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*Unraveling the secrets of the **Universe***

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Main cover picture
Reflection nebula NGC 1999, lying in the Orion Constellation. This image was taken by the MEGACAM camera, developed at CEA, which is positioned at the focus of the Canada–France–Hawaii Telescope (CFHT), set up on top of the Mauna Kea volcano, at an altitude of 4,200 m, on the main island of Hawaii.
MEGACAM (CEA) image by CFHT & Coelum

Inset
top: Functional inspection, and control of the imager for the MIRI infrared camera, one of the instruments due to be fitted to the James Webb Space Telescope. CEA has scientific, and technical oversight for this imager.
L. Godart/CEA

bottom: Alignment tests for the MIRI imager, carried out at CEA.
F. Rhodes/CEA

Pictogram on inside pages
Our Galaxy, the Milky Way.
NASA/JPL-CalTech/R. Hurt (SSC)

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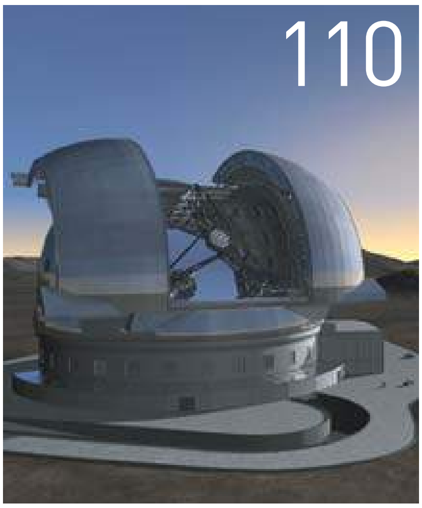
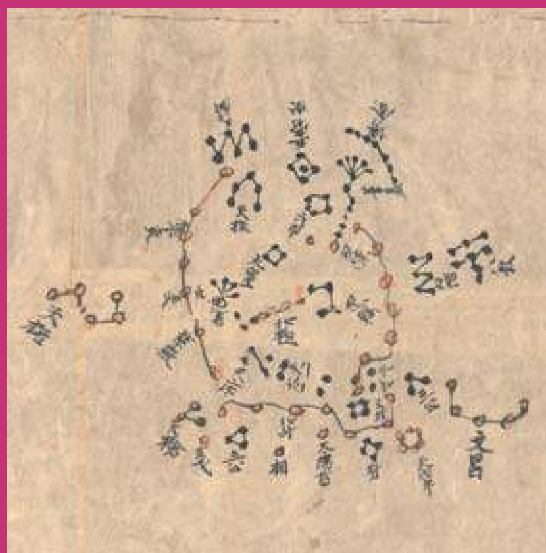
Unraveling the secrets of the Universe

I. ASTROPHYSICS AND THE EXPLORATION OF THE UNIVERSE

II. TOOLS TO PROBE THE UNIVERSE



A spectacular document from the history of astronomy has just been brought back to light, through the study conducted by a group of researchers led by Jean-Marc Bonnet-Bidaud (CEA/SAp). This document, known as the Dunhuang Map, kept at the British Library, in London, is a comprehensive sky chart, discovered in 1900 as one of 40,000 invaluable manuscripts held in the Mogao Caves, a Buddhist monastery complex along China's Silk Road. Hidden in a cave around the 11th century CE, these manuscripts – chiefly Buddhist religious treaties – were miraculously preserved, owing to the very dry climate. The detailed scientific study of this chart, carried out by these researchers, allowed the conclusion to be drawn that the atlas, containing as it does more than 1,300 stars, was composed in the years 649–84. Making use of accurate mathematical projection methods, it retains a precision of 1.5–4° for the brighter stars. This is the oldest known star chart, from any civilization, and it sets out the first pictorial representation to have reached us of all Chinese constellations. The atlas was the subject of a presentation in the journal *Nature*, in its issue dated 11 June 2009, and of a publication in the *Journal of Astronomical History and Heritage*.



> FOR FURTHER INFORMATION...

You can look up CEA's astrophysics programs on the Internet:
http://irfu.cea.fr/Sap/

Foreword

Throughout 2009, we will have been commemorating the four hundredth anniversary of the first observations made by Galileo, this being marked by international celebrations, as part of the International Year of Astronomy, organized at the initiative of the United Nations, and steered, worldwide, by the International Astronomical Union (IAU) and UNESCO. As the outgoing President of IAU, I am wont to say that this year 2009 is also a celebration of the golden age of astrophysics. Indeed, the spectacular advances achieved by technology, over the past 30 years or so, and the outstanding uses our astrophysicists have been able to put them to, have brought about an utter transformation of our vision, and understanding of the Universe, and its components – from the internal behavior of the Sun to star formation, from the evolution of galaxies, now delineated virtually throughout the 14 billion years the Universe has existed, to the evolution of large-scale structures, these vast cosmic webs traversing space. Fundamental physics is likewise undergoing an upheaval, particularly as regards particle physics, as it seeks to identify the engine driving the acceleration in the expansion of the Universe, and the baffling mass carriers that make up dark matter, the largely dominant component of matter, across the Universe.

In the midst of this upwelling of knowledge, CEA can draw on its own outstanding assets, ranking as a significant player, gaining worldwide recognition, and indeed increasingly so. Thus, three research scientists at CEA, involved in such topics, have already been awarded European Research Council (ERC) grants. Initially, CEA elected to embark on a space science, and technology effort as France, and Europe made the decision to go in for space science. Consideration was immediately given to the detection of high-energy cosmic radiation (X-ray and gamma photons, particles), which are unable to penetrate the Earth's atmosphere – and thus to CEA, which, owing to its chief remit, was recognized for its expertise as regards the detection of such radiation. From the outset, CEA had been one of the main laboratories, in Europe, engaged in mounting high-energy radiation detectors on balloons, rockets, and, subsequently, satellites.

Working alongside the researchers, and engineers developing the instruments came astrophysicists, their arrival strengthening the link between experimental know-how, and the interpretation of the findings obtained, advancing our knowledge of the Universe. Over the years, this fruitful collaboration resulted in markedly boosting CEA's ability to suggest the instruments, and missions best suited for the purposes of resolving the most pressing issues, this allowing CEA to be selected by the relevant French, and international organizations, to provide numerous instruments, both spaceborne, and ground-based. The outstanding success may be noted, for instance, of the SIGMA gamma-ray camera, carried on a Russian satellite, which allowed the discovery of microquasars, i.e. stellar-mass black holes giving rise to phenomena similar to those arising in quasars.


L. GODART/CEA

« CEA can draw on its own outstanding assets, ranking as a significant player, gaining worldwide recognition, and indeed increasingly so. »

The interest being shown for new scientific issues, e.g. the gas content of galaxies, and the investigation of star formation, together with the opportunity this afforded, of taking advantage of the synergies arising with teams at CEA's Technological Research Division (DRT), led the astrophysicists at CEA to further become involved in infrared astronomy, in the early 1980s. The European Space Agency (ESA) was readying the first infrared space observatory, ISO, and there was an opportunity for CEA to take on main project leadership for a crucial instrument, the camera. This entailed securing the availability of arrays of infrared detectors, which, at that time, could not be imported from the United States. These detectors called for a specific development effort, if they were to operate at low noise levels, and the Infrared Laboratory, at CEA/LETI, took on this venture, quite successfully. The findings obtained by ISOCAM, as regards star formation, and the evolution of galaxies, showing that starbursts, and infrared-bright galaxies had been far more frequent in past epochs, brought about a revolution in this area. Nowadays, very large numbers of astrophysicists, around the world, are investigating the various stages in galaxy evolution; ISOCAM findings have been corroborated, and considerably expanded, by the US Spitzer satellite, and major advances are presently anticipated, with the Herschel satellite, which has just been launched. For Herschel, DRT developed innovative detector arrays, also used for ground-based purposes, on the APEX radiotelescope, while CEA's Physical Sciences Division (DSM) was very actively involved in the construction of two of the three instruments carried by the satellite.

Ground-based astronomy has likewise made major strides, and the development of instruments, for such purposes, now calls for quasi-industrial methods. The know-how gained by CEA, with regard to space technologies, has enabled the organization to deploy a major instrument, VISIR, on one of the giant unit telescopes at VLT, providing unique information regarding protostellar disks, within which planets are formed. Research scientists at the Institute for Research on the Fundamental Laws of the Universe (IRFU) are also heavily involved in cosmology, carrying out observational investigations from the ground, with the MEGACAM camera they have constructed for the CFHT telescope, and from space, with XMM–Newton, pending the wealth of data on the cosmic microwave background being anticipated from the Planck satellite.

Currently, CEA has also gained strong expertise in the area of numerical simulation. This enables major advances to be made on topics that are also subject to ground-based, and spaceborne investigations by CEA researchers. Thus, subsequent to the success of the GOLF experiment, which measured the oscillations of the Sun, a detailed modeling effort is currently ongoing, of the interior of our star. The acceleration of cosmic rays is likewise being simulated, synergetically with observations from satellites to which CEA has made a contribution in terms of instrumentation (XMM–Newton, INTEGRAL), and from others, for which CEA is associated to the science involved, e.g. the recently launched Fermi satellite, or, on the ground, HESS, which is detecting high-energy gamma rays to a high locating precision. The most spectacular results concern simulations of the evolution of the large-scale structures of the Universe. These highlight the importance of the infall of cold gas flows in those regions where mass is coming together, making it possible to ensure better preparation for forthcoming missions, to measure the properties of dark matter, and of dark energy, missions in which CEA is acting as a driving force.

The near future is highly promising, with the ongoing stream of findings from XMM–Newton – which, among other results, is providing CEA with extraordinary findings regarding galaxy clusters – as from INTEGRAL, Fermi, and ground-based instruments, together with the initial operation of Herschel, and Planck; concurrently, at CERN, LHC could be achieving a breakthrough, as regards the puzzle of the nature of dark matter. At the same time, CEA is playing a major part in the design of an infrared imaging camera and spectrometer, intended for JWST, the ambitious successor to Hubble; likewise for a new instrument for gamma-ray astronomy, being constructed in collaboration with China; and it is the prime mover, in Europe, of a new cosmology mission.

As regards the more distant future, many possibilities are shaping up, in the realm of space science, while the quest for high-energy neutrinos, from the bottom of the seas, is about to begin. CEA's grand cosmic adventure is set to continue.

> **Catherine Cesarsky**
High Commissioner for Alternative Energies
and Atomic Energy Commission.

Seeing the invisible: a short account of a grand conquest

For more than 2,000 years, astronomers remained ignorant of the lights pervading the cosmos, except, of course, for visible light. There was a good reason for this: most other kinds of radiation are unable to get past the barrier formed by the atmosphere. Bypassing this barrier entailed using suitable instruments: balloons first, then rockets, and ultimately satellites.


CEA

The discovery of gamma radiation from pulsars. The payload, and stratospheric balloon at Aire-sur-l'Adour (July 1969).

On 27 January 1959, facing the abrupt coastline of the Corniche des Maures, out on Levant Island – a dependency of the French coastal municipality of Hyères (Var *département*, southern France) – preparations were under way for an event that would remain as a landmark in the history of French astrophysics. In the late afternoon, from the secrecy of the naval base on the island, a thin streak of light rose up into the sky, swiftly losing itself in the clouds. Was this a test launch, to try out some new weapon for the nascent French nuclear deterrent? Nothing of the sort! This, indeed, was a converted missile, taking up, to an altitude of more than 100 kilometers, the first French experiment in space astrophysics, built in CEA laboratories.

CEA's pioneering role in space

CEA's space saga began virtually from the time the organization was set up. Indeed, on 18 October 1945, the French Government approved the ordinance – as drafted by Jean Toutée, a member of the French Council of State (which has oversight on all administrative acts of state) – setting up the Atomic Energy Commission (CEA) the then head of the government, General de Gaulle, had decided to create, for the purposes of "[…] conducting scientific and technological research to promote the uses of atomic energy in various fields of science, industry, national defense." No-one could yet imagine that this new research organization would become a tremendous melting-pot of expertise, with regard to discovering the Universe. And yet…

On 2 January 1946, General de Gaulle appointed as High Commissioner for Atomic Energy the head CEA, Frédéric Joliot, who had been awarded the Nobel Prize in Chemistry, in 1935, jointly with his wife Irène Curie, for their discovery of artificial radioactivity. This novel property exhibited by matter is characterized by the disintegration of **atomic nuclei**, which then emit strange, hitherto unknown forms of **radiation**, which were dubbed alpha, beta, gamma, for want of any better inspiration. While the first two of these forms of radiation are, in fact, made up of particles (**helium** nuclei, and **electrons**, respectively), on the other hand, the third kind would soon be found to be the most powerful form of light extant in nature.
From then on, the engineers at CEA would put all their energy in devising instruments affording the ability to sense, and measure these forms of radiation. For several years, these investigations were carried out in the laboratory; however, the date of 4 October 1957 marked a veritable revolution, for these scientists: Sputnik I had been put in orbit, this being followed, a few years later, in 1961, by the first spaceflight by a Soviet cosmonaut, Yuri Gagarin, opening the way to space exploration.


CEA

The first space experiment to be carried out by CEA, on 27 January 1959. A Geiger counter was mounted on board a converted missile, to effect one of the first measurements of gamma radiation from the sky.

Such was the motive for the launch carried out, on 27 January 1959, on Levant Island, using a Daniel rocket, originally designed by the French National Aeronautical (subsequently Aerospace) Design and Research Bureau (**ONERA**: **Office national d'études et de recherches aérospatiales**).

Of course, that mission, led by physicist Jacques Labeyrie, had the prime objective of providing answers to the queries raised by atmospheric nuclear tests, and, consequently, concerning the possible dissemination of radioactive materials in the upper atmosphere. However, the battery of Geiger counters carried by that rocket proved equally able to measure gamma radiation from the sky. While the experiment allowed the conclusion to be drawn that no radioactivity was to be found in the upper atmosphere, it equally achieved a breakthrough, in world terms, in the area of astrophysics: it brought back one of the first records of gamma rays originating in the cosmos. Until that time, no researcher had imagined that the Universe yielded such radiation. There was a good reason for this: apart from visible light, which is able to reach the surface of the Earth, most other kinds of radiation are blocked by the atmosphere. As a result, from the beginnings of astronomy, more than 2,000 years ago, astronomers had had no means of sensing the other forms of cosmic light. The sole exceptions that could be adduced being the discovery of the radio wave emission from our own **Galaxy**, realized, in 1932, by US physicist and radio engineer Karl Jansky; and the demonstration, by German scientists working in the United States, after the Second World War, of X-ray emissions from the **Sun**, using a V–2 rocket.

Such a finding propelled CEA into the ranks of world astrophysical expertise, a position it has never relinquished. Fifty years on, a new generation of research scientists, now gathered within CEA's Astrophysical Service (SAp), has just delivered a very-high-technology camera, to be mounted at the core of Herschel, the largest space telescope ever to be placed in orbit, but equally a gem of research capability, able as it is to capture the faintest infrared radiation from the Universe. In the interval, spanning these two ventures, astronomers at SAp were to make their mark at every step, in one of the most exciting adventures of all times: the detection of the "invisible" radiation from the cosmos, totally inaccessible as this is to our human eyes, which are solely suited to the light reaching us from our own **star**, the Sun.

Success with available resources

In June 1962, a major discovery brought about an upheaval, once again, in the view astronomers then had of the sky. This was due to a US team, led by Riccardo Giacconi, who was awarded the Nobel Prize in Physics in 2002. He had had the idea of mounting X-ray detectors on board an Aerobee rocket, for an attempt to measure X-radiation from the Sun, reflected from the surface of the Moon. Virtually no X-rays could be sensed coming from the Moon, however, as they swept the sky, the onboard instruments recorded an intense X-ray spike, coming from a region lying within the Scorpius Constellation (the Scorpion). Given the name Scorpius X–1, this source was long to remain as a puzzle to astrophysicists. It took more than five years before it was understood

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The discovery of cosmic X-radiation: a stratospheric balloon being prepared for takeoff, and another being released, at Aire-sur-l'Adour (May 1965).

that X-rays yielded by the Universe originate in very dense, exotic stars – **white dwarfs**, **neutron stars**, or even **black holes**. With that discovery, a new observation window was opened up onto the cosmos.

At the time, France had not yet developed a rocket program of its own, so researchers at CEA had to be inventive, if they were to carry their observations forward. For want of a better solution, they hit on the idea of mounting their measuring instruments on stratospheric balloons, giving the ability to go up to a height of 40 kilometers.

On 21 May 1965, an inaugural flight was sent off from the Aire-sur-l'Adour base (Landes *département*, southwestern France), using such resources as were available. For instance, to shield the detectors against the

CEA

The payload carried by the balloon: detectors shielded from the vacuum in a leaktight pressure cooker, data being recorded on a tape recorder, recovered after the flight (May 1965).

vacuum, and cold conditions, the astrophysicists used a pressure cooker, and polystyrene; to record their data, they could only use a run-of-the-mill commercial tape recorder. Recovered after the flight, this simple data recorder gave CEA one of its historic firsts: the detection of high-energy X-rays emanating from a number of sources lying in the Cygnus Constellation (the Swan).
However, those were just the first surprises researchers were to come up against. In 1967, British radioastronomers discovered rapid, regular sequences of radio signals coming from the sky. Once the – briefly entertained – hypothesis of signals sent by extraterrestrial beings had been ruled out, another surmise came up: these "pulses" could be emanating from very rapidly rotating neutron stars, dubbed **pulsars** (as an abbreviation of "pulsating stars").

From Kourou to Gap

In the meantime, the development, by France, of its own rocket program had come to fruition, with Véronique. Astrophysicists could not let such an opportunity go by. In 1967, the team led by Robert Rocchia mounted, on one such rocket, detectors previously developed by CEA for the purposes of studying radioactivity. The outcome was a terrible disappointment: the rocket's trapdoors had failed to open. Another opportunity was to arise, however, and success came, as a Christmas present, on 23 December 1968, from the newly opened Kourou space center (French Guiana), just a few months after it had been commissioned. The results of the experiment proved conclusive: during the 200 seconds of observation, some 25,000 X-rays were recorded, emanating from one of the most powerful pulsars in our Galaxy. The astrophysicists at CEA had just demonstrated that pulsars emit high-energy X-rays – another first.
Not content with this, however, the following year, they took up another challenge: using a novel dedicated detector, for the purposes of observing gamma rays from pulsars. This complex instrument had been developed by Bruno Parlier, Bernard Agrinier, and Yves Koechlin from CEA, in collaboration with Giuseppe Occhialini, a renowned physicist from Milan University (Italy). In effect, this was a spark chamber, in other words an enclosure kept under vacuum, and to which a voltage is applied. The chamber, contains a stack of lead plates, having the ability to stop gamma rays, causing them to decay, yielding charged particles which generate sparks along their track. To reconstruct the direction of the incident gamma ray, these tracks were photographed, using a 16-mm movie camera. This time, the operation was carried out at Gap (Hautes-Alpes *département*, southeastern France). A balloon took up the detector to a height of 40,000 meters. Results were forthcoming, once again, for the CEA research scientists, who were able to show, for the first time, that pulsars also emit gamma rays across the Universe.

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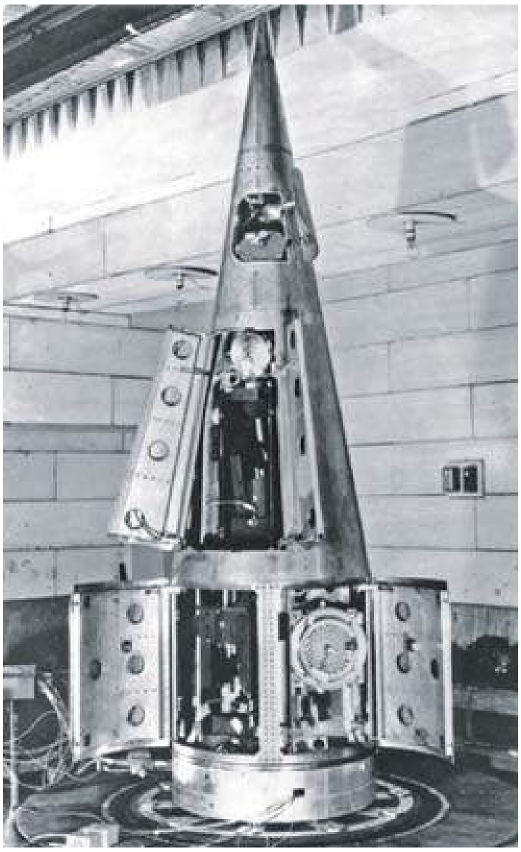
A Skylark rocket unit, used for the purposes of detecting celestial X-ray sources (1972).



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The first detection of high-energy X-rays from pulsars: the nosecone of the French Véronique rocket, carrying the X-ray detectors (December 1968).

From balloon to satellite

Carrying this line of research further, at that time, entailed that an essential limitation be overcome: to wit, the all-too-short observation time afforded by balloons, and rockets. To that end, it was imperative that the availability of scientific satellites be secured, thus ensuring sustainable access to space. Europe had to wait until 1972 before such a satellite became available, in the form of TD–1. Astrophysicists at CEA made use of this first opportunity to be offered to them, placing three instruments on board the satellite, which was to remain in orbit through to 1974. These included S–133, a brand-new 40-kg spark chamber, now fitted with an electronic video camera, dubbed VIDICON. Unfortunately, this flight experiment proved to be a failure, owing to the proximity of other instruments, inducing an overwhelming background of spurious particles, drowning the experiment in false detections. This served as a learning lesson, benefiting the COS–B satellite, launched in August 1975, carrying a 114-kg spark chamber, as the outcome of a broad Europe-wide collaboration. With a completed lifetime of 7 years, this program outshone its US competitor, SAS–II, this having been planned to last just 6 months. It provided a major scientific result: the first complete gamma-ray picture to be obtained of our Galaxy.
This exploration of the high-energy X-ray and

gamma-ray domain was to carry through to the present time, with CEA's involvement in the SIGMA/GRANAT (1989), XMM–Newton (1999), and INTEGRAL (2002) missions. Nowadays, the view available to astrophysicists has opened out to cover thousands of sources, bearing witness to that tumultuous Universe, in which temperatures run to millions of degrees. By contrast, going over to the infrared radiation side, obstacles were not readily overcome: first of all, the Earth's atmosphere stands as a barrier that must be bypassed; and, second, detector technology, arising as it does from military applications, does not always progress in step with the requirements of researchers. CEA's involvement in this new domain was the outcome of a chance circumstance, to wit the delay that affected international collaborations on high-energy projects, subsequent to two different events: the accident that befell US Space Shuttle Challenger, in 1986, and the demise of the former USSR, in 1991.

Waiting for the grand symphony of the cosmos...

Europe then decided to take up the challenge, with the Infrared Satellite Observatory (ISO) project, designed to carry the first spaceborne infrared camera. It should be said that the US Infrared Astronomical Satellite (IRAS), placed in orbit in 1983, for 6 months, had yielded but an initial glimpse of the infrared sky. Be that as it may, no European laboratory appeared to have the capability to build the camera for ISO. Only two units at CEA, SAp, and the Electronics and Information Technology Laboratory (LETI: Laboratoire d'électronique et de technologies de l'information) were able to undertake providing detectors for the instrument, and carrying out their integration into a complex optical unit, to weigh less than 10 kg. Through the drive of Catherine Cesarsky, the ISO camera (ISOCAM) was readied to go into space, in 1995, for three years. Featuring an array of semiconductor detectors of just 32 × 32 **pixels**, this camera produced a mosaic of images, revealing, in full detail, the gas and dust **nebulae** inside which stars are born. It has been bettered, at the present time, only by the recently launched Spitzer satellite.

Currently, out of the vast rainbow of nonvisible light, only one region remains as yet unexplored: that of the far infrared, close to radio **waves**. If this new challenge, set by the observation of such very-low-energy radiation, is to be met, the present boundaries of technology will need to be pushed further back yet. The camera of the future is to be fitted with specific detectors, known as **bolometers**. The challenge is to preclude its being blinded by its own environment. To achieve this, astrophysicists must ensure cooling down to a few thousandths of a degree above absolute zero. Some cameras of this type are already being operated from the ground, using narrow atmospheric windows that let through part of that radiation. However, the first major exploration is now being carried out in space, with the Herschel satellite, successfully launched by the **European Space Agency** (**ESA**), on 14 May 2009. It is carrying the Photoconductor Array Camera and Spectrometer (PACS), a camera featuring the largest bolometer array ever constructed, standing as a major success for CEA. As all true scientific breakthroughs, and indeed as all technical successes, PACS nevertheless gives some grounds for humility, when the size of this camera, with its 2,048 picture elements, is compared to that of the large dedicated astronomical cameras, for the purposes of visible light observation, featuring millions of picture elements.

In many observational domains, the "glasses" used by researchers prove barely better, in terms of performance, than Galileo's telescope. Space exploration has always had to adjust to the pace of technological innovation: at every step, specific tools had to be invented, and, most crucially, taken outside of the atmosphere. Thus, bit by bit, the unknown fraction of the Universe is relentlessly being narrowed down. For a long time, astrophysicists had thus been in the situation of a music-lover able to hear but the sound of one instrument, in the interpretation played by a musical ensemble, and then gradually extending their perception, to cover the full orchestra. Presently, what scientists desire would be finally to be in a position to listen to the full range of the grand symphony of the cosmos.

> Jean-Marc Bonnet-Bidaud
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Physical Sciences Division (DSM)
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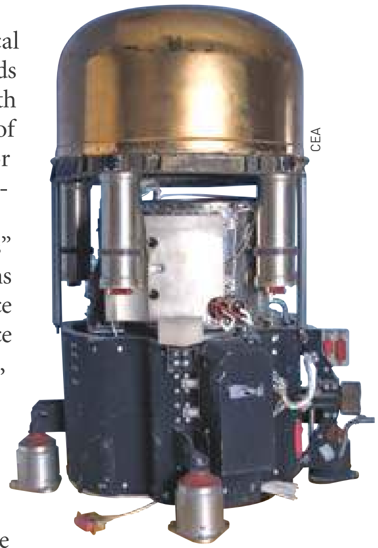

CEA

The first spark chamber to be placed in a satellite: the S–133 experiment, carried on board the European TD–1 satellite (March 1972).

Cosmic radiation: key dates in the discovery of the various kinds

No confidence may be placed in the colors that are plain for all to see in the rainbow, since these are but a minute fraction of the true extant gamut of colors. Our own human eye is unable to perceive them, as it is solely adapted to the light reaching us from our own star, the Sun. It was thus through work in the laboratory that other kinds of radiation could be discovered, step by step, by researchers:

• 1800: physicist William Herschel, by means of a mere prism, and thermometers, is able to show that, beyond "red", there is another type of radiation, having the ability to heat a thermometer: the infrared. This was the first truly significant breakthrough.
• 1800: carrying out a similar experiment, Wilhelm Ritter discovers that, beyond "violet," a radiation is found, that is able to darken paper prepared with silver chloride: this is ultraviolet.
• 1810–64: James Clerk Maxwell unifies electricity and magnetism, this enabling him to suggest that visible light is but a special case of a more general phenomenon: electromagnetic waves.
• 1895: Wilhelm Röntgen discovers that electrical discharges inside vacuum tubes yield hitherto unknown rays (therefore named by him "X-rays"), having the ability to go through glass.
• 1896: Henri Becquerel discovers natural radioactivity: emanating from within the nuclei of uranium atoms, unknown rays are found to be able to make an impression on photographic plates.
• 1898: Pierre and Marie Curie discover further "radioactive" materials (polonium, thorium, radium), which emit forms of radiation dubbed alpha, and beta radiation (in fact consisting of particles).
• 1900: Paul Villard discovers a form of radioactive radiation that has the ability to go through lead: gamma radiation.

