogs of galaxy clusters. The Planck satellite, launched in May 2009, will detect massive, or nearby clusters, the entire sky being covered. The OLIMPO instrument, which is scheduled to collect its first data in 2011, will only scan 300 square degrees in the sky, with enhanced depth, however.

(3) This effect had been predicted in 1970 by Soviet physicists Rashid Alievich Sunyaev and Yakov Borisovich Zeldovich.

(4) For further information on this satellite, see: http://public.planck.fr.

Figure 3.
The launch, from an Antarctic base, of the BOOMERanG (Balloon Observations of Millimetric Extragalactic Radiation and Geophysics) stratospheric balloon, the forerunner to the OLIMPO experiment. Detection of the cosmic microwave background with OLIMPO will be carried out by means of four plane bolometer arrays, positioned at the focus of a 2.6-m diameter telescope.

Now, in cosmology, owing to the finite speed of light, seeing far means seeing far back in time. These galaxy cluster catalogs will thus recapitulate the mass distribution of such clusters, across time, enabling cosmologists to check whether their structure formation models, devised, and selected as they are for the purposes of reproducing the measured CMB inhomogeneities, do indeed predict the correct abundance of galaxy clusters in the present-day Universe, and over time… Cross-referencing these data with those yielded by other cosmological observations, e.g. the brightness distribution of type-Ia **supernovae** across epochs, will contribute to the selection of valid cosmological models, and, ultimately, to the drawing up of a reliable history of the way our Universe arose.

Towards a detailed scenario

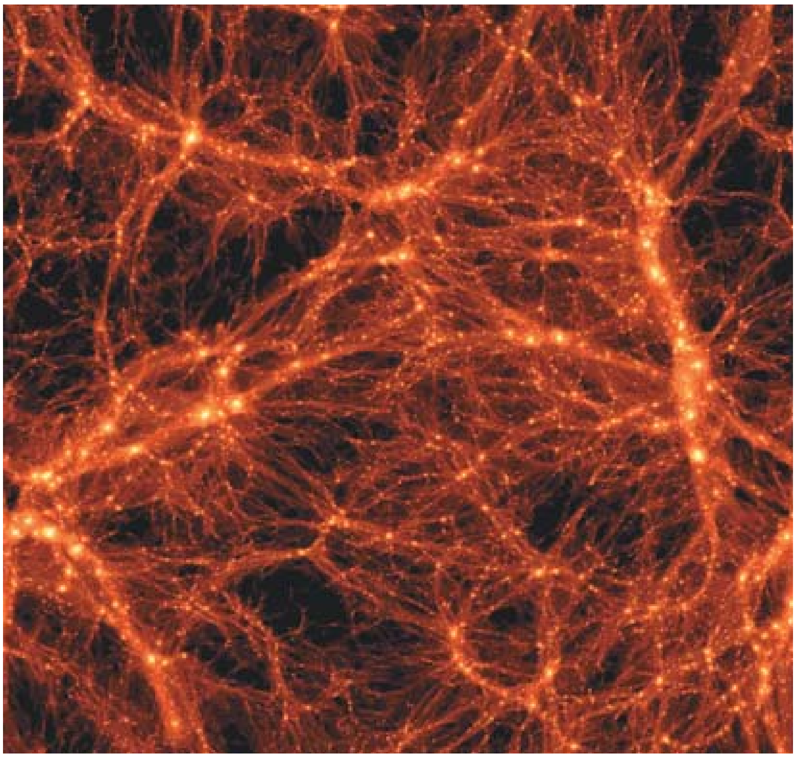
The future, for CMB observation experiments, is set to follow a twofold course. In the short term, numerous ground-based experiments (the South Pole Telescope, the Atacama Cosmology Telescope…) are planned, for the purposes of mapping the CMB at a very high angular resolution, i.e. better than 1 **minute of arc** (arcmin). Such experiments require large-diameter mirrors (about 10 meters), and leading-edge technologies as regards detectors (**bolometers**). They should result in the detection of most of the galaxy clusters lying within their fields of observation. In the longer term, European and US teams are proposing a satellite, as a follow-on to Planck – the BPol, CMBPol projects – along with ground-based experiments, e.g. BRAIN (Background Radiation Interferometer), EBEX (***E*** and ***B*** Experiment), and numerous other projects. All of these projects have the purpose of measuring the **polarized** components of the cosmic microwave background, these reflecting the motions of matter, at the time when that radiation was emitted. Thus, 17 years after the initial findings from COBE were released for publication, marking the birth of modern observational cosmology, a new scientific community is seeking to avail itself of the resources it requires, to set out, in full detail, the scenario governing the formation of the large structures of the Universe.

> Dominique Yvon
Particle Physics Service (SPP)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
CEA Saclay Center

The cosmic web

The Universe, initially practically homogeneous as it was, now stands as a discontinuous structure (objects, and "voids"), and a strongly hierarchical one. The largest objects, at present, are galaxy clusters. These stand as the outcome of the evolution of the Universe, due to gravity.

The Universe, as we now observe it, is anything but homogeneous. It even exhibits a markedly hierarchical organization: **stars** are herded into **galaxies**, which in turn come together, marking out a veritable three-dimensional network, or "web." Indeed, galaxies are distributed across sheets that delimitate vast, nearly empty cells. The intersections of such surfaces stand out as filaments, along which most of the galaxies are concentrated. At the intersections of these filaments, in turn, **galaxy clusters** are to be found, huge concentrations that may hold up to several thousand galaxies. How did the Universe come to be so structured? This is one of the main issues faced by **cosmology**. Observation of the **cosmic microwave background** (see *The grand thermal history of the Universe*, p. 62) shows that the Universe consists, to 85%, of **dark matter**, this being distributed, initially, in near-homogeneous fashion. The tiny departures from homogeneity that are found in the diffuse cosmic background undoubtedly stand as the origin of such structures as are observed at the present time, these arising chiefly owing to **gravitation** (see *Seeking out the great ancestors*, p. 52). Denser regions draw in to themselves the matter surrounding them, while less dense regions gradually become depleted. The Universe thus becomes increasingly heterogeneous, as time goes on. However, the expansion of the Universe, tending as it does to dilute matter, does limit this process.



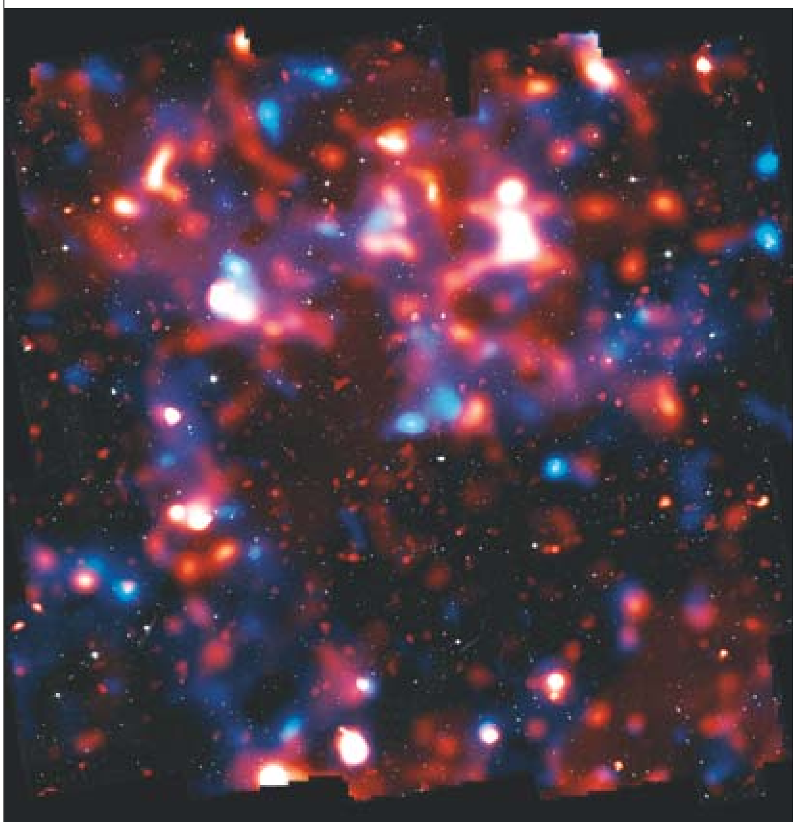
C. Pichon, R. Teyssier 2007

Present distribution of dark matter, in a region 100 × 100 × 10 million **parsecs** across, from a model of the Universe simulated under the aegis of the **Horizon Project**.

Dark matter as the motive power of evolution

In order to control their understanding of structure formation, astrophysicists constantly compare the predictions from their **models** with observations. This however raises twin issues. The characteristics of the initial distribution of dark matter are presently known with sufficient precision to allow its evolution – due to the effects of gravitation, in an expanding Universe – to be simulated, using powerful computers. The outcome is indeed a large-scale, web-like structure. The first issue, inherent in **simulation**, has to do with visible matter. Intuitively, this should "follow" the concentration of dark matter, and be structured in similar manner; however, demonstrating this is no easy task. Indeed, star and galaxy formation, as indeed the evolution of intergalactic gas, within dark matter structures, involve highly complex processes, that are not readily modeled (see *The formation of the structures of the Universe: the interplay of models*, p. 68). The other issue, of an observational nature, is, obviously, that of mapping actual dark matter. A real challenge for astronomers…

Be that as it may, in 2007, an international team of astronomers, including participants from the Astrophysics Service at CEA/IRFU, published the first three-dimensional map of all matter – both luminous, and dark matter – for a portion of the sky. This, in the event, is the COSMOS (Cosmic Evolution Survey) field, a region of the sky about 9 times the size of the apparent area of the Moon. Astronomers made use of the **gravitational lensing effect** to obtain an indirect measurement of the large-scale distribution of dark matter (using the Hubble Space Telescope). As for the distribution of visible matter, this was measured using ground-based instruments, including Japan's Subaru Telescope, sited in Hawaii, the Very Large Telescope (VLT), sited in Chile, and the Canada–France–Hawaii Telescope (CFHT); and, in space, the XMM–Newton observatory (see *Journey into the lights of the Universe*, p. 90) (see Figure 1). For the first time, maps were obtained for a range of different distances, and thus of different ages of the Universe. These show that the distribution of dark matter undergoes an evolution over time, in accordance with the laws of **gravity**. The various components of visible matter are distributed within structures determined by the density of dark matter. These findings corroborate the cosmological model, which predicts that the formation of the structures of the Universe is dominated by the dynamics of dark matter.



NASA, ESA and R. Massey (California Institute of Technology)

Figure 1.
This image shows the three components observed in the COSMOS survey: dark matter (shown in blue), X-ray luminous matter, as viewed by XMM–Newton (red), and the stars and galaxies observed in visible light with the Hubble Space Telescope (white).

The nodes in the cosmic web

The model for galaxy, and galaxy cluster formation, within large structures, is based on the concept of "hierarchical collapse" (see *The grand thermal history of the Universe*, p. 62). Once a clump of matter becomes sufficiently dense, it collapses onto itself, thus decoupling from expansion.(1) Initially, small overdensities collapsed, resulting in the formation of the first stars, and galaxies. The first groups of galaxies arose subsequently, at a redshift(2) of around 2. Since that epoch, clusters have formed, and have grown, through continued **accretion** of the matter surrounding them, and the occasional merging of clusters. Galaxy clusters thus stand as the most recent manifestation of such hierarchical formation of structures. Located at the intersection of cosmic filaments, these are the largest "objects" in the Universe, i.e. the most massive structures to be decoupled from expansion. Their composition reflects that of the Universe as a whole: 85% dark matter, 15% visible matter. The latter chiefly consists of hot gas (at several tens of million degrees), observable in the **X-ray** region. Galaxies, observed in **visible light**, account for less than 3% of the total mass.

What kind of evolution did clusters themselves undergo? X-ray observation, involving such modern observatories as XMM–Newton, and Chandra, played a central part in the advances recently achieved in this area. XMM–Newton, featuring as it does a very large collecting area, has the ability to detect, and investigate distant clusters. A CEA team, steering the XMM Large-Scale Structure Survey program, thus discovered new groups, and clusters of galaxies, at distances of several billion **light-years**. The most distant cluster known to date, XMMXCS 2215–1738, observed at an epoch when

(1) As the Universe is expanding, particles and objects are receding from one another. This is true except within an "object," inside which gravitation holds the constituent parts together, the general expansion notwithstanding.

(2) As the Universe is expanding, light sources recede from the observer, and their frequency, as detected, appears to decline over time. An object's **emission spectrum** thus proves further shifted to lower energies, the more distant it is (i.e., the older its light is). This spectral shift (redshift), noted z, yields a measure of the age of the emitting object.

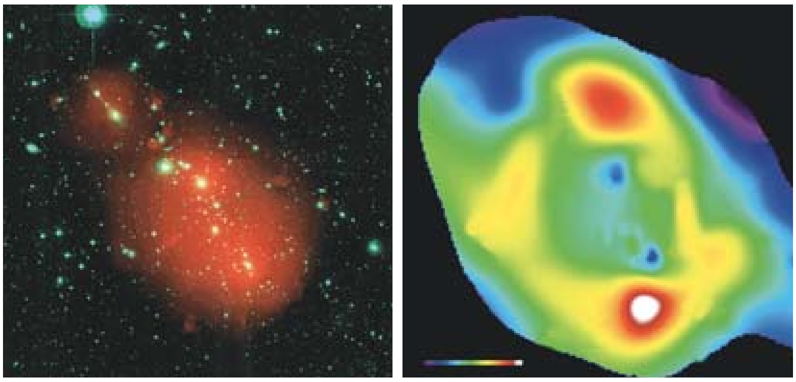
the Universe was one third of its present age, was likewise discovered using XMM–Newton. Such observatories make it possible not only to obtain images, in other words to map the gas density distribution, but equally to ascertain the X–ray emission **spectrum** for every point in the cluster, thus allowing a precise temperature map to be drawn up. Astrophysicists were thus able to compute in what manner gas pressure declines, from the center of the cluster to the periphery. When the cluster stands at equilibrium, the forces of gravitation due to dark matter counterbalance gas pressure. Observing a sample of equilibrium clusters, the teams at CEA, and at the **Max-Planck-Institut für extraterrestrische Physik** (**MPE**) found that the distribution of dark matter stands in remarkable agreement with predictions from numerical simulations of cluster formation. More astonishing still: these observations even yield some information as to the nature of dark matter. The distribution, indeed, is found to be strongly peaked (narrow) at the center, which rules out models in which dark matter particles undergo strong interaction by way of processes other than gravitation.

Matter that is visible... but poorly understood

While the formation and evolution of clusters, seen as large dark-matter structures, do appear to be adequately understood, such is not the case as regards the behavior of visible matter, which proves far more complex than that of dark matter. The gas temperature maps obtained with XMM–Newton and Chandra show that some clusters are indeed in the process of merging (see Figure 2), in accordance with the hierarchical formation scenario. These maps further highlight the full extent of the violent character, and complexity of this phenomenon. During the collision, kinetic energy is dissipated in the form of thermal energy, by way of the formation of shockwaves, but equally of **turbulence**. Astrophysicists observe, in some merging clusters, a **synchrotron emission**, indicating the presence of **relativistic** particles. The shockwaves and turbulence probably also act to accelerate these particles. The gas, and dark matter end up gradually stabilizing, forming a new, more massive, hotter equilibrium cluster. However, observation of such equilibrium clusters shows that the energy of that gas is higher than anticipated. Astrophysicists have no clear understanding of where such excess energy comes from, a number of processes, apart from gravity, being liable to alter the gas's thermal balance. The gas undergoes radiative cooling. On the other hand, **supernova** explosions, and **active** galactic **nuclei** may inject energy into the intergalactic medium. The evolution gas undergoes, within clusters, is thus affected by the galaxies. Conversely, the evolution of galaxies depends on their environment. This evolution is found to be different for cluster galaxies, and isolated galaxies.

Questions for the future

What is the part played by processes other than gravity, in the formation of visible matter structures? To what extent is evolution interdependent,



J.-L. Sauvageot/SAp/CEA - S. Maurogordato/OCA/CNRS

Figure 2.
Galaxy cluster A2440. The composite image, at left, shows the galaxies observed in visible light, using **ESO**'s 2.2-meter telescope – the MPG–ESO telescope (run by the **Max-Planck-Gesellschaft** [**MPG**, Germany]), at the La Silla observatory (Chile) – (shown in green), and hot gas, as viewed in X-radiation by XMM–Newton (red). The image of the gas reveals that this cluster comprises, in fact, two smaller clusters, centered on the two largest galaxies, and a third group, seen top left. The temperature map (right) shows that the two clusters are in the process of merging: the hotter regions (yellow/red) correspond to a shockwave, generated by the encounter.

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.

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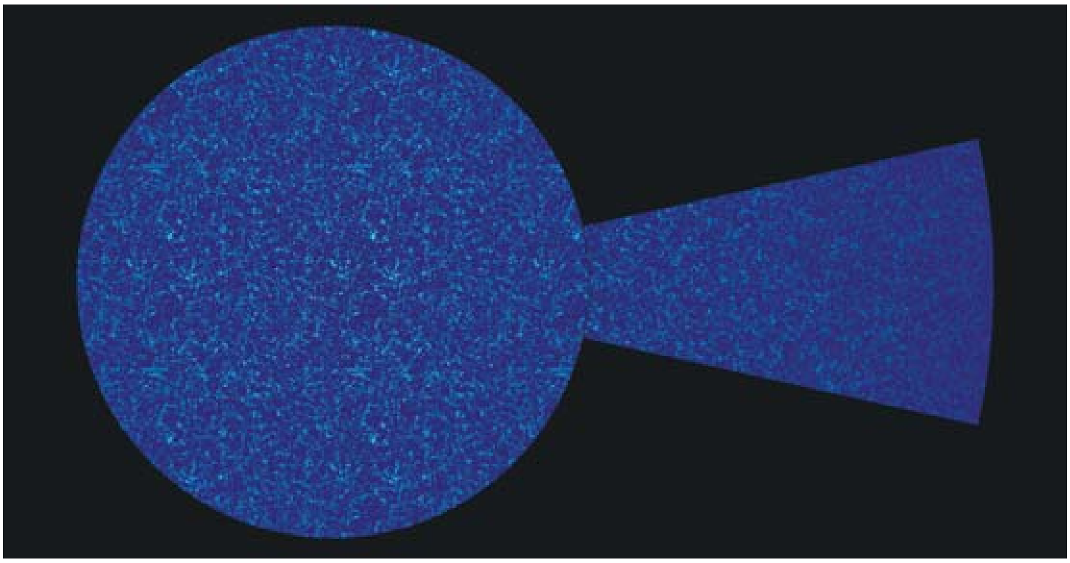
a crucial role. Advances made with new techniques, e.g. measurement of the **Sunyaev–Zeldovich effect**, of the gravitational lensing effect, or of galactic **infrared** emissions, will make it possible to survey clusters at several **wavelengths** simultaneously, which had proved unfeasible so far, except for small samples. The Herschel Space Observatory, put into orbit, along with the Planck satellite, by an Ariane 5 launcher, in May 2009, will help elucidate the impact of the environment on star formation, within galaxies. The Planck satellite will detect, by way of the Sunyaev–Zeldovich effect, most of the massive clusters, across the entire sky, these clusters subsequently being investigated more closely by XMM–Newton (see *Journey into the lights of the Universe*, p. 90). The European Low-Frequency Array (LOFAR) **radio-wave** observatory will enable a better understanding to be gained of particle acceleration in galaxy clusters.
Direct observation of the history of galaxy clusters, from the formation of the first groups of galaxies, does however remain beyond the capabilities of current X-ray satellites. This is one of the chief remits of the next generation of satellites, such as the International X-ray Observatory (IXO), proposed under the aegis of **ESA**'s "Cosmic Vision" program. The Euclid project, likewise being put forward as a candidate for this program, will use the gravitational lensing technique to carry out a survey of dark matter across one half of the sky, and to effect the direct detection of clusters, as dark matter structures (see *Euclid, mapping the extragalactic sky*, p. 111).

> Monique Arnaud
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

The formation of the structures of the Universe: the interplay of models

Unable as they are to take the Universe into the laboratory, astrophysicists are developing numerical models for the purposes of describing the evolution of the Universe. The resolution of such models is improving, from one generation to the next, however many puzzles do remain, in particular as regards the nature of dark matter, and dark energy.



The light cone representing the fraction of the observable Universe simulated, in 2007, by the Horizon collaboration, using the Bull Platine computer at **CCRT**, a component in CEA's scientific computing complex. This high-performance simulation, taking in nearly 70 billion particles, and more than 140 billion mesh cells, will allow astrophysicists to predict the distribution of matter, across the Universe, with unprecedented precision, and realism.

R. Teyssier/CEA

Our vision of the Universe has much changed, over the centuries. In the *Divine Comedy*, Dante Alighieri (1265–1321) described the Cosmos in these terms: the **planets** move on concentric spheres, referred to as mobiles, with the Earth at the center. The fixed **stars** revolve on an outer sphere, beyond which lies the ultimate, outermost sphere, known as the *Primum mobile*, or "first moved." The imaginary traveler of which Dante tells the tale discovers that, beyond this *Primum mobile*, there is a tremendous light, which, by way of the *Primum mobile*, sets in motion all of the other spheres. This poetic vision of the cosmos could stand as a **model** of the medieval Universe, however its language is oddly consonant with the modern view of **cosmology**. Going beyond the poetic aspect, this vision is further akin to a scientific model, inasmuch as it allows predictions to be made of planetary motions across the heavens. The retrograde motion that some planets are ill mannered enough to describe did seem to run counter to the model, however, by means of the theory of *epicycles*, it proved possible to account for this relatively simply, without ruining the entire edifice.

The content of the Universe

Before going on to give an account of the current model of the Universe, it will be in order to draw up a succinct gallery of the objects making up the large-scale population of the cosmos. As for the planets, on the other hand, they lie within our own immediate environment. Modern cosmology has the purpose of describing far larger, much more distant objects: **galaxies**, including our own Galaxy, the **Milky Way**. These huge, awesome objects consist of hundreds of billions of stars just like our own **Sun**. Exhibiting a wide variety of colors, and shapes (**spiral**, **elliptical**, **irregular**), galaxies follow a distribution, across the Universe, that conforms to a highly distinctive structure, known as the cosmic web. Galaxies are formed, and evolve within the vast filaments of this web (see *The cosmic web*, p. 65).