For the most part, these various types of radiation are blocked at varying heights in the Earth's atmosphere. Only space astrophysics affords the ability to capture such radiation, and thus study it. At the present time, this discipline is just 50 years old.

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.

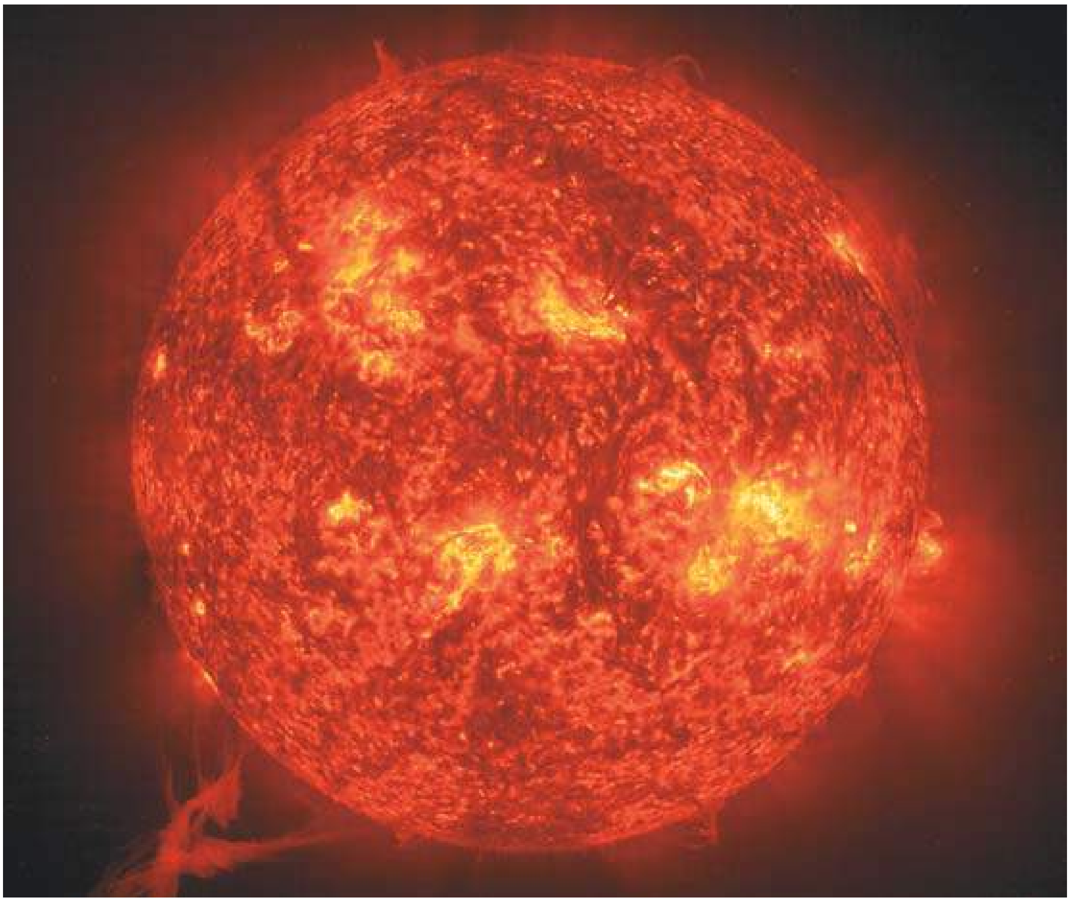
There remain, finally, the fundamental queries, as to the shape, and finite character of the Universe. Surprisingly, such essential queries may yet find an answer, well before the finer "details" in the history of the objects involved can be worked out.

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.

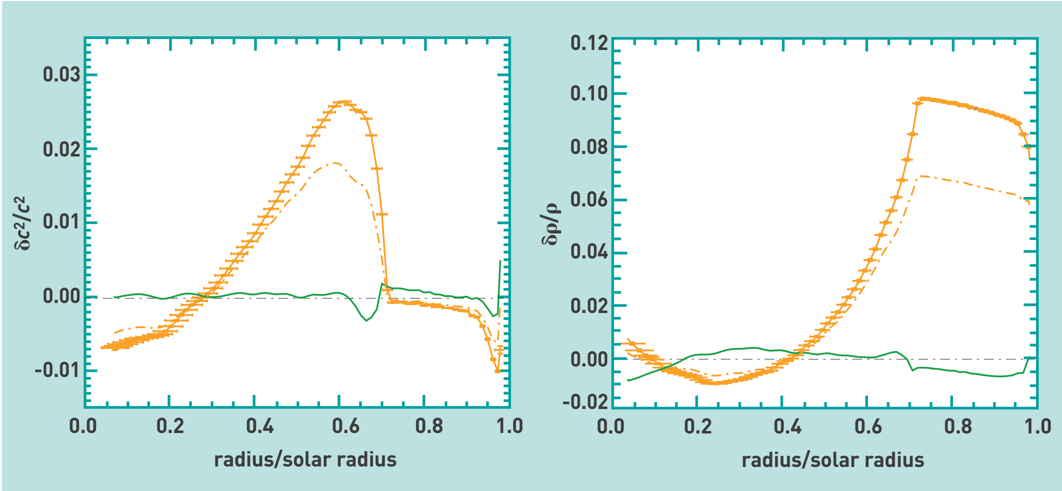
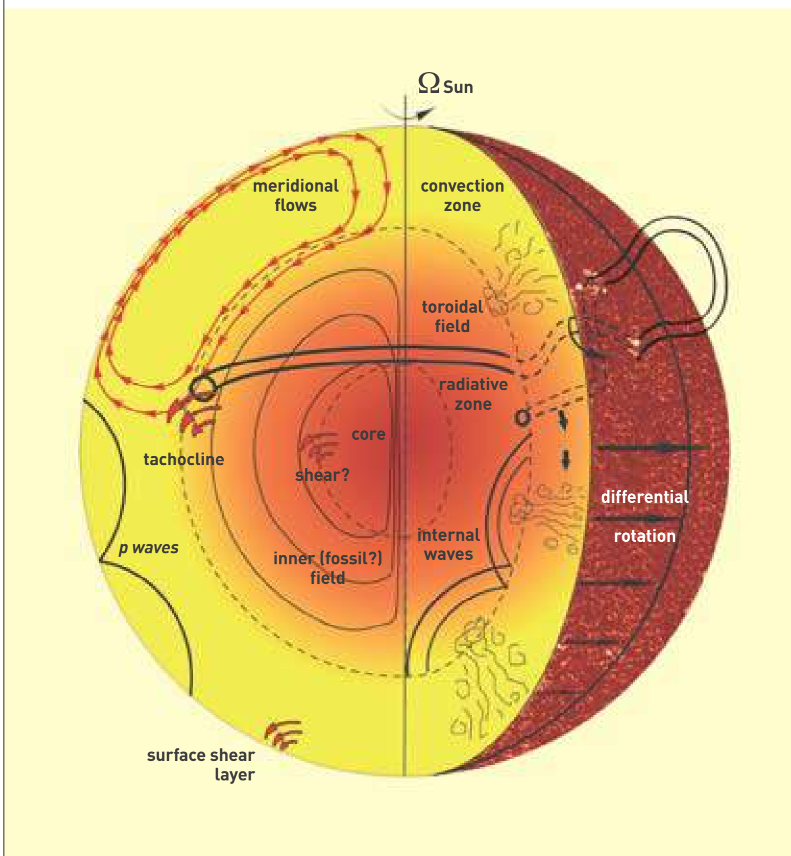


Figure 1.
To the left, radial difference between the squares of sound speed (*c*), as extracted from the acoustic modes detected by the GOLF and MDI instruments, and that obtained with a seismic model of the Sun (in green), or with a classical model, based on relative abundances, as determined from absorption 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/cm³ in the core to 10^{-7} g/cm³ 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.



A. S. Brun/CEA

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

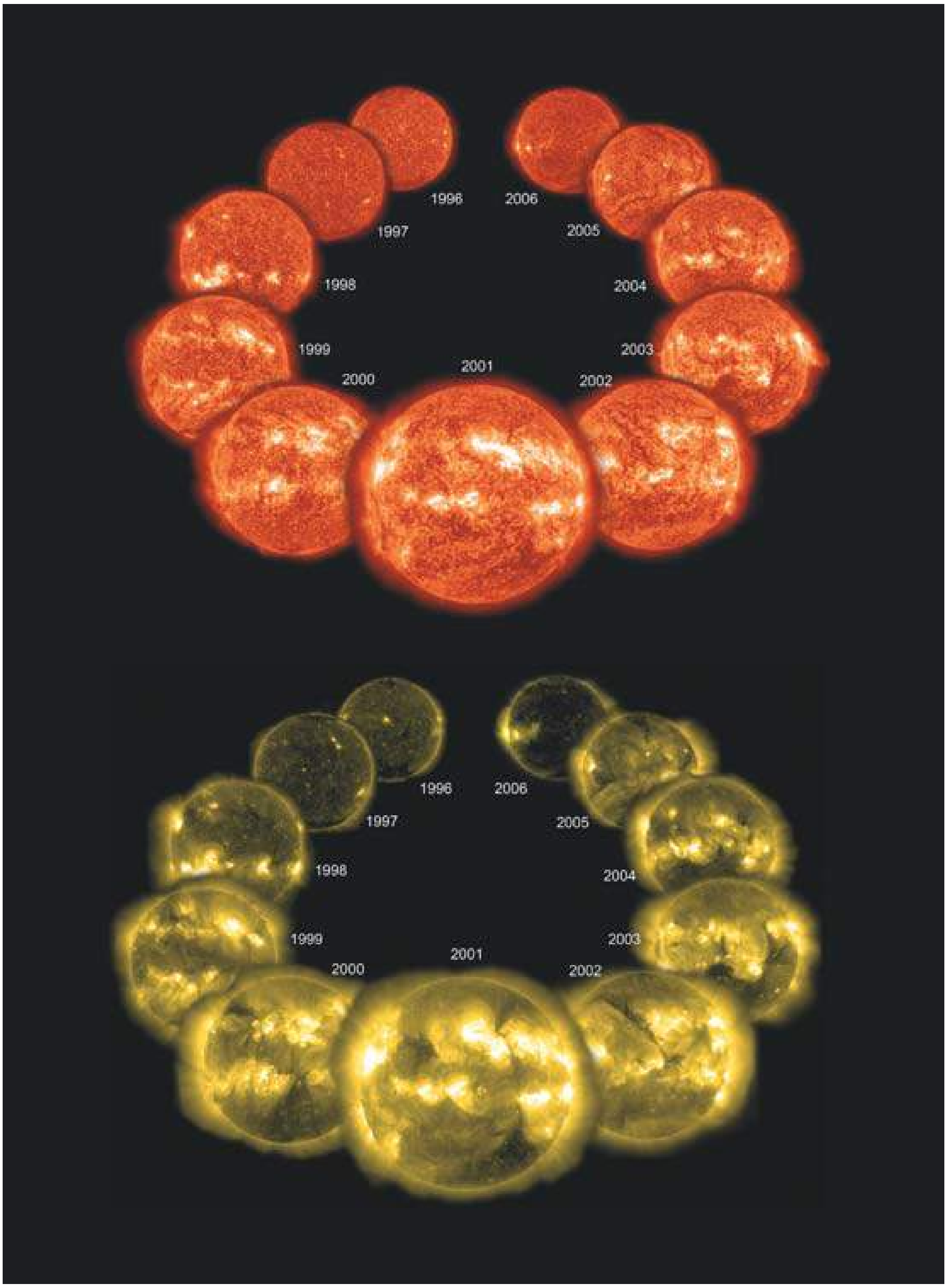
Many questions, however, do as yet remain unanswered. For instance, recent solar composition measurements lead to major discrepancies between the classical model of the Sun, and that derived from seismic observations (see Figure 1). Laboratory experiments should allow the role to be tested, of a second 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).

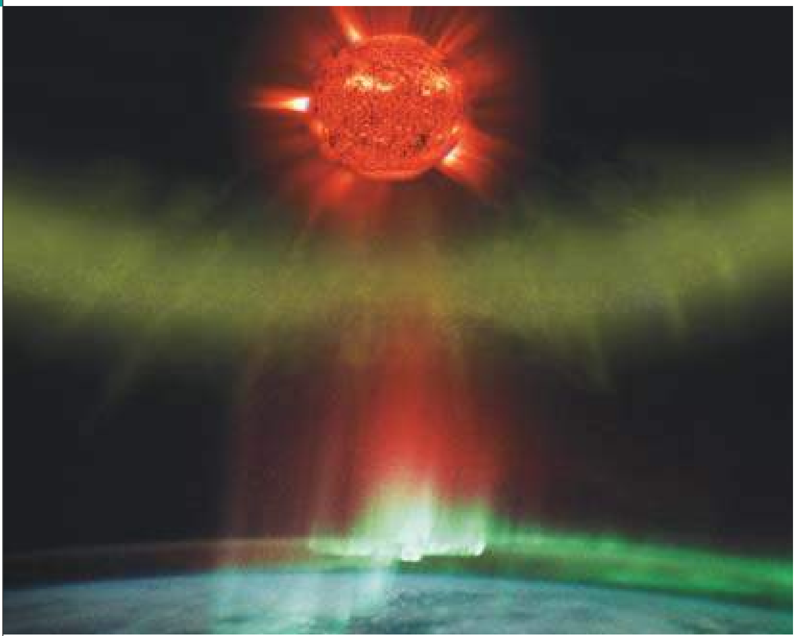
(5) Named after US astronomer George Ellery Hale (1868–1938).



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

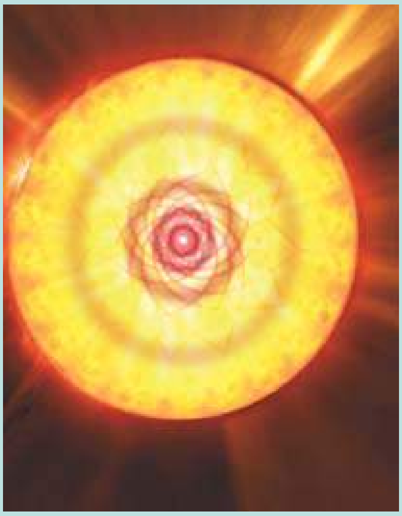
Astrophysicists at CEA are presently seeking to understand what internal source, or sources drive the Sun's activity, to achieve an improved evaluation of its variability. Indeed, the Sun, when it is very active, ejects particles, which escape from the solar corona. Such regular, or occasional – as regards 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.

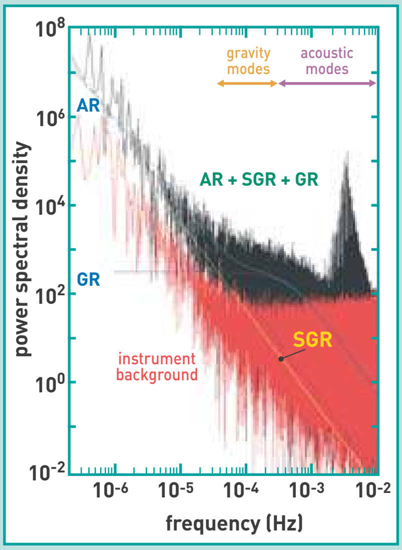


SMM/IAC

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 $5 \cdot 10^{-4}$ Hz), the solar spectrum exhibits a maximum around $3 \cdot 10^{-3}$ 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.

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FOR FURTHER INFORMATION

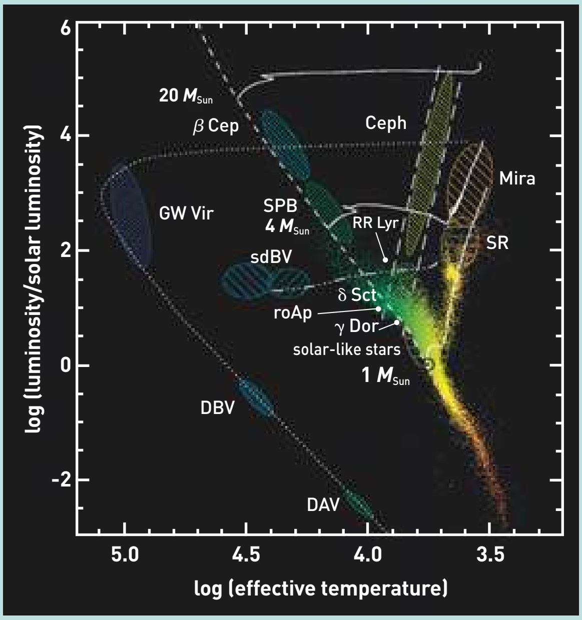
Clefs CEA No. 49, Spring 2004, "The Sun and the Earth."

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 (·······).

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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.

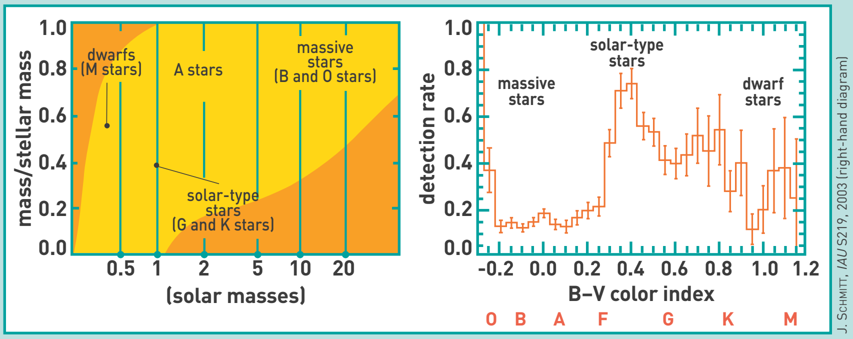

Figure 1.
On the left, spatial, and mass distribution of convection zones, as a function of stellar mass (involving convective cores for massive stars, convective envelopes for low-mass stars).
The transition between surface convection and core convection occurs at about 1.3 solar masses.
On the right, 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.

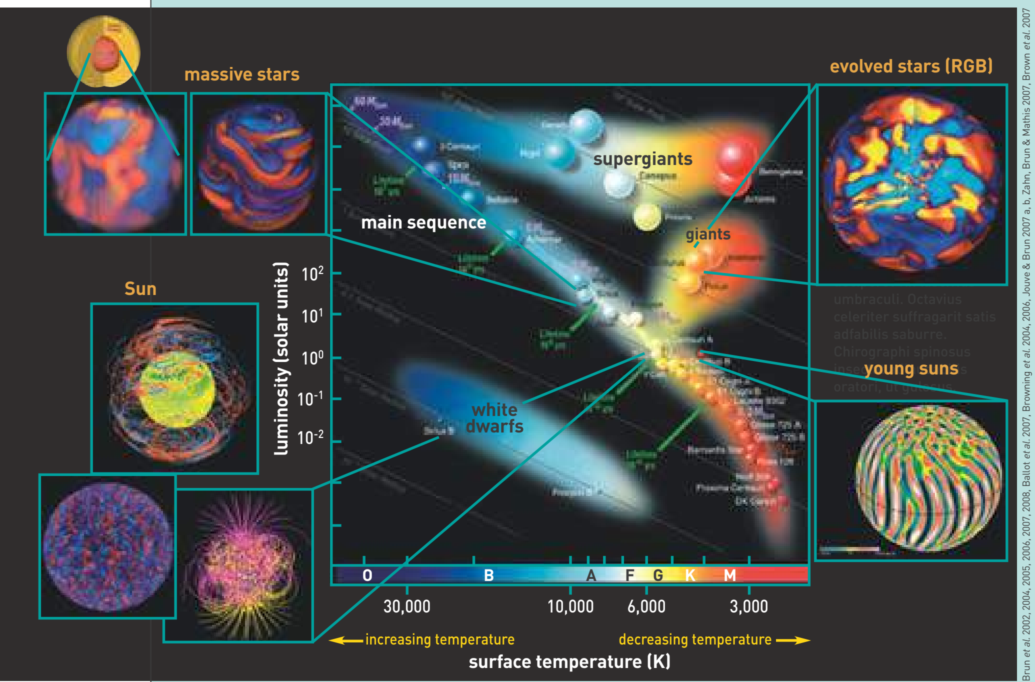

Figure 2.
3D numerical simulations of the **magnetohydrodynamics** of various star types, with their positions indicated on the Hertzsprung–Russell diagram, carried out under the aegis of the European STARS2 program (www.stars2.eu). RGB stands for "**red giant** branch."

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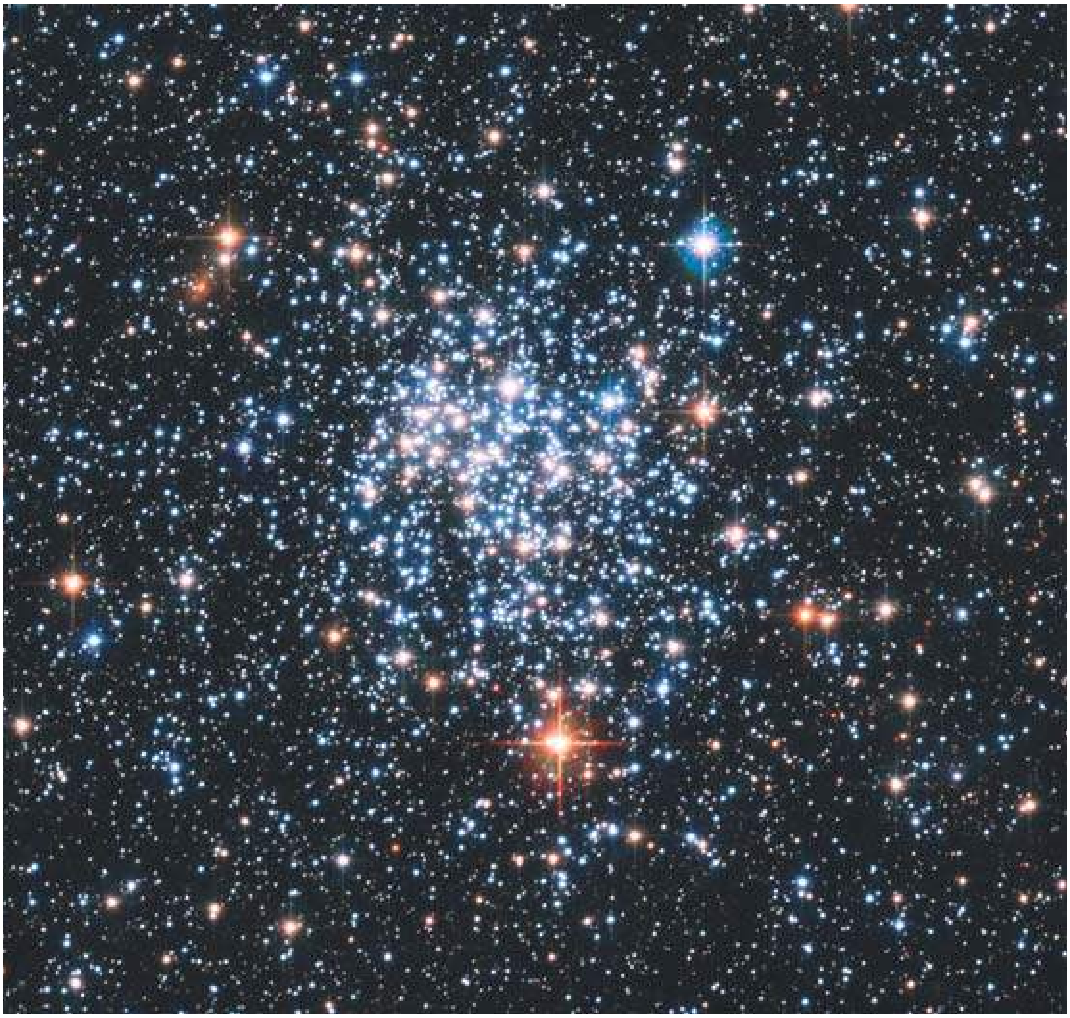
A tour of stellar nurseries

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

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

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.

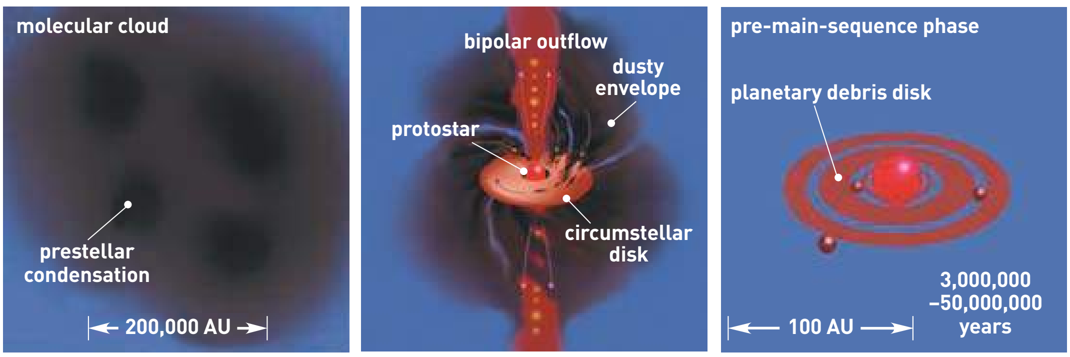
objects? How do certain regions of a molecular cloud turn into veritable star "populations"? What are the main stages in star formation? Why are small stars, such as **red dwarfs** and solar-type stars, invariably more numerous than massive stars, in any given population?

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!



From T. Greene

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.

Nature and nurture

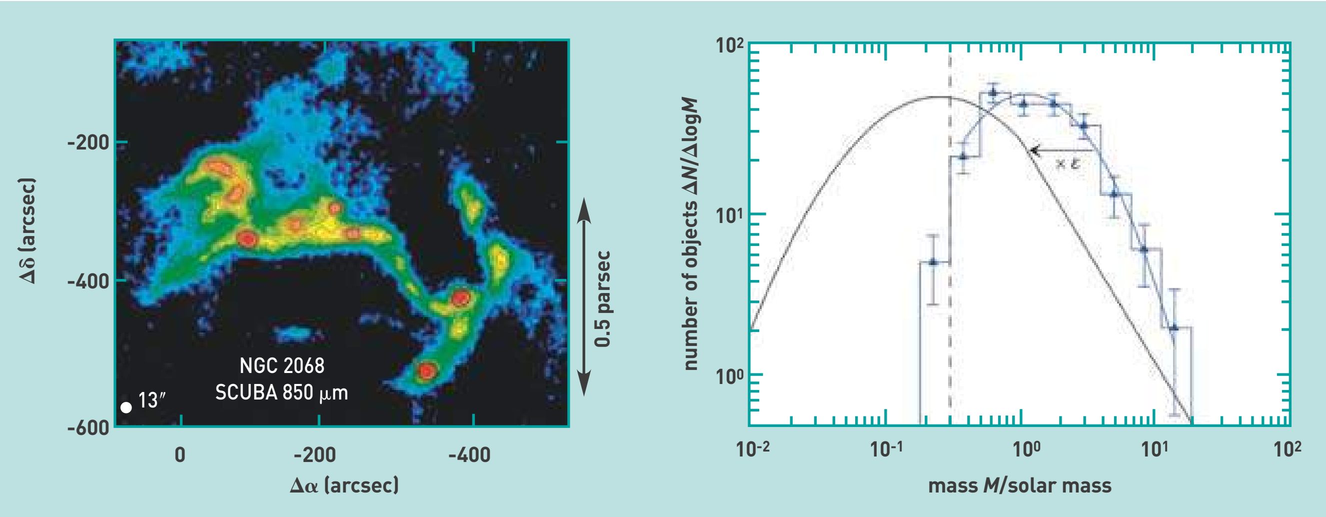
The vast majority of stars are born into large sets of siblings, i.e. clusters. Observations of young clusters show that massive stars (8 solar masses or more) are in a minority in these clusters. The same holds for very small stars (one-tenth of a solar mass, or less). The greater part of newborn stars 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.