Pushing their observations even further out, astronomers discovered the now widely known **microwave** radiation – the **diffuse cosmic background**, or fossil radiation (see *The grand thermal history of the Universe*, p. 62) – that yields a snapshot of the Universe, as it stood when it was 380,000 years old. This yellowing likeness of a juvenile Universe is of prime importance: it gives us access to the initial conditions that prevailed in the Universe. What does the observer find there? An essentially homogeneous sky, exhibiting minute fluctuations, with an amplitude of 1 part in 100,000. A fitting simile would be that of a quiet lake, at the surface of which, nevertheless, a careful observer can make out tiny wavelets, ever so slightly disturbing it. The origin of these fluctuation remains, as yet, a mystery. The most plausible theory is inflation theory. This involves fluctuations in density, at **quantum** scales, in the **primordial** Universe, followed by a phase of inflation, blowing up these quantum fluctuations to cosmic scales. Be that as it may, astronomers can observe these fluctuations directly, at the point, 380,000 years after their root cause, when the Universe became transparent, dropping the veil that had cloaked its actual nature.

The Big Bang... and after

The current structure formation model is based on the **Big Bang** theory, itself based on the assumption of an expanding Universe, as described by **general relativity**. Intended as a derogatory term by British astrophysicist Fred Hoyle, to deride this notion, the term "Big Bang" has nonetheless become the "official" name for the theory! Subsequent to the initial singularity – this playing the selfsame role as Dante's *Primum mobile*, in initiating universal expansion – the Universe expanded, and cooled down, this gradually resulting in the emergence of particles, and their **interactions**. This model involves three main components: ordinary matter (the **atom**, and its constituents), this only accounting for 4% of total energy; **dark matter** (about 24%); and **dark energy** (72%) (see *The formation of galaxies: a story of paradoxes*, p. 56). As is apparent from their names, the nature of the latter two new components still eludes physicists. Dark matter is a self-gravitating[(1)] fluid, a collisionless fluid however, this precluding, for the time being, the detection of dark matter.[(2)] Its **gravitational** signature does, on the other hand, provide indirect evidence of its presence. Dark energy, in turn, proves yet more baffling. This was introduced recently into the model, to account for the sudden acceleration that seems to have become a characteristic of universal expansion, over the past few billion years. Dark energy could be related to some new fluid, exhibiting novel properties, involving only very-large-scale action. These components do stand as two "hard points" in the current theory: it would be but a simple step to compare them to the notorious *epicycles* of the medieval model.

To continue with the sequence of structure formation. The primordial fluctuations then grew, due to the effects of gravitational instability: to go back to our lacustrine simile, the ripples gradually turned into a swell, with increasingly higher waves, to the point, ultimately, 100 million years later, where they formed breakers, resulting in the formation of the first stars. This phase of gravitational amplification is known as the *Dark Ages*, ending with the appearance of the first luminous objects. This marked the onset of the hierarchical formation of cosmological objects. The first galaxies to form were quite small: they would hold just one million stars or so. They subsequently came together, yielding larger galaxies. These in turn evolved, and collided with one another, yielding the massive galaxies that are found in the Universe at present: one of these being the Milky Way.

The simulated Universe

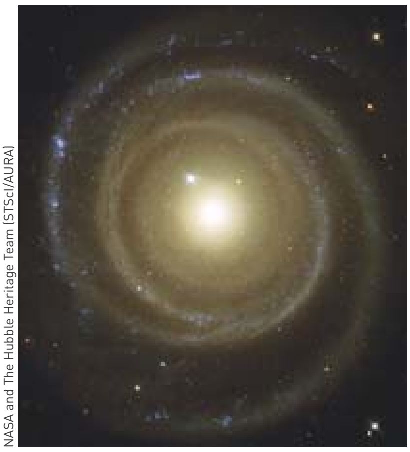
The model that allows this hierarchical assembly of galaxies to be described is identified as self-gravitating fluid mechanics. This is a relatively simple model, involving a few conservation laws, and gravitational interaction in the weak field approximation.[(3)] This model, simple though it may be, makes for analytical calculations that are extremely arduous to carry through. The equations involved are highly nonlinear, and involve chaotic processes. Now, it is a fundamental criterion, for a theory, to have the ability to make quantitative predictions. A good theory, indeed, needs must be falsifiable: it must lend itself to comparison with actuality, by way of the predictions it yields.

For the purposes of calculating the predictions entailed by its complex models, modern science consequently resorts to the computer. The triptych of theory, simulation, and experiment stands at the core of any scientific activity: nowadays, science "walks on three legs." This is all the more true of astrophysics, which science, obviously, is unable to reduce the objects it investigates to a laboratory experiment. Astrophysicists may only access actual reality by way of highly complex objects, that altogether resist any attempt at simplification. The computer thus plays a fundamental part, as mediator between theory, and observation. Nowadays, it is feasible to **simulate** the evolution of 70 billion pseudoparticles, through intensive use of supercomputers (see illustration, p. 68). It still proves unfeasible, unfortunately, to simulate the entire observable Universe, in sufficient detail to access the level of galaxies. Large-scale cosmological simulations only allow dark matter to be simulated. To allow comparisons to be made with observations, dark matter **halos** have to be furnished with a population of galaxies. This step is carried out, as a rule, by way of a phenomenological approach, also known as a semi-analytical approach, as it involves a mix of **numerical modeling**, and analytical modeling. While one should be aware of the limitations of such an exercise, the spectacular agreement should be emphasized, that is found to arise between this model, and the actual distribution of galaxies. Gravitational instability of cold dark matter would thus appear to afford the ability to account for large-scale structure formation in the Universe.

(1) As is the case for ordinary matter, dark matter is sensitive to gravitation, which slows down its dispersion.

(2) Collisions between particles cause the emission of **photons**, which may be detected at a distance.

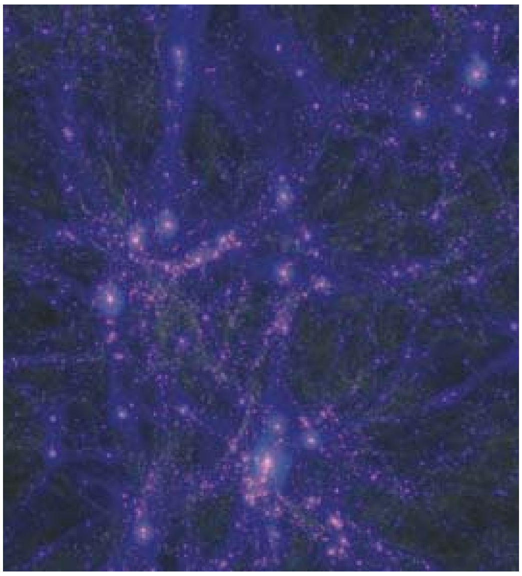
(3) This so-called "weak-field limit" restriction is required, if the Newtonian theory is to retain its validity. In strong (or nonstatic) fields, Einstein's theory (relativity) must be used.



At left, a true-color image of galaxy NGC 4622. At right, true-color image of a galaxy simulated with the RAMSES code, developed at the Astrophysics Service at CEA/IRFU, in the context of the hierarchical model. The agreement between model, and observation is outstanding.

Pending issues

At a smaller scale, the puzzle of galaxy formation stands undiminished. The theory, as worked out in the 1970s, assigns a central role to radiation. Collisions, arising between **hydrogen** atoms, result in the rapid



R. Teyssier/CEA

Mapping of gas, and star distribution in the MareNostrum simulation, carried out on the MareNostrum computer at the Barcelona National Supercomputing Center (Spain).

cooling down of the cosmic **plasma**. The latter is no longer able to resist **gravitational attraction**, and the gas halos swiftly collapse, yielding structures where a centrifugal equilibrium prevails: galactic disks. The microscopic properties of the hydrogen atom would thus stand as the root cause for the galaxies' mass. Numerical modeling, for this scenario, raises numerous issues, chiefly relating to the limited resolution featured by the computations. To overcome this difficulty, the **Horizon collaboration** opted to model an artificially small (150 million **light-years**) virtual Universe, in order to access the scale of galaxies. The MareNostrum simulation – carried out on the MareNostrum computer at the Barcelona National Supercomputing Center (Spain) – nevertheless stands as one of unrivalled magnitude. This evidenced the emergence of disks featuring a spiral structure, involving several thousand mesh **cells** per galaxies. Be that as it may, numerous problems still remain: the galaxies, as simulated, are too small, while containing

Does the Universe have a shape? Is it finite, or infinite?

Cosmological models are constructed within the framework of Einstein's **general relativity**, which theory interprets **gravitation** as the outcome of the curvature of space, induced by the distribution of matter, and energy. On the assumption that space is homogeneous, and **isotropic**, the most recent cosmological measurements would appear to point to a very slight curvature of space. Astrophysicists consequently assign a Euclidian geometry to the Universe. Repugnant as it is to them to entertain the notion of a Universe bounded by an edge – to preclude the unsettling question: "What is there, beyond the edge?" – they deem the Universe to be infinite. And yet, mathematicians have long since shown that a space may be both finite *and* without edges – the surfaces of a sphere, or of a torus being two such instances. A hypothesized being, making its way across the surface of a torus, would have the illusory impression of living on an infinite surface, since there would be no edge to restrict its movements. It would doubtless draw the conclusion, from this, that its observable Universe is infinite, whereas its actual Universe is in fact finite (see Figure 1). The application of this notion to cosmological models is quite telling.

What would the Universe look like, were it to close back onto itself, in the manner of a torus? In order to reach the observer, the light emitted by a distant **galaxy** could follow a number of different paths: it could take the most direct path, but equally, out of an infinity of other possibilities, it might follow another path that would go round the Universe – the surface of the torus – by setting off in the "opposite" direction to the previous path. The selfsame source would thus be seen a multiplicity of times, in various directions, and the sky would appear to be filled with numerous phantom galaxies – the images of a handful of actual galaxies. The observer would have the illusion of living in a Universe much larger, and altogether fuller than it actually is (see Figure 1).

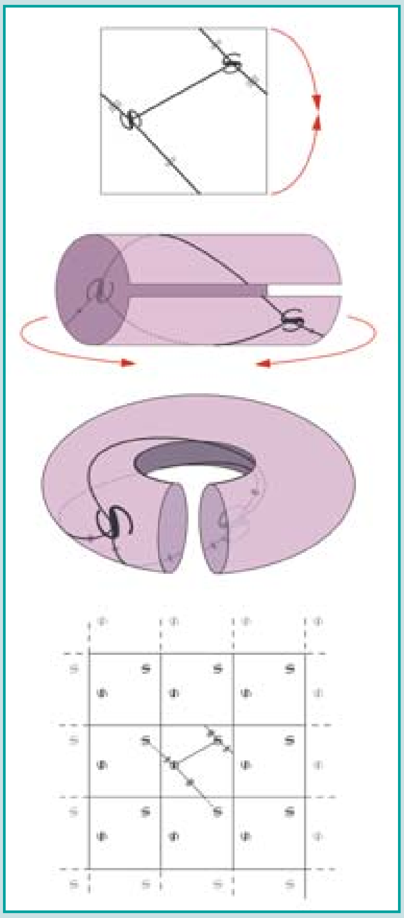


Figure 1.
Principle construction of a finite, two-dimensional Universe featuring no edges: the opposite sides of a square are identified. An observer living on the surface of such a Universe would have the illusion of living on an infinite plane.

ESO

What is the shape of the Universe? Is it finite, or infinite? It would appear that the answers to such millennia-old queries may at last be accessible to our observations, and our cosmological models.

too many stars, to mention but two issues. This type of simulation, indeed, has to address a new problem: the simulation of star formation. Current star formation models likewise rely on a phenomenological approach. Every time an advance is made, by physicists, with respect to the mathematical description of the model, a new cognitive horizon emerges, and the solution yet escapes them. The previous generation of simulations sought to simulate dark matter, galaxies standing as the model's boundary. The current generation addresses the modeling of galaxies, the new boundary being star formation. Extrapolating Moore's law,(4) it seems certain that the next 10–20 years will see the advent of simulations affording the ability to simulate every star individually, this presumably involving some new cognitive barrier, that will have to be overcome.

(4) The empirical law, stated in 1965 by US electronics engineer Gordon Moore, and which stands uncontradicted by events to this date. This law states that component density, on a processor chip, doubles every 2 years (a figure subsequently brought down to 18 months). Computing power follows the same curve. This exponential progression should come up against physical limits around 2015.

> Romain Teyssier
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

FOR FURTHER INFORMATION

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What the cosmic microwave background tells us

Indications as to the shape of the Universe may be looked for in the **cosmic microwave background**. This radiation, emitted 13.7 billion years ago, at the time when the Universe became transparent, appears to have been emitted by the surface of a vast sphere, with the Earth at its center.(1) The temperature of this radiation exhibits minute fluctuations, of the order of one-thousandth of one percent. The angular distribution of these fluctuations may be decomposed into its spherical harmonics,(2) just as a sound is analyzed into its ordinary harmonics. The amplitudes appearing in this decomposition depend on the geometry of the space involved, and the physical conditions prevailing at the time when the cosmic background radiation was emitted. The shape of that space likewise has an impact on these amplitudes. Thus, amplitudes are equal to zero, if the wavelengths are longer than the "circumference" of the Universe. Just such an absence of long wavelengths was found in the observations made by the US Wilkinson Microwave Anisotropy Probe (WMAP) satellite, from 2003 to 2006. On the basis of this finding, a new cosmological model was put forward, as an alternative to the standard model, which is Euclidian, and infinite: the Universe would have the topological structure of the Poincaré dodecahedral space, which features a spherical geometry (see Figure 2). At the same time, this model predicts the existence of specific correlations within the cosmic microwave background – pairs of "homologous" circles, along which temperature fluctuations would be identical.

From 2003 on, three separate teams (one US, one German, one Polish team) have been looking at ways to test this model, using a variety of statistical indicators, and massive **numerical simulations**. No clear answer has emerged, since the anticipated signal is degraded, owing to a variety of cosmological effects, contaminations of astrophysical origin, and instrumental inadequacies. Be that as it may, the most recent analysis, carried out using sophisticated statistical methods, would seem to favor the existence of dodecahedral symmetry in the map of the sky produced by the WMAP satellite. New observations will be required, obviously, for that model to be validated, or otherwise. To assist in the debate on the issue, the data from the European Planck satellite, launched in May 2009 (see *Journey into the lights of the Universe*, p. 90), are eagerly anticipated. Presently, the issue of the shape of the Universe(3) has left the realm of metaphysical speculation. The coming years will bring a wealth of finescale cosmological observations, and should result in further, novel departures in our representations of the Universe. Doubtless they will allow the issue of the shape of the Universe to be decided...

(1) The Earth, or, more accurately, the position from which the observation was made. There are good grounds, indeed, for believing that the picture would be identical, regardless of the position. The Earth has no special position in the Universe.

(2) Spherical harmonic: a spherical function, used, in a mathematical context, when the notion of direction (**anisotropy**), and thus of rotation, is involved. It is characterized by a Laplacian (differential operator) equal to zero.

(3) For further information: Roland Lehoucq, *L'Univers a-t-il une forme ?* Flammarion, "Champs" series, 2004.

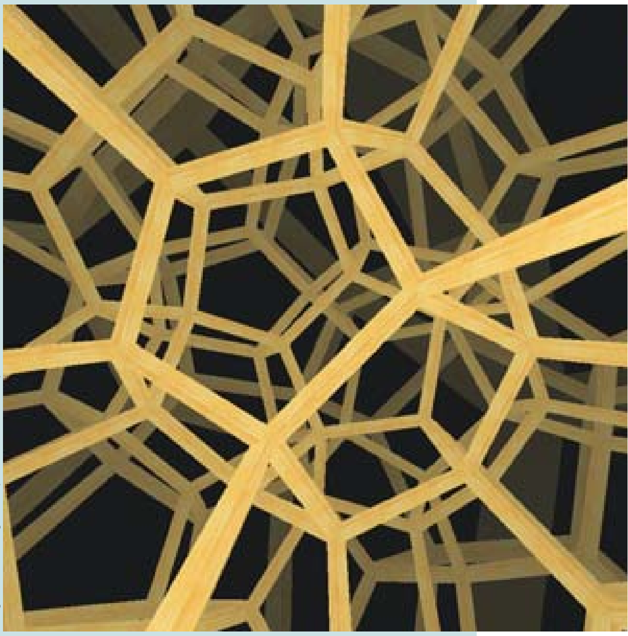


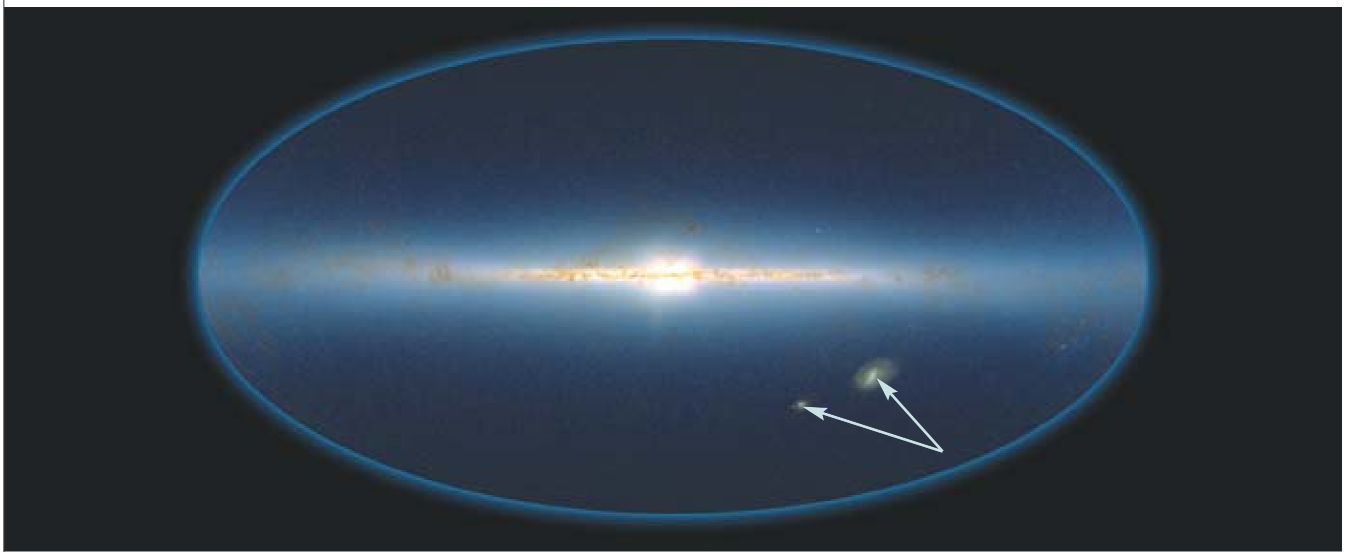
image made using Jeffrey Weeks' Curved Spaces software

Figure 2.
The Poincaré dodecahedral space is a finite, spherical space having no edges, constructed by identifying the opposite sides of a regular dodecahedron, after rotating it by one-tenth of a turn. This model accounts in satisfactory fashion for the temperature fluctuations appearing in the cosmic microwave background, at large angular scales.

> Roland Lehoucq
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling"
(CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

Odyssey across **the dark side of the Universe**

Could cosmology have entered one of the most exciting stages in its history?
Astrophysicists, and particle physicists are inclined to think so, considering the wealth of data yielded by the observatories they have set up, whether ground-based, underground, or in space, in their endeavor to unravel the mysteries of the way the Universe is structured. From the analysis of these data, they anticipate a clearer picture, regarding the various versions that have arisen, of the best known of cosmological models: the Big Bang.
At the same time, they further hope that these data may soon enable them to roll back part of the veil cloaking the twin puzzles of dark matter, and dark energy.



California Institute of Technology-NASA

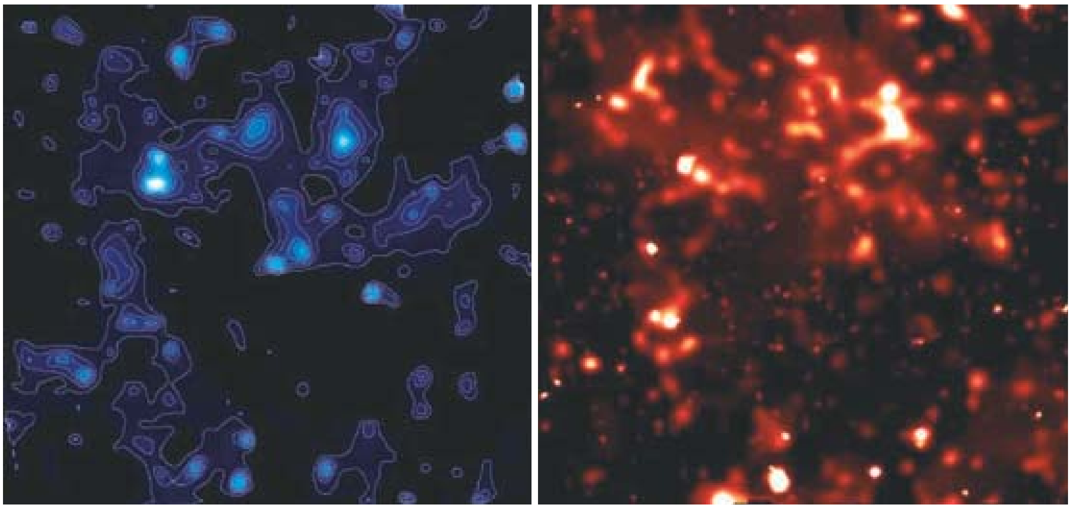
The Milky Way, viewed in the infrared region, together with the Magellanic Clouds, two satellite galaxies of our own Galaxy, appearing at bottom right in the picture. This is a mosaic image, obtained by the Two-Micron All-Sky Survey, a joint program of the University of Massachusetts and the California Institute of Technology, funded by NASA.

1. The puzzle of dark matter

Astrophysics and the observation of dark matter

Bringing together tens of billions of stars as they do, galaxies may in turn form groups of tens, or hundreds of galaxies, likewise coming in clusters. The motions of such galaxies have long puzzled astrophysicists, the more so since recent investigations have found that a fraction of the mass of the Universe eludes the observations of researchers. Might the atom then prove to be just the emerged froth of matter?