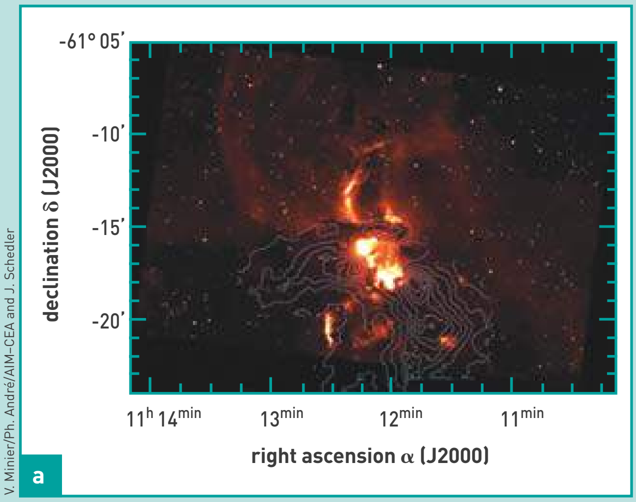


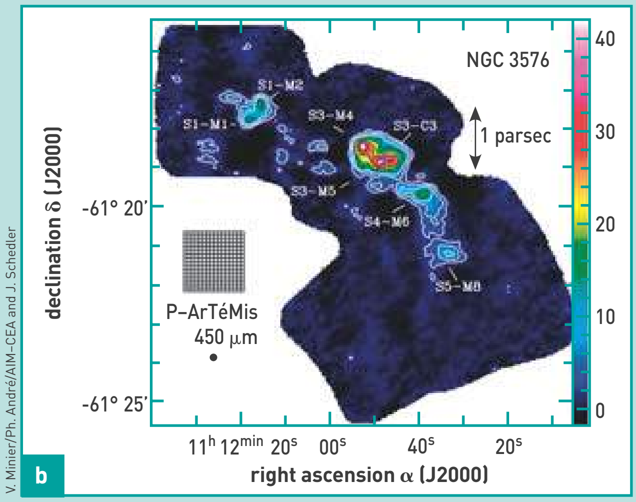
F. Motte/Ph. André/AIM-CEA

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.





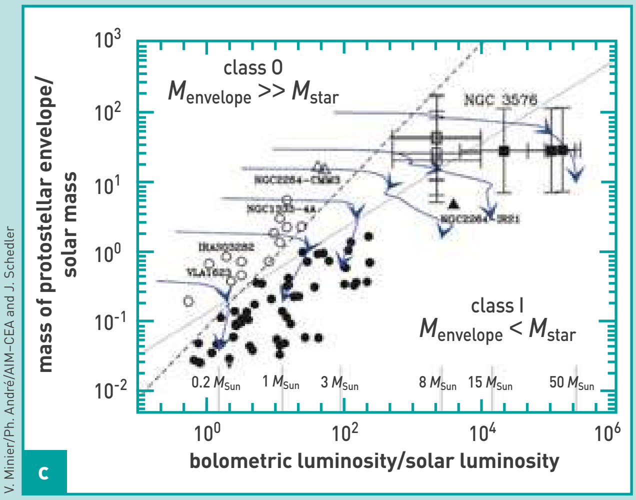


Figure.

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.

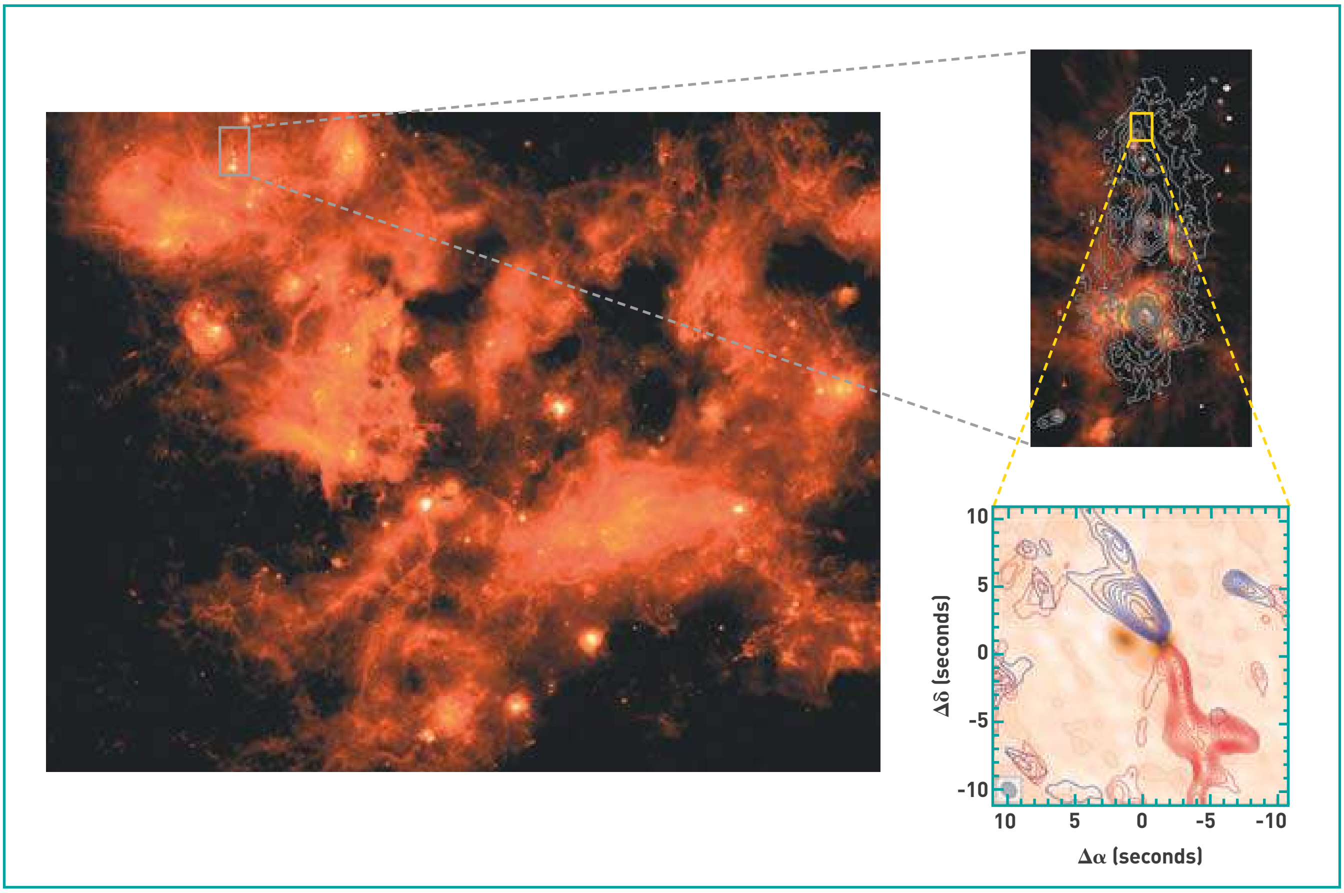
c. This diagram sets out the masses of protostellar dust cocoons, and their luminosities, these determining which early stage (class 0, class I) the protostars in NGC 3576 have reached. Class I designates a stage that has evolved further than class 0. On the basis of theoretical models, the final mass 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.



F. Motte/N. Schneider/AIM-CEA

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.

ESO

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).

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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?*,

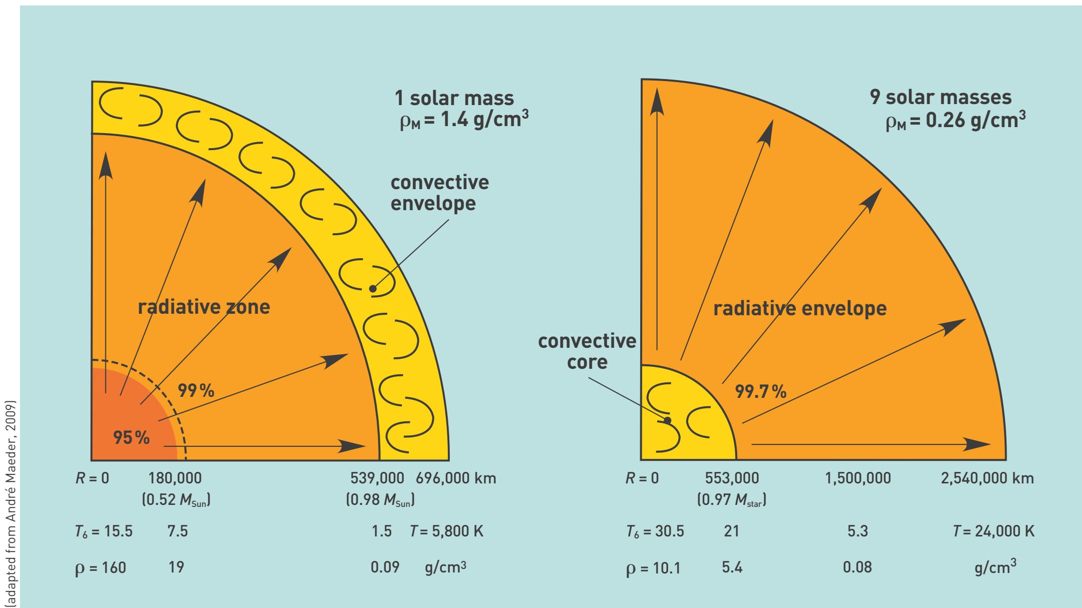


Figure 1.
Structures of a star having the same mass as the Sun (left), and of a star 9 times more massive (right). Radius R, temperature T (in K) or T_6 (million K), along with density ρ values are shown for the star center, and the boundaries of the radiative and convective zones. ρ_M is the star's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

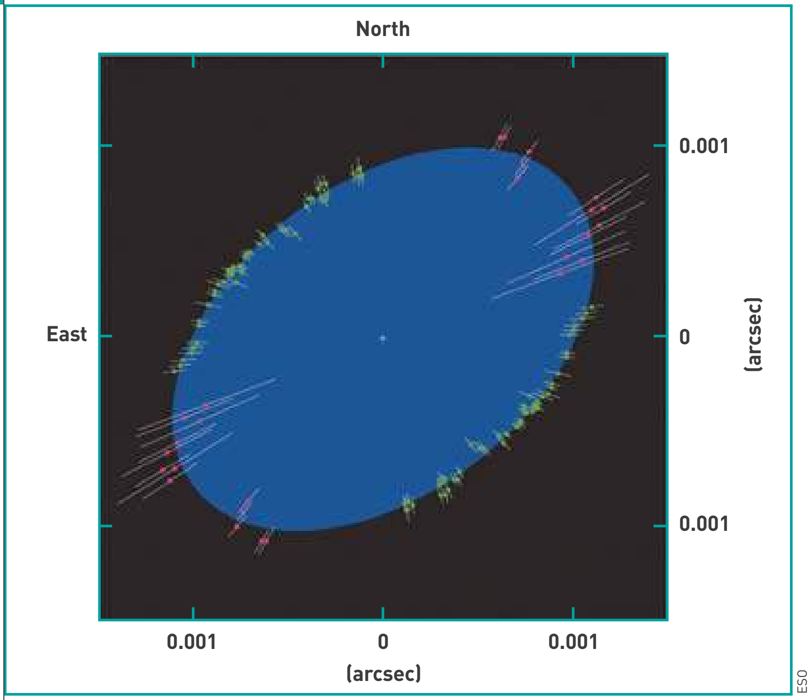


Figure 2.
Achernar, a **B-type** star, with a mass of 6.07 solar masses. It is highly flattened (oblate), owing to its very rapid rotation: at the surface, its rotational velocity is 150 times higher than that of the Sun.

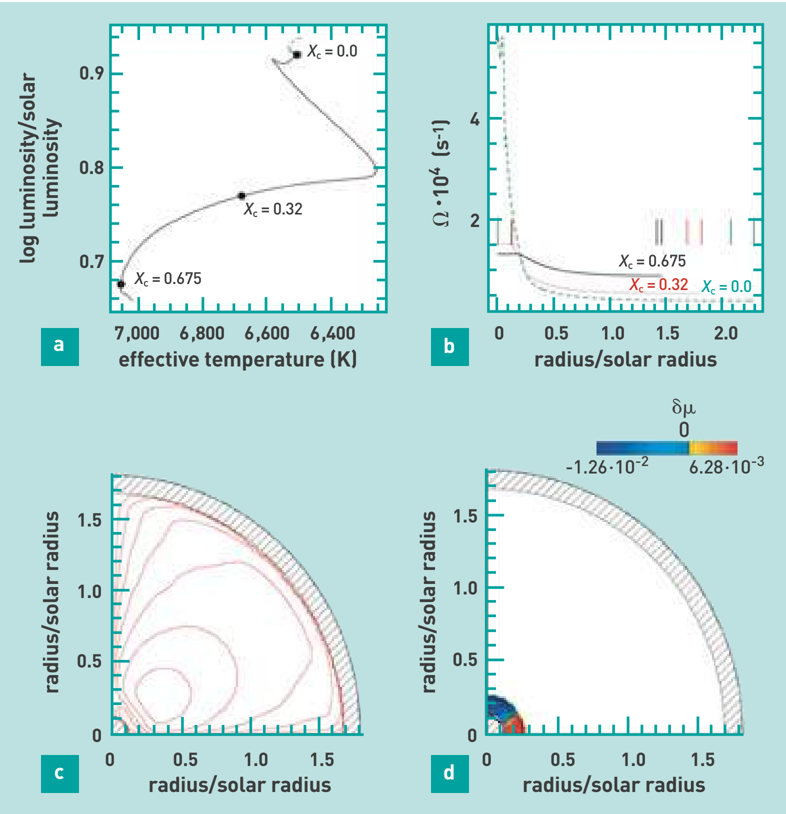


Figure 3.
Dynamic model of a rotating star, of 1.5 solar masses. At (a), evolutionary track across the **Hertzsprung–Russell diagram**; X_c stands for the hydrogen mass fraction, in the star's core. At (b), the internal rotational velocity profile, at three points in the star's lifetime. The star's radius 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).

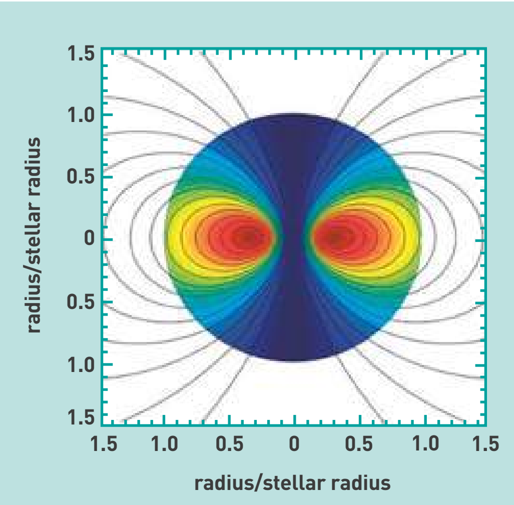
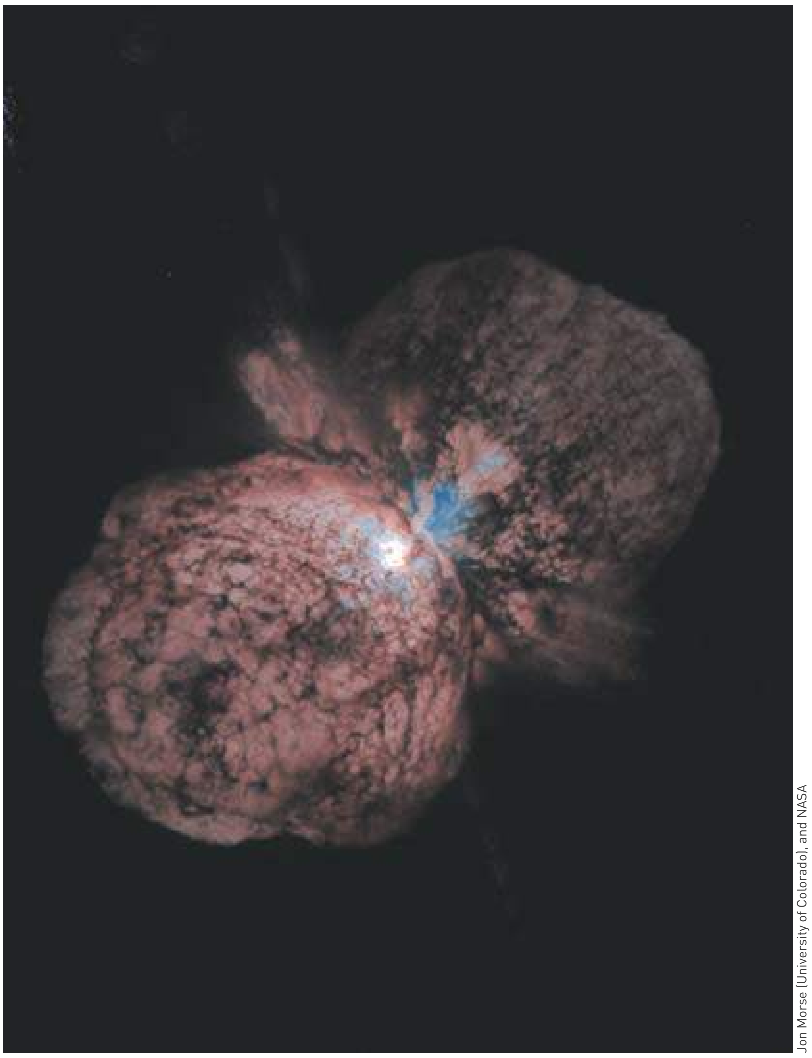


Figure 4.
The fossil magnetic field of an **A-type** star (2.37 solar masses, 3 times the **solar radius**).



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.

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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.

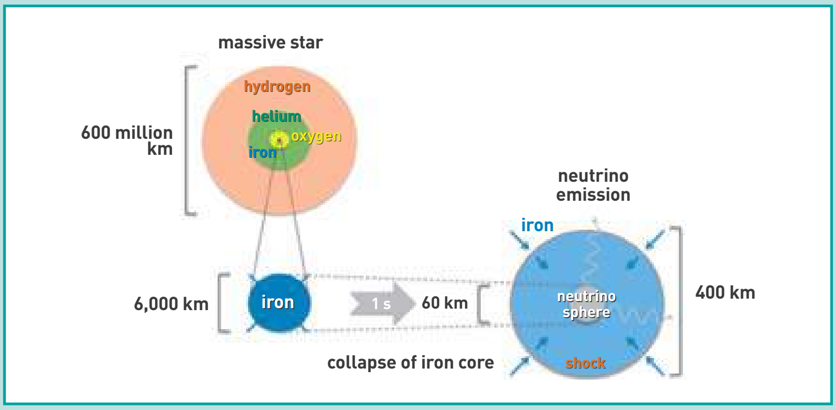

Figure 1.
Schematic of a gravitational supernova. The collapse of the iron core is slowed down by a standing shockwave, about 200 kilometers from the center.

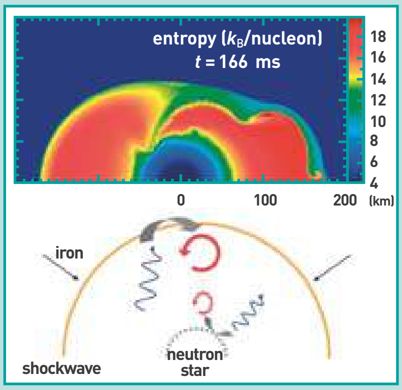

Figure 2.
Numerical simulation of the instability – as defined by entropy, expressed in terms of k_B per nucleon – which distorts the shockwave, in asymmetrical fashion (in collaboration with MPA, Garching [Germany]). Its mechanism is based on the interaction between acoustic waves (blue arrows), and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

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Supernova remnants

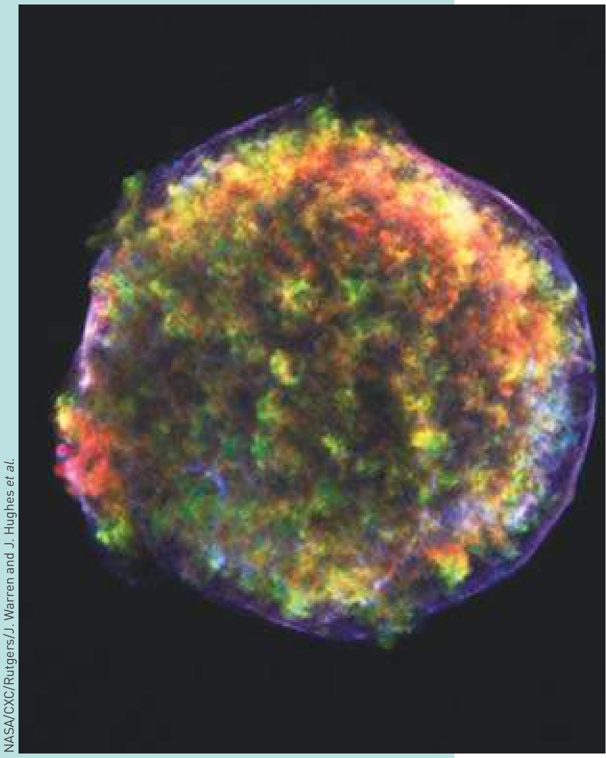
The explosion of a supernova releases a huge amount of energy (around 10^{44} J), only a small fraction of this arising in the form of visible light. When the explosion occurs, a supernova is as bright as an entire galaxy, however its visible light declines fairly swiftly thereafter, and vanishes after 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.

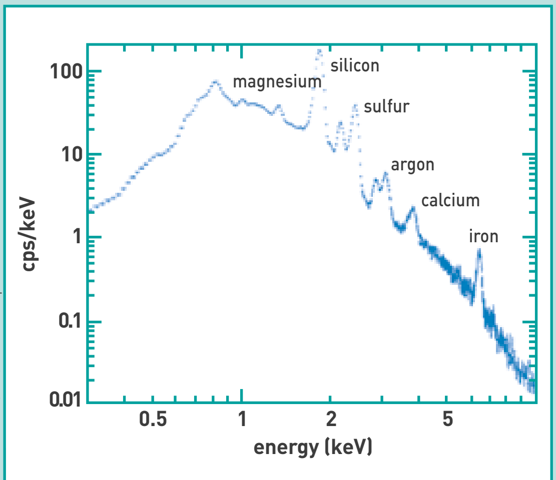
Highly instructive radiations

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).

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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).

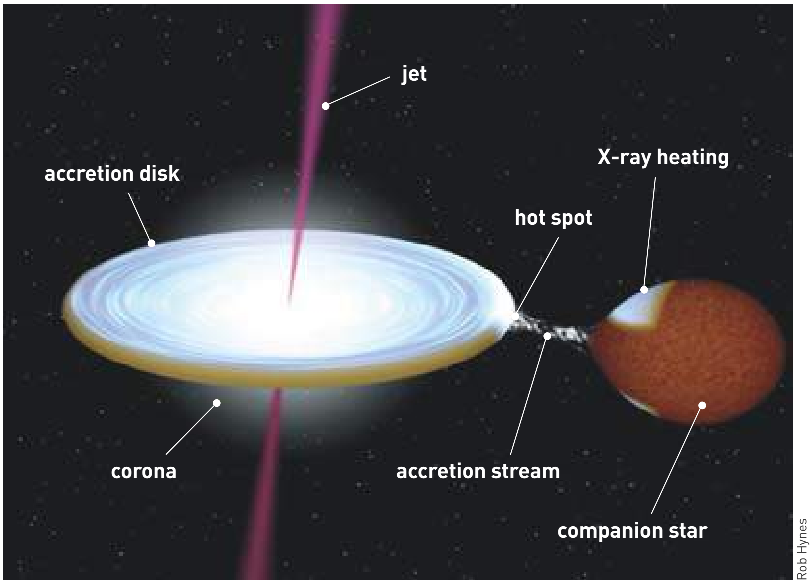

Figure 1.
Artist's impression of a microquasar. Matter stripped from the companion star falls into the black hole through a spiraling motion. A disk forms around the dense object, and jets of matter arise.

"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.

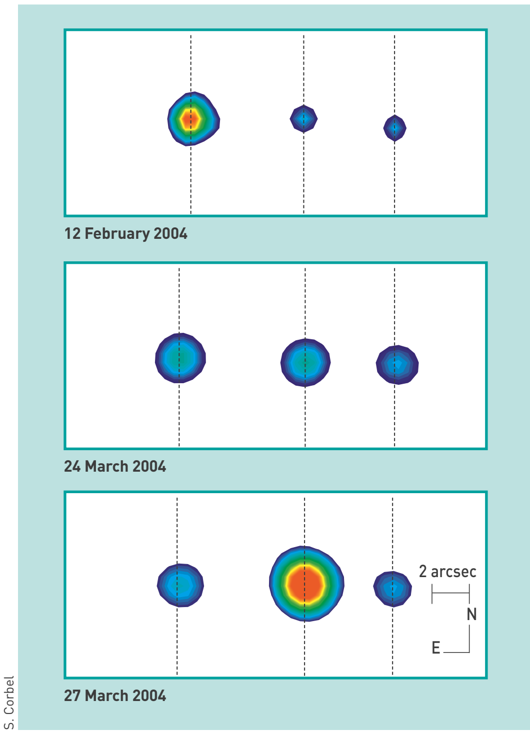

Figure 2.
An image of the X-ray emission around microquasar H 1743–322. On either side of the central source, two moving X-ray sources may be seen, due to the interaction between relativistic plasma bubbles, and the interstellar medium.

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.