Occasionally, it does happen that a heavenly body is discovered through sheer calculation. Thus, in 1844, German astronomer Friedrich Bessel(1) attributed anomalies found in the apparent proper motion of the star Sirius to the presence of an unseen "companion." 18 years later, this calculation was corroborated, with the discovery of a **white dwarf**, resulting in Sirius being seen as a binary **star**. Shortly after this, Urbain Le Verrier(2) and John Couch Adams(3) both considered that an unknown planet might be the cause of disturbances in the motion of Uranus, a motion that was, here again, held to be "anomalous." Taking up Le Verrier's indications, German astronomer Johann Galle(4) subsequently observed the **planet** Neptune, less than one degree away from the position computed on the basis of the discrepancies in the motion of



R. Massey/NASA

Map of dark matter (shown in blue, at left), and visible matter (red, at right), for the same region of the Universe. The denser concentrations of matter are found to be identically located in both images, this showing that visible matter concentrates in those regions where dark matter predominates.

Uranus, with respect to **Newton's laws**. In 1932, Jan Oort[5] was investigating the velocity distribution for stars lying in the vicinity of the **Sun**, in order to determine the local gravitational field. He suggested that these stars only amounted to one half of the quantity of matter required to account for their motions. Concurrently, US physicist Fritz Zwicky[6] was investigating the velocity distribution for **galaxies** in the great galaxy cluster lying in the northern constellation known as Coma Berenices (Berenice's Hair). In 1933, he was likewise able to suggest that the galaxies in this **cluster** only totaled 10% of the mass required to account for the velocities measured. The major part, by far, of the mass of the cluster should thus be a nonluminous form. Despite its importance, this discovery made but little impact, and more than 40 years had to go by, before the buildup of data, all pointing to the same conclusion, again made it come to the fore. Nowadays, nearly 80 years after Fritz Zwicky's observations, his conclusions are seen as confirmed: a major fraction of the mass of the Universe is indeed nonluminous!

Dark matter thus raises a range of issues – related, or unrelated – which arise equally at the scale of galaxies, of galaxy clusters, or of the Universe as a whole.

Galactic dark matter

The rotational velocity of a spiral galaxy is measured by way of the **Doppler shift**, either of the light from stars making up the disk of that galaxy, or from neutral **hydrogen** clouds located outward of the galaxy's luminous edge. The curve thus obtained, plotting the disk's rotational velocity, as a function of distance from the galaxy's center, makes it possible to determine the galaxy's mass distribution, just as a planet, orbiting around the Sun, makes it possible to derive the Sun's mass, once the distance between the Sun and that planet is known. However, the fact is that the comparison between this mass distribution, as determined on

(1) Friedrich Bessel (1784–1846), German astronomer and mathematician, founder of the German school of observational astronomy.

(2) Urbain Le Verrier (1811–77), French astronomer and mathematician, specializing in celestial mechanics.

(3) John Couch Adams (1819–92), British astronomer and mathematician; he predicted the existence of the planet Neptune, and its position, purely on mathematical grounds.

(4) Johann Galle (1812–1910), German astronomer, working at the Berlin Observatory.

(5) Jan Oort (1900–92), Dutch astronomer, director of the Leiden Observatory, 1945–70; he carried out numerous investigations concerning our Galaxy.

(6) Fritz Zwicky (1898–1974), US Swiss-born astrophysicist, renowned as the greatest discoverer of supernovae.

ESA

Image of spiral galaxy NGC 3198, the rotation curve for which shows that its constituent stars contribute but a small fraction of its mass. It would appear that, as is the case for many other galaxies, this galaxy is embedded in a massive halo of dark matter.

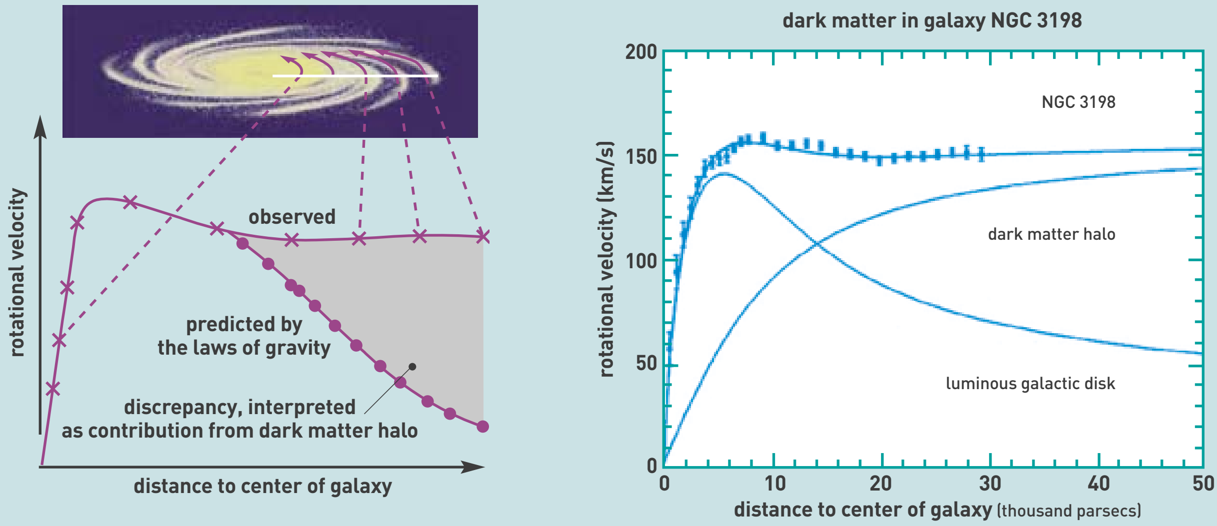


Figure 1.
The rotational velocity of spiral galaxies suggests that they contain a major quantity of dark matter. Indeed, contrary to the decline predicted, on the basis of the decreasing luminosity of the stellar disk, as distance from the galactic center increases, rotational velocity, as measured, remains constant.

the basis of the galaxy's gravitational influence, and as estimated on the basis of stellar **luminosity**, shows up a marked discrepancy. Indeed, as the luminosity of the stellar disk declines exponentially with increasing distance from the galactic center, everything would seem to point to the mass of the galaxy being chiefly concentrated at the center; on the other hand, as rotational velocity remains constant, as far out as may be measured, this finding shows, on the contrary, that a major quantity of matter should be located in regions of low, or zero luminosity (see figure 1).
Systematic studies, covering thousands of galaxies, bear witness both as to the universal character of this phenomenon, and as to the presence of an excess of dark matter in virtually all spiral galaxies. This anomaly may be accounted for by the presence of a massive, broadly spherical **halo**, extending some 10–20 times further out than the stellar disk. According to the most widely held hypothesis, this dark halo was held to consist of compact, very dim bodies: planets, end-of-life stars that have burned all of their fuel (white dwarfs), or **black holes**. This hypothesis yet had to be verified: this was the purpose of the EROS experiment (Expérience de recherche d'objets sombres: Dark Objects Search Experiment), conducted by IRFU, which measured, night after night, the light from stars in two satellite galaxies of the **Milky Way**: the Magellanic Clouds. The aim was to look for a temporary light amplification, due to gravitation from a dim object in the halo, as it passed across the line of sight for one of the stars observed. Ten years' "hunt" made it possible to rule out the hypothesis whereby the dark halo of our own Milky Way was chiefly made up of nonluminous objects. As a result, the nature of this dark matter remained altogether baffling.

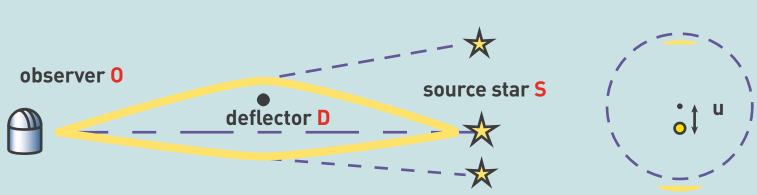
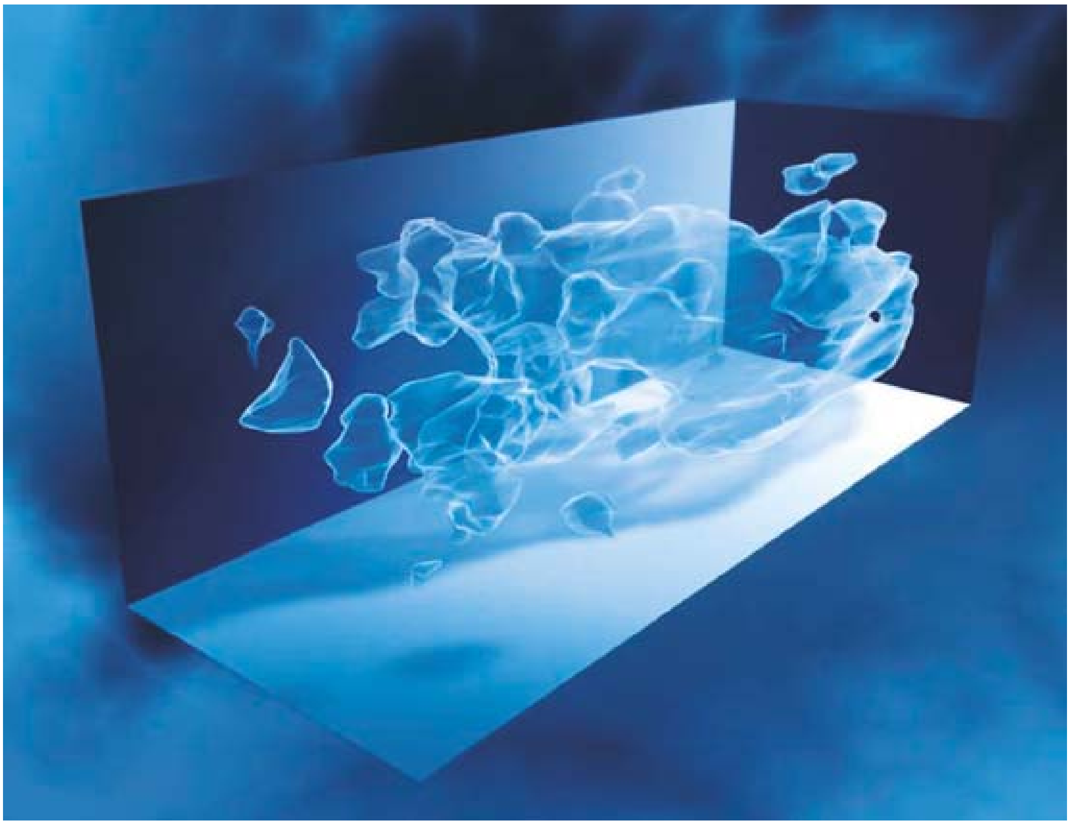


Figure 2.
Principle schematic of a gravitational mirage.
Left: the dim object at center distorts spacetime, altering the path of light rays passing in its vicinity.
Right: the two possible light paths each yield a distorted image of the star, or galaxy lying behind the object responsible for the gravitational mirage ("u", the impact parameter, stands for the distance between the massive object, and the line of sight to the star; the gravitational mirage effect is all the more pronounced, the smaller "u" is found to be).

Dark matter in galaxy clusters

The presence of dark matter in galaxy clusters was first suspected by Fritz Zwicky. In 1933, he suggested that the Coma Cluster contains markedly more dark matter than luminous matter. His analysis was based on a result from classical mechanics, the so-called *virial theorem*, whereby, in a system that stands dynamically at equilibrium, the sum of the potential energy, and double the kinetic energy is equal to zero. Hence, an immediate estimate of the mass of the galaxy cluster may be obtained, on the basis of its size, and the velocities of its constituent galaxies. This method, however, does leave a number of uncertainties, owing to the difficulties of making an inventory of the constituent galaxies in a cluster, while excluding galaxies that lie outside it, when very faint galaxies have to be counted. Moreover, the cluster does not always stand in



ESA/NASA

Three-dimensional map of dark matter, as derived from the distribution of arclets in the region of the Universe observed.

dynamic equilibrium (this being the condition of applicability, for the virial theorem), since the time for such equilibrium to be reached may exceed 10 billion years. Finally, conditions only allow a partial view to be achieved, since all distances are seen in projection, allowing measurement of radial velocities only.

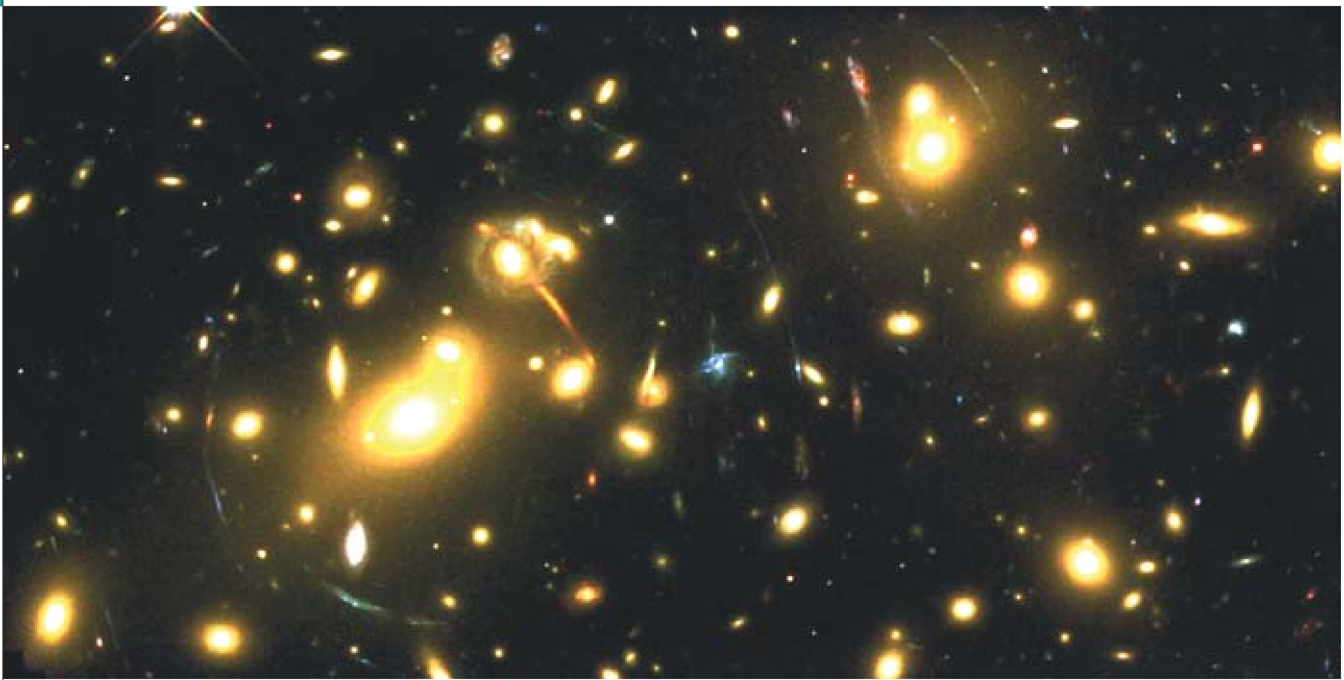
Be that as it may, the findings obtained by way of the analysis of X-radiation emitted by the diffuse hot gas located between the galaxies, in clusters, did subsequently corroborate this hypothesis. Measurements carried out by such satellites as Röntgensatellit (ROSAT), launched by Germany in 1990; or the **European Space Agency**'s (**ESA**) XMM–Newton, or **NASA**'s Chandra, both launched in 1999, yield unanimous findings: the gas lying around the galaxies does seem to be at equilibrium in the cluster's gravity field, this being generated by the galaxies, the hot gas itself, and dark matter. Further, the intensity of the X-ray emission from the gas allows not only the mass of gas to be computed, but equally the gravitational potential it lies in, and thus the total mass of the cluster. For a typical cluster, stars are thus understood to account for 2–4% of total mass, and hot gas for 12–16% only. Even allowing for their dark matter, as derived from investigation of their rotation curves, galaxies may thus be seen as negligible quantities, in the clusters' mass balance.

In 1986, another method, relying on the investigation of gravitational mirages, arising around galaxy clusters, corroborated these findings (see Figure 2). Among the more spectacular observations, mention may be made of **luminous arcs**, exhibiting redshifts markedly higher than that of the cluster. Astrophysi-cists interpret these as images of galaxies lying behind the cluster, distorted by the cluster's gravitational field. These are gravitational mirages, which may be understood by way of Einstein's **theory of general relativity**. Indeed, if gravitation is the outcome of the distortion imparted to **spacetime** by matter, and energy, then light itself becomes sensitive to gravity, since it travels along the shortest-path lines across spacetime, as curved by matter. Aside from luminous arcs, these observations further identified an even more frequent phenomenon, that of "arclets," these being small images of background galaxies, slightly distorted by the cluster's field. The distribution, orientation, and intensity of such distortions make it possible to reconstruct, with remarkable precision, the mass distribution for the cluster responsible for them. An international scientific team, including scientists from IRFU, thus produced the first three-dimensional map of the distribution of dark matter, across a region of the Universe.

These investigations, independent as they are from one another, are convergent in coming down in favor of high masses, for galaxy clusters. They thus corroborate the findings obtained by way of velocity distributions, and X-ray emissions.

Dark matter at the scale of the Universe

Investigation of the **radiation**, at 2.7 K, that pervades the Universe, at the present time, likewise makes it possible to determine the composition of the Universe as a whole. Where does that radiation come from? As our Universe is expanding, it needs must have gone through a phase where it was denser, and hotter than at present. After expanding for 380,000 years, the Universe had cooled down sufficiently for electrons and protons to come together, and form neutral hydrogen atoms. All the conditions required were thus present for the propagation of light, free from


NASA

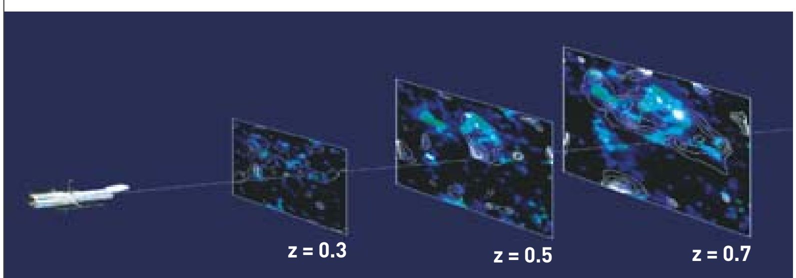
The luminous arcs, appearing around galaxy cluster Abell 2218, are distorted images of galaxies lying behind the cluster photographed here. The cluster's gravitational field acts as a lens, distorting background objects.

excessive interaction with matter. This fossil light has thus been carrying, down to our time, valuable information as to the conditions then prevailing in the Universe. Now, in this snapshot, taken at 2.7 K, minute temperature inhomogeneities appear, reflecting the existence of other inhomogeneities, in terms of density of matter, in particular. For astrophysicists, these are the seeds of galaxies, and galaxy clusters. In the context of the **Standard Model** of **cosmology**, statistical investigation of these inhomogeneities made it possible to arrive at an estimate of the density of matter, and energy present in the Universe, this resulting in a surprise: not only does the density of matter exceed, by a factor 10, that of luminous matter (stars, gas…), but the total density of energy, in the Universe, likewise exceeds that of matter (see *Astrophysics and the observation of dark energy*, p. 81). From this may be inferred the presence of a hitherto undetected energy component.

On the other hand, this investigation still holds some uncertainties. Thus, the validity of the findings being announced had to be tested, by way of independent studies. Recent measurements, relating to the spatial distribution of galaxies, would seem to favor an intergalactic separation of 150 million **parsecs**, matching a prediction from cold dark matter models (see *The theory of dark matter*, p. 77). This may be accounted for by the fact that small fluctuations, working across the primordial Universe – i.e. when it contained **photons**, electrons, and dark matter – evolved in the manner of a spherical **wave**, due to the effects of photon pressure, this persisting right up to the formation of the first hydrogen atoms. The photons, at that point, departed from the mixture, and the wave remained frozen, at the distance it had traveled over 380,000 years (this being the age of the Universe, when the wave froze). At the present time, this corresponds to a size of 150 million parsecs. Galaxies form in the denser regions, thus being located, essentially, at the position of the initial fluctuations, or lumps of matter, at distances of 150 million parsecs. The measurement of this distance confirms the density of matter across the Universe, thus corroborating the findings yielded by investigations of the 2.7 K radiation, together with the existence of a large quantity of dark matter, at the scale of the Universe.

> Nathalie Palanque-Delabrouille
Particle Physics Service (SPP)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
CEA Saclay Center (Gif-sur-Yvette)

> Roland Lehoucq
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)



R.Massey/NASA

Map of dark matter, according to distance, across three slices of Universe, corresponding to ages of 7 billion (z = 0.7), 9 billion (z = 0.5), and 10 billion years (z = 0.3), showing the gradual concentration of dark matter as cosmic evolution proceeds. z stands for the redshift. The higher z is, the greater the object's spatiotemporal distance.

The theory of dark matter

Even if the existence of dark matter has been suggested as early as in 1930 – that is as much as 80 years ago –, even if astrophysicists no longer question its existence, and even though it does prove five times more abundant, in all of the Universe, than ordinary matter... its true nature still stands as a puzzle, the solution of which is the driving force behind countless investigations, both at the theoretical and experimental level, each with its own bold vision. On the basis of our present knowledge, dark matter is an invisible form of matter which pervades galaxies, deflects light rays as they pass through galaxy clusters, and plays a crucial part in the formation of the large structures of the Universe, the cohesion of which structures it is deemed to ensure. What could it be?

Fifty years of investigations, in the fields of **cosmology** and particle physics, have resulted in researchers suggesting tens of "exotic" particles, bearing curious names such as "**neutralinos**," or "Kaluza–Klein particles." These particles owe their existence to theoretical constructions, e.g. supersymmetry, or **extra dimensions**, or yet more outlandish suggestions. Let us recap the stages that allowed scientists to become convinced of the existence of **dark matter**, and gave theorists the opportunity of exerting their imagination, in the endeavor to find the right solution to the puzzle.