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(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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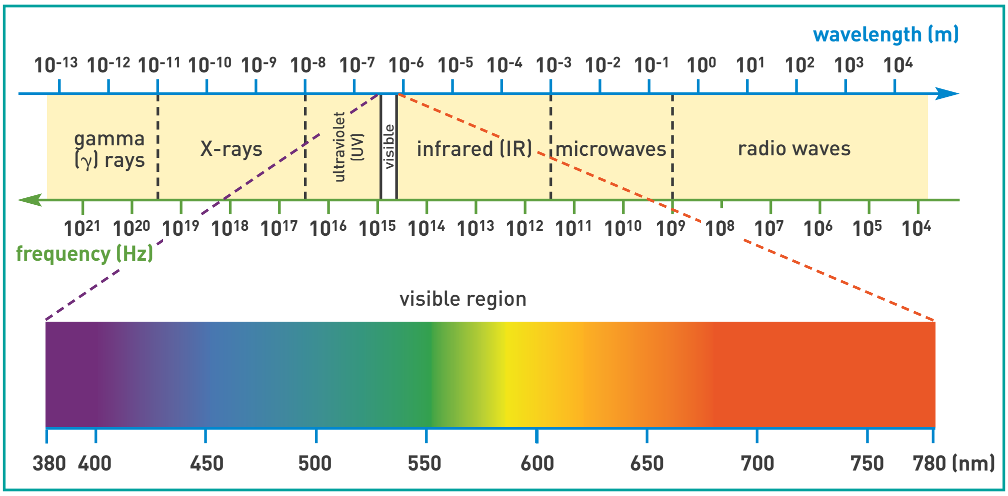


Figure 1.
The electromagnetic spectrum. Electromagnetic waves are grouped into families, of differing frequencies and wavelengths.

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.

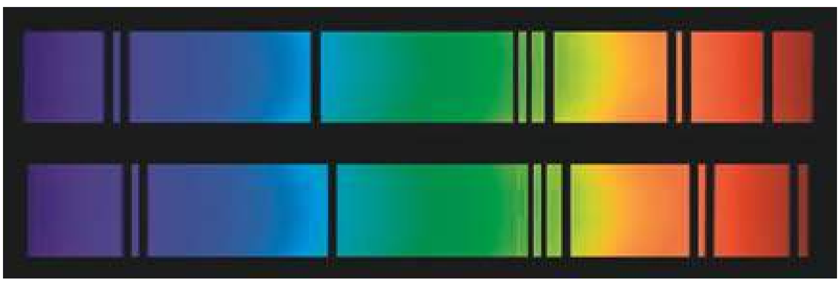


Figure 2.
Spectrum of a light source, exhibiting no shift of spectral lines (top), and featuring a redshift (bottom).

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' spatio-temporal distance, making it possible to range them in terms of increasing distance (see Table).

The lights of the Universe

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

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

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

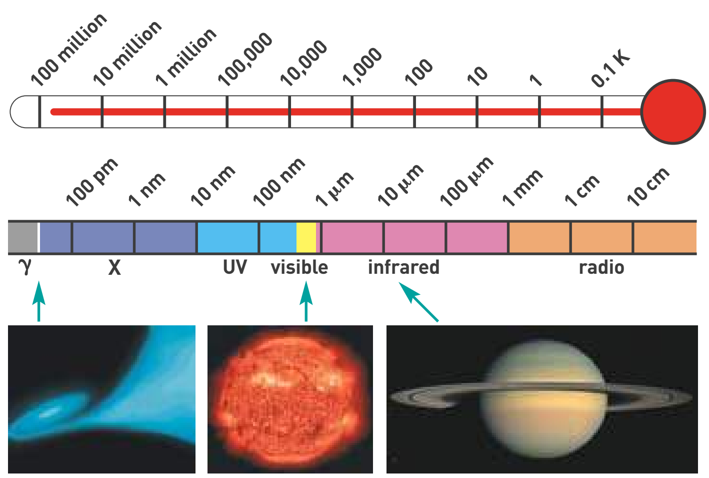
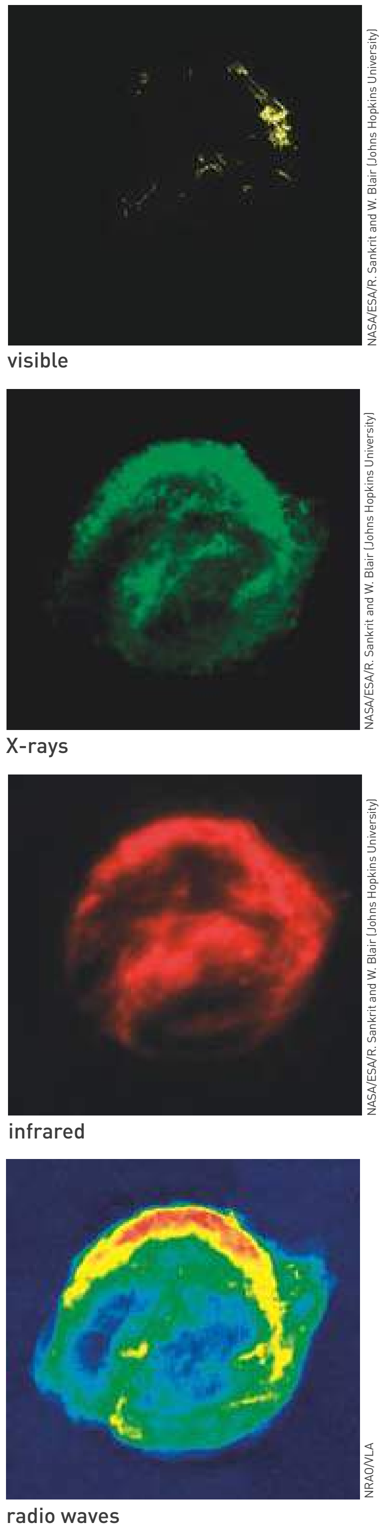


Figure 3.
The distribution of radiation yields information as to the temperature of a celestial body, and its characteristics. In two major segments of the electromagnetic spectrum, infrared on the one hand, X-rays and gamma rays on the other, advances in spaceborne detection are making it possible,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



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

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

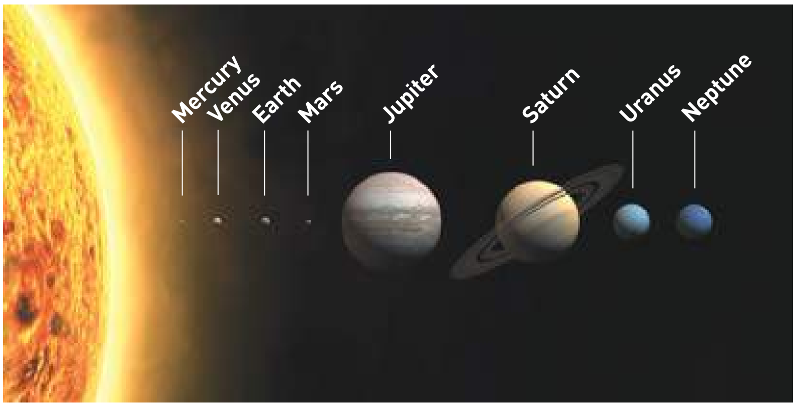
The exploration of the Solar System, the discovery of extrasolar planets, new ideas, and powerful numerical simulations have made it possible to gain a better understanding of the way planets are formed. It became apparent, at this point, that the outcome might have been altogether different, given the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

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.

NASA/JPL/Space Science Institute

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.



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.

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.

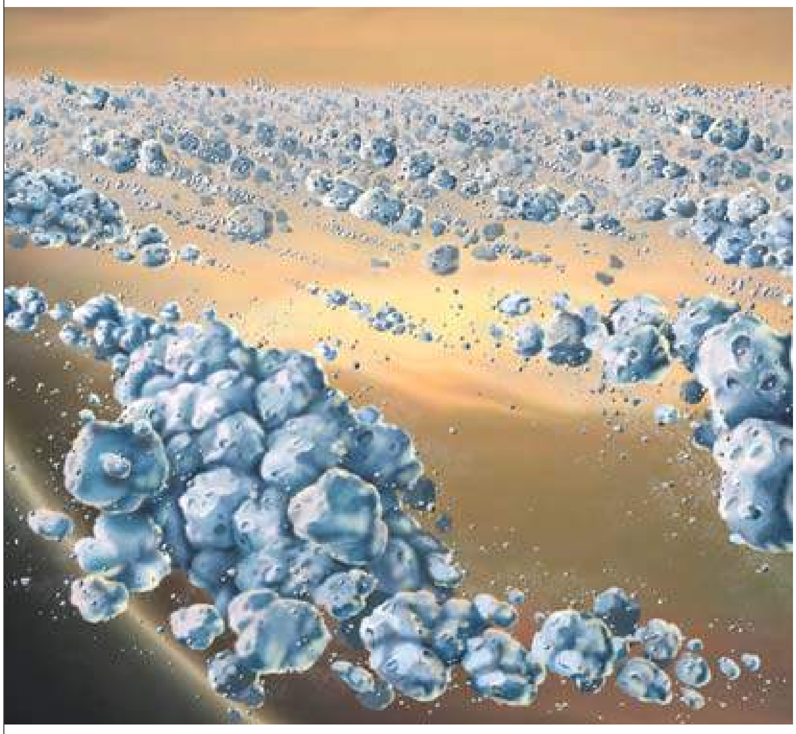
The Carina (Keel) Nebula. Through the observation of star-forming sites, astrophysicists are able to conceive how the transition might occur, from interstellar cloud to protostellar nebula, and subsequently through to a sun surrounded by a dust, and gas disk.

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

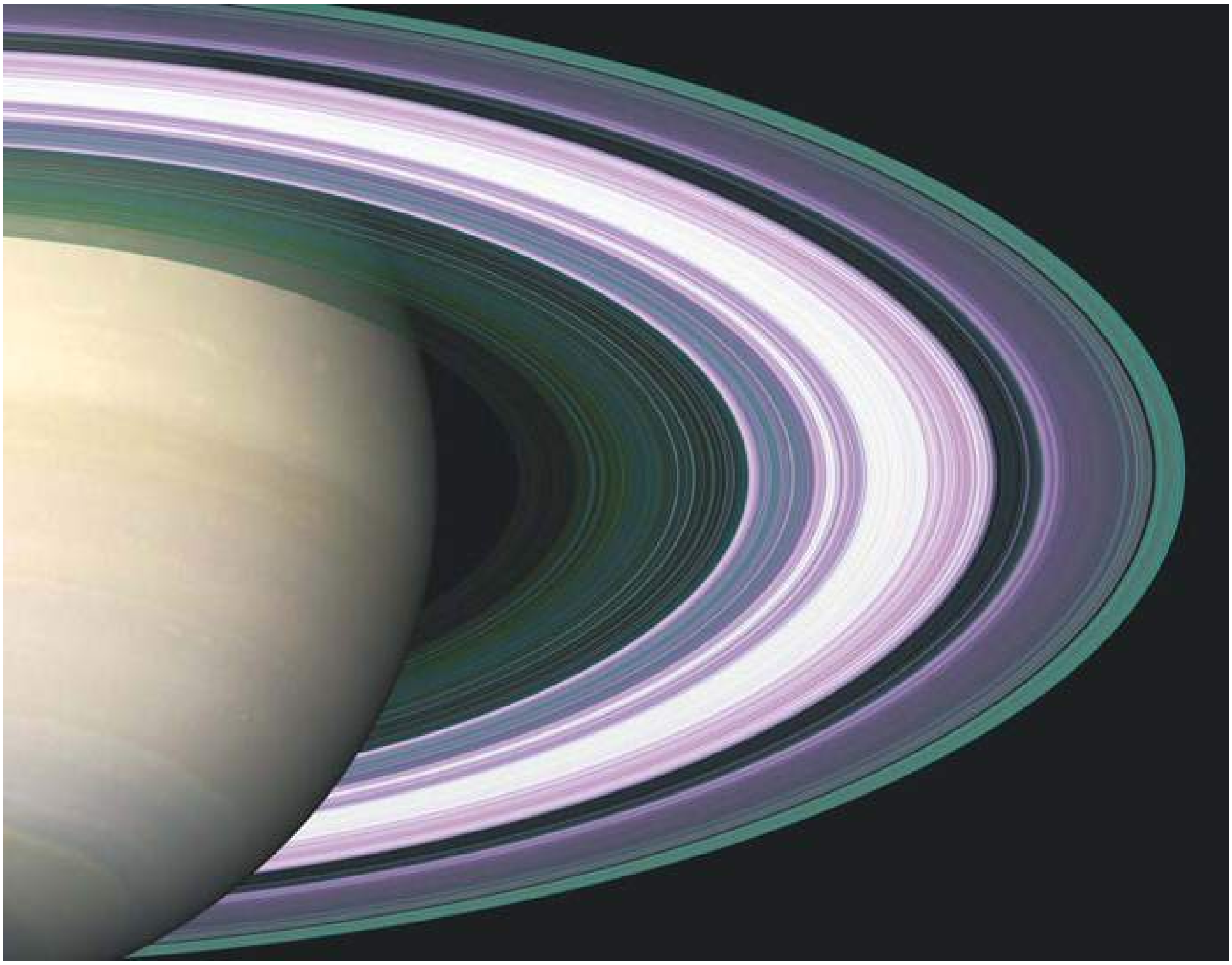
By promoting gas condensation in the outer regions, and evicting planetesimals to the confines of the disk, through its gravitational action, the young Jupiter provided raw materials for the formation of the other giant planets. Owing to that role played by Jupiter, in collecting materials, Saturn could 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°.



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.

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.

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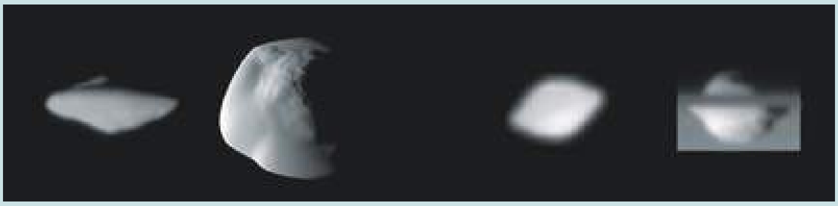
The rings of Saturn: a magnificent research laboratory

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).


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.

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.

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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.

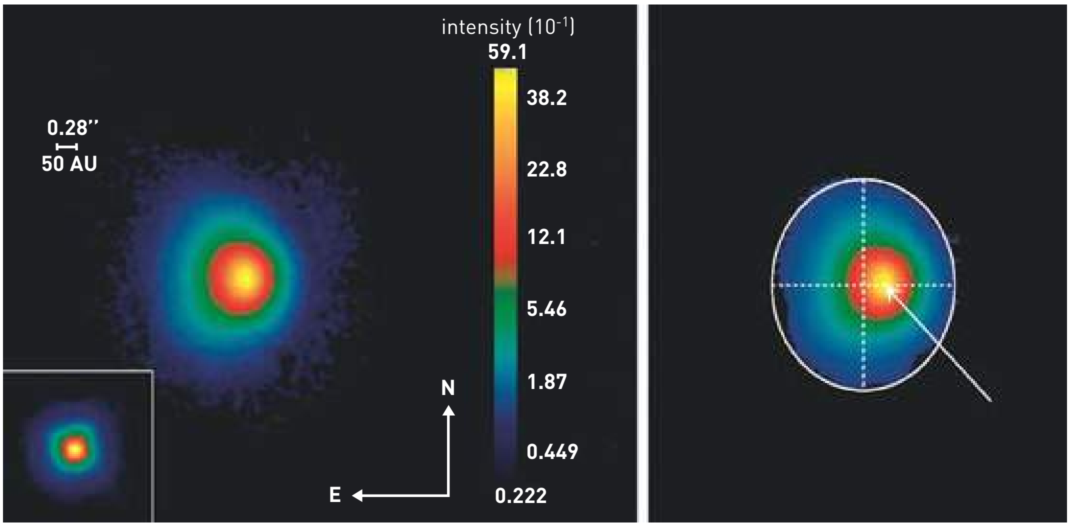
Since 1995, when the first such object was discovered, the search for extrasolar planets has proved highly fruitful. To date, astronomers have totted up more than 350 such planets on their scoreboards. "Exoplanets" – as indeed the **planets** in the Solar System – very likely formed in the gas and dust 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



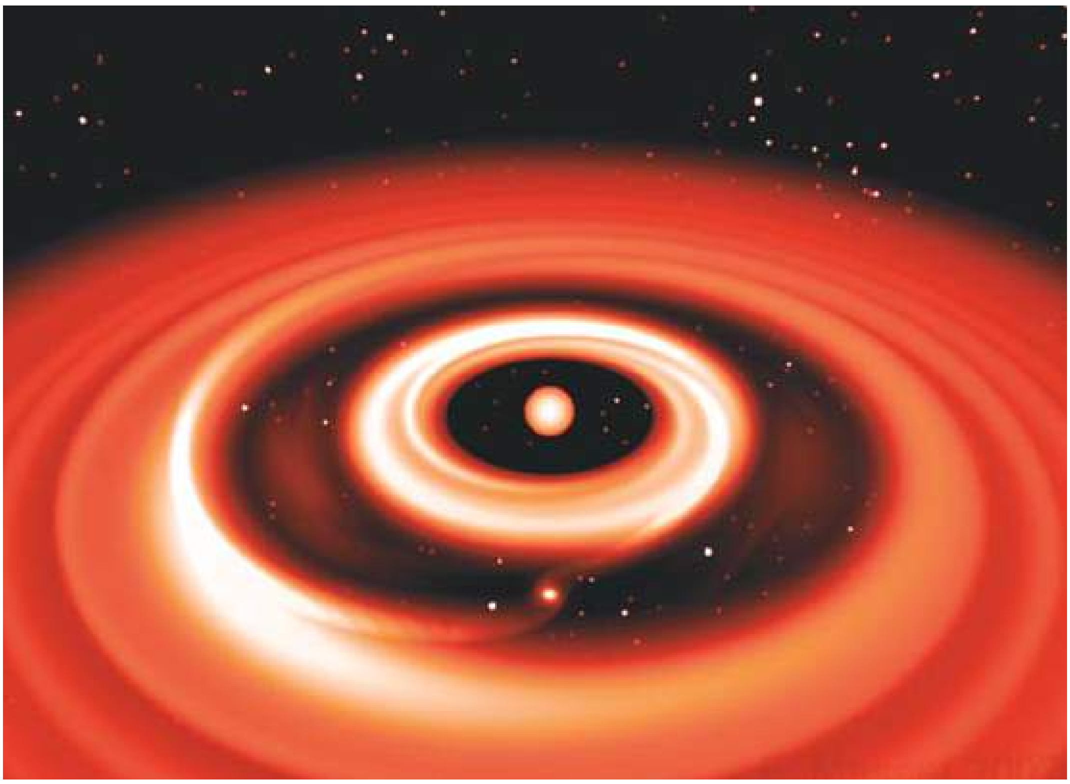
CEA/SAp

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



CEA

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

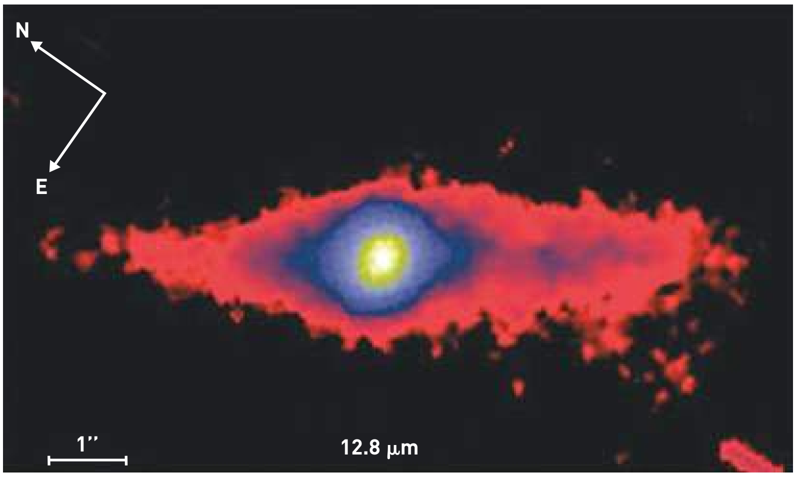


Figure 3.
An image of the debris disk around star β Pictoris, as observed by the VISIR instrument, fitted to VLT. The disk's asymmetry is particularly worthy of note.

within the Solar System, the dust thus yielded being the cause of "zodiacal" light.(4)

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.

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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."

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.

Serge Brunier

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.

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).

(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.

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.

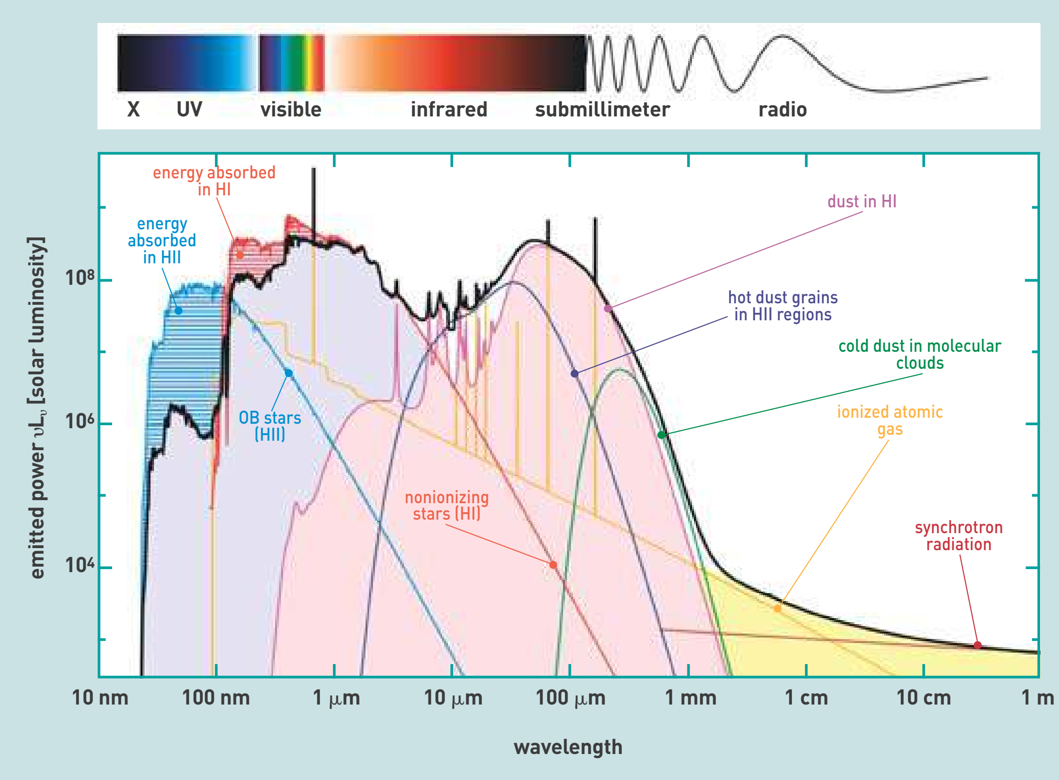

Figure 2.
Electromagnetic spectrum from a galaxy (shown in black), this resulting from emissions from the more massive stars (blue); from gas in regions ionized by these stars (yellow), and dust mingled with this gas (purple); from other stars (red), and interstellar dust heated by their radiation (mauve); 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).

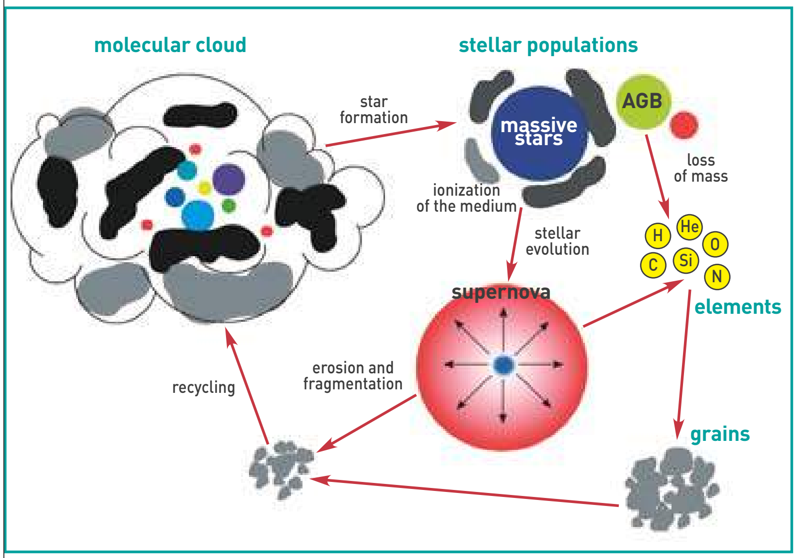

Figure 3.
The stellar evolution cycle, and its impact on galactic composition. Star formation, and stellar evolution make a contribution in terms of a modification, not just of the galaxies' chemical composition, but equally of their energy content. The AGB (Asymptotic Giant Branch) population corresponds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

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 fragmentation (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.

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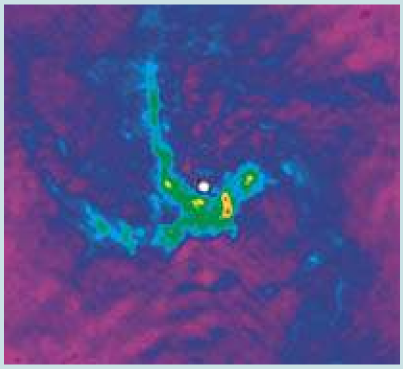
A mysterious black hole

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.



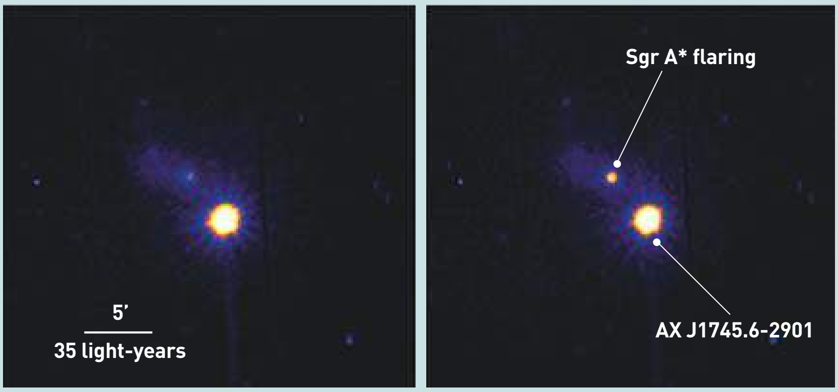
NSF/VLA/F. Yusef-Zadeh (NWU)

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 super-massive 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).