What if dark matter didn't exist after all?
Observations show that **stars** at the periphery of some rapidly rotating **spiral galaxies** are subjected to a much stronger **gravitational attraction** than it would result from applying **Newton's law** to the visible matter present in the central regions of such **galaxies**. An idea then arises: what if, rather than hypothesizing the existence of invisible matter, some modification could be made to Newton's law, so that gravitational attraction would become stronger at large distances from the galactic center? Suggested, in the 1980s, by Mordehai Milgrom[1] under the name of modified Newtonian dynamics (MOND) theory, this idea, however much of a "rough-and-ready" solution it may be, does nevertheless raise a number of difficulties, particularly at the scale of **galaxy clusters**, and even more so at cosmological scale. These difficulties stem from the fact that the **spectrum** of the **cosmic microwave background** (**CMB**) – also known as the **diffuse cosmic background** – as well as the gravitational formation process of large structures show without doubt that the Universe really does require more matter than it is observed. As a result, the community of cosmologists is now of the opinion that it is unlikely that MOND could provide the solution to the dark matter problem.

What if dark matter was just ordinary matter "in disguise"?
The need to invoke the presence of an invisible mass led researchers to turn, as a first step, to already known, but elusive, ordinary-matter components: **black holes**, a rarified interstellar gas consisting of **protons**, or large numbers of neutrinos relics from the **Big Bang**. Here again, cosmological observations rule out these possibilities. If large numbers of black holes were present in galaxies, their effects would be seen, in the form of gravitational lensing, as they passed in front of light sources. If large amounts of protons occurred in gas form, they would abundantly emit X-rays, and would yield greater quantities of **helium** than is observed. Finally, the current constraints on the mass of neutrinos (which must be smaller than a few **electronvolts**) indicate that they are too light to stand in for the missing mass. Moreover, having such a tiny mass, neutrinos travel at high speed across the Universe: this prevents them from forming large structures, such as galaxies, which may only originate from heavy matter, able of gravitationally "condensing" in potential wells.

(1) Mordehai Milgrom, Israeli physicist, and professor at the Weizmann Institute.

NASA/Goddard Space Flight Center/General Dynamics

Artist's impression of the Fermi satellite, which has been orbiting the Earth since June 2008, with the purpose, in particular, of detecting high-energy (hundreds of gigaelectronvolts) gamma rays yielded by the annihilation of dark matter.

So, we really do need a new particle: what general properties should it exhibit?
Fortunately, even though still unidentified, this particle does leave clues as to its properties. First of all, dark matter must undergo weak, or very weak interactions – or even no interactions – with the remaining fraction of matter: it is thus very hard to detect. In particular, this particle exhibits no electric

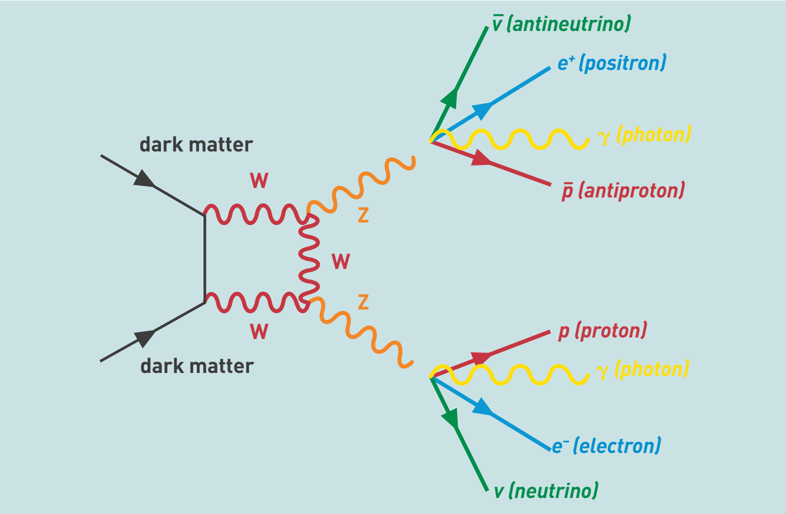


Figure 1.
Feynman diagram (so called after US physicist Richard Feynman, 1965 Nobel laureate) showing the annihilation of dark matter, yielding ordinary-matter end-products. Physicists use this type of diagram to work out the properties of the expected flux: each diagram describes, in precise mathematical fashion, the characteristics of the particles involved and their interactions. In the present case, two dark matter particles come together and annihilate into two weak Z bosons. Annihilation occurs by way of the creation, and instant destruction, of a complex loop of W bosons. Subsequently, the Z bosons decay into ordinary-matter particles, e.g. photons, neutrinos, positrons, antiprotons, etc. Such end-products are being actively looked for by a number of ground-based, and satellite-borne experiments.

charge, and thus does not interact with light (hence the name of "dark" matter). Second, cosmological data tell us that it must be "cold" (i.e. it must travel at velocities much lower than the speed of light) – this being the case for a particle that is fairly heavy, or created at rest. Finally, as it presumably was produced during the initial moments of the Universe, it must be stable, or possess a very long average lifetime – longer than the present age of the Universe. Otherwise, it would have decayed into ordinary particles well in the past.
The weak interactions undergone by dark matter with the rest of matter could very well be the well known Weak Interactions of the **Standard Model** of particle physics, namely those responsible for beta radioactive decay. Theorists actually consider this hypothesis as highly likely. Indeed, calculations show that the present abundance of a particle that had been produced at the time of the Big Bang and that has the typical properties of Weak Interactions would precisely amount to the missing mass. Such particles are known as **Weakly Interacting Massive Particles**, or **WIMPs**.

A few candidates matching the desired profile

Many particles exhibiting these properties, and thus many suitable dark matter candidates have been suggested, in the context of many novel theories in particle physics. One of the most widely investigated such particle is the neutralino, predicted by the theory of supersymmetry. Introduced into particle physics in the 1980s, this highly elegant theory suggests that, for every ordinary particle, a supersymmetric partner ("superpartner") particle exists, exhibiting the same properties (e.g., with the same electric charge), but much higher mass, estimated at around 100 gigaelectronvolts or so. The neutralino is one such particle, or, more accurately, it stands as a mixture of the superpartners of the **photon**, of the **Z boson** and of the **Higgs boson**. Moreover, the neutralino is supposed to possess one further property (known as **R-parity**) which may be seen as a new kind of charge to be preserved in any physical process. Consequently, the neutralino may not decay into ordinary particles, and it would thus be stable. For all these reasons, the neutralino ranks as a good dark matter candidate and it belongs to the WIMP category. The profusion of theoretical parameters involved means that the phenomenology of supersymmetric dark matter is actually richer and more complex than this simple sketch. The mass, composition, and precise interactions of the various constituents have been investigated in detail, for a number of models.
In the late 1990s, scenarios involving **extra spatial dimensions** (know as Kaluza–Klein(2) scenarios, after the two visionary theorists who first proposed them at the beginning of the 20th century) caught the attention of researchers. The assumption is that a fifth dimension exists, in addition to the three spatial dimensions, and time. Its configuration, in the form of extremely tight loops, would render it inaccessible to direct observation. A particle, if plunged into such


PAMELA collaboration

The Italian–Russian PAMELA (Payload for Antimatter–Matter Exploration and Light-nuclei Astrophysics) satellite, shortly before launch, in 2006. The data collected by this satellite revealed the existence of anomalous cosmic rays, causing an upheaval in the scientific community working on dark matter. Could these rays be due to the annihilation of dark matter particles in the galactic halo?

(2) Theodor Franz Eduard Kaluza (1885–1954), German physicist and mathematician; he was the first to devise a theory involving extra dimensions for the Universe.
Oskar Klein (1894–1977), Swedish theoretical physicist; he came up with the idea that the extra dimensions may have a physical existence, but are rolled up, and very small.

a (4 + 1)-dimensional space, would look like a veritable tower of similar particles, with masses increasing by successive steps of about 1 **teraelectronvolt**. Assuming the "0th step," or ground floor of such a tower, comprises ordinary particles (a four-dimensional projection of the five-dimensional reality), the first floor would then be a heavy replica of that ground floor. Now, should an additional mechanism, known as **Kaluza–Klein** parity, impose stability of the first-floor particles, similarly to the way **R-parity** works in supersymmetry, then these heavy particles constitute perfect dark matter candidates – as suggested, in particular, by Geraldine Servant, working at CEA's Institute of Theoretical Physics, in 1999.

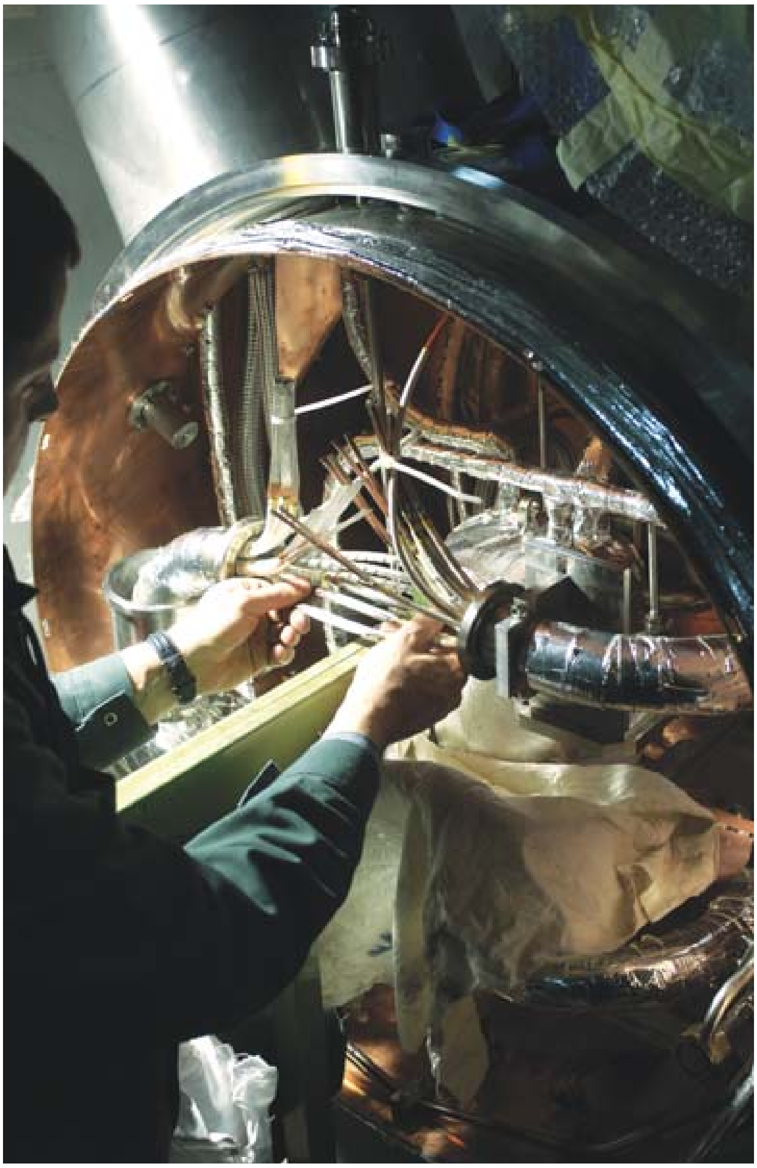
Supersymmetric dark matter, and Kaluza–Klein dark matter provided the momentum for most of the theoretical studies and experimental investigations that have been carried out since the 1980s. However, since researchers did keep an open mind on the issue, many other suggestions were put forward. For instance, in the WIMP dark matter category, so-called "minimal dark matter" models have suggested adding only the particles that are strictly necessary as dark matter candidates, rather than adding to the Standard Model an entire range of particle replicas. Further hypothesized particles include: "sterile neutrinos", these being particles similar to ordinary neutrinos, but heavier, and undergoing no interactions with ordinary matter; or *axions*, low-mass particles that might have been produced during the first, very hot moments of the evolution of the Universe.

With several candidates for just the one job, how to select the right one?

Such a large number of "candidates" is a reflection of the strong interest scientists have shown for all of these issues. However, it does also reflect a glaring absence of any direct experimental data. Fortunately, the coming years do look promising in this respect. A combination of various experimental techniques will doubtless be required, if discrimination between the various theories and identification of the nature of dark matter are to be achieved. Great expectations reside in the creation of dark matter by the Large Hadron Collider (LHC), the particle accelerator coming alive at **CERN**, the European Organization for Nuclear Research (see *Could dark matter be generated some day at LHC?* p. 80). Another prospect concerns the detection of the end-products from the annihilation of pairs of dark matter particles in the galactic halo (see Figure 1). A third thrust is banking on sensitive underground experiments, e.g. EDELWEISS (see *EDELWEISS*, p. 99), in which CEA is a major participant, which has the purpose of detecting a particularly rare phenomenon: the collision of a dark matter particle passing by. This vast, multidirectional experimental activity, indispensable as it is if the various predictions are to be tested, goes hand in hand with intense theoretical work.

Interestingly enough, the PAMELA (Payload for AntiMatter. Exploration and Light-nuclei Astrophysics) satellite, placed in orbit by a Russian rocket in 2006, has recently detected "anomalous" **cosmic rays**, possibly generated by annihilations of galactic dark matter. These data, which prove hard to be accounted for in terms of supersymmetric or Kaluza-Klein dark matter, are already stimulating the construction of a number of new models.

The issue of dark matter entails close linkages between particle physics, cosmology and astrophysics. In all likelihood, such a problem of galactic and cosmological scale will find its solution in terms of a new one of the smallest constituents of matter. The exploration of physics at the teraelectronvolt scale at LHC, the astronomical gamma-ray observations carried out by the Fermi satellite, together with the coming generation of underground detectors such as EDELWEISS, give good grounds for believing that dark matter will soon reveal its secret.



P. Stoppa/CEA

Fundamental research in particle physics has made huge advances, as regards validating a theoretical framework known as the Standard Model. New particles, such as the Higgs boson, and new processes are anticipated, in the context of the LHC experiments. Will one of these particles prove to be the dark matter?

> Marco Cirelli
and **Camille Bonvin**
Institute of Theoretical Physics
(CNRS associate research unit)
Physical Sciences Division (DSM)
CEA Saclay Center

Could dark matter be generated some day at LHC?

In order to address the most fundamental issues known to physics, CERN (the European Organization for Nuclear Research) brought into operation, in 2008, the Large Hadron Collider (LHC). As host country, France took part in the construction of LHC, through its two major research organizations: CNRS, and CEA. In the context of this large instrument, physicists are at work, seeking to set up collisions between proton beams, each involving energies of 7 **TeV** (i.e. 7,000 **GeV**), these being observed by way of two general-purpose experiments:

• ATLAS (A Toroidal LHC Apparatus): this is one of the largest, most complex detectors constructed to date. This physics experiments at LHC is being conducted by a worldwide collaboration of scientists (1,800 physicists and engineers, from 150 laboratories, in 34 different countries), for the purposes of finding the **Higgs boson**, if it does exist (see Figure 1), or other new particles;

• CMS (Compact Muon Solenoid), the other large detector, this being set up for the same scientific purposes as ATLAS, but involving different technical options.

Two further programs are pursuing specific investigations:

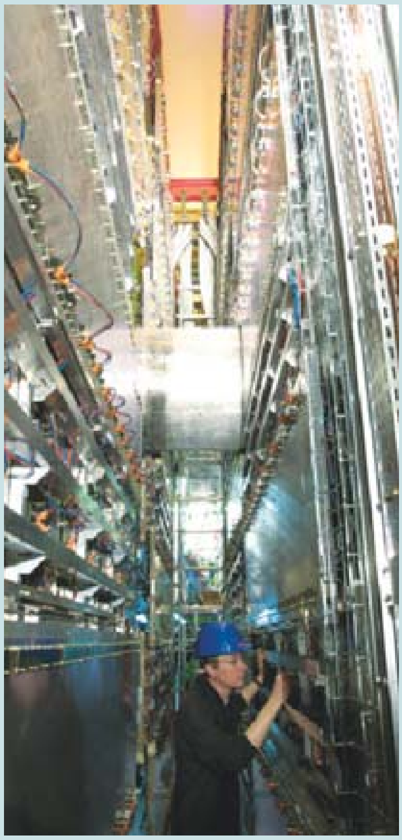
• ALICE (A Large Ion Collider Experiment) will endeavor to reproduce, in the laboratory, the conditions prevailing just after the **Big Bang**, for the purposes of investigating, in this manner, the evolution of matter, from the inception of the Universe to the present time;

• LHCb (Large Hadron Collider beauty) will seek to gain an understanding of the reason why we live in a Universe apparently entirely consisting of matter, with no **antimatter** present.

The energy involved in the LHC collisions (14 TeV, i.e. 7 times higher than achieved by the previous collider, operated in the United States) will help in conducting an exhaustive exploration of the energy scale covering the region around 1 TeV, this being a key scale in the **Standard Model** of particle physics. The prime purpose of the experiments carried out at LHC remains that of discovering the mysterious Higgs boson, or whatever plays the part assigned to it, in ensuring the unification of the **weak**, and **electromagnetic interactions**. However, currently, new theories are opening up a framework extending further than the Standard Model, for the purposes of seeking answers to the issues left pending by this model, particularly with regard to the nature of the much-discussed Higgs boson, but equally as regards the nature of **dark matter**, and **dark energy**.

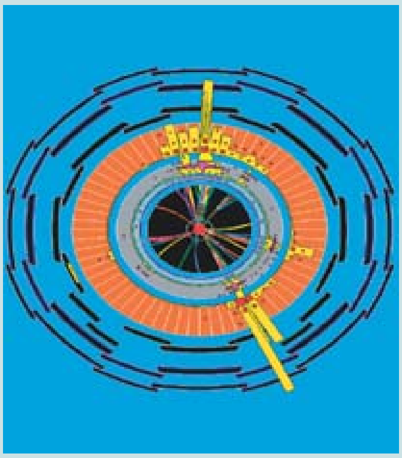
All of these issues, indeed, do seem to be related, by way of the one central question: what is the origin of the mass exhibited by particles? With regard to dark energy, researchers come up against a major difficulty, in terms of our current knowledge of elementary particles, in that computation of the density of dark energy in the Universe yields a result that is much too large, billions of billions of times larger than what is found by observation! On the other hand, the position would appear to be more favorable, as regards gaining an understanding of dark matter. Indeed, with cosmological measurements pointing to weakly interacting massive particles, these would involve a "typical" mass scale of about 100 GeV, this being the unification scale for the Standard Model.

A natural conclusion would thus seem to be that dark matter, and electroweak unification stem from a common origin. Should this prove to be the case, such particles could be generated by LHC. This is predicted, for instance, by one of the many theories put forward, for the purposes of going further than the Standard Model – and doubtless the best known such theory – namely the "**supersymmetry**" theory, propounded in the 1970s, but as yet still purely hypothetical. Many versions of this theory exist, however, in general terms, the lightest supersymmetric particle (LSP) would be an excellent "candidate." Thus, by way of its high energy, and **luminosity**, LHC could be able, in the near future, to yield evidence of supersymmetry. The common feature of the various types of events predicted by supersymmetry theories is the appearance, in the energy balance for the collision, of missing (transverse) energy, this being carried away by one or more LSPs. Researchers hope that such events, involving missing transverse energy, may soon be observed. Set against the background noise from the Standard Model, the slightest excess thus found would then favor supersymmetry. In like manner, other theories (extra dimensions, axions, etc.) predict that, if dark matter and electroweak unification do stem from a common origin, then there is a real chance that LHC could produce the constituent particle, or particles, of the dark matter found in the Universe.



P.Stroppa/CEA

The ALICE experiment, dedicated to the investigation of matter in extreme states.



CEA

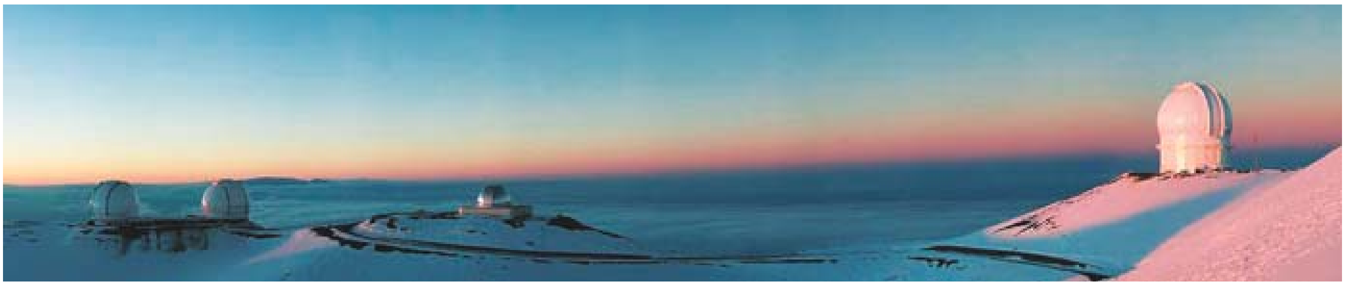
Figure 1.
Simulation of an event involving supersymmetry in the ATLAS experiment, viewed transversely to the beams' axis. In this event, two LSPs, and two jets of ordinary-matter particles are generated. The LSPs are not detected directly, rather the balance of the pulses shows up a deficit: "something" is missing on the left-hand side; this balance makes it possible to characterize the presence of LSPs. The axes involved are purely geometrical: X, Y, while the unit used is the meter: X (m), Y (m).

> **Bruno Mansoulié**
Particle Physics Service (SPP)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
CEA Saclay Center (Gif-sur-Yvette)

2. A Universe dominated by dark energy

Astrophysics and the observation of dark energy

One of the major surprises in modern cosmology will remain, unquestionably, the discovery of the acceleration of the expansion of the Universe, due to the so-called dark energy. Its existence was confirmed by the major findings of the Canada–France–Hawaii Telescope (CFHT), to which the teams at the Institute of Research into the Fundamental Laws of the Universe (IRFU) have been contributing, both on the instrumental side and on data analysis.



Jean-Charles Cuillandre/CFHT

The Canada–France–Hawaii Telescope (at right in the picture).

From the Big Bang to the accelerated expansion of the Universe

During the 20th century, **cosmology** made considerable advances, such as the discovery of the expansion of the Universe, the discovery of the **cosmic microwave background**, or the good agreement between measurements and predictions for the abundances of light elements. Thus, step by step, these observations contributed to the validation of the **Big Bang** model (see Box 1). However, all conundrums of the Universe have not been unraveled, since further observations revealed the existence of a large amount of **dark matter** whose precise nature remains unknown.

This puzzle is compounded by another one. Owing to universal attraction, the expansion of the Universe should be slowing down. To verify this, astrophysicists

The main steps in the Big Bang model — 1

Associated to Albert Einstein's theory of **general relativity** and to nuclear physics, the **Big Bang** model involves a Universe arising from an initial singularity, with the explosion of a dense, hot grain of matter. There ensues an expansion of the Universe, during which it is deemed to have undergone regular cooling, which was the condition for the synthesis of the first **atomic nuclei** (**hydrogen**, **helium**) to occur, during the first three minutes subsequent to the Big Bang. This step, known as the primordial nucleosynthesis phase, was followed by a period of equilibrium between matter and radiation, which had the effect of destroying the more complex atomic structures as soon as they were formed. After some 380,000 years, the Universe had, by then, sufficiently cooled down, and atom formation was no longer countered by radiation. Matter and radiation then decoupled, following separate evolutions thereafter. The radiation was free to travel across the Universe, where it remains even now, in the form of fossil, low-energy radiation, known as the **cosmic microwave background**. As for matter, owing to the effect of universal attraction, its atoms came together, forming vast gas clouds. By collapsing, these gave birth to the first **stars**, and subsequently to the first **galaxies**, 600 million years after the Big Bang. The effect of the initial explosion is still being felt by these objects, which are receding from one another, with velocities proportional to their distance.

ESA/NASA

By comparing distances with velocities (as derived from measurements of their luminosity and redshift) of several tens of galaxies, Edwin Hubble discovered, in 1929, that the Universe is expanding: galaxies are receding from us, with a velocity that is proportional to their distance. From this law, the age of the Universe may be derived: some 13.8 billion years.

Type-Ia supernovae as standard candles

2

Most type-Ia **supernovae** (SNIa) that have been observed to date exhibit highly homogeneous spectral and photometric properties. This has led to the hypothesis that they are the outcome of the thermonuclear explosion of a **white dwarf** – this being an end-of-life star – **accreting** matter from a companion giant star. This white dwarf gains mass, up to the point where it approaches the so-called **Chandrasekhar limit**. The star's internal temperature then rises sufficiently to set off explosive nuclear combustion. From that point on, the elements occurring in the core of the star (chiefly carbon, and oxygen) are burned, yielding 56Ni. This combustion releases so much energy that the star ultimately explodes. The subsequent decay of 56Ni, yielding 56Co, then 56Fe, determines the supernova's **luminosity**, making it as bright as several billion **suns**, i.e. as bright as a small galaxy. As the star's mass, and therefore the quantity of nickel yielded, is practically invariably the same at the time of explosion, SNIa all exhibit similar luminosities. They may then be used as "standard candles", for the purpose of measuring distances, since their apparent flux is solely dependent on the distance traveled by **photons**, from the time of the explosion, to the time of observation.

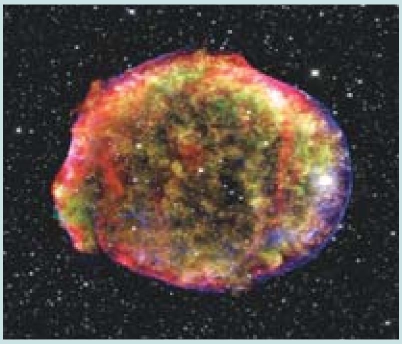


Image of the remnant of the type-Ia supernova observed by Tycho Brahe in 1572. This image combines X-ray, infrared, and optical radiation observations. The supernova remnant appears as a hot, rapidly expanding cloud, comprising a large amount of debris (shown in green, and yellow), inside a shell of very-high-energy electrons (blue), yielded by the external, outward shockwave, generated by the explosion. The dust surrounding the remnant (whether generated at the time of the explosion, or preexisting) emits in the infrared region (as shown in red in the image).

observed the flux from type-Ia **supernovae** (SNIa) – these being exploding end-of-life **stars** – lying several billion **light-years** away. Such supernovae are of interest owing to their reproducible **luminosity** (see Box 2). Measuring their apparent flux thus amounts to measuring the distance **photons** have traveled since the explosion – which distance is dependent on the content of the Universe and on its geometry. Now, in the late 1990s, initial observations of distant SNIa revealed that their apparent flux turned out to be lower than would be anticipated for a Universe solely consisting of matter. The distance traveled by photons emitted by the supernovae is thus larger than anticipated. This finding suggests the existence, in the Universe, of an energy component that can accelerate expansion, and that would be neither matter, nor radiation. Such a component was provided for in the equations of Albert Einstein's **general relativity**, once a constant, the so-called "**cosmological constant**," was inserted into them. Other descriptions have been put forward, which assign to this component a more fundamental content. Pending a resolution of the issue, this component has become known as **dark energy**. Its density accounts for three quarters of the energy content of the Universe, against just one quarter for matter.

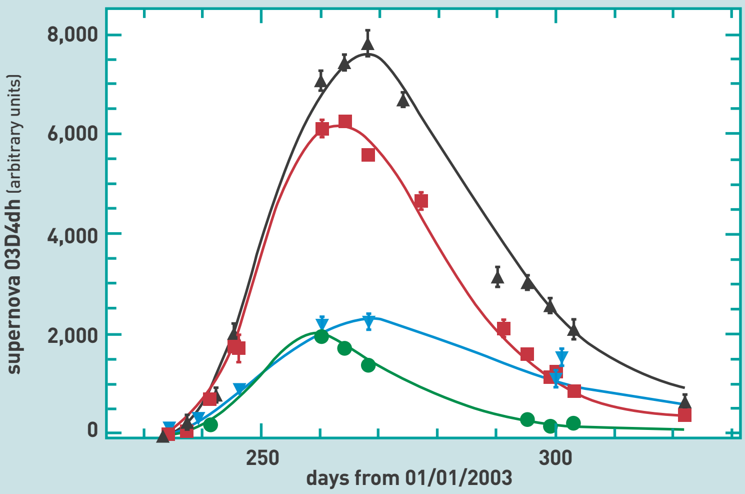


Figure 1.
The light curve for supernova 03D4dh, as measured by SNLS (flux is expressed in arbitrary units). Measurements were carried out every 3 or 4 days, apart from full Moon periods, using four separate filters: blue (circles), green (squares), red (triangles), and near infrared (downward pointing triangles).

The CFHT survey of supernovae

As this finding was unexpected, researchers embarked on new investigations of distant SNIa, such as the Supernova Legacy Survey (SNLS) experiment. From 2003 to 2008, using the 3.6 m diameter Canada–France–Hawaii Telescope (CFHT), sited in Hawaii (USA), SNLS detected and measured about one thousand SNIa, to be compared with the 50 or so collected by previous experiments. This achievement is all the more convincing, since SNIa are scarce: barely one explosion per century, for a **galaxy** similar to our own. To detect these, SNLS could avail itself of the MEGACAM wide-field camera, a 340 million-**pixel** CCD camera, designed at IRFU.
This is a unique instrument, the world over, its 1-square-degree field (4 times the area of the full Moon) making it possible to observe, in one session, extended regions of the sky, which may contain up to ten supernovae or so. As SNLS would constantly be going back over the same fields, as long as they were observable, detections could extend over the whole year, and "candidates" could be monitored throughout. This gave the ability to reconstruct the temporal profile of their light emissions, known as their "light curves." Flux measurements were effected every three or four days, using four filters, ranging from optical radiation to the near infrared (see Figure 1). Such sampling was a considerable advance over previous programs, which only involved monitoring supernovae at intervals of several weeks, using just two filters. Finally, as soon as it was detected by SNLS, any potential supernova, close to its light peak, would be

observed with spectrographs mounted on 8–10-meter diameter telescopes (VLT, Keck, Gemini), so that its redshift, and type (thermonuclear, for SNIa; or gravitational) could be precisely determined. As gravitational supernovae are of little use for cosmological purposes, owing to their wide variations in luminosity, only type-Ia supernovae were retained after spectroscopy. Once the survey was completed, SNLS totaled 500 SNIa, confirmed by spectroscopy, with redshifts ranging from 0.2 to 1.2. This means they were formed in a Universe that was younger by about 2 to 8 billion years. These supernovae thus extend back to the very distant past of the Universe. In order to reach us, their light has traveled over considerable distances, of several billion light-years. Now, over such ranges, the distance traveled by photons is significantly dependent on the past evolution of the Universe. As a result, measuring the flux of SNIa across an extended range of redshifts is tantamount to looking back across the evolution of the Universe, which in turn is determined by the Universe's matter and energy contents. This operation was undertaken by SNLS, from the first year of observations, on the basis of 70 SNIa confirmed by spectroscopy. Measurements showed that the flux from distant SNIa proves smaller than would be anticipated in a matter-dominated Universe. On the other hand, these measurements do agree with findings for a Universe undergoing accelerating expansion, dominated to 74% by dark energy (see Figure 2). The data yielded by SNLS further make it possible to test the evolution, over time, of the density of dark energy. Viewed as a fluid filling all of space, dark energy is characterized by its pressure. The ratio of this pressure over dark energy density – this being noted w, and known as the "dark energy **equation-of-state** parameter" – governs the evolution, over time, of the dark energy density. A value of $w = -1$ corresponds to a dark energy density that is constant over time. The findings from the first year of SNLS, coupled with those from other observations, lead to a value of w compatible with -1, with a relative uncertainty of 10% (see Figure 4, left panel). The analysis of the first three years of SNLS data (i.e. for 250 SNIa) is nearing completion, and the findings are consistent with that initial result, with improved precision: 6%, rather than 10%. Refining this test stands yet as a major challenge: a density of dark energy that was constant over time would favor an interpretation in terms of the cosmological constant.

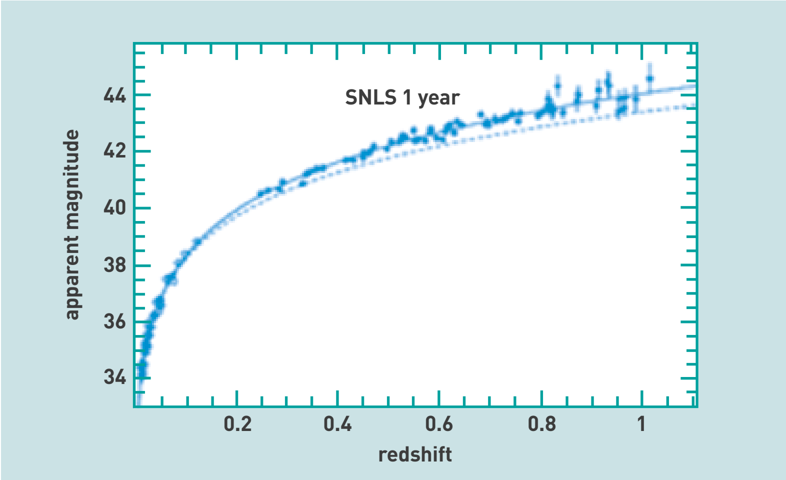


Figure 2.
Apparent magnitudes of SNIa (as derived from peak light flux), as a function of redshift. (The common usage, in astrophysics, is to plot light fluxes over an inverse logarithmic scale, known as the magnitude scale: the more luminous an object is, the smaller its magnitude.) Measurements carried out during the first year of SNLS operations (dots), combined with measurements carried out on nearby supernovae (circles), are compared with predictions for a Universe consisting solely of matter (dotted line), and for a Universe undergoing accelerated expansion, consisting of 74% of dark energy and 26% of matter (full line).

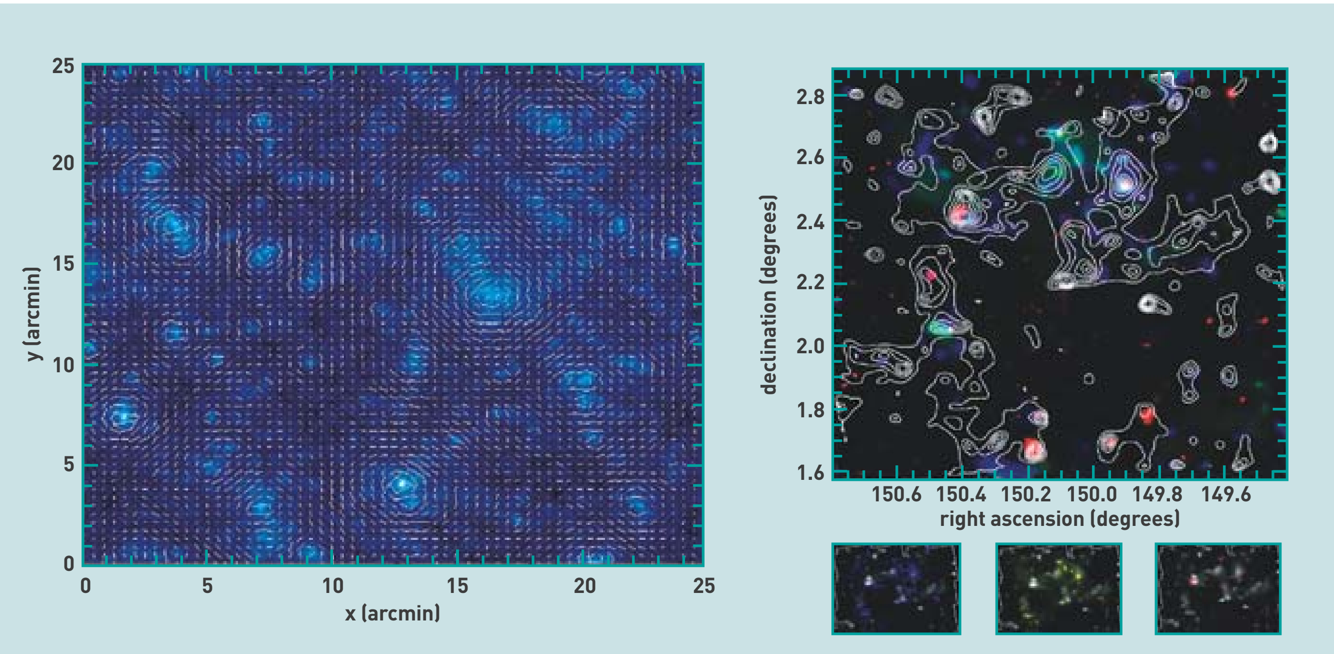


Figure 3.
Map of dark matter, obtained by way of the gravitational shear effect.
At left: image yielded by numerical simulation, showing the distribution of dark matter (color scale), and the gravitational shear the images of distant galaxies are subjected to (segments); "x" and "y" are the coordinates in the plane of the image.
At right: map of dark matter, in galactic coordinates (contours), and of visible matter (colors), as derived, by way of the gravitational shear technique, from the observations of the COSMOS (Cosmic Evaluation Survey) program, using the Hubble Space Telescope.

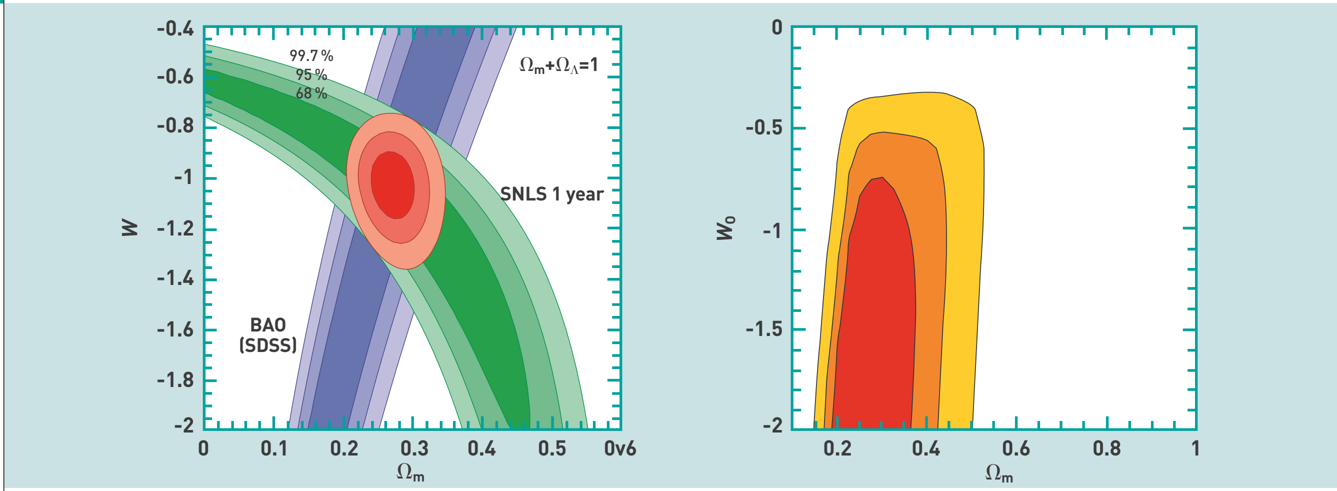


Figure 4.
Current constraints on dark energy, as derived from investigations carried out at CFHT (supernovae at left; gravitational shear at right), and the measurements of the Sloan Digital Sky Survey (SDSS) regarding baryonic acoustic oscillations (BAO). Constraints are expressed in terms of percentages of the density of the Universe in dark matter form (Ω_m=1- Ω_Λ, where Ω_Λ is the density of dark energy), and of the dark energy equation-of-state parameter, *w* (or w_0) (i.e. the ratio of dark energy pressure, over density).

Measurement of the gravitational shear effect by CFHT

Two further cosmological observations should make it possible to gain yet more in terms of precision:

• measuring more precisely the **baryonic acoustic oscillations**, i.e. the fluctuations in the matter–radiation **plasma** in the **primordial** Universe, which have left their imprint on galaxy distribution;

• mapping the distribution of matter, across the Universe, by way of the gravitational shear effect. This relies on measuring the shapes of distant galaxies, as distorted by the large structures of the Universe lying along the line of sight. This technique is a large-scale generalization of the gravitational mirage technique, used for the purposes of reconstructing mass distributions, within galaxy clusters, and evidencing their dark matter content. Gravitational shear contributes to the description of dark matter distribution, at the scale of the Universe (see Figure 3). By way of the redshifts, as derived from the colors exhibited by galaxies in a number of wavelength bands, such mapping is effected in three dimensions – the measurement of statistical properties related to the history of structure formation in the Universe thus being all the more precise. The largest survey of the gravitational shear effect was performed using the MEGACAM camera, mounted on CFHT, on the basis of an analysis of the "wide-field" survey carried out during the 2003–2008 observation campaign. This gravitational shear survey made it possible to measure the dark energy density, from its effects on the geometry of the Universe and on the growth rate of its structures. Figure 4 (right panel) sets out the constraints obtained on the basis of the first 20 square degrees of this survey. These constraints are in agreement with the values derived from supernovae and baryonic acoustic oscillations. Ultimately, the survey of the gravitational shear effect will extend the area covered by a factor 10, setting more precise constraints on dark energy.

Prospects

Measurements at a yet finer scale should serve to finally elucidate the behavior of dark energy. Indeed, current experiments are sensitive only to the mean value of *w*, across the range of redshifts observed. Future experiments will have to take on board the possibility of a variation of *w* with redshift. This is the only way to discriminate between a simple cosmological constant, and a more dynamic model of dark energy. IRFU is preparing two experiments addressing this issue:

• the first one is a survey of baryonic acoustic oscillations across the entire sky and in three dimensions, by means of radio interferometry. Detection of the 21-cm neutral **hydrogen** line will result in retracing galaxy distribution as far back as a redshift of 2. With an **angular resolution** of 1 minute of arc, and a resolution of 0.001 for redshift, the HSHS (Hubble Sphere Hydrogen Survey) interferometer should achieve a sensitivity of 25% on the evolution of *w*, within a few years;

• the second experiment corresponds to a longer-term goal, and involves a spaceborne wide-field imager, known as Euclid. This instrument will investigate, with very high precision, the dark Universe, by way of gravitational shear and baryonic acoustic oscillations. For that purpose, it will use a 1.2-m telescope, which, over its field of view of 0.5 square degree, will combine imaging and spectroscopy, in the visible and near infrared regions. The desired precision stands at 5% on the evolution of *w*, which should allow scientists to discriminate between models of dark energy derived from modifications of the theory of general relativity (see *Telescopes of the future*, p. 102).

> Vanina Ruhlmann-Kleider
Particle Physics Service (SPP)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
CEA Saclay Center (Gif-sur-Yvette)

> Alexandre Réfrégier
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling" (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

Theories of dark energy

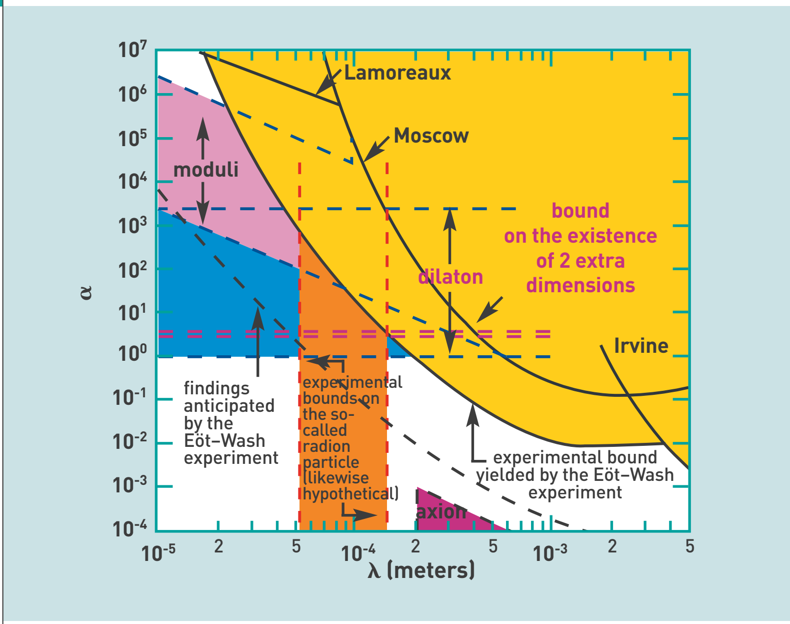
While observations, as regards the acceleration of the Universe, prove ever more precise, its theoretical description, on the other hand, remains problematic. Indeed, more than ten years after the initial observation of type-Ia supernovae and the measurement of their luminosity distance, no theory accounts for the phenomenon as a whole. It is likely that new theoretical tools will be required in order to unravel the mysteries of the accelerating Universe.

NASA

The Universe consists of luminous matter, forming the stars, and galaxies. There is also a background content of so-called dark (nonluminous) matter, forming haloes around every galaxy. Finally, it would appear there is a third type of matter, seen as causing the acceleration of the Universe. This dark energy – it is not luminous – is uniformly distributed across the entire Universe.