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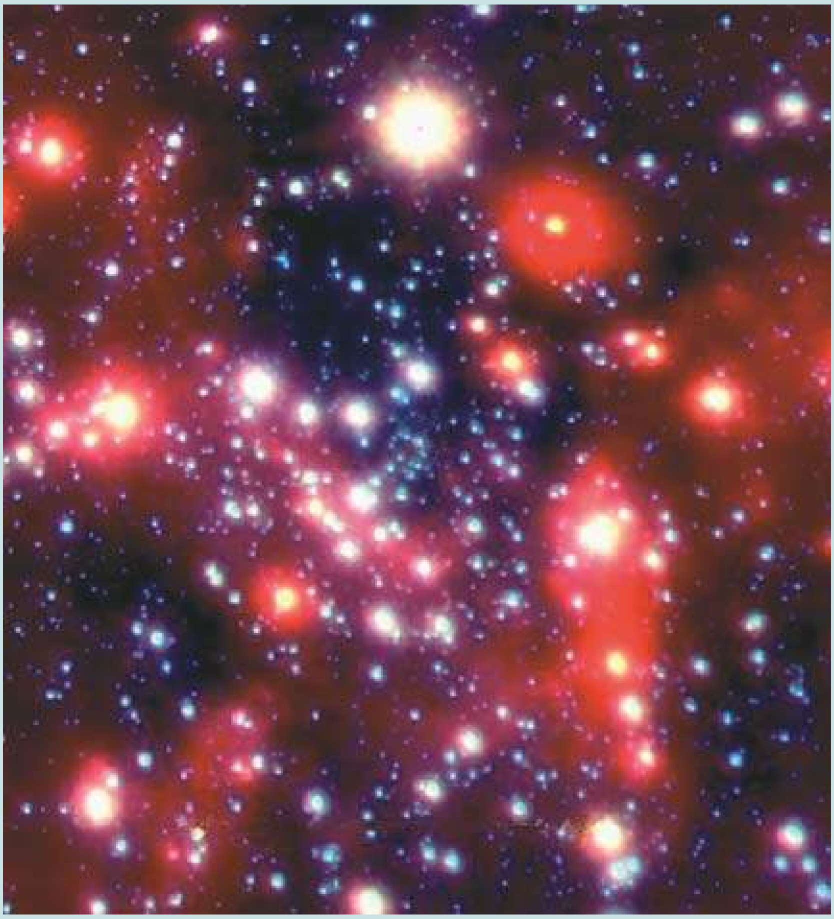


Image of the galactic center, taken by the NACO infrared camera, mounted at the focus of the Yepun telescope, part of ESO's Very Large Telescope (VLT), sited on the Cerro Paranal mountain, in Chile. This shows the more luminous stars in the region, feeding, through their powerful stellar winds, the central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

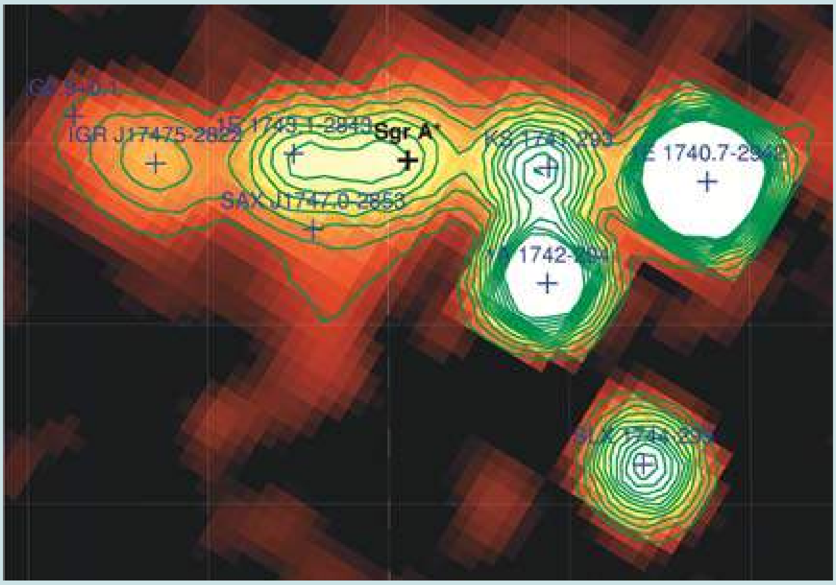
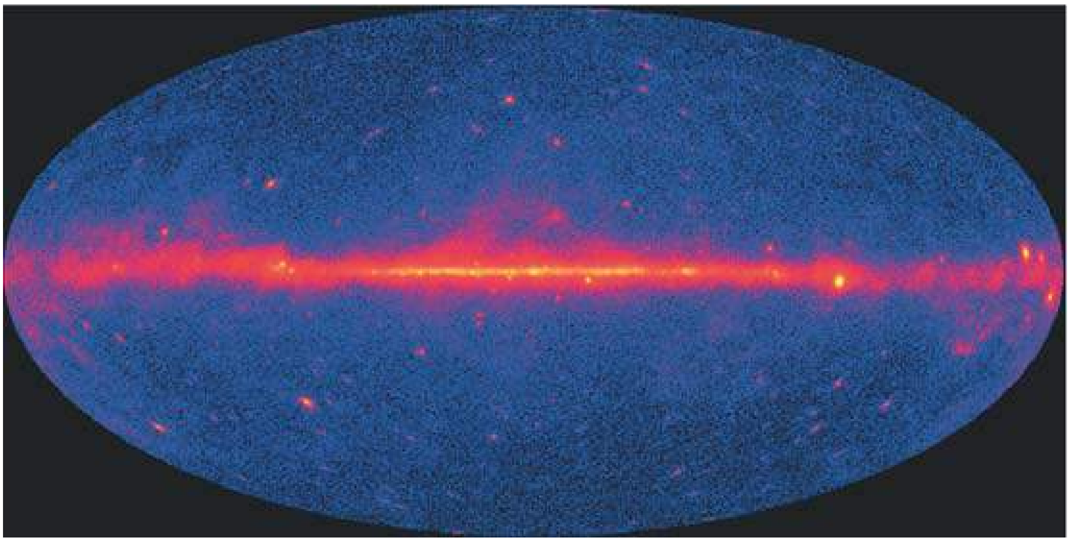


Figure 3.
Image (with intensity contours) of the central region of our Galaxy, as recorded by the IBIS telescope, mounted on INTEGRAL (20–40 keV gamma-rays). The position of Sgr A* is indicated, showing that the gamma-ray source at the center may well be related to the supermassive black hole. The other 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.



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.

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

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 shockwave, 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.

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.

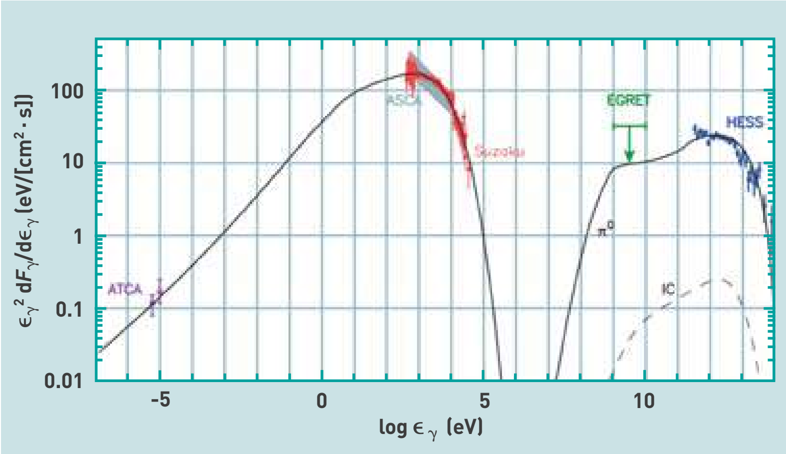
Pending issues

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

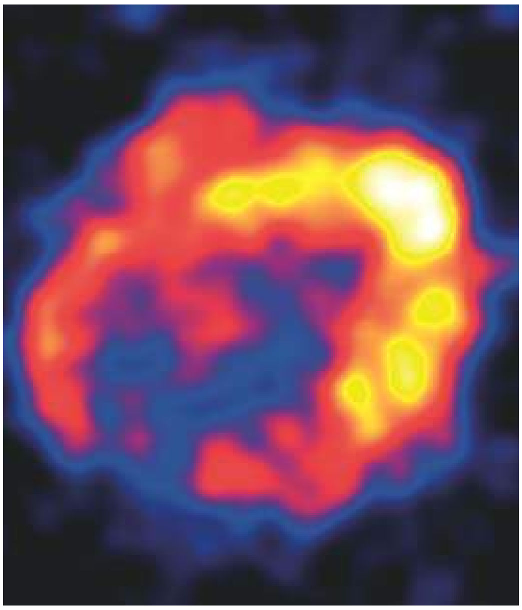


(taken from E. G. Berezhko and H. J. Völk, *Astronomy and Astrophysics 492*, 2008, p. 695)

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).

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.

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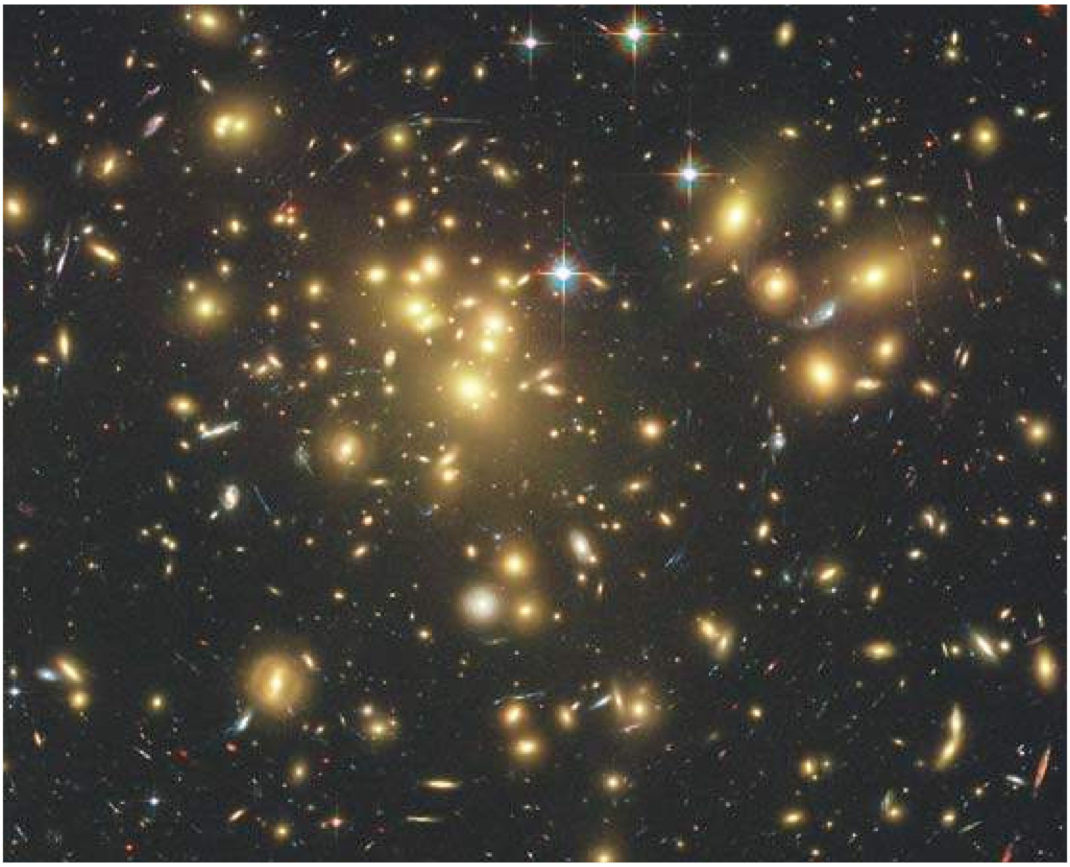
Seeking out the great ancestors

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

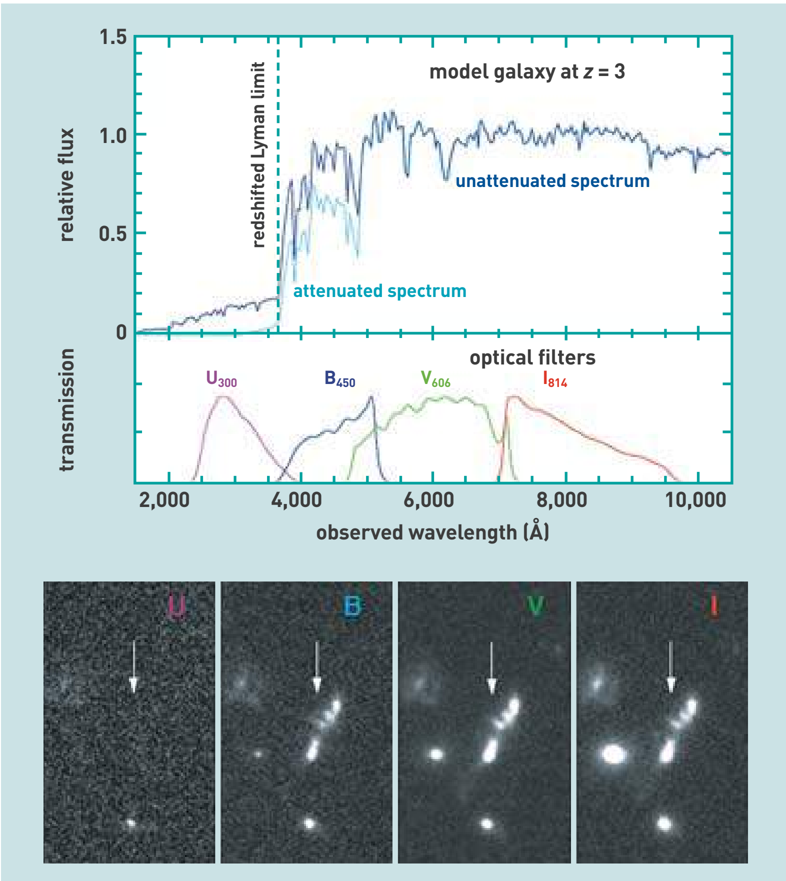
The cosmic microwave background (or diffuse cosmic background), emitted as it was by a Universe that was 380,000 years old, exhibits a z value slightly higher than 1,000. For most of the stars, and galaxies surveyed, z ranges from 0 to 3. The latter value corresponds to an age of the Universe of around 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

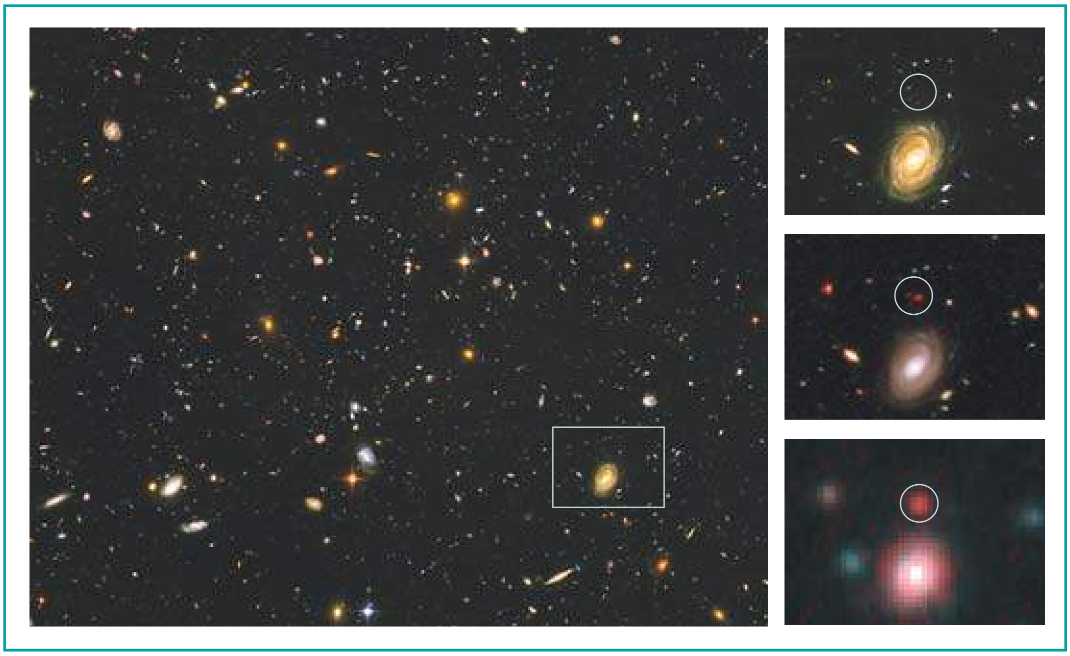
(1) The Hubble Ultra-Deep Field, a small region in the sky measuring about 3 × 3 **arcmin**², was thus observed over an interval of some 400 hours, by means of **NASA–ESA**'s Hubble Space Telescope, using four filters at different wavelengths, from 4,000 Å to 9,000 Å.

(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.

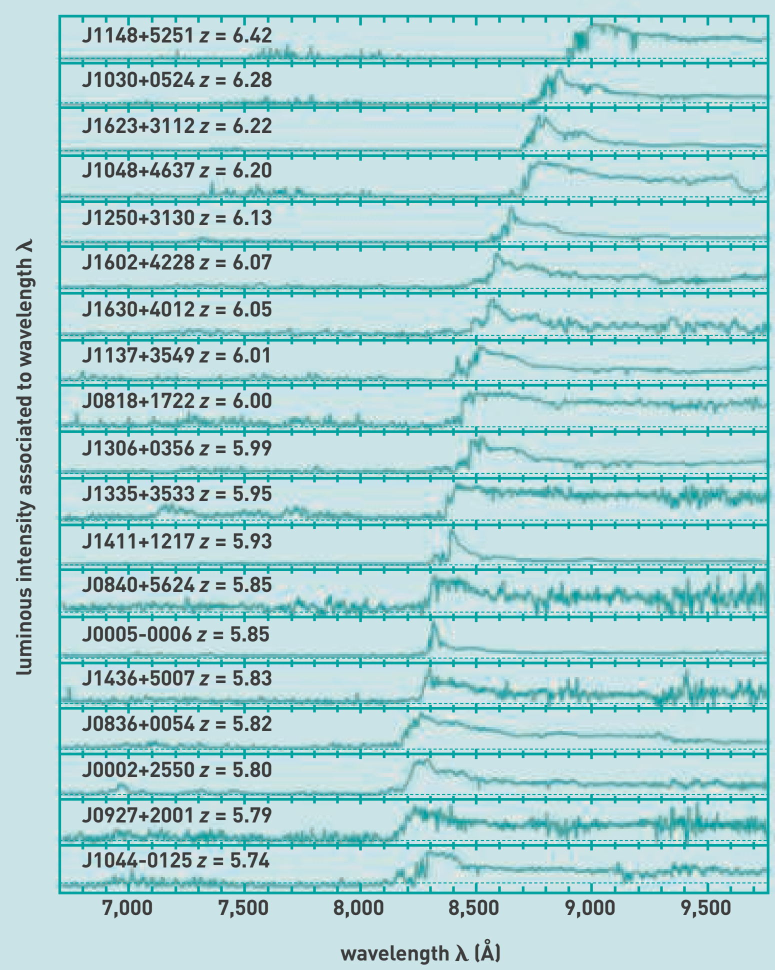


(M. Dickinson, in *The Hubble Deep Field: Proceedings of the Space Telescope Science Institute*, May 1997, STScI, eds. M. Livio, S. M. Fall and P. Madau)



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.

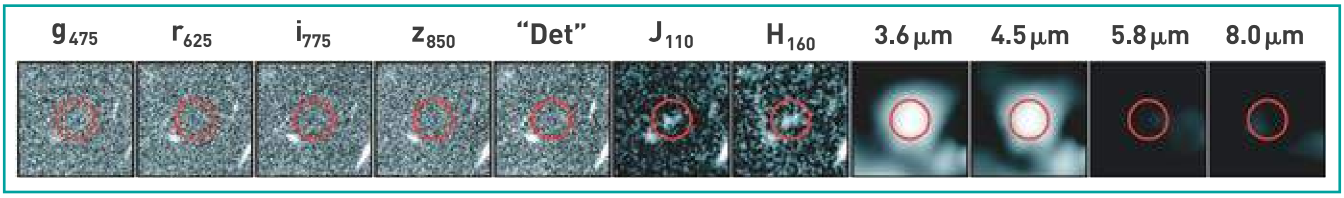
instance, if z is equal to 3, the break is observed at around 3,600 Å, corresponding to **ultraviolet radiation**. Very distant galaxies (involving z values greater than 3) exhibit a break at **visible** wavelengths. As redshift increases, a further phenomenon, tending to shift the break to longer wavelengths, 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.

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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…

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.

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

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.

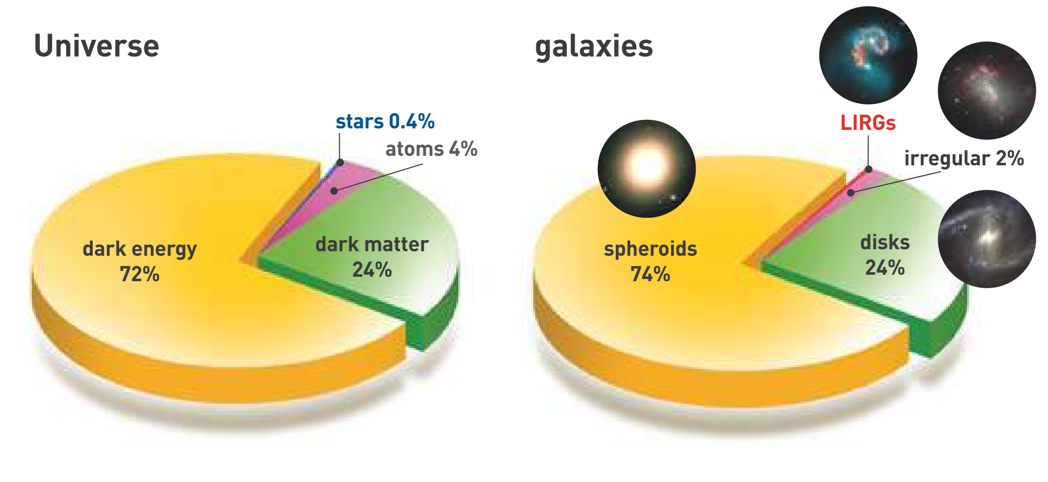


Figure 1.
Compared distribution of energy-bearing components in the Universe (at left), and of galaxies into morphological types (right). The parallel is striking, however nothing warrants, at the present time, seeing anything else than a coincidence in this.

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.

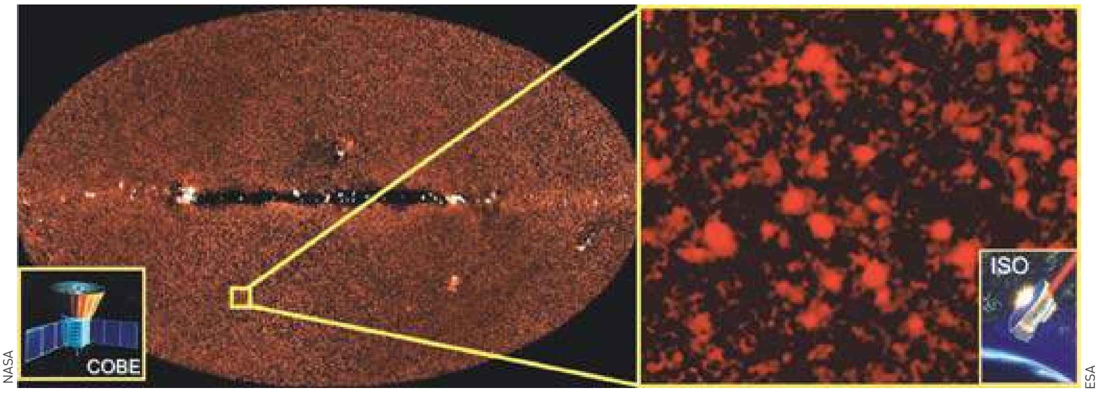


Figure 2.
The diffuse infrared background, as measured by NASA's COBE satellite (at left), and the resolution of this background into individual galaxies, by ESA's ISO satellite (right).

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

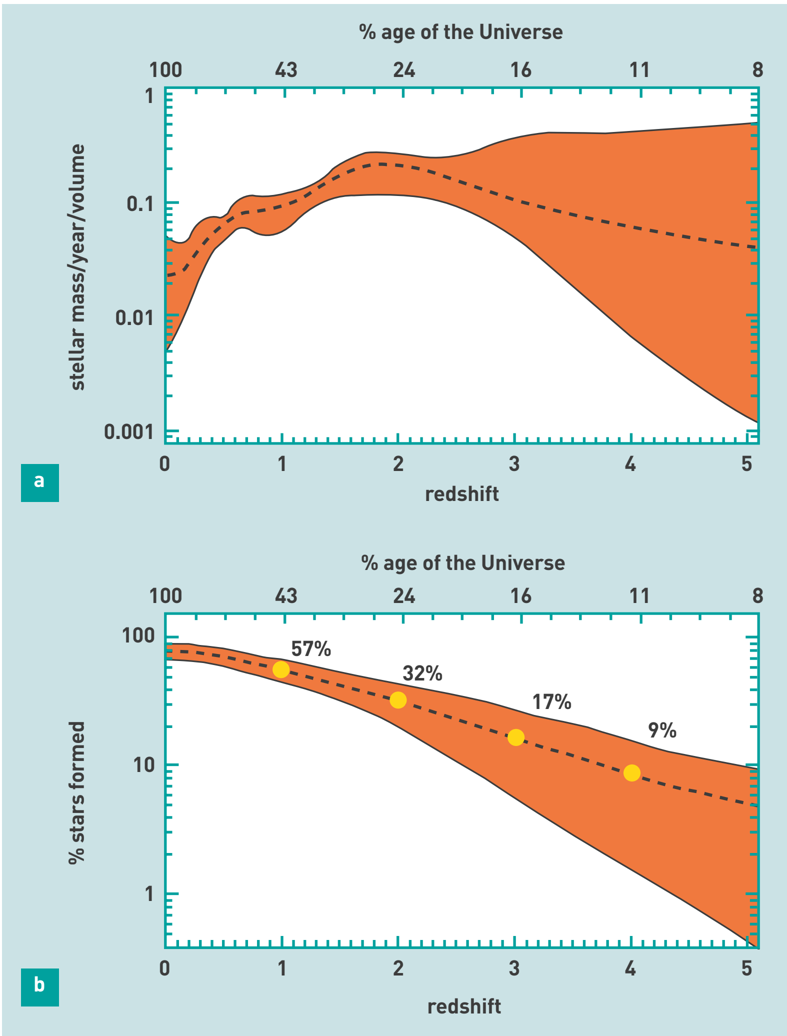
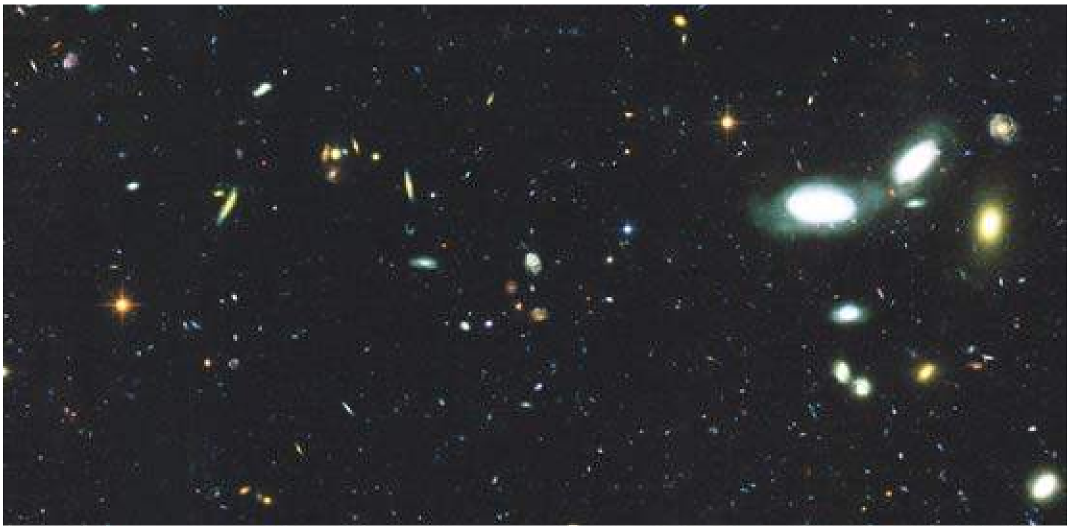


Figure 3.
The topmost curve plots the intensity of star formation in the Universe, over time. This is measured in terms of the stellar mass (in solar mass units) formed, per year, in a given volume (in the present case, inside "boxes" of 3 million light-years per side). This intensity peaked when the 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.

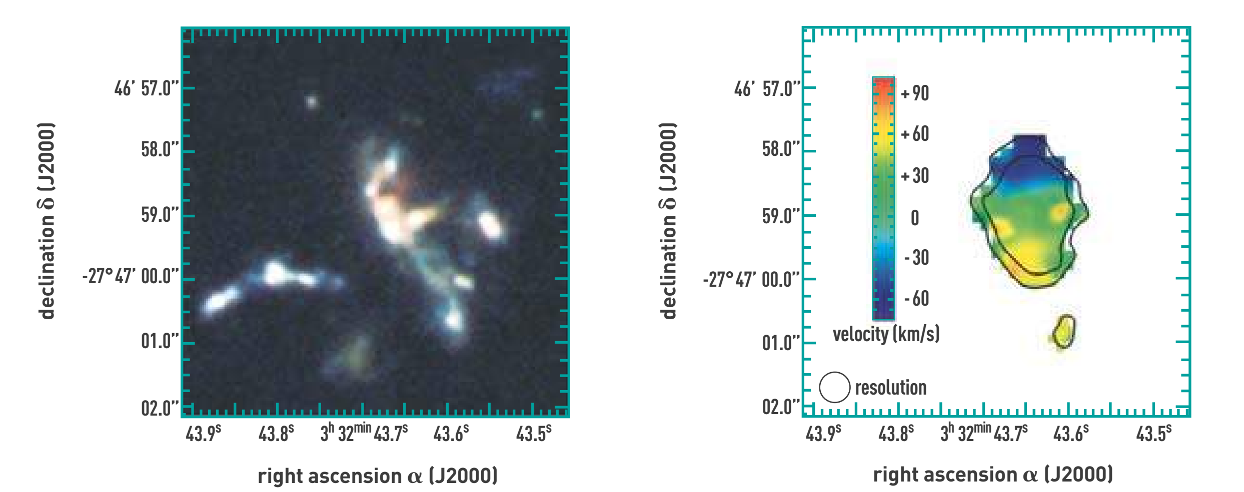


NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

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.

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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).

ESO

An elliptical galaxy (NGC 1316).

ESO

A spiral galaxy (NGC 6118).

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.

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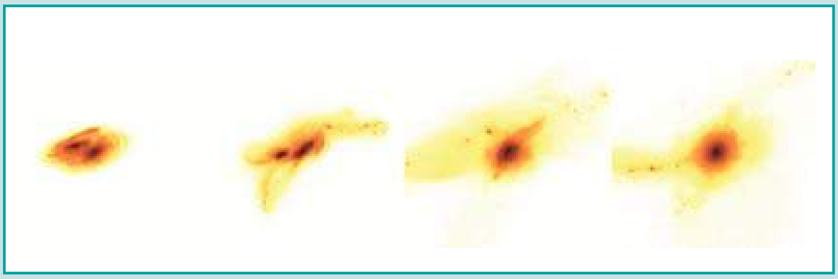


F. Bournaud/CEA/CCRT

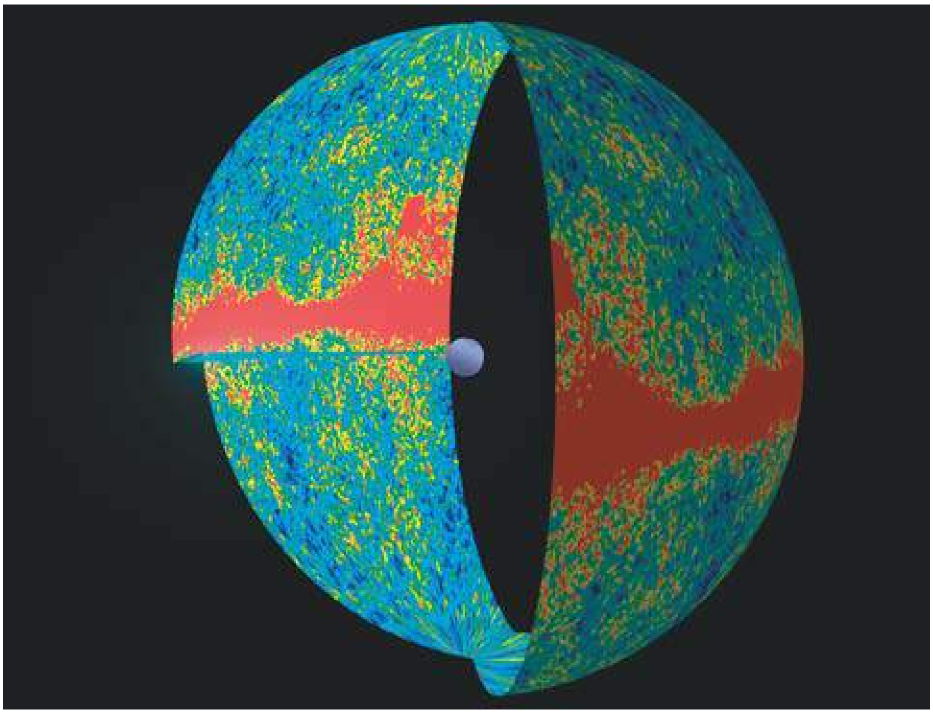
Figure 2.
Numerical simulation of a collision between two spiral galaxies. The two galaxies merge, their disks are disrupted, and the outcome is an elliptical-type galaxy.

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.



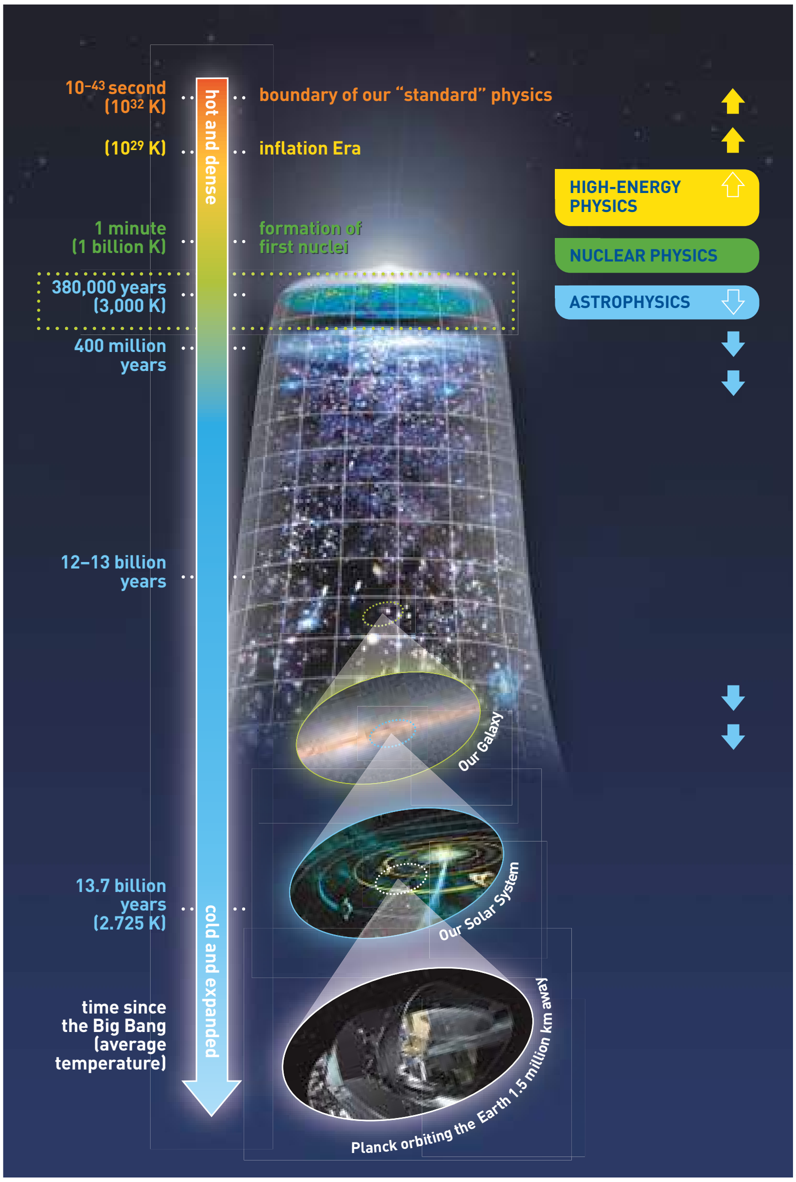
C. Carreau/ESA

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).



(http://public.planck.fr/pedago/plaquette_Planck.pdf) - Agence Canopée

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.

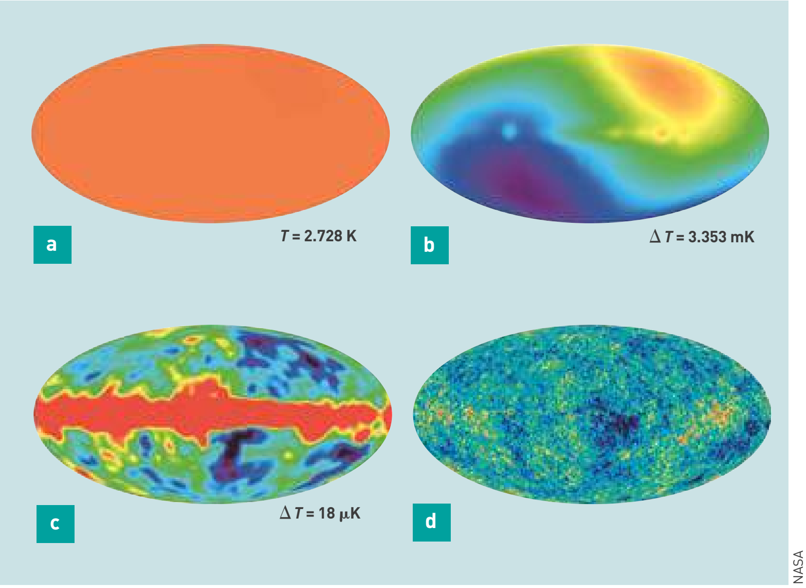


Figure 2.
Maps of the sky, showing the structures appearing in the cosmic microwave background at various levels of detail.

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.

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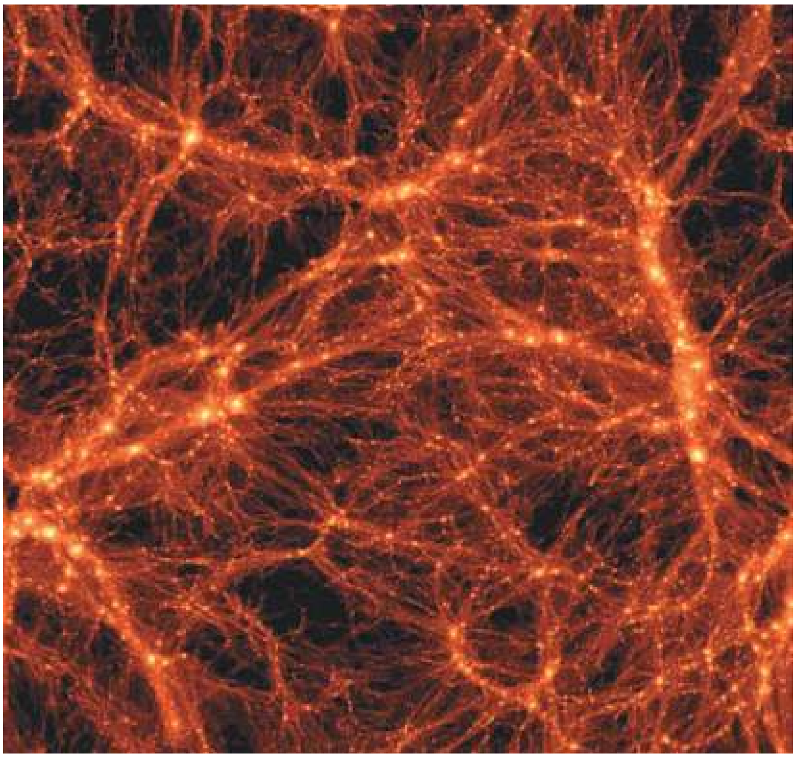
The cosmic web

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.



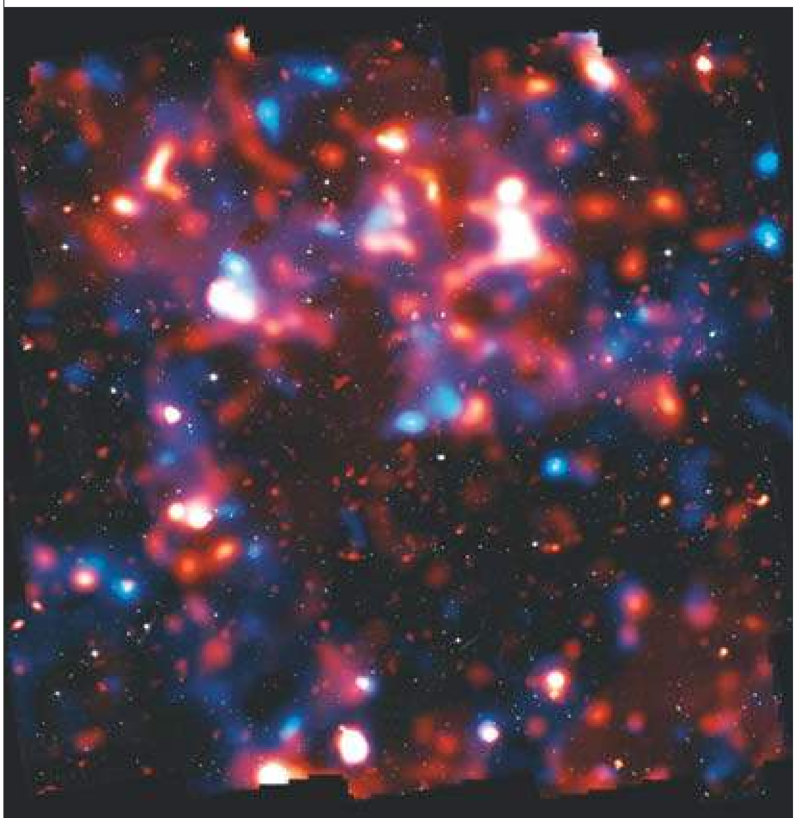
C. Pichon, R. Teyssier 2007

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, at the various scales involved, from galaxies to large structures? Such are the main issues astrophysicists have to solve. X-ray astronomy will keep on playing 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).

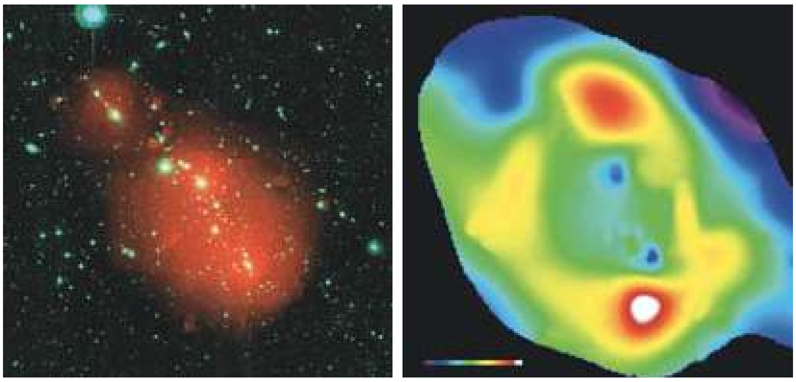

J.-L. Sauvageot/SAp/CEA - S. Maurogordato/OCA/CNRS

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.

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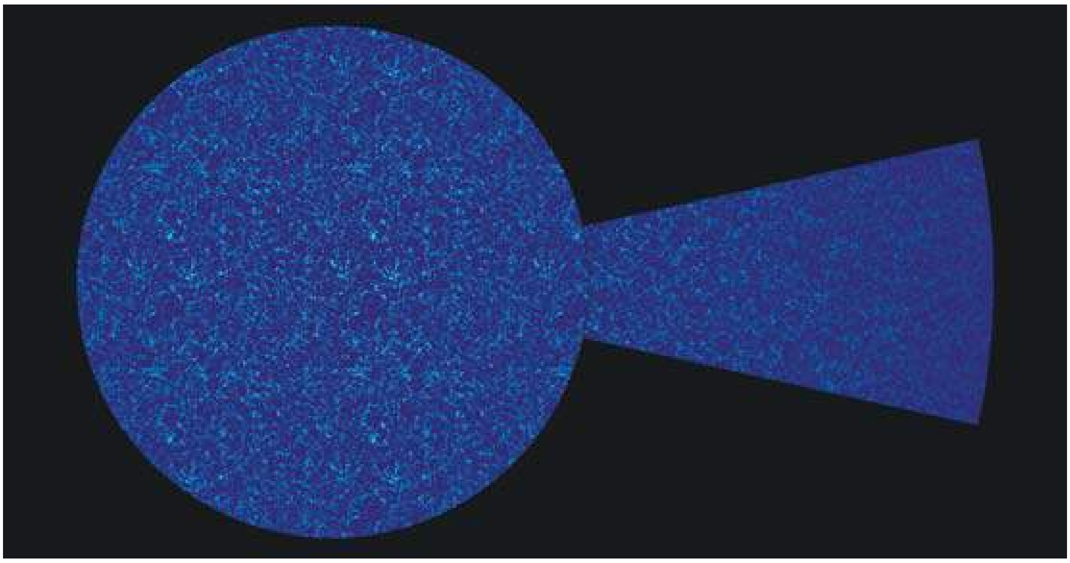
The formation of the structures of the Universe: the interplay of models

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.



R. Teyssier/CEA

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.

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.

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

NASA and The Hubble Heritage Team (STScI/AURA)

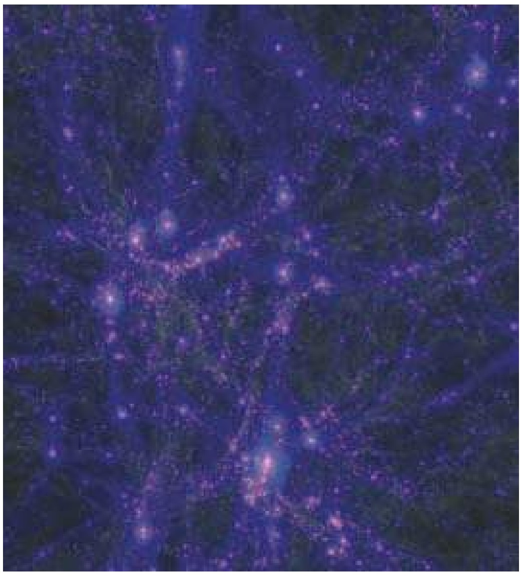
R. Teyssier/CEA

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.

(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.



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

R. Teyssier/CEA

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).

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.

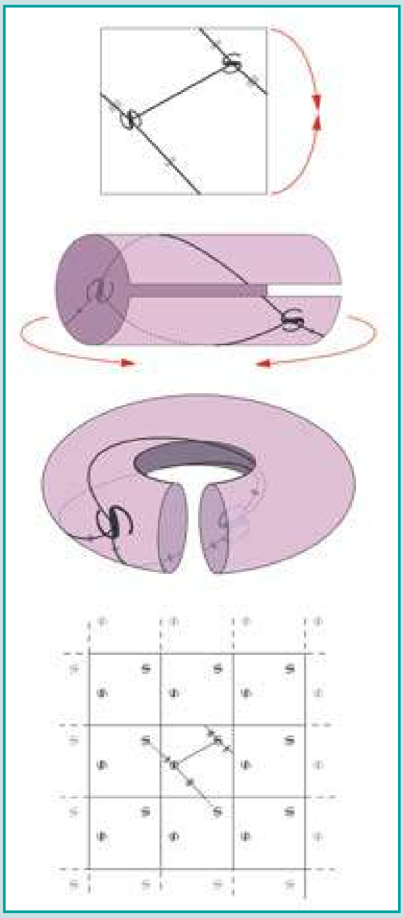


Figure 1.
Principle construction of a finite, two-dimensional Universe featuring no edges: the opposite sides of a square are identified. An observer living on the surface of such a Universe would have the illusion of living on an infinite plane.

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.

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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.

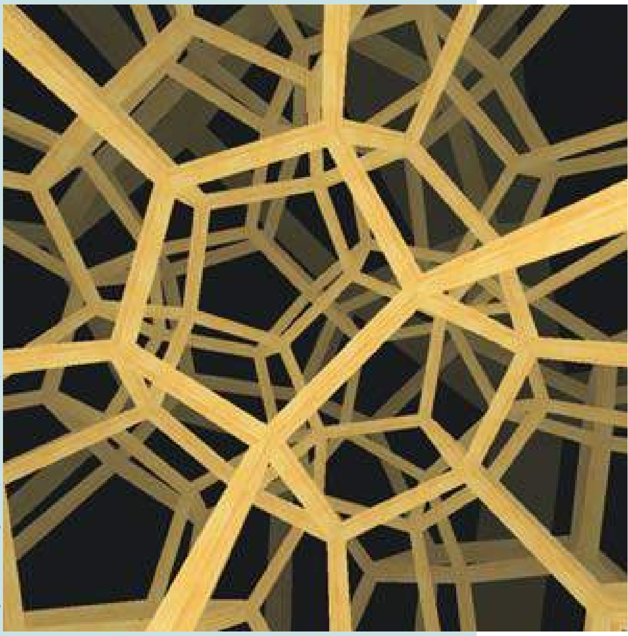

image made using Jeffrey Weeks' Curved Spaces software

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.

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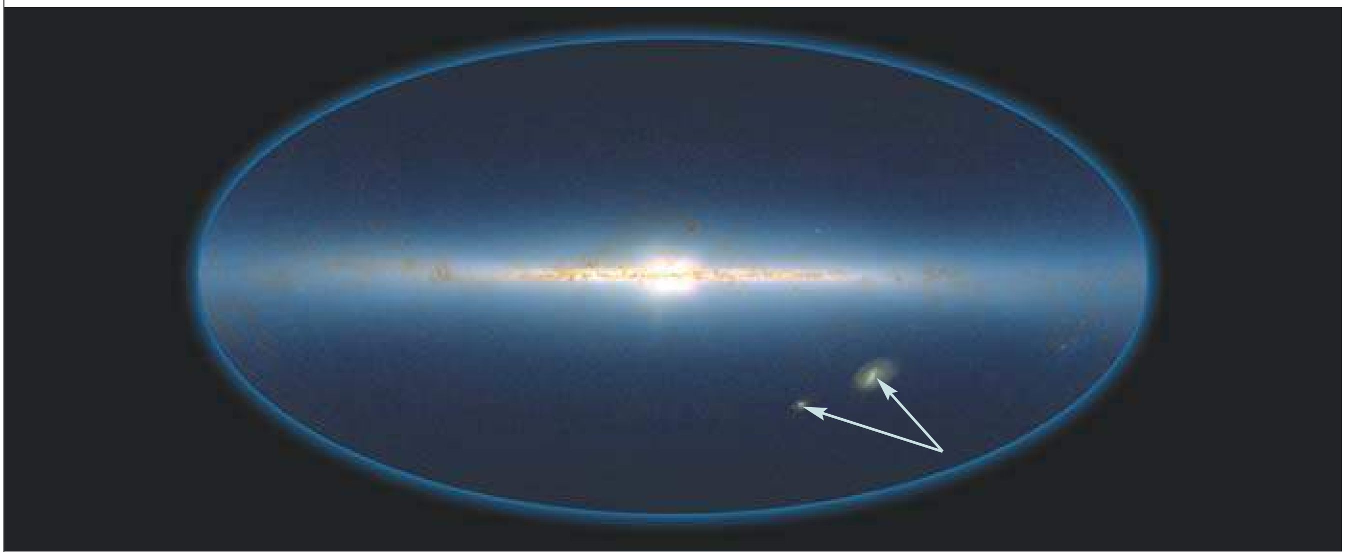
Odyssey across **the dark side of the Universe**

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

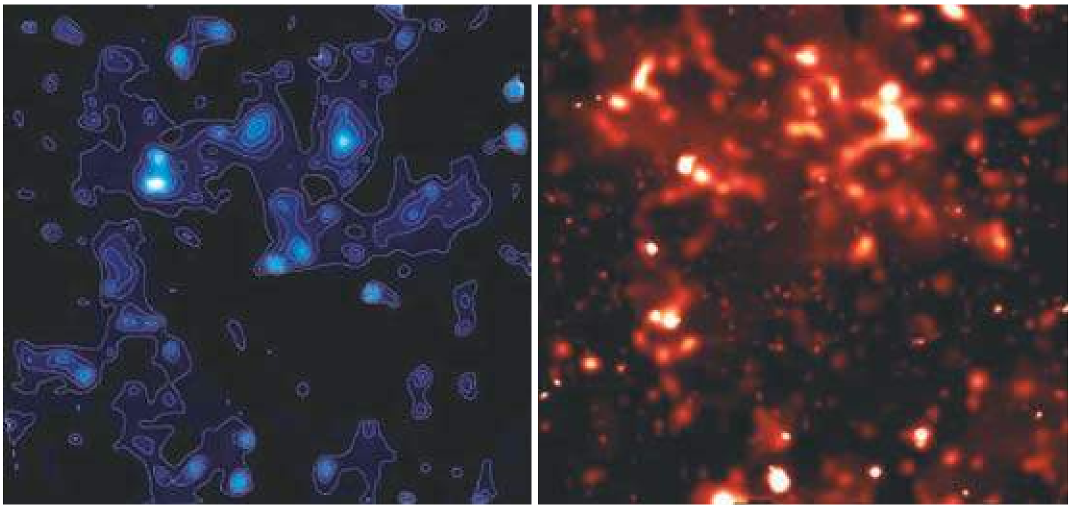
The Milky Way, viewed in the infrared region, together with the Magellanic Clouds, two satellite galaxies of our own Galaxy, appearing at bottom right in the picture. This is a mosaic image, obtained by the Two-Micron All-Sky Survey, a joint program of the University of Massachusetts and the California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



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

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.

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

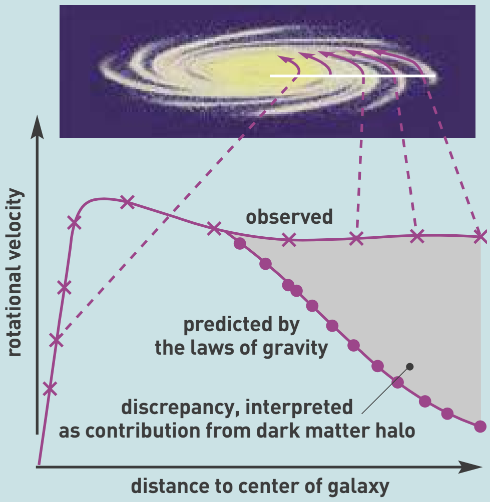
(2) Urbain Le Verrier (1811–77), French astronomer and mathematician, specializing in celestial mechanics.

(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.