Which routes have been followed to describe the acceleration of the expansion of the Universe, and why did they lead to dead ends? The analyses of the observational data which have led to the discovery of the acceleration of the Universe are based on the **theory of general relativity**, a cornerstone of 20th-century physics. As formulated by Albert Einstein in 1915, this theory reconciles Newtonian gravitation and the theory of relativity. This remarkable theory has been tested numerous times, in particular at scales ranging from the Solar System to distant **galaxies**. It has even found an unanticipated application with the GPS Global Positioning System! However, in order to model the evolution of the Universe as whole, larger scales must be considered – far larger than the scales involved in the description of the most distant **galaxy clusters**. At such distances, the Universe appears to be isotropic and homogeneous, i.e. no direction, or location seem to be privileged. This observation has become a principle: the **cosmological principle**. General relativity and the cosmological principle are the building blocks of all the theories developed since the 1930s in order to describe the evolution of the Universe, from the formation of **atomic nuclei** to the **cosmic microwave background**.

General relativity states that energy and the geometry of **space-time** are intimately related. For instance, the Sun warps space-time in its vicinity, and deflects light rays. In **cosmology**, the dynamics of the Universe depend on the nature and the amount of energy



Eöt-Wash Collaboration, Seattle (USA)

Figure 1.
The investigation of gravitational attraction, from the smallest scales to the largest ranges, is fundamental, if an understanding is to be achieved of the acceleration of the Universe. A small-scale modification of gravity (in this figure, at millimeter scale, along the *x*-axis) could well reveal the presence of particles causing the acceleration. These particles would augment the force of gravity, by a percentage shown on the *y*-axis. The indication "Lamoreaux," in the diagram, refers to the experimentalist whose findings are shown here, while "Irvine" refers to the University of that name (the same goes for "Moscow"). The dilaton is a hypothesised particle in string theory: the boundaries for its existence are shown in the diagram (and likewise for the modulus). The axion is a hypothetical particle, which could be the source of dark matter.

contained in the Universe. Furthermore, general relativity implies that all forms of energy gravitate, by contrast with the Newtonian point of view whereby only matter gravitates. Now – and this does come as a very big surprise – an acceleration phase is not possible in general relativity, assuming the validity of the cosmological principle, should the energy content of the Universe solely consists of light radiation, **neutrinos**, the matter making up galaxies and **dark matter haloes**. Describing the acceleration thus entails "violating" one of these assumptions, i.e. modifying general relativity, the cosmological principle, or the energy content of the Universe. Over the past decade, a large number of models have appeared, seeking to account for the acceleration of the Universe by modifying one of these assumptions. Indeed, well before the acceleration of the Universe had been discovered, Albert Einstein himself had suggested a modification to general relativity. Opting for an Aristotelian view of the cosmos, he believed in a static celestial sphere. According to general relativity, such a sphere may not remain stationary: gravitational attraction, due to matter implies that it must contract (see Figure 1). To counteract such a "gravitational collapse," Albert Einstein introduced a new term in the equations: the **cosmological constant** – its desired effect being the stabilisation of the celestial sphere, thus ensuring that the Universe would be static. However, when the British astrophysicist Edwin Hubble discovered the expansion of the Universe in the 1920s, the description of the Universe as static and unchanging became obsolete and the introduction of the cosmological constant irrelevant. This view prevailed until the 1990s.

It took some time to obtain a valid description of the physical nature of the cosmological constant. It was only in the 1960s that the equivalence with the energy density of the vacuum emerged. In classical physics, the vacuum means the absence of matter, and no energy density can be involved. This point of view was to be challenged in quantum mechanics. Indeed, in the vacuum, virtual particles arise and disappear before they can even be observed. Such a frantic activity undoubtedly leads to the existence of a vacuum energy. An experimental manifestation of this phenomenon has been detected, this being known as the *Casimir*[(1)] *effect*. Between two metallic plates, fluctuations in the **electromagnetic** field generate an attractive force. The mysterious cosmological constant, introduced by Albert Einstein thus turns out to reflect the quantum nature of the cosmic vacuum. It corresponds to a modification of the energy content of the Universe.

The effect of a cosmological constant on the dynamics of an expanding Universe has been well known since the work of Alexander Friedmann and Willem de Sitter[(2)] in the 1920s. As the energy density of matter and radiation decreases with time, the cosmological constant remains invariable, eventually becoming the dominant fraction of the energy content of the Universe. Once the cosmological constant dominates, the force of repulsion induced by this constant can no longer be counterbalanced: there follows a period of accelerating expansion which may be identified with the one observed at the present time. The cosmological constant may thus be seen as the simplest way to account for the acceleration of the Universe. As the onset of such acceleration occurred only "recently," the cosmological constant should have a value close to the present density of matter in the Universe. This density is very low: 25 orders of magnitude lower than the density of the Earth atmosphere, 6 orders lower than the intergalactic vacuum! The existence of such a minute energy density is at odds with what is known in particle physics. Other explanations have to be considered.

Thus the cosmological constant may also be interpreted as the energy density of a fluid filling the Universe, exhibiting a pressure that is precisely equal and of opposite sign to its energy density. The pressure/energy density ratio, known as the "**equation-of-state** ratio" (or parameter), is then equal to –1. In more general terms, the acceleration of the Universe could also result from the presence of a new type of substance discovered in the Universe: **dark energy**. Observations lead to constraints on

(1) Hendrik Casimir (1909–2000), Dutch physicist, a director of the Philips Research Laboratories, and a professor at Leiden University. Specialising in work on superconductivity, and dielectrics, he discovered the effect named after him, whereby two parallel metallic plates held in a vacuum attract one another.

(2) Alexander Friedmann (1888–1925), Russian physicist and mathematician; he was the first to foresee that Einstein's theory of general relativity would make it possible to investigate the structure of the Universe as a whole.

Willem de Sitter (1872–1934), Dutch mathematician, physicist, and astronomer; he was amongst the first to suggest, in 1917, the possibility that the Universe might be expanding, on the basis of Einstein's work on general relativity.

this equation-of-state ratio which must lie close to –1. Should its value fall below –1, the Universe would prove unstable. There is nothing, on the other hand, that precludes it from being larger than –1 and lower than –1/3, this being the maximum value, above which any acceleration becomes impossible. The thermodynamic description of the fluid governing the acceleration of the Universe is only the first step in the modeling process. Indeed, if the equation-of-state ratio is not precisely –1, the dark energy density cannot remain constant over time. Such behaviour is modeled using a **scalar field** whose potential energy plays the role of dark energy. This scalar field varies as a ball rolling down a gentle slope, while slowed down by friction (see Figure 2). After a long roll, the field grinds to a halt and its potential energy stays constant. It is this energy which results in the acceleration of the Universe (see Figure 3). This new form of energy is known as quintessence. All of these attempts, seeking to account for the acceleration of the Universe using a new energy component fail to provide a solution to the cosmological constant problem: The vacuum energy due to **quantum** fluctuations proves to be 120 orders of magnitude larger than the observed value. A mechanism is thus required to preclude such a disaster. The most promising "candidate" appears to be **supersymmetry** which involves the existence of "superpartners" associated to every elementary particle. In this case, the vacuum energy becomes precisely equal to zero. The discovery of such "superpartners" could occur at the Large Hadron Collider (LHC) in the coming months. Unfortunately, since "superpartners" have so far eluded observation, supersymmetry may not be seen as an exact symmetry of nature. The breaking of supersymmetry reintroduces vacuum fluctuations whose energy density is still 60 orders of magnitude too large.

Another explanation has been put forward involving the **anthropic principle** which states that the Universe must be such as to make its observation possible. For instance, from the mere fact that galaxies have been formed, it follows that the cosmological constant must not exceed 100 times the observed density of matter. Recent advances in **string theory** have led to the prediction of the existence of a multiverse, i.e. a multiplicity of universes, each featuring a different vacuum energy density. It then becomes conceivable that our own Universe is simply one of these universes, namely one that is associated to a low vacuum energy density, and home to observers.

Another possibility would involve modifying general relativity at cosmological scales by suggesting therefore, that the acceleration of the Universe is the outcome of the way the laws governing gravity are realised at very large distances. Such a hypothesis runs into further difficulties. As is the case of all physical theories describing the four fundamental interactions, general relativity is a **Lagrangian** theory, its equations being derived from the principle of least action. Modifying general relativity is tantamount to altering the Lagrangian of the theory. Now, **Ostrogradski's theorem** entails that this would result in nonphysical theories and the vacuum would become unstable. Only one family of theories escapes this conclusion; however it involves a generalisation of quintessence models, and features the same shortcomings.

One further possibility has also been explored, involving the "violation" of the cosmological principle. While the measurement of the cosmic microwave background does show that the Universe is isotropic, the homogeneity of the cosmos is still a very strong assumption. The acceleration found from the motion of **supernovae** could be caused by local inhomogeneities. The Copernican principle which underlies the principle of homogeneity, stating that the Earth holds no special position in the Universe, would in turn prove questionable: the whole of cosmology

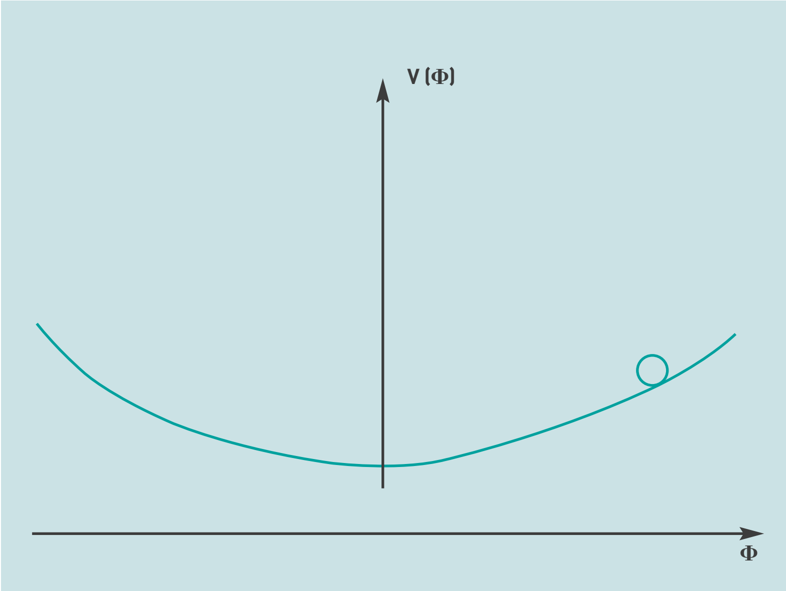


Figure 2.
The dynamics of the scalar fields, which might be responsible for the acceleration found, is akin to the motion of a ball rolling down a slope, when subject to friction. Once it has rolled down the slope, the ball stabilizes itself at the potential minimum. If the energy is positive, this acts as a reservoir of energy for acceleration.

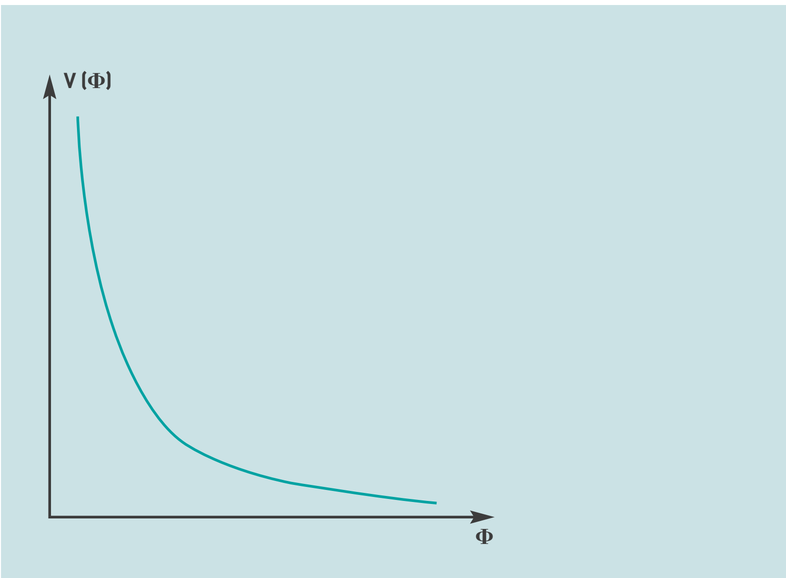


Figure 3.
Should the potential exhibit no minimum, the scalar field rolls down the slope, before being stabilised. The residual potential energy causes the acceleration of the Universe. The potential energy for dark energy is noted V (Φ), while the value of the dark energy field Φ is plotted along the *x*-axis.

may then be recast using Tolman–Bondi[3] spaces (rather than Friedmann–Lemaître[4] spaces) whose main characteristic is that the curvature varies spatially around a centre that holds a special position in the Universe. Such scenarios have not been fully explored yet. Finally, there is another underlying assumption in the interpretation of the acceleration of the Universe. This is based on the four dimensions of space-time. As early as the 1920s, Kaluza and Klein introduced a fifth dimension in their endeavour to unify general relativity and electromagnetism. Subsequently, string theory introduced ten or eleven dimensions, resulting in two types of models. The first type assumes that our Universe stands as the edge (termed a **brane**) of a five-dimensional space. Should such an assumption prove correct, then the huge vacuum energy due to quantum fluctuations along the brane would have the effect of curving the fifth dimension while just retaining a minute trace, this causing the acceleration of the Universe. Highly promising as it is, this scenario does nevertheless lead to the presence of space-time singularities. The second model assumes that gravity propagates both on the brane and into

(3) Richard C. Tolman (1881–1948), US physical chemist and cosmologist; he was the first to look into cosmological perturbations.

Hermann Bondi (1919–2005), Austrian-born mathematician, known for his development of the steady-state theory of the Universe.

(4) Alexander Friedmann (1888–1925), a Russian physicist and mathematician, and Georges Lemaître (1894–1966), a Belgian astrophysicist, were two of the founding fathers of the theory of the expansion of the Universe.

The matter–antimatter asymmetry of the Universe

Stars, **galaxies**, **clusters**... all the observed structures consist of **baryons** (**protons** and **neutrons**) and electrons, i.e. of matter, with no significant amounts of **antimatter** present. This matter–antimatter asymmetry is measured by way of the ratio of the density of baryons over the density of **photons**: $\eta \equiv n_B / n_\gamma = (6.21 \pm 0.16) \cdot 10^{-10}$, a quantity often referred to as the **baryon asymmetry** of the Universe. This is determined by two separate, independent methods. The first method relies on measuring the abundances of light elements (D, ^3He, ^4He, ^7Li), which are predicted as a function of the parameter by nucleosynthesis. The fact that one and the same interval of values for ($\eta = (4.7 - 6.5) \cdot 10^{-10}$) is found to be compatible with the abundances of all four elements stands as one of the major successes of the Big Bang theory. The second, more precise measurement of η is derived from the **anisotropies** arising in the **cosmic microwave background** radiation, and agrees with the value given above. The remarkable agreement found between these two measurements ranks as another major success of the Big Bang theory (see Figure 1).

Small as it may seem, the parameter η turns out in fact to be very large. To understand this, let us first assume that the Universe initially contained the same number of baryons and antibaryons. In that case, their mutual annihilation would result in a value $n_B / n_\gamma \sim 10^{-19}$, much smaller than the baryon asymmetry observed. Could the observed value then be accounted for by an excess of baryons over antibaryons at the time of the Big Bang? This hypothesis comes up against two objections. First, the initial densities of baryons and antibaryons would have to be very finely tuned (to within 10^{-9}). Second, one would have to further assume that the Universe did not go through a phase of inflation, contrary to what observations suggest (the effect of inflation is to erase all memory of initial conditions). Now if the baryon asymmetry is not due to initial conditions, it must have arisen dynamically during the history of the Universe: this is termed **baryogenesis**. In 1967, Andrei Sakharov[1] showed that three conditions must be satisfied for baryogenesis to take place:

- the existence of processes in which the total number of baryons is not conserved;
- in thermal equilibrium, processes yielding baryons occur at the same rate as the reverse processes, which destroy the asymmetry created by the former processes: there must therefore be a departure from thermal equilibrium;
- to any process generating baryons is associated, by what particle physicists term "charge conjugation" (C) and "charge–parity conjugation" (CP), a "mirror" process generating antibaryons; if a baryon asymmetry is to persist, these two processes must occur at different rates. This requires a violation of C and CP at the level of particle interactions.

Remarkably, the three conditions identified by Andrei Sakharov are met in the **Standard Model** of particle physics. Indeed, some processes known as sphalerons do not conserve the baryon number; the C and CP symmetries are violated by the interactions responsible for beta decay; the departure from thermal equilibrium occurs at the "electroweak phase transition", i.e. at the time of the history of the Universe during which particles acquire their mass. The corresponding baryogenesis scenario, known as "standard electroweak baryogenesis", fails however to yield the observed level of baryon asymmetry because the departure from thermal equilibrium is not strong enough. One must then invoke a new physics beyond the Standard Model, which is being actively searched for at particle colliders.

Theorists are currently investigating two classes of scenarios. In the first class, new physics affects the electroweak phase transition, thus enforcing the required departure from thermal equilibrium. In the second class of scenarios, the baryon asymmetry is generated before the electroweak phase transition. For instance, in the **leptogenesis** scenario, the decay of heavy neutrinos generates a lepton asymmetry which is subsequently converted into a baryon asymmetry by the sphalerons.

(1) Andrei Sakharov (1921–89), Russian nuclear physicist, and human rights campaigner; he was awarded the Nobel Peace Prize in 1975.

> Stéphane Lavignac
Institute of Theoretical Physics
(CNRS associate research unit)
Physical Sciences Division (DSM)
CEA Saclay Center

the fifth dimension. It would thus end up being modified at large distances. As for four-dimensional theories, this model is plagued with the issue of the instability of the vacuum. The construction of theories involving extra dimensions has thus not, as yet, proved successful in providing the key to the acceleration of the Universe.

This review of the explanations for the acceleration of the Universe has highlighted the difficulties involved in building a physical theory for this phenomenon. However, from the confrontations between the various hypotheses may well emerge great advances in the understanding of the connections between cosmology, gravitation, and particle physics. To date, however, the puzzle of the acceleration of the Universe remains unsolved. The issue of the acceleration of the Universe is being investigated at the Institute of Theoretical Physics, based at the CEA Saclay (near Paris, France). The connections with particle theory, string theory, and gravity are being analysed. The presence of teams of particle physicists and astrophysicists involved in experimental programs related to the acceleration of the Universe is also an asset allowing for a regular and ongoing dialogue between experimentalists and theorists.

> Philippe Brax
Institute of Theoretical Physics
(CNRS associate research unit)
Physical Sciences Division (DSM)
CEA Saclay Centre

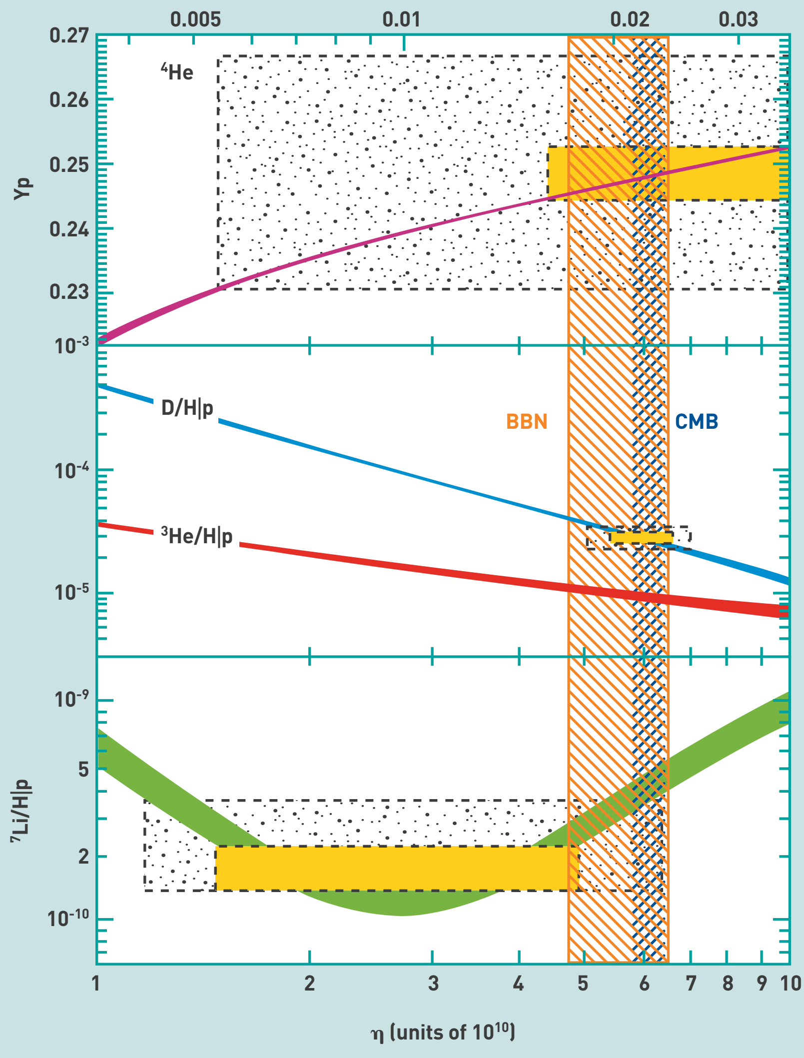


Figure 1.
Abundances of the light elements ^{4}He (conventionally noted Y_p), D, ^{3}He, and ^{7}Li as predicted by Big Bang nucleosynthesis (BBN), as a function of the parameter η (in units of 10^{10}). The horizontal rectangles indicate the observed abundances, with the associated experimental uncertainties (small rectangles: statistical errors; large rectangles: statistical and systematic errors). The vertical strips correspond to the values of η derived from the observed abundances [orange hatching] and from the anisotropies in the cosmic microwave background (CMB) [blue hatching].

Journey into the **lights of the Universe**

For a long time, astronomers could only look to visible light, to observe the Universe. **Nowadays, with the advent of space observatories, they can avail themselves of a whole range of instruments, affording the ability to capture all of the lights of the Universe** from radio waves to gamma rays.

1. Microwave

ESA Planck surveyor

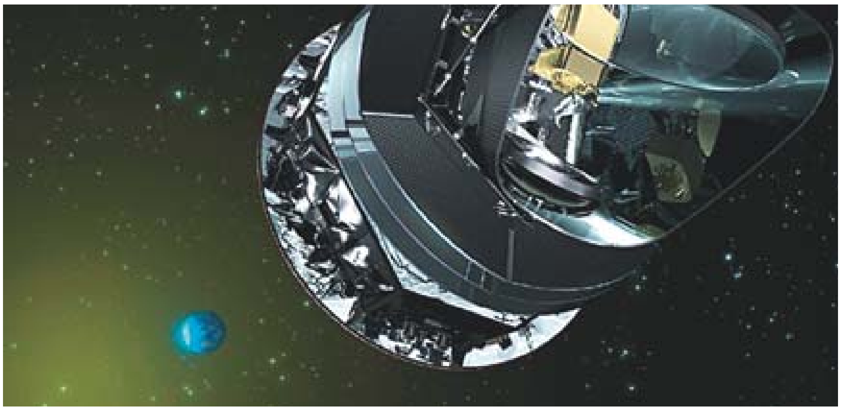
This satellite has the remit of mapping the cosmic microwave background, this being radiation emitted 13.7 billion years ago, at the time when the Universe became transparent to light. This radiation conforms to the black-body spectral distribution law, established by German physicist Max Planck (1858–1947), at the beginning of the 20th century.

Spectral range
Frequencies in the 30–857 GHz range, corresponding to wavelengths ranging from 1 cm to 350 microns.

Description
- 1.5-m diameter telescope.
- Dimensions: 4.20 m high × 4.20 m wide.
- Weight: 1.8 tonne.
- Launch: by Ariane 5 launcher, on 14 May 2009, from the Guiana Space Center, Kourou (French Guiana).
- Position: around Lagrangian point L2 of the Earth–Sun system (i.e. the metastable Lagrangian point lying behind the Earth, 1.5 million km away).
- Mission duration: 21 months.

Scientific goals
- Measuring, with a precision better than 1%, the parameters for the Standard Model of cosmology, also known as the "Big Bang model."
- Detecting minute deviations in the properties exhibited by fluctuations in the cosmic microwave background, at 3 K, with respect to those predicted by that model: every deviation contributing to the demonstration that the physics involved in the primordial Universe turns out to be different from what is presently seen as the most likely.

Instruments
- High-Frequency Instrument (HFI): a submillimeter instrument, developed under project leadership by the Space Astrophysics Institute (Institut d'astrophysique spatiale), at Orsay (near Paris). This is a bolometer array, operating at a temperature of 0.1 K, featuring an angular resolution of 5 minutes of arc, and a temperature sensitivity of 50 μK at 100 GHz. It will observe the 100–850 GHz spectral region.
- Low-Frequency Instrument (LFI): a microwave instrument, developed in Italy, comprising four channels of 56 tunable (27–77 GHz) radio receivers each, operating at a temperature of 20 K; it features an angular resolution of 10 minutes of arc, and a temperature sensitivity of about 12 μK at 100 GHz.


ESA

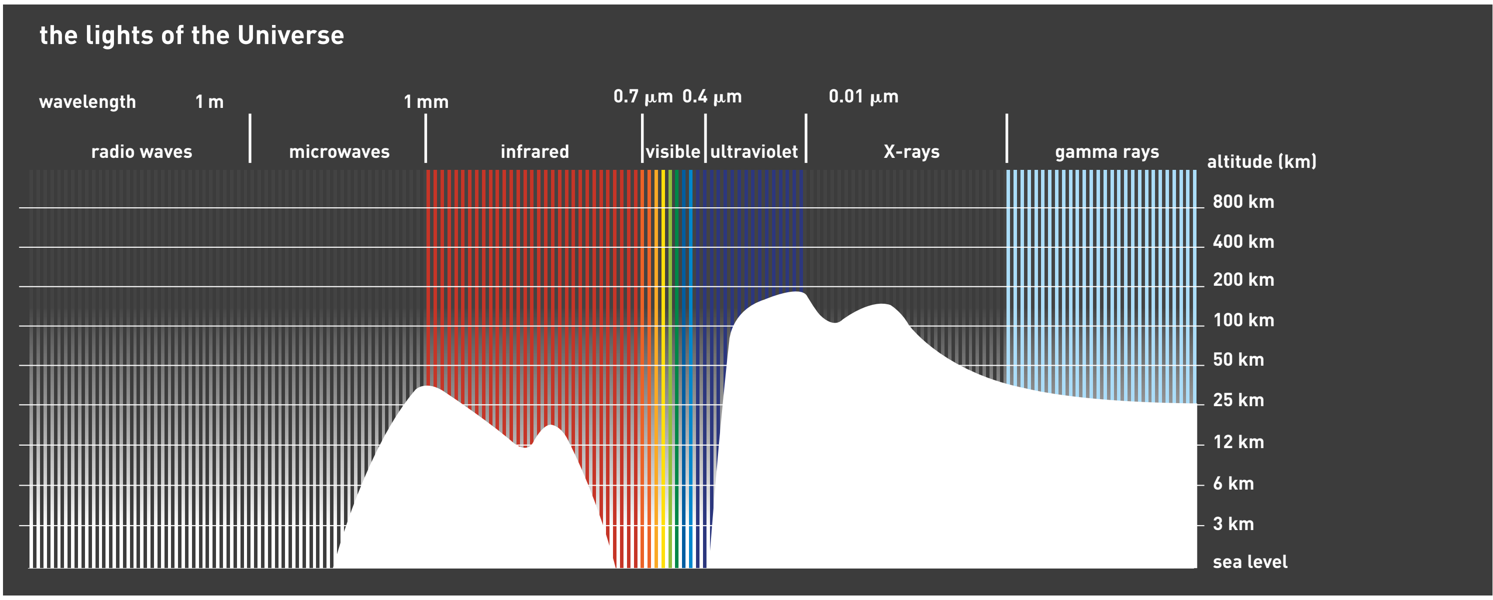
Artist's impression of ESA's Planck satellite.

Collaborations
Constructed by an international consortium, under project leadership by the European Space Agency (ESA).

CEA contribution
Contributions to:
- development of the low-noise electronics, during the payload construction phase, in particular through the coordination of electromagnetic compatibility studies for the HFI instrument;
- implementing sophisticated data analysis software packages;
- data processing, and scientific analysis for the mission.

Planck is drawing up a map of the anisotropies in the cosmic microwave background, by scanning the entire celestial canopy, with a resolution of 5 minutes of arc. These data will be used to derive fundamental information regarding the birth of the Universe, and its shape, content, and evolution. Data processing sets a real challenge. Indeed, each one of the maps obtained will contain information yielded by various microwave radiations, not just the cosmic background radiation. It will thus prove necessary to separate out the information originating in the cosmic microwave background, and that coming from other microwave radiation.

> Jean-Luc Starck
Detector Electronics and Informatics Service (SEDI)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
Joint Astrophysics Research Unit on Multiscale Interactions (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)



A considerable fraction of the lights of the Universe never reaches ground level. Such lights may only be observed from above the atmosphere, by means of balloons, rockets, and satellites.

2. Submillimeter and infrared

ArTéMis

Taking its name from the acronym for "*Architecture de bolomètres pour les télescopes submillimétriques au sol*" ("Bolometer architecture for ground-based submillimeter telescopes"), this camera will be used, among other purposes, to observe stellar nurseries, such as the Orion Nebula (in Greek mythology, Orion was said to have tried to seduce the goddess Artemis).

Spectral range

Wavelengths in the 200–500 µm range.

Description

- Dimensions: 1 meter high × 1 meter wide × 0.5 m deep.
- Weight: 250 kg.
- Launch: not applicable.
- Position: at an altitude of 5,100 m, in the Atacama Desert high plateau (Chile).
- Mission duration: no set cutoff date for physical reasons; however duration is closely bound up with the scientific lifetime of the Atacama Pathfinder Experiment (APEX) Telescope.

Scientific goals

Investigation of the birth, and early phases of a wide range of astrophysical objects, e.g. the molecular clouds inside which stars are being formed in our Galaxy, prestellar cores and embedded protostars, protoplanetary disks around young stars, and nearby starburst-type galaxies, along with, finally, high-redshift galaxies from the primordial Universe.

Instruments

- One camera, intended for the APEX Telescope; this will feature three focal planes, having the ability to observe simultaneously one and the same region in the sky: 2,304 pixels at 450 µm; 2,304 pixels at 350 µm; 1,152 pixels at 200 µm.
- One 12-m antenna, set up in Chile.

Collaborations

The Institute of Space Astrophysics (IAS: Institut d'astrophysique spatiale) at Orsay (near Paris, France); Institut Néel, Grenoble (France); Paris Astrophysics Institute (IAP: Institut d'astrophysique de Paris); and CEA.

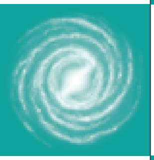
CEA contribution

Complete design and construction of the camera, fitted with its three focal planes, comprising several thousand bolometer pixels, cooled to 0.3 K; and development of a self-standing, integral cryogenic solution.
A prototype version of this camera (256 pixels at 450 µm) was constructed first, to achieve initial validation of the innovative technology developed by CEA's LETI, for submillimeter bolometers. Initial images of the sky, at 450 µm, were obtained, in 2006, with this prototype, mounted on the KOSMA (Kölner Observatorium für Submillimeter-Astronomie) Telescope, set up at an altitude of 3,100 m, in the Swiss Alps. Since then, two campaigns of observations have been carried out, using the APEX antenna, in Chile, and it proved feasible to publish initial scientific findings, using this prototype camera, paving the way for the arrival of the future ArTéMIS camera. Using this prototype, astronomers have already mapped the thermal emission, at 450 microns, from dust grains, across star-forming regions; and they have obtained initial images, at this wavelength, of protoplanetary disks, and debris disks. Regions observed include high-mass star-forming regions NGC 3576, G327.3–0.6, S255, NGC 2264; along with HD97048 (protoplanetary disk), and Beta Pictoris (debris disk).


ESA

The APEX Telescope, due to be fitted with the ArTéMIS camera, mounted at its focus.

> **Michel Talvard**
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling"
(CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)



Herschel Space Observatory

This large space telescope takes its name from William Herschel (1738–1822), a German-born British astronomer, who discovered infrared radiation in 1800. He was also responsible for discovering the planet Uranus, and its two principal satellites.

Spectral range

60–670 μm range, corresponding to radiation from cold cosmic objects (around 10 kelvins): clouds in the interstellar medium, star-forming regions, envelopes of envolved stars.

Description

- Dimensions: 7 m high, with a diameter of 4.3 m.
- Weight: 3.25 tonnes.
- Launch: by Ariane 5 launcher, on 14 May 2009, from the Guiana Space Center, Kourou (French Guiana).
- Position: around Lagrangian point L2 of the Earth–Sun system.
- Mission duration: 3 years.

Scientific goals

Identifying, and investigating the initial phases in star formation, along with the main epochs in galaxy assembly.

Instruments

- Photoconductor Array Camera and Spectrometer (PACS): this comprises an imaging photometer, together with its two channels of bolometer arrays, cooled to 300 mK (the largest bolometer-array camera ever constructed), carrying out observations in the 60–200 micron wavelength range; and a spectrometer, comprising two photoconductor arrays, covering bands ranging from 57 μm to 210 μm;
- Spectral and Photometric Imaging Receiver (SPIRE): this comprises an imaging photometer, operating simultaneously over three bands (250 μm, 350 μm, 500 μm), and a complementary medium-resolution imaging Fourier-transform spectrometer (200–300 μm and 300–670 μm), so as to cover wavelengths over the 200–600 micron range;

These two instruments may only operate at a temperature close to absolute zero. A cryostat is therefore used to ensure an average temperature of 2 K (–271 °C) in Herschel, while cryocoolers serve to cool the PACS and SPIRE bolometers to 0.3 K (–272.85 °C). Control of cold temperatures is a twofold imperative. First, in order to cool the structures, to ensure their temperature does not exceed that of the objects being detected; second, to allow operation of the bolometers, relying as this does on measurement of variations in temperature: as they absorb photons from radiation, their temperature rises; thus, if a cold structure is used, the slightest photon absorption can be detected;

- Heterodyne Instrument for the Far Infrared (HIFI): a very-high-spectral-resolution spectrometer, using more conventional radioastronomy techniques, and covering the 170–625 μm region.

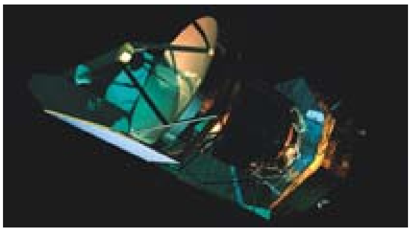
Collaborations

Construction by a consortium of European space laboratories, with the European Space Agency (ESA) as project leader.

CEA contribution

Design:
- of the PACS camera, and its detectors;
- of the electronics for the SPIRE instrument.

As a complement to the detection systems, IRFU developed the electronic functions that are indispensable, once they are deployed. Indeed, owing to the reduction in, or absence of, interfering radiation, the space environment allows measurements to be achieved involving very low noise levels. The internal noise in the onboard electronics must therefore be kept lower than the detection noise,



ESA

Artist's impression of the Herschel telescope.

this calling, in particular, for the use of detectors fitted with cryogenic cooling equipment, and thus requiring development of the associated electronic functions. SPIRE includes an electronics unit featuring 350 very-low-noise (a few billionths of a volt), high-dynamics (more than 1 million) channels, designed in collaboration with NASA's Jet Propulsion Laboratory (JPL); while PACS uses an analog electronics unit wholly designed by SAp. This unit features, aside from the 160 analog signal-processing channels, detector biasing functions, and the functions associated to the cryogenic circuit. Temperature measurement channels were developed with the Nanosciences and Cryogenics Institute (INAC: Institut Nanosciences et cryogénie). A resolution of 10 K at –273 °C was achieved. To ensure communications between this unit and the rest of the instrument, an interface compliant with ESA's SpaceWire standard was developed by SAp, in the form of an intellectual property module, distributed within the PACS consortium.

> **Marc Sauvage** et **Christophe Cara**
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
Joint Astrophysics Research Unit on Multiscale Interactions (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

VLT-VISIR

VISIR is an infrared camera–spectrometer, fitted to the third unit telescope for the European Very Large Telescope (VLT), sited in Chile; the acronym stands for "VLT Imager and Spectrometer for the Infrared."

Spectral range

The mid-infrared, covering two windows of observation from the ground: wavelengths in the 8–13 μm, and 17–24 μm ranges.

Description

- Dimensions: 1.2 m diameter × 1 m high.
- Weight: 1.6 tonne.
- Launch: not applicable (ground-based).
- Position: camera–spectrometer mounted at the focus of VLT Unit Telescope No. 3 (UT3, named Melipal), set up on the Cerro Paranal mountain (Chile), at an altitude of 2,600 meters.
- Operational lifetime: until 2014, by which time VISIR will be surpassed by the Mid-Infrared Instrument (MIRI), mounted in the James Webb Space Telescope (JWST).

Scientific goals

Observing warm (50–500 K) dust grains, and gases in the Universe: from comets to quasars, with the emphasis on the observation of circumstellar disks, within which planets are forming.

Instruments

One camera, and one spectrometer, held inside a cryostat, to be cooled to 15 K (–258 °C) as regards the mechanical structure, and optics; 8 K (–265 °C) for the detectors. VISIR is mounted rigidly on the telescope, and is rotated with it to be aimed at the object being investigated.

Collaborations

French–Dutch collaboration, under the aegis of a contract passed with the European Southern Observatory (ESO).

ESO

The four 8-meter diameter unit telescopes involved in ESO's VLT program.

Cassini-CIRS

The Composite Infrared Spectrometer (CIRS) is one of the instruments being used in the Cassini mission, which is investigating Saturn, its rings, and satellite system. This probe was so named as a token of our indebtedness to astronomer Jean-Dominique Cassini (1625–1712), for his discovery of four of the main satellites of Saturn, along with one of the divisions in its rings.

Spectral range

Infrared light, emitted by the planet Saturn, its rings, and its moons (7–9 μm, 9–17 μm, 17–1,000 μm).

Description

• Dimensions: 50.8-cm diameter telescope.

• Weight: 40 kg.

• Launch: on board the Cassini spacecraft, launched in 1997 from Cape Canaveral.

• Mission duration: for the 78 revolutions completed during the nominal mission (2004–2008), and the 250 revolutions to be completed during the extended mission (2010–2017).

Scientific goals

Investigate the dynamics, and structure of Saturn's rings particles, identifying their chemical constituents, and study the composition and meteorology of the atmospheres of the planet and its moon Titan.

Instruments

CIRS carries out its observations by way of a spectrometer, over three detectors:

• the first one, known as FP1 (Focal Plane 1), covers the submillimeter region (20–1,000 μm);

• the other two detectors, FP3 and FP4, each comprising an array of ten detectors, carry out observations in the mid-infrared (7–18 μm).

The measurement resolution achieved, with these detectors, is 10 times better than the IRIS spectrometer on board the Voyager probes, while their sensitivity is at least 1,000 times higher.

Collaborations

United States, United Kingdom, and France.

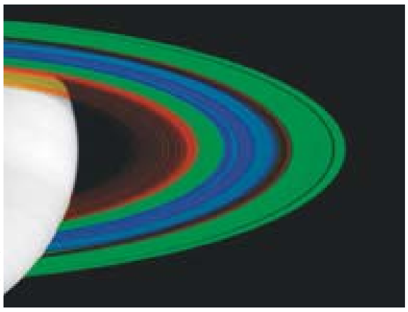
CEA contribution

Design and construction:

• of the detector line array for Focal Plane FP4, together with its processing electronics. This array comprises 10 photovoltaic detectors, featuring very high detectivity over the 7–9 μm range. The development of high-sensitivity arrays set a real challenge, especially with regard to ensuring the material is free from noise-generating defects;

• of the signals-processing electronics, involving high-discrimination filters.

The rings of Saturn were observed as they never had been before: from different angles of incidence, and at regular intervals, at the scale of a few hours, of several months, or several years, to monitor seasonal effects. For the first time, the CIRS instrument was able to measure the rings' temperature, on the south side, lit up by the Sun, and on the north side, in shadow. The temperature contrast makes it possible to probe the disk's vertical structure. At the same time, it was found that the ring particles exhibit one hemisphere that is cooler than the other one, this standing as indirect evidence that a fraction of these particles undergo slow rotation. A variation in thermal emission was also detected, along the entire length of the A ring, this being the ring lying furthest away from the planet, in the main, inner series. This is accounted for by the presence of clumps of particles, known as self-gravitating waves, which form at the rim of the rings, where tidal effects prove weak enough for these particles to be able to attract one another, through the effects of gravitation. The measurements made by CIRS make it possible to determine, very precisely, the size of such structures, which are barely ten meters or so high, and of similar length – well below the instrument's spatial resolution, which stands at several thousand kilometers. 2009 was the year of Saturn's equinox, when the Sun crossed from the south side to the north side of the rings, providing a rare opportunity to study their structure.



CIRS/JPL/NASA

The temperature of Saturn's rings, as determined by the CIRS infrared spectrometer: from the coldest (shown in blue) to the warmest (red). The blue ring, which is the thickest ring, is coldest, as its particles are more readily shielded from the Sun, which is the source of heat.

> Cécile Ferrari and **Louis Rodriguez**

Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling
(CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

CEA contribution

• Prime contractorship for the project.

• Scientific leadership.

• Design, and construction of the entire instrument, except for the spectrometer, this being of Dutch construction.

• Design of an original type of actuator, to ensure the rotation of the various wheels in the instrument (filter wheel, fields of view...), and highly accurate positioning for the optical elements; the actuator may equally be operated at ambient temperature, or at very low temperature (–253 °C).

From the inception of the VLT program, ESO had envisaged an ambitious instrumentation schedule for the unit telescopes. ESO thus appealed to the European astrophysical community, so that the most relevant instruments might be considered. The astrophysicists at CEA, European trailblazers as they are, as regards ground-based observations involving mid-infrared imagery, then suggested VISIR, which was selected. Design, and construction of the instrument took 10 years, and involved many areas of expertise in the various services at IRFU (management, project control, systems engineering, optics, mechanical engineering, vacuum, cryogenics, command and control, electronics, detection...). Since infrared instruments must be cooled, so as to preclude their emitting infrared radiation, this requires keeping them in a vacuum enclosure, ensuring thermal isolation from the environment. Three high-performance coolers make it possible to achieve the requisite low temperatures. The instrument comprises a 256 × 256 pixel array, constructed by Boeing. Following intensive tests, carried out at CEA/Saclay, VISIR was delivered in 2004, and, since that time, has been providing images featuring a fineness of detail 10 times better than that achieved by small space telescopes, e.g. NASA's Spitzer satellite. On the other hand, its sensitivity, restricted as it is by the strong infrared background emitted by the telescope, and the atmosphere, does prove much lower.

> Pierre-Olivier Lagage

Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling"
(CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

3. Visible

SoHo-GOLF


G. Perez/IAC

Artist's impression of the SoHO satellite observing the Sun.

The SoHO (Solar and Heliospheric Observatory) satellite carries out observation of the Sun from space, on a continuous basis. The onboard GOLF instrument has the more specific duty of monitoring the oscillations of our star, so that the conditions prevailing in the solar interior may be derived from them (the acronym stands for "Global Oscillations at Low Frequency").

Spectral range

Visible light: specifically, the sodium doublet: Na D1 (589.6 nm) and D2 (596 nm) lines.

Description

- Dimensions: 800 mm long × 325 mm wide × 170 mm high.
- Weight: 90 kg.

Launch

GOLF is one of the instruments carried by the SoHO satellite, which was put in space by an Atlas Centaur IIAs launcher, in 1995, from Kennedy Space Center (Cape Canaveral).

Position

Around Lagrangian point L1, about 1.5 million km sunward from the Earth; this privileged position allows SoHO to keep the Sun permanently in its sights, by contrast with ground-based instruments, which must be duplicated, and positioned at different longitudes, in observatories spread around the Earth, if data are to be secured on a continuous basis.

Mission duration: until 2012 at least.

Scientific goals

Measuring the motions of the Sun's surface, generated by solar oscillation modes, by making global observations of the star, on the basis of the Doppler velocity measured between the satellite and the Sun, in the sodium absorption line. In this way, the more penetrating modes (radial, dipolar...) may be detected, providing a wealth of information on the Sun's nuclear region. Further, GOLF is intended to test stellar modeling, with regard to the first phase of stellar evolution, by introducing some dynamical processes, that are not included in classical stellar evolution codes.