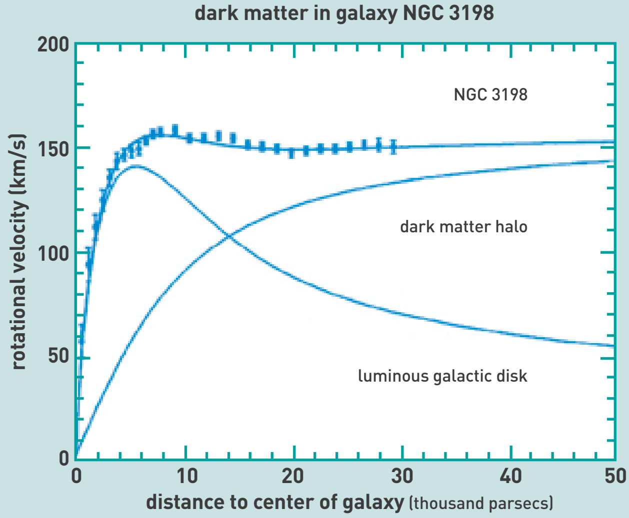


Figure 1.
The rotational velocity of spiral galaxies suggests that they contain a major quantity of dark matter. Indeed, contrary to the decline predicted, on the basis of the decreasing luminosity of the stellar disk, as distance from the galactic center increases, rotational velocity, as measured,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

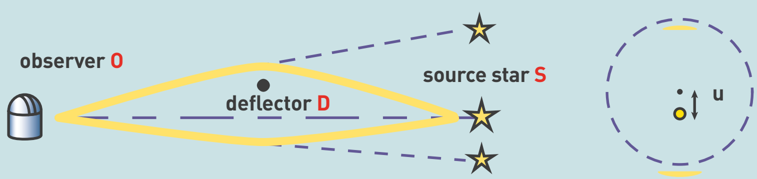
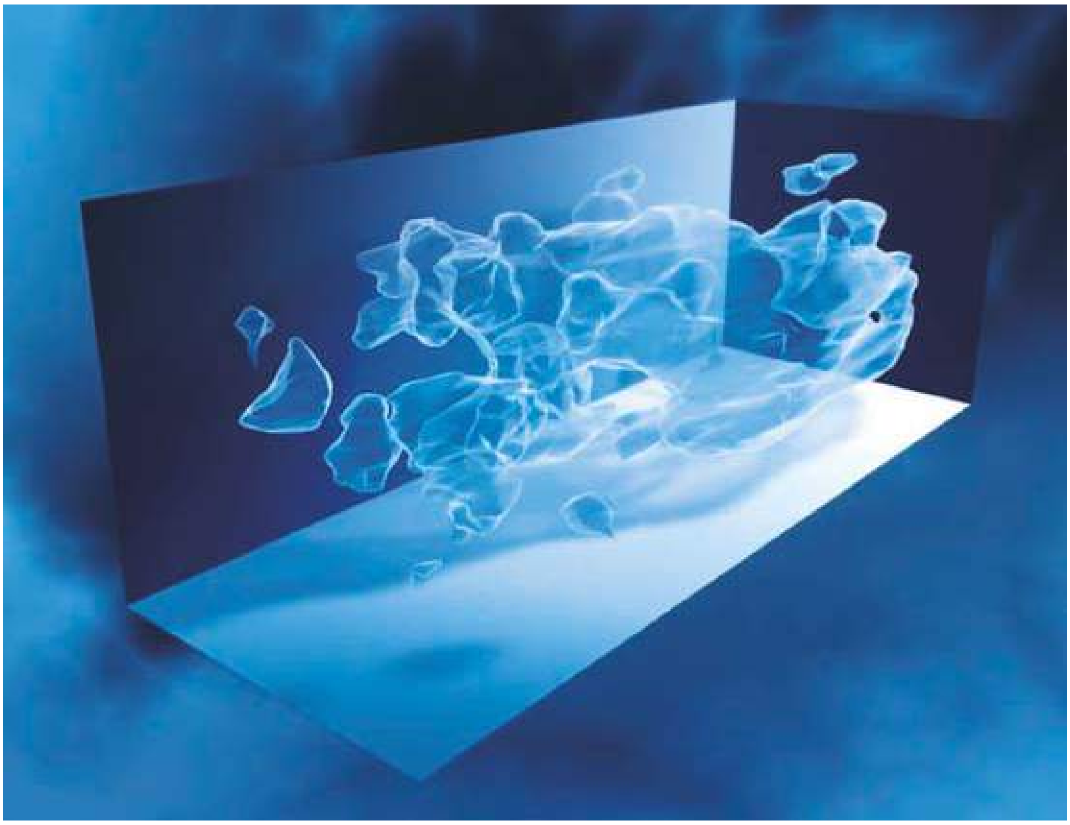


Figure 2.
Principle schematic of a gravitational mirage.
Left: the dim object at center distorts spacetime, altering the path of light rays passing in its vicinity.
Right: the two possible light paths each yield a distorted image of the star, or galaxy lying behind the object responsible for the gravitational 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.

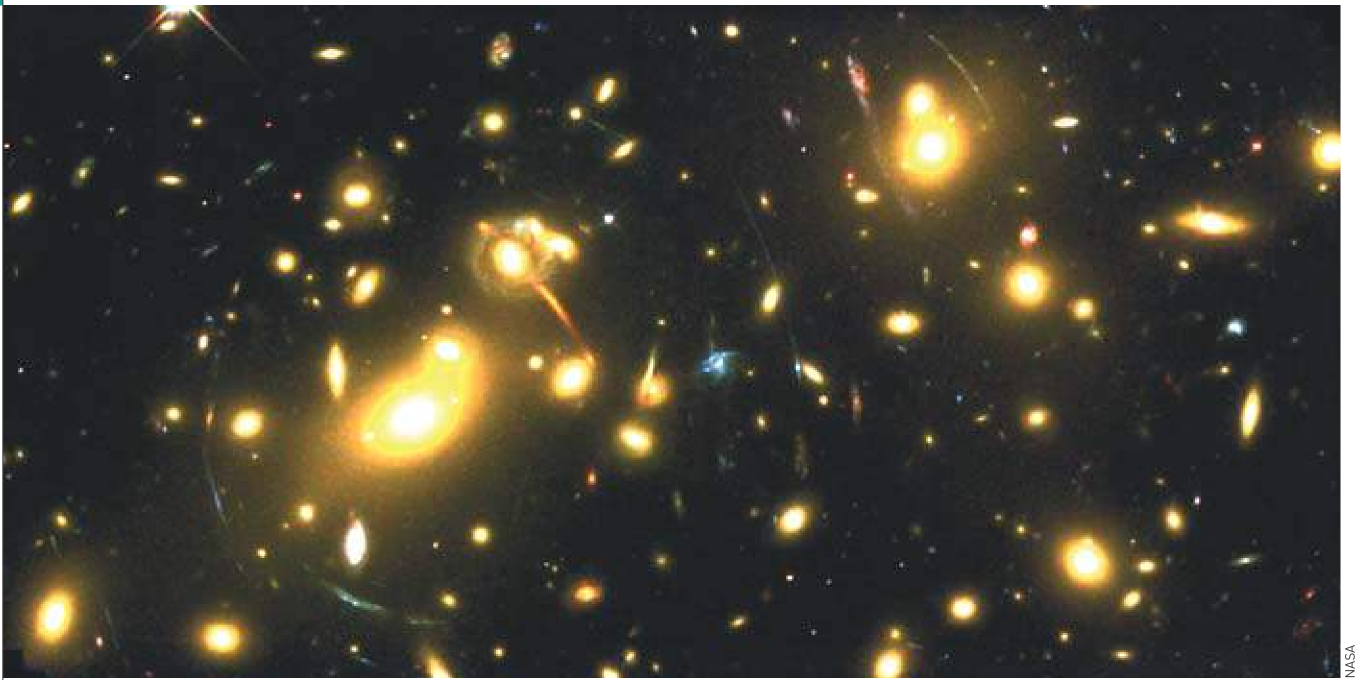
Be that as it may, the findings obtained by way of the analysis of X-radiation emitted by the diffuse hot gas located between the galaxies, in clusters, did subsequently corroborate this hypothesis. Measurements carried out by such satellites as Röntgensatellit (ROSAT), launched by Germany in 1990; or 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



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.

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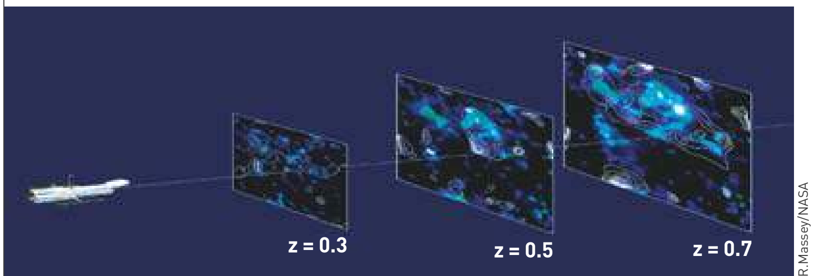


Map of dark matter, according to distance, across three slices of Universe, corresponding to ages of 7 billion (z = 0.7), 9 billion (z = 0.5), and 10 billion years (z = 0.3), showing the gradual concentration of dark matter as cosmic evolution proceeds. z stands for the redshift. The higher z is, the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

(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.

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.

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

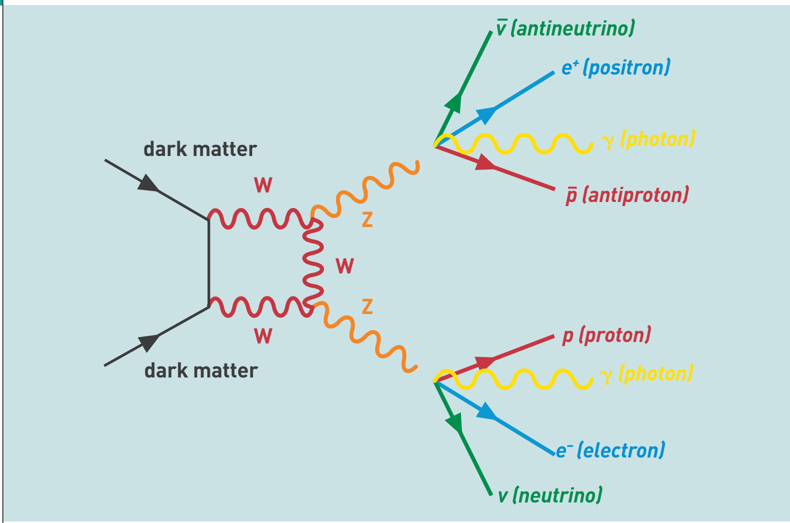


Figure 1.
Feynman diagram (so called after US physicist Richard Feynman, 1965 Nobel laureate) showing the annihilation of dark matter, yielding ordinary-matter end-products. Physicists use this type of diagram to work out the properties of the expected flux: each diagram describes, in precise mathematical 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.

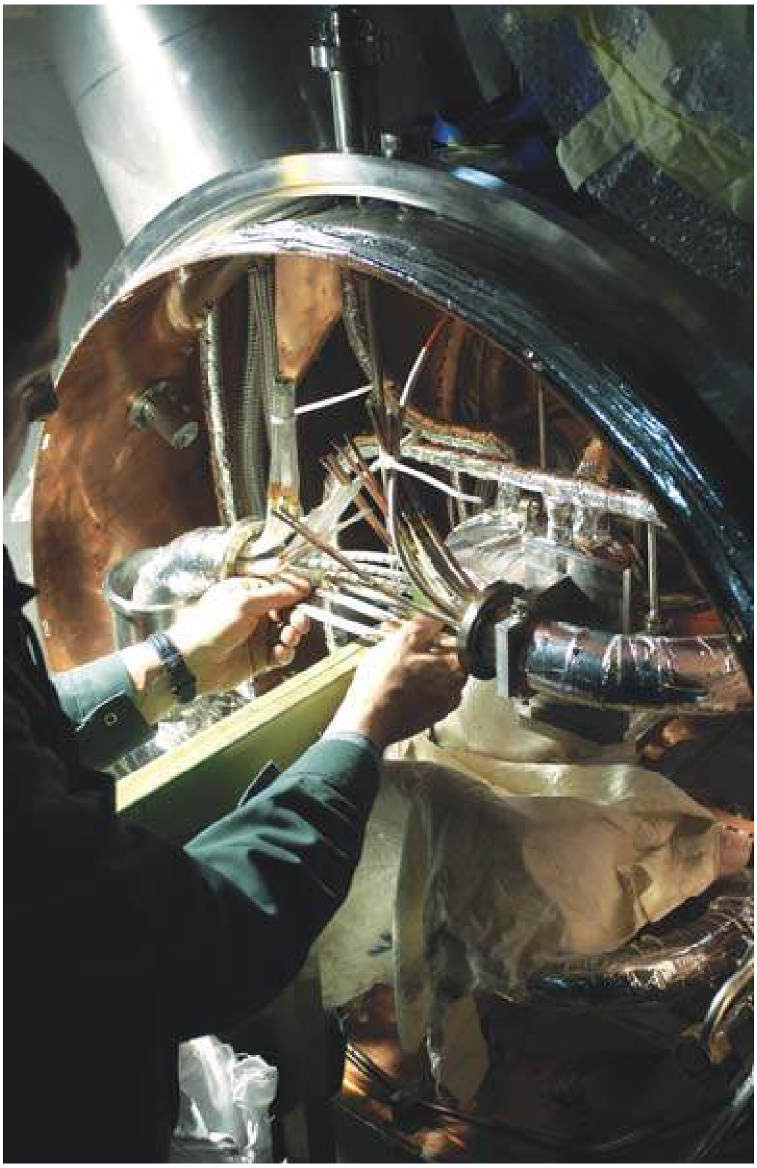
Supersymmetric dark matter, and Kaluza–Klein dark matter provided the momentum for most of the theoretical studies and experimental investigations that have been carried out since the 1980s. However, since researchers did keep an open mind on the issue, many other suggestions were put forward. For instance, 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?

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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.

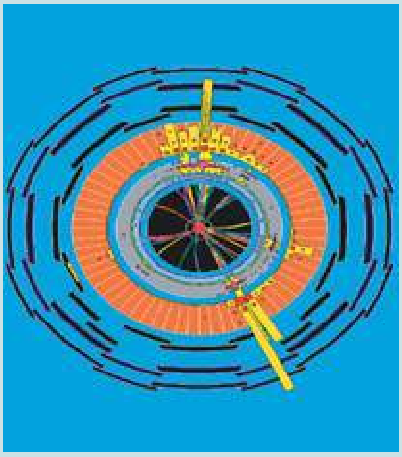

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Figure 1.
Simulation of an event involving supersymmetry in the ATLAS experiment, viewed transversely to the beams' axis. In this event, two LSPs, and two jets of ordinary-matter particles are generated. The LSPs are not detected directly, rather the 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).

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

P.Stroppa/CEA

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

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.

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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.

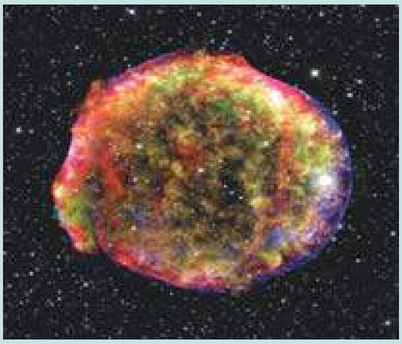
ESA/NASA

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.



CFHT

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.

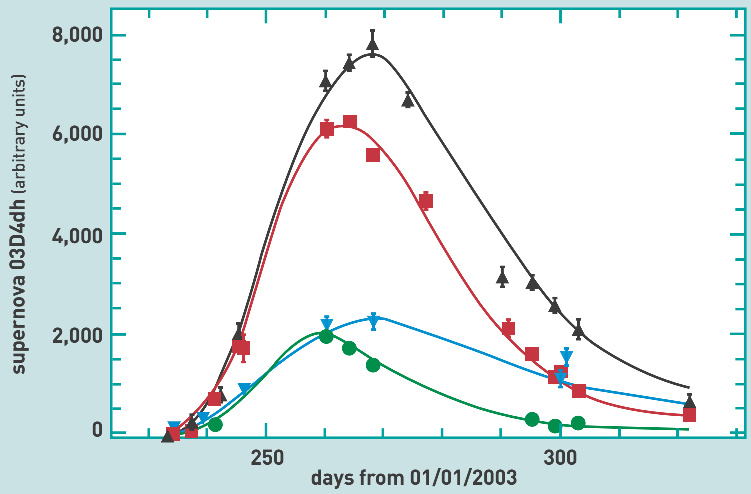


Figure 1.
The light curve for supernova 03D4dh, as measured by SNLS (flux is expressed in arbitrary units). Measurements were carried out every 3 or 4 days, apart from full Moon periods, using four separate filters: blue (circles), green (squares), red (triangles), and near infrared (downward pointing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

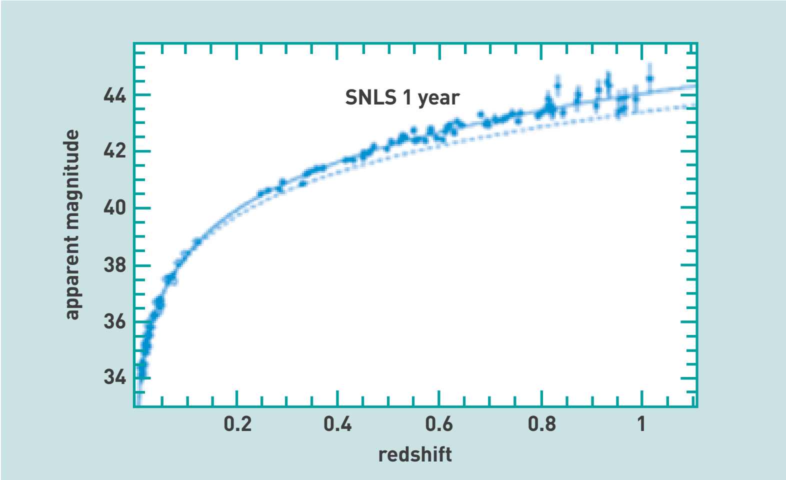


Figure 2.
Apparent magnitudes of SNIa (as derived from peak light flux), as a function of redshift. (The common usage, in astrophysics, is to plot light fluxes over an inverse logarithmic scale, known as the magnitude scale: the more luminous an object is, the smaller its magnitude.) Measurements carried 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).

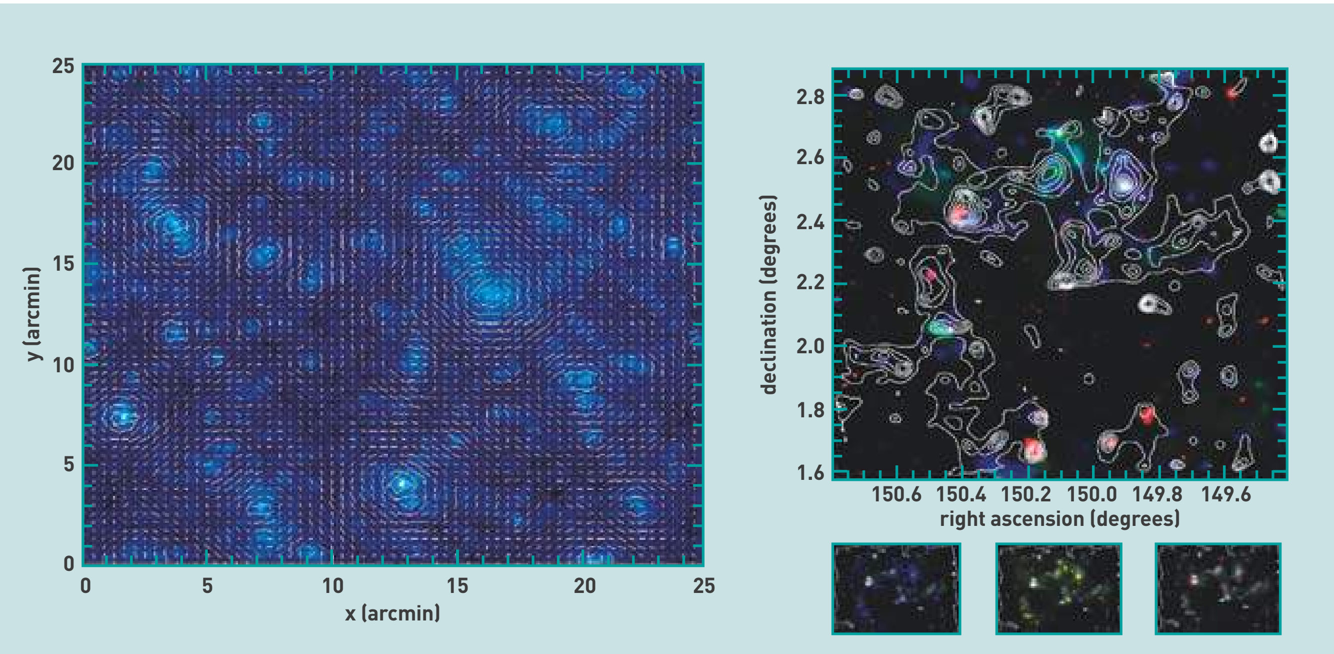


Figure 3.
Map of dark matter, obtained by way of the gravitational shear effect.
At left: image yielded by numerical simulation, showing the distribution of dark matter (color scale), and the gravitational shear the images of distant galaxies are subjected to (segments); "x" and "y" are the coordinates 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.

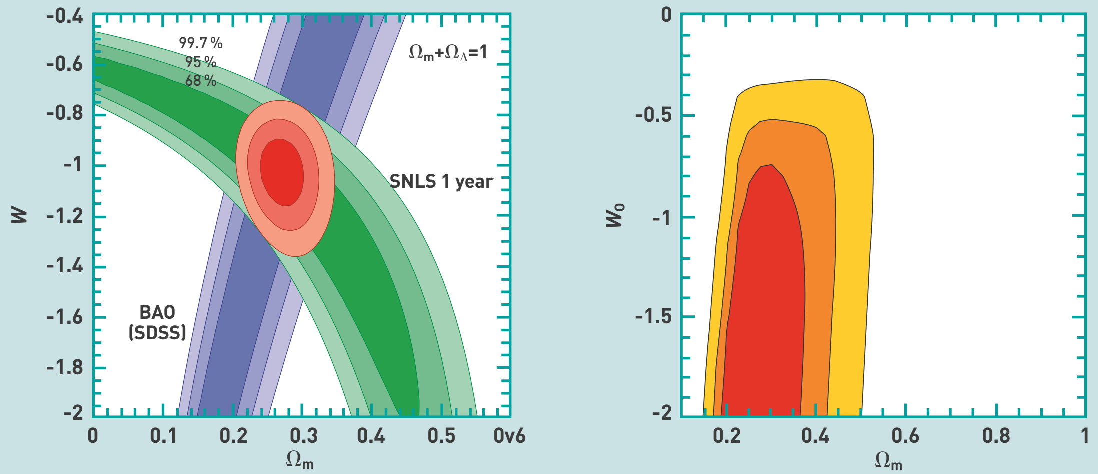


Figure 4.
Current constraints on dark energy, as derived from investigations carried out at CFHT (supernovae at left; gravitational shear at right), and the measurements of the Sloan Digital Sky Survey (SDSS) regarding baryonic acoustic oscillations (BAO). Constraints are expressed in terms of percentages 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).

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Theories of dark energy

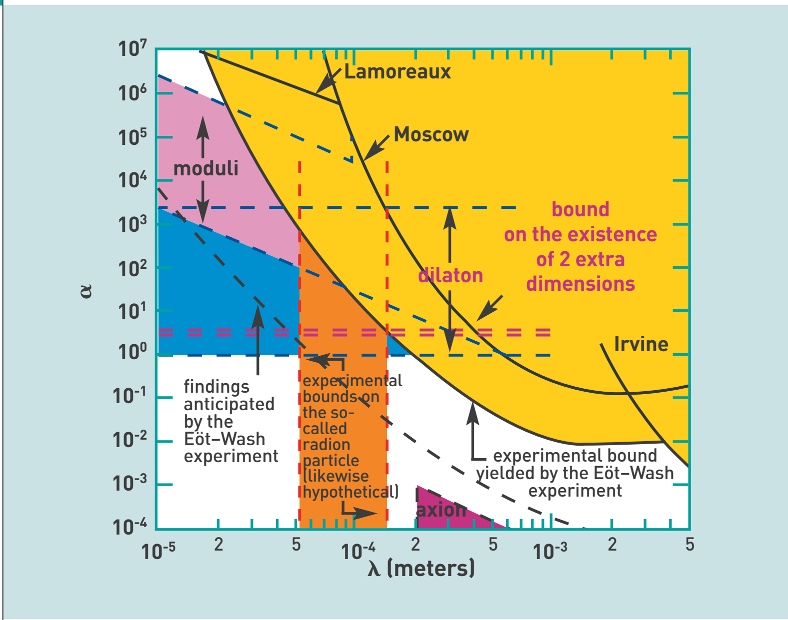
While observations, as regards the acceleration of the Universe, prove ever more precise, its theoretical description, on the other hand, remains problematic. Indeed, more than ten years after the initial observation of type-Ia supernovae and the measurement of their luminosity distance, no theory accounts 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

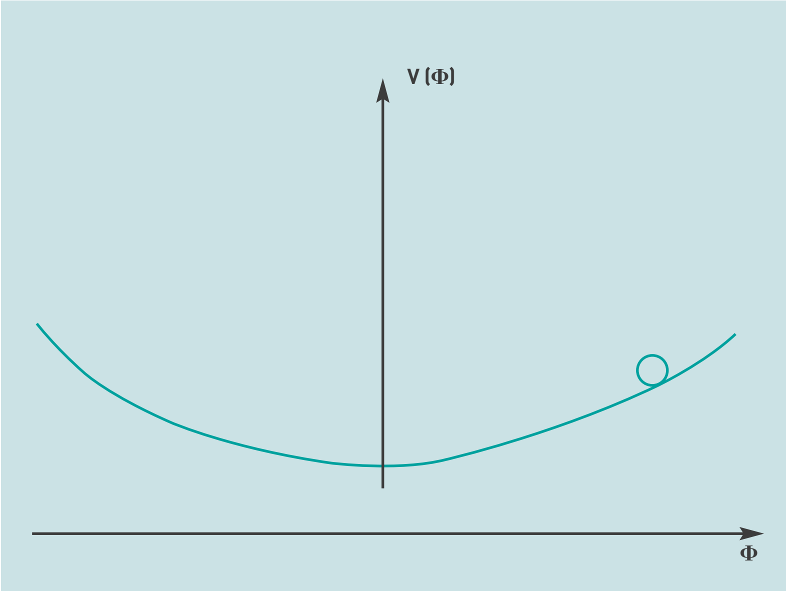


Figure 2.
The dynamics of the scalar fields, which might be responsible for the acceleration found, is akin to the motion of a ball rolling down a slope, when subject to friction. Once it has rolled down the slope, the ball stabilizes itself at the potential minimum. If the energy is positive, this acts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

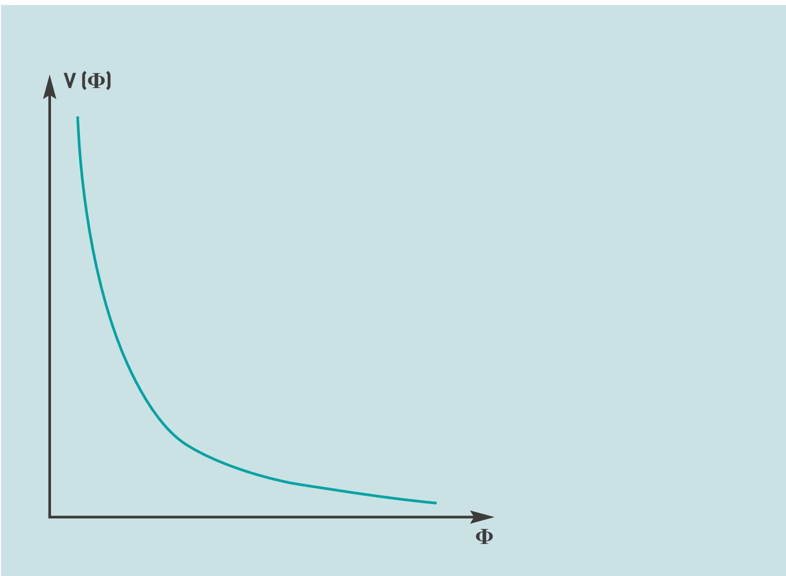


Figure 3.
Should the potential exhibit no minimum, the scalar field rolls down the slope, before being stabilised. The residual potential energy causes the acceleration of the Universe. The potential energy for dark energy is noted V (Φ), while the value of the dark energy field Φ is plotted along the *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, ^{3}He, ^{4}He, ^{7}Li), 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.