Instruments

GOLF is a resonant scattering spectrophotometer, measuring the offset of the sodium lines, relative to an absolute reference, provided by sodium vapor, contained in a cell located in the instrument. Solar photons, as they pass through this cell, are absorbed, and reemitted, and subsequently measured by two detectors. The cell is held in a magnetic field of about 5,000 gauss, the reemitted line being split into two components, by Zeeman effect. Further, a variable magnetic field (±100 gauss) allows a small extra offset to be obtained.

Collaborations

French–Spanish.

CEA contribution

- Detection, by photomultiplier tubes, together with the associated electronics.
- Overall electronics architecture.
- Cell heating electronics, and magnetic modulation electronics for the magnet.
- Construction of the flight computer, and compilation of the associated software.
- Support with computer resources for data management, and ground communications.
- Scientific leadership with regard to data interpretation, in terms of solar modeling.
- Production of calibrated velocity time series.

GOLF has allowed advances to be made, as regards our knowledge of the Sun's structure, and internal dynamics, and resolving the issue of solar neutrinos – all of this being achieved by the measurement of low-order acoustic modes (p modes). Such waves propagate right across the Sun, however they hold diminishing amounts of information, as regards layers at increasing depths. In order to probe the Sun's nuclear core, physicists found they had to seek out another type of wave: gravity modes, which had never been measured prior to SoHO. GOLF was the first instrument to evidence the signature of some of the properties exhibited by these gravity modes, subsequent to the detection of potential candidates. This was a major advance. The detection of several gravity modes will result in enhanced knowledge of the Sun's dynamics, and internal structure, with regard, in particular, to its core. GOLF would appear to indicate that the rotational velocity of the solar core is, on average, some 3–5 times higher than that of the radiative zone, a finding never previously ascertained.

> **Rafael-A. Garcia**
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling"
(CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

4. X-Ray

XMM-Newton

This space telescope (the acronym stands for "X-ray Multi-Mirror Mission") observes the Universe in the X-ray domain. For that purpose, it is fitted with a multiple grazing-incidence mirror system, affording the ability to form images at these high energies. This is the most sensitive X-ray telescope ever to have been sent out in space.

Spectral range
The band covering the 0.3–14 keV range.

Description
• Dimensions: 10 m long × 4-m diameter; 16-m span.
• Weight: 3.8 tonnes.
• Launch: by Ariane 5 launcher, in 1999, from the Guiana Space Center, Kourou (French Guiana).
• Position: perigee 7,000 km; apogee 114,000 km.
• Mission duration: 10 years (nominal lifetime).

Scientific goals
Investigating young stars lying at the core of dense clouds; black holes, and neutron stars; the production, and recycling of heavy elements; the formation, and evolution of large structures; or the nature of the diffuse X-ray background.

Instruments
• Three grazing-incidence mirrors, operating in the X-ray domain. Each one is equipped with a CCD (charge-coupled device) imaging spectrometer, operating in like manner to digital photo cameras. These instruments make it possible to acquire spectra from selected regions in the sky, and obtain the images that are indispensable, for the purposes of determining the temperature, or the nature, of emissions from hot gas, in supernova remnants, or galaxy clusters.
• One optical telescope, optimized for the blue, and ultraviolet ranges.

NASA

Artist's impression of the XMM satellite.

Collaborations
This is an observatory coming under the European Space Agency (ESA); construction of the European Photon Imaging Camera (EPIC) involves a consortium of laboratories from Germany, Italy, the United Kingdom, and France.

CEA contribution
• Development, and calibration of the cameras.
• Supply of the dedicated electronics allowing real-time investigation of interactions from every X-radiation photon.
• Computation of some 10 parameters, to allow incident photon energies to be determined by the ground station. Such onboard processing makes it possible to transmit to the ground all of the useful scientific data, and that data only.

The major differences involved in the operation of the X-ray and "optical" CCD detectors lie in the way visible radiation detectors receive a light flux, from which astrophysicist merely extract an image; whereas, in the X-ray range, they have the ability to detect, and measure photons individually, and are thus able to yield both images, and spectra, simultaneously. Whereas, for visible radiation, CCDs are used as imagers, they act as imaging spectrometers for X-radiation. In such use, CCDs are read out as quickly as feasible, to preclude a pileup of photons. In other words, the elementary exposure time is kept as short as feasible, the observation is built up from all of these elementary exposures. In such conditions, the detector allows the energy, time of arrival, and direction to be determined, for every incident photon. Images, and spectra are built up subsequently, using the list of photons received in the course of the observation. To sum up, XMM–Newton stands as a highly sensitive X-ray observatory, which has been in continuous operation for 10 years already, and which the European scientific community hopes to see in continued operation, up till 2020.

> Jean-Luc Sauvageot
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
Joint Research Unit "Astrophysics Instrumentation Modeling"
(CEA–Paris-VII University–CNRS)*CEA Centre de CEA Saclay Center (Orme des Merisiers)*

5. Ray Gamma

INTEGRAL

High-energy light readily passes through matter, and focusing such light calls for mirrors involving very long focal distances, and exhibiting a roughness comparable to that of a crystal plane. It thus proves extremely difficult to form images by way of reflection, or refraction. To work around such difficulties, the telescopes used in the INTEGRAL (International Gamma-Ray Astrophysics Laboratory) space observatory make use of "coded masks." The coded mask is a device taking its root from the camera obscura used by early photographers, while taking advantage of present-day computing capabilities.

Spectral range
15 keV–10 MeV.

Description
- Dimensions: 4-m diameter × 5 m high.
- Weight: 4 tonnes.
- Launch: by Proton launcher, in 2002, from the Russian Baikonur space station (Kazakhstan).
- Position: in a high-eccentricity orbit: 10,000/150,000 km.
- Mission duration: 2 years; designed however for 5 years, with funding allocated up to 2012.

Scientific goals
In-depth exploration, by way of imaging, spectrometry, and polarimetry, of low-energy gamma-ray emitting sites around the sky.

Instruments
- Imager on Board the INTEGRAL Satellite (IBIS): for the purposes of providing high-angular-resolution images, together with medium-resolution spectral information.
- Spectrometer for INTEGRAL (SPI): to carry out very-high-resolution gamma spectrometry.
- Two small accompanying instruments: Joint European X-ray Monitor (JEM–X), and Optical Monitor Camera (OMC), operating, respectively, in the X-ray and visible regions.

Collaborations
This is an observatory coming under the European Space Agency (ESA); construction of the instruments involves a consortium of laboratories based in Denmark, France, Germany, Ireland, Italy, Norway, Poland and Spain.

CEA contribution
- Design of, and joint leadership for, the IBIS instrument.
- Simulation of the experimental setup, and computation of the IBIS instrument's spectral response.
- Design study, development, and prime contractorship for the ISGRI (INTEGRAL Soft-Gamma-Ray Imager) new-generation camera, forming the upper plane in the IBIS telescope.
- Development, and maintenance of the scientific analysis software packages for IBIS, and ISGRI.
- Supply of the digital front end electronics for the SPI spectrometer.
- Oversight of SPI calibration, at the tandem accelerator set up at CEA's Bruyères-le-Châtel Center (near Paris).
- Design of calibration for the INTEGRAL satellite, with supply of an X-ray generator, and radioactive sources.


ESA

Artist's impression of INTEGRAL.

Does our Galaxy stand as a Milky Way, in the true sense of this expression, i.e. is its emission attributable to nebulae, or stars? Since Galileo, it is known that stars predominate, as regards visible emissions. On the other hand, it was not before INTEGRAL arrived that the situation could be ascertained, with regard to low-energy gamma-ray photons. The answer depends on photon energy. Below 200 keV, IBIS showed that the emission from our Galaxy proves wholly dominated by accreting binary systems. These comprise a black hole, or a neutron star, which strips matter away from its companion. It is the emission from such matter, brought as it is to a temperature of 100 million degrees, that IBIS detected. If an interstellar emission occurs, it is much fainter in this energy domain. On the other hand, binary systems produce little by way of emissions above 200 keV, and it is probably emission from positronium decay – the positronium being a pseudo-atom, comprising one electron, and one positron – across the interstellar medium, that dominates galactic emissions in this range. This is the case at 511 keV, at which energy the spectrometric performance afforded by SPI made it possible to evidence the emission morphology. This comprises a spheroid, having an extension of 8°, taking pride of place at the center of our Galaxy, together with a disk, of comparable luminosity. It would appear that a higher level of 511-keV emission is found in the direction in which higher numbers of X-ray binary systems are also found. Is this differential an actual feature? Does this involve a causal effect, or are these two findings simply due to a more general asymmetry in our Universe? These are some of the questions to which INTEGRAL has yet to shed some light, in the coming years.

> **François Lebrun**
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
APC, Astroparticle and Cosmology laboratory (CNRS–Paris-VII University– CEA–Paris Observatory)
CEA Saclay Center (Orme des Merisiers)

Fermi Gamma-Ray Space Telescope

Affording the ability of capturing very-high-energy radiation, Fermi is a dedicated telescope, for the purposes of investigating particle acceleration. It takes its name from Enrico Fermi (1901–54), an Italian physicist who suggested a mechanism whereby particles are accelerated by shockwaves, arising in many objects.

Spectral range

The energy band ranging from 20 MeV to 300 GeV.

Description

• Dimensions: 2 m × 2 m.
• Weight: 2.8 tonnes.
• Launch: in 2008, from Kennedy Space Center (Cape Canaveral).
• Position: in orbit at an altitude of 565 km.
• Mission lifetime: 5 years, with possibly a further 5 years.

Scientific goals

Investigating particle acceleration around:
• black holes of stellar origin (microquasars);
• giant black holes lurking at the center of galaxies (quasars);
• neutron stars (pulsars), and their winds of ultrarelativistic particles;
• supernova explosion remnants, the shockwave from which probably acts to accelerate cosmic rays;
• hypernova explosions, resulting in gamma-ray bursts.
Investigating interstellar clouds, irradiated by cosmic rays, that conceal invisible dark gas.

Instruments

• One telescope sensitive to γ rays (20 MeV–300 GeV), comprising a precision tracker, consisting of stacks of interleaved planes of silicon-strip detectors and tungsten sheets, serving to convert γ rays into electron–positron pairs, and subsequently track these, in order to reconstruct the direction of the incident γ rays. Under the tracker lies an array of cesium iodide scintillator crystals, inside which the pairs deposit their energy, making it possible to infer the energy of the original γ rays. The entire device is surrounded by plastic scintillator tiles, serving to identify the passing through of the numerous charged particles that hit the telescope, so that they may be rejected, only the rare γ rays being retained. The device as a whole affords an outstanding field of view (2 sr), providing the ability to cover the entire sky every 3 hours.
• One γ rays burst detector, operating in the 8 keV–30 MeV range.

Collaborations

The United States, France, Italy, Germany, Japan, Sweden.

NASA

The Fermi observatory in its shroud, prior to being mounted on the launcher that placed it into orbit.

CEA contribution

Overall, or partial responsibility for fundamental components in the data analysis process: catalog of sources, Milky Way emission model.

The instrumental performance exhibited by Fermi (formerly known as the Gamma-ray Large Area Space Telescope [GLAST]) fully matches expectations. The map of the sky obtained, at the end of just 3 months' operations, already shows more details than had been gained from the 9 years' observations carried out with the preceding EGRET (Energetic Gamma-Ray Experiment Telescope) satellite. Hundreds of sources were detected, and image sharpness was enhanced by a factor 2. The gain in terms of sensitivity shows a highly animated sky, the rhythm being set by the rapid winking of pulsars, rotating at rates of hundreds, or thousands of revolutions per second; by the frequent flares from quasars, as the hours, and days go by; and the slow periodicity exhibited by binary systems, over the months the black hole, or pulsar takes to orbit around its companion star. Fermi has already discovered γ rays pulses from several tens of pulsars, some of which were unknown at other wavelengths, together with tens of new quasars, that had been inactive during the time of EGRET operation. The furthest such object, lying nearly 12 billion light-years away as it does, illustrates the huge range covered by the telescope, which has also detected (at up to 10 GeV) the most powerful γ-ray burst ever witnessed, 12.4 billion light-years away.

> Isabelle Grenier
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
Joint Astrophysics Research Unit on Multiscale Interactions (CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)

HESS

HESS Colaboration

The four 12-m diameter telescopes involved in HESS phase 1, set up in Namibia.

The High-Energy Stereoscopic System (HESS) is an array of ground-based telescopes, aimed at detecting very-high-energy gamma radiation. The acronym commemorates Austrian physicist Victor Hess (1883–1964), who discovered, in 1912, that the Earth is constantly bombarded by a flux of high-energy cosmic particles.

Spectral range

For HESS: very-high-energy (100 GeV–50 TeV) gamma radiation, observable from the ground by way of its interaction with nuclei in the upper atmosphere, yielding a very faint flash of blue light, also known as Cerenkov light. For HESS 2: 20 GeV–50 TeV.

Description

- Dimensions: 12-meter diameter mirrors for HESS; 28-meter diameter mirror for HESS 2.
- Weight: telescopes 50 tonnes each; camera: 1 tonne (HESS).
- Launch: not applicable.
- Position: ground-based, in the Khomas Highlands (Namibia), near the Gamsberg mountain, at an altitude of 1,800 meters.
- Mission lifetime: 5 years at least.

Scientific goals

Investigating the acceleration processes prevailing in objects as diverse as supernova remnants, or active galactic nuclei. Looking for exotic processes producing photons, e.g. the annihilation of dark matter in particle form. For HESS 2, the aim is to be sensitive to photon energies of a few tens of gigaelectronvolts.

Instruments

- For HESS: 4 × 12-meter diameter telescopes, positioned at the corners of a 120-meter square. For HESS 2: one 28-meter telescope, positioned at the center of the previous array of four.
- For HESS: 4 segmented mirrors (380 small, 60-cm diameter spherical mirrors), 12 meters in diameter. For HESS 2: 600 × 1-m^2 hexagonal mirrors.
- For HESS: 4 cameras (1.6-m diameter × 1.5 m long; weight: 800 kg), each comprising 960 photomultipliers (devices sensitive to blue light, featuring an extremely fast response time, of the order of 1 nanosecond), covering a field of view of 5°. For HESS 2: one 3-ton camera, fitted with 2,048 photomultipliers, covering a field of view of 3°.

Collaborations

About 150 participants, for the greater part from Germany, and France.

CEA contribution

- Specific integrated-circuit electronics, dubbed ARS0 (Analog Ring Sampler), initially developed for the ANTARES experiment. Only a few laboratories, around the world, have the capability to work on fast analog memory circuits. To meet the requirements of the planned HESS 2 telescope, the ARS0 will be replaced by the SAM (Swift Analog Memory). The SAM has the same operating principle as the ARS0, but with a faster readout capacity of 2 microsecond per event
- Leadership as regards design, and construction of the second-level trigger card for HESS 2. This trigger card is a crucial component for the collection of photons with energies less than 50 GeV.

The photons, involving energies of several hundred GeV, detected by HESS originate in sources of nonthermal radiation such as pulsar nebulae, supernova remnants, active galactic nuclei. Their emissions are due to collisions of fast electrons, and positrons with ambient photons ("inverse" Compton effect), or to the decay of neutral pions, yielded by proton collisions. The energy spectrum, for these two processes, peaks somewhere between a few gigaelectronvolts (GeV), and a few teraelectronvolts (TeV), i.e. in the energy regions covered by the Fermi satellite, and HESS. The combined exploitation of the data provided by these two experiments may yield evidence that supernova remnants act as proton accelerators, and thus stand as sources of cosmic rays. Owing to its angular resolution, HESS provided the first detailed map of very-high-energy photon sources in the galactic plane. Most of these sources are supernova remnants, or pulsar nebulae. HESS also discovered new classes of gamma-ray emitting cosmic objects, e.g. binary stars LS5039 and PSR B1259–63, or the young star cluster Westerlund 2. Other, more exotic sources of very-high-energy photons are also being looked for, including the annihilation of hypothesized dark-matter particles, as predicted by extensions to the Standard Model of particle physics. Scheduled for 2010, the HESS 2 experiment should allow energies of a few tens of gigaenlectronvolts to be taken in. The initial four telescopes, set up during the first phase, will be complemented by a fifth telescope, featuring a 28-meter mirror, and fitted with a camera involving 2,000 photomultipliers.

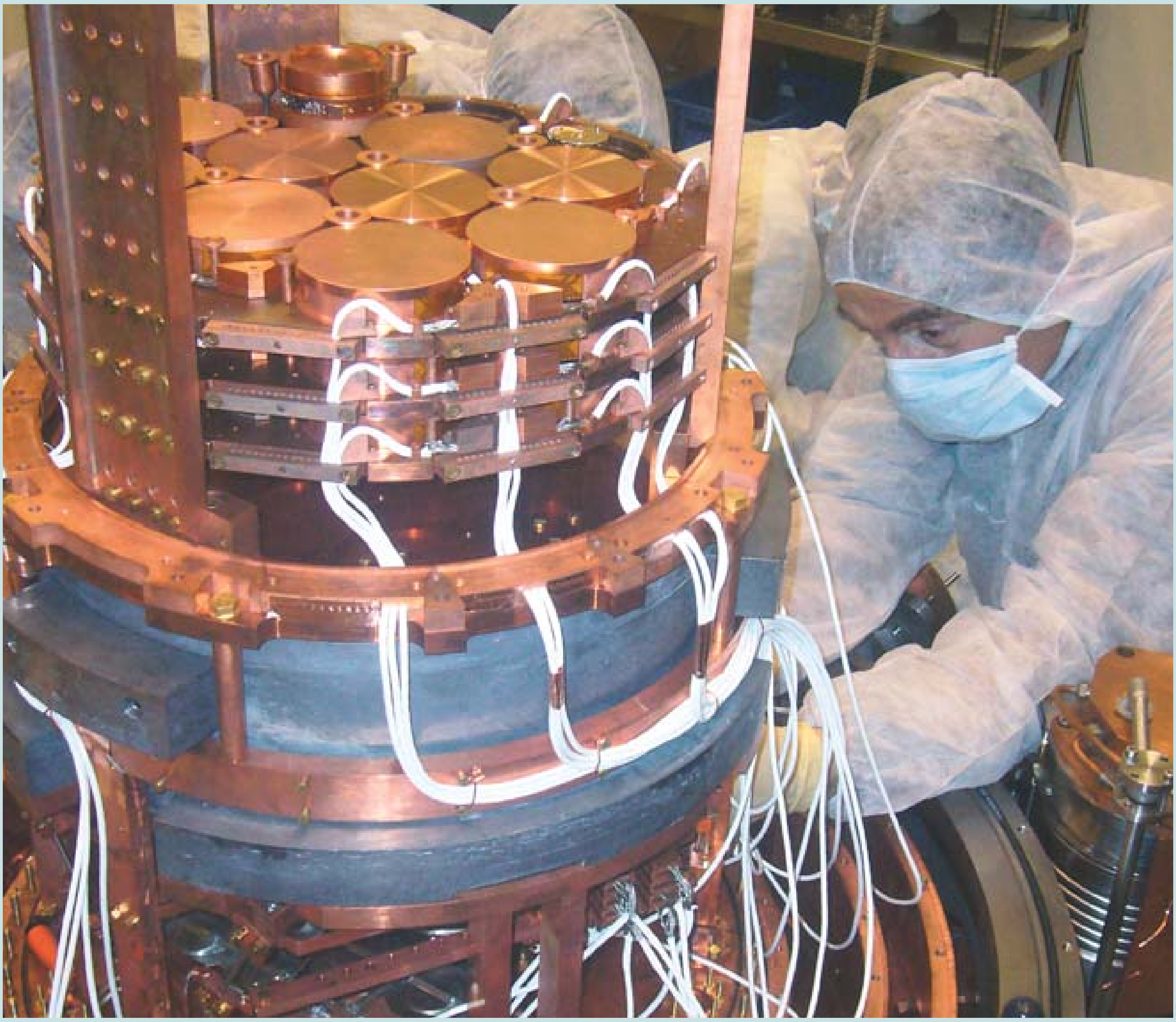
> Jean-Francois Glicenstein
Particle Physics Department (SPP)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
CEA Saclay Center (Orme des Merisiers)

EDELWEISS

The acronym stands for "*Expérience pour détecter les WIMP en site souterrain*" ("Experiment to detect WIMPs [weakly interacting massive particles] in an underground site").

Located neither on the ground, nor yet in space, this instrument, having the purpose of identifying the nature of dark matter (accounting for 25% of the energy content of the Universe), was set up 1,700 m below ground, in the hall of the Modane Underground Laboratory (LSM: Laboratoire souterrain de Modane), sited alongside the Fréjus road tunnel, under the French Alps, close to the Italian border. The reason for this is that, according to the most widely agreed hypothesis, dark matter is assumed to consist of particles, known as WIMPs. Now, supersymmetry (SUSY) theories, in subatomic physics, predict the existence of a new type of particle, neutralinos, which would be coextensive with WIMPs. These fossil particles – elusive relics from the Big Bang – are deemed to be concentrated in and around galaxies, forming halos, as is the case, in particular, around our own Milky Way, in which our Solar System – and thus the Earth – is "immersed." If such particles prove so hard to detect, it is owing to their very weak interaction with ordinary matter, and thus, by way of consequence, with detectors. Hence, there is a need to shield such detectors from spurious signals, due in particular to cosmic radiation, and natural radioactivity (this emanating, among other sources, from the human body, rocks, materials...). This accounts for the underground setting of the experiment, the use of materials of high radioactive purity, and the multiple shielding around the detectors (80 tonnes lead, and polyethylene). Taking advantage of its cryostat, unique over the world in terms of its volume (100 liters), and ultrasensitive detectors (bolometers made from germanium, operating at 20 mK), physicists are able to measure the very small rise in temperature (barely one-millionth of a degree) generated by the minute shockwaves produced by WIMPs. This experiment called for collaboration between nine laboratories, including seven French, two German, one in United Kingdom and one Russian laboratory.

> Gilles Gerbier
Particle Physics Service (SPP)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
CEA Saclay Center (Orme des Merisiers)



CEA

The EDELWEISS cryostat, standing open during detector mounting operations.