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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.

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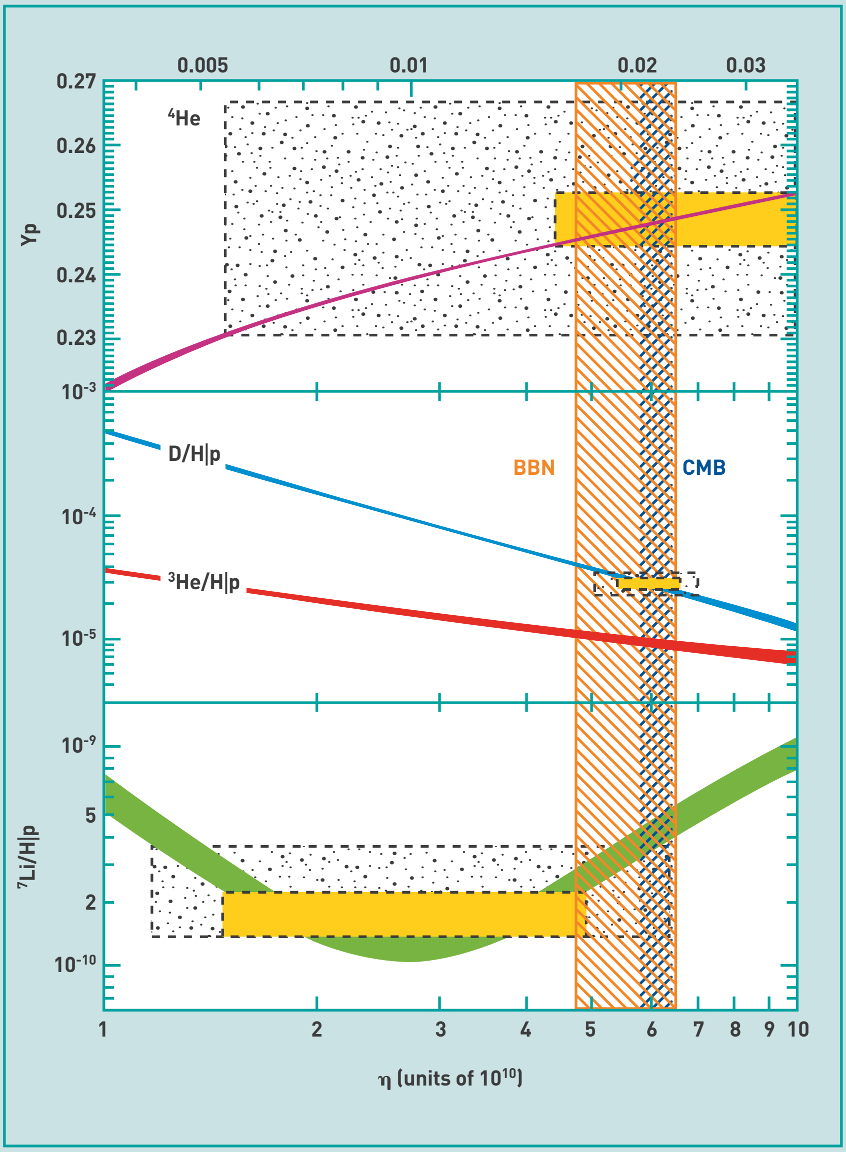

Figure 1.
Abundances of the light elements ^{4}He (conventionally noted Y_p), D, ^{3}He, and ^{7}Li as predicted by Big Bang nucleosynthesis (BBN), as a function of the parameter η (in units of 10^{10}). The horizontal rectangles indicate the observed abundances, with the associated experimental uncertainties (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.

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.

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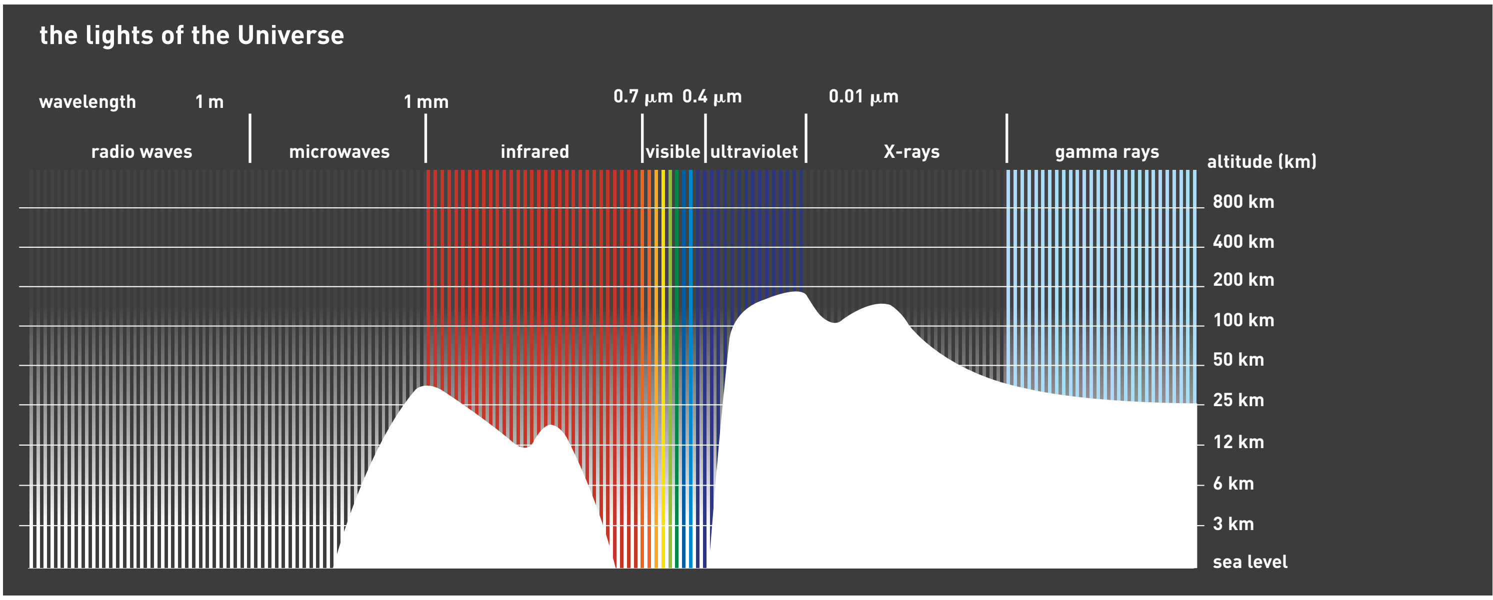

A considerable fraction of the lights of the Universe never reaches ground level. Such lights may only be observed from above the atmosphere, by means of balloons, rockets, and satellites.

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.

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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,

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.

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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).

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.

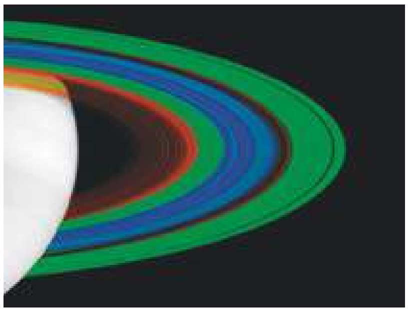
Instruments
CIRS carries out its observations by way of a spectrometer, over three detectors:
- the first one, known as FP1 (Focal Plane 1), covers the submillimeter region (20–1,000 μm);
- the other two detectors, FP3 and FP4, each comprising an array of ten detectors, carry out observations in the 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.

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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.

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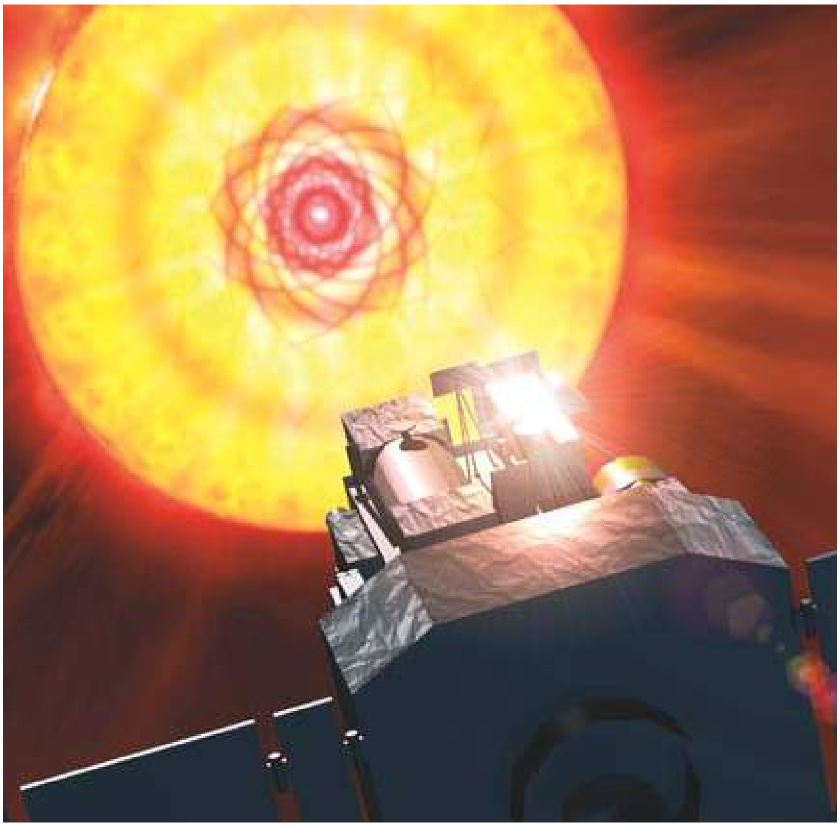
3. Visible

SoHo-GOLF



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.

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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.

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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.


ESA

Artist's impression of INTEGRAL.

- 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.

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.

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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.

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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.

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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 **shock**waves produced by WIMPs. This experiment called for collaboration between nine laboratories, including seven French, two German, one in United Kingdom and one Russian laboratory.

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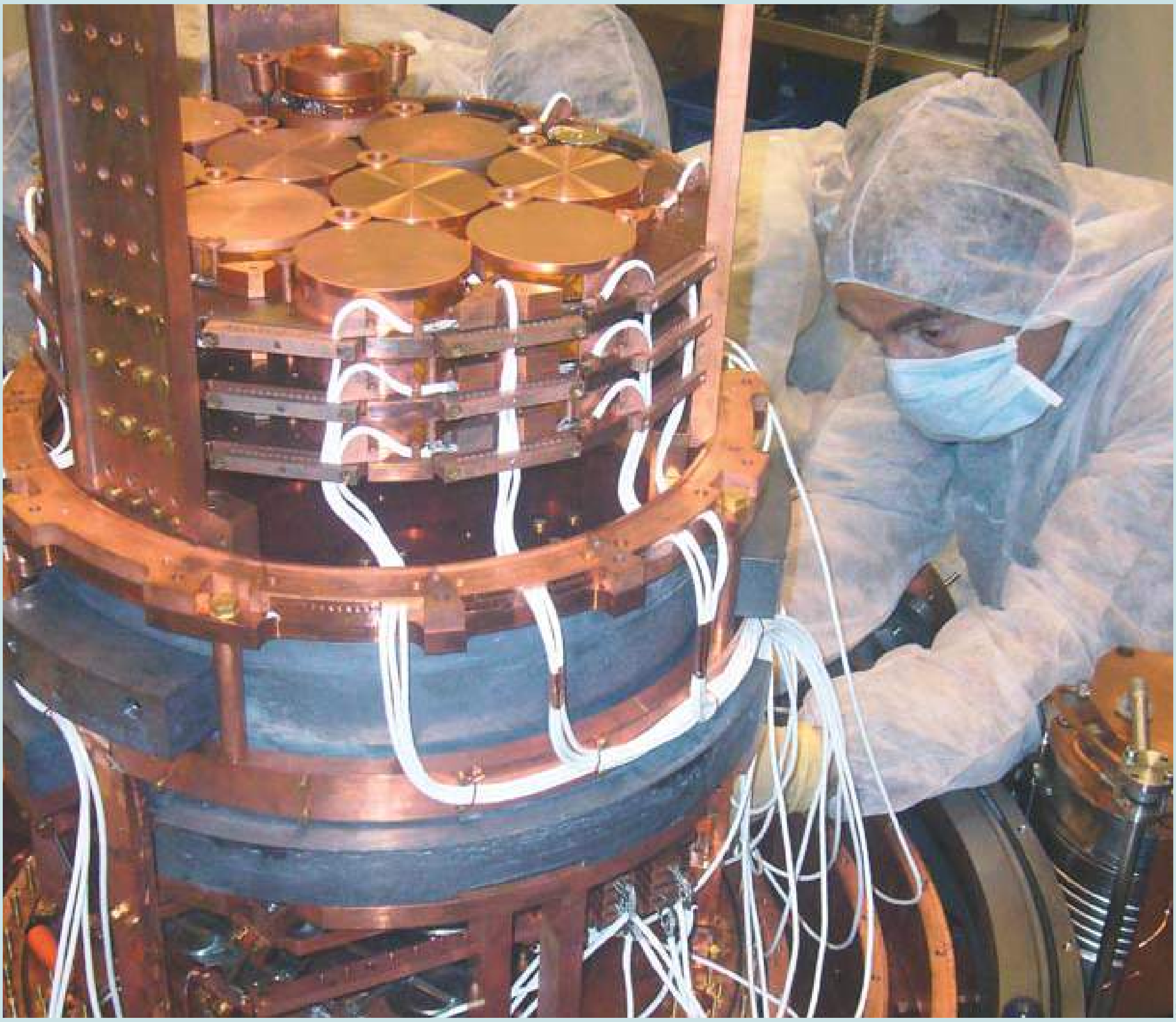
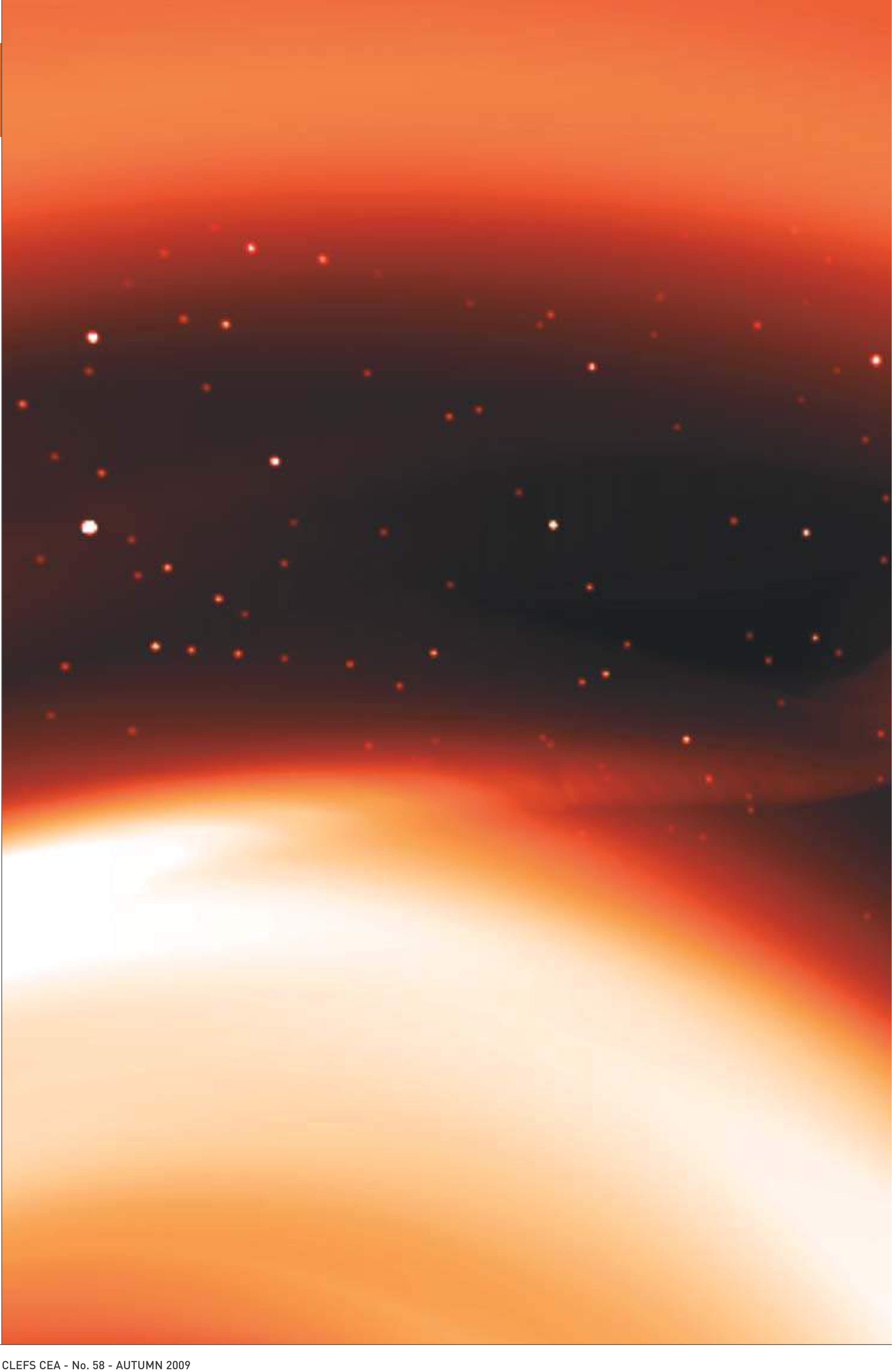

CEA

The EDELWEISS cryostat, standing open during detector mounting operations.



Proto-Jupiter, embedded in its protoplanetary disk. The protoplanet is setting up a one-armed spiral wake, voiding a gap around its own orbit. On the heels of instrumentation, and observation, simulation is the third path taken by research in astrophysics. The goal set for the COAST project is the modeling of complex astrophysical phenomena, to corroborate current theories on the physics of celestial objects, and lay the ground for future astronomical observations. The chief areas of study benefiting from this project are cosmology, stellar physics, the investigation of protoplanetary disks, and that of the interstellar medium. Protoplanetary disks: the FARGO (2-D) and JUPITER (3-D) codes are used to describe, across a grid, the evolution of the gas making up the protoplanetary nebula.

F.Masset/CEA

II. TOOLS TO PROBE THE UNIVERSE

How is the mass distribution of stars to be accounted for? How do galaxies end their existence? What is the cause of the acceleration in the expansion of the Universe? In their endeavor to resolve these issues, astrophysicists are developing a new generation of revolutionary telescopes, providing the ability to see further, more precisely, and with a wider field of view than their predecessors. These telescopes, whether ground-based or out in space, will collect light that is to be analyzed, in minutest detail, by instruments that are the embodiment of leading-edge detection technology. Affording as they do the ability to yield very finely detailed images, while carrying out spectrometry of remarkable quality, these highly sophisticated instruments known as "imaging spectrometers" stand as one of CEA's proven areas of excellence.

Their remit? To collect the information sent out by cosmic sources, so that this may be converted into digital signals, subsequently subjected to a variety of data processing methods. Such methods are currently undergoing spectacular developments. Thereafter, it will be the astrophysicists' task to analyze the results thus obtained. To ensure their ability to do this, researchers are turning to numerical simulations of the Universe and of the objects in it, carried out on massively parallel supercomputers.

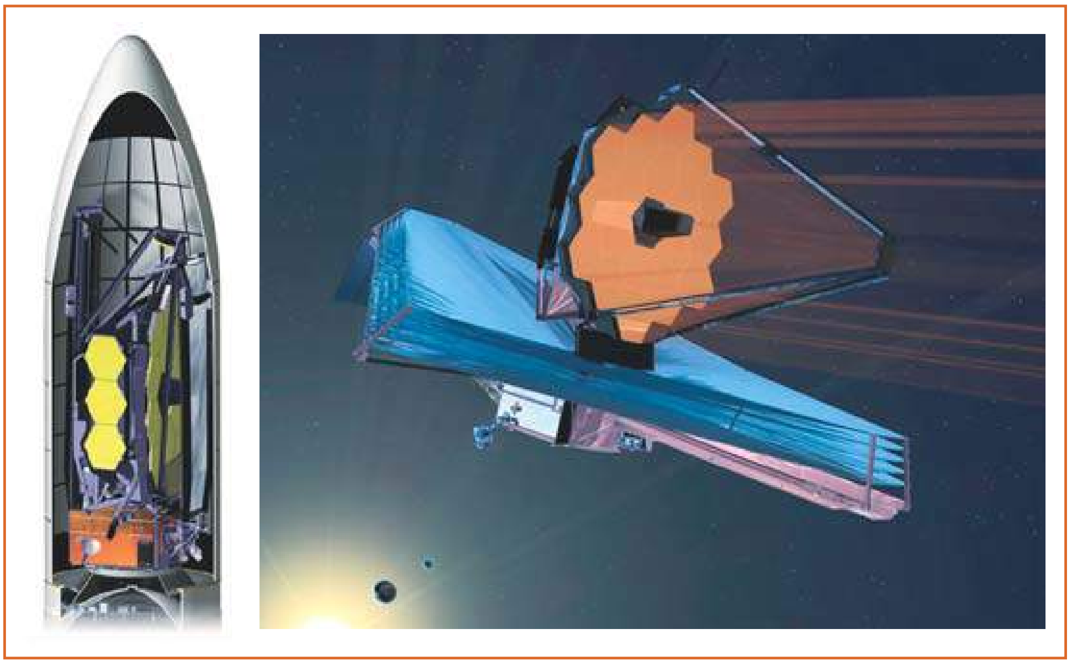
Thus, the age-old scientific diptych, "theory–observation," has been enriched by the intervention of a new tool, numerical simulation – coming in as the bridging link between ever more complex theoretical models and yet indispensable observation. Of the outcome of such work, research scientists anticipate it may yield the corroboration, or invalidation, of their present knowledge of the Universe.

Telescopes of the future

While astrophysicists have shed completely new light on our knowledge of the Solar System, and while they have detected some 400 exoplanets; and even though the expansion of the Universe is fully confirmed by observation, and even though telescopes are able to probe almost to the confines of the Universe, into the regions where the first stars, and galaxies were born... Yet **major issues do still stand, while new issues have arisen, e.g. the origin of the acceleration currently found in the expansion of the Universe, which, as yet, presents a major conundrum.** This is what has led to the emergence of a new generation of telescopes, affording the ability to observe the cosmos further out, more precisely, and providing a wider view.

1. Seeing further out

JWST : looking back on a past 13 billion years old



NASA

Artist's impression of JWST, in folded configuration inside its shroud, atop the Ariane 5 launcher (at left), and unfurled in space (right panel), in which configuration, aside from the primary mirror (gold), the thermal shields (blue) may be seen, these preventing the Sun's rays from heating the telescope.

At the present time, the Hubble Space Telescope (HST) still stands as one of the most stupendous observatories ever, the source of an impressive number of discoveries. Nevertheless, featuring as it does a telescope with a diameter no larger than 2.4 meters, it is unable to detect the faint glimmer that is received from the most distant cosmic objects. Achieving such capability would call for the design, and construction of a telescope featuring a larger collecting area, affording the ability to observe **infrared** (**IR**) **light** – the **visible light** emitted by a very distant object, in an expanding Universe, being shifted to the infrared, for an observer. Thus arose the concept of the James Webb Space Telescope (JWST),[1] to provide a successor to HST. With its 6.5-meter diameter mirror, the new telescope will have the ability to observe the Universe as it stood 13 billion years ago, at the time when the first **stars** were formed.

This is a **NASA** program, with contributions from Europe, and Canada. Working in partnership with **CNES**, CEA, acting through the Astrophysics Service (SAp) at the Institute of Research into the Fundamental Laws of the Universe (IRFU), will be taking on two major responsibilities: first of all, steering the French contribution to the Mid-Infrared Instrument (MIRI), one of the four onboard instruments carried by JWST,

(1) So named to commemorate NASA's second administrator, James E. Webb (1906–92).

dedicated to observation of cosmic **infrared radiation** in the 5–28 micrometer **wave**length range; second, responsibility for the planned Expertise Center, to be based in France, which will be dedicated to analysis of the data collected by MIRI.

JWST is due to be placed in orbit, in 2014, by an Ariane 5 launcher, the only launcher having the ability to cater for such a giant. As the volume provided by the shroud featured by the Ariane 5 launcher is insufficient to accommodate the new telescope, it will be launched in folded configuration, being deployed only once out in space. Owing to major technological developments, it proved feasible to make substantial weight savings on the device as a whole. Thus, despite a diameter nearly three times larger than that of its predecessor, HST, JWST will weigh in at 6.5 tonnes, i.e. half the mass of its forerunner. There remained one further, major constraint to square, for engineers. Dedicated as it is to the detection of cosmic infrared radiation, JWST will be operating at temperatures of about –220 °C, to preclude its own light emission interfering with its observations of the cosmos. This was the reason for the decision to position JWST at **Lagragian point** L2, lying 1.5 million kilometers away from the Earth (see Figure 1), by contrast to the position of HST, in low orbit, a mere 600 km or so from the Earth. Given the distance, there can be no question of going out to repair the telescope, should a problem arise!

Three main instruments will be positioned at the focus of JWST, to capture the light concentrated by the telescope, and turn it into a digital signal, sent back to Earth:

- the Near-Infrared Camera (NIRCAM), a camera for the near infrared (1–5 micrometers), designed, and constructed in the United States;
- the Near-Infrared Spectrometer (NIRSPEC), a **spectrometer**, likewise dedicated to the near infrared, designed, and constructed by European manufacturers, under project leadership, and with funding, from the **European Space Agency** (**ESA**);
- the Mid-Infrared Instrument (MIRI), an imaging spectrometer for the mid-infrared (5–27 micrometers), designed, and constructed by a collaboration, one half being accounted for by the United States (**Jet Propulsion Laboratory/NASA**), the other half by a consortium of space laboratories, from 10 countries (by decreasing rank, in terms of funds contributed: the United Kingdom, France, Belgium, the Netherlands, Germany, Spain, Switzerland, Sweden, Denmark, Ireland), led by the UK's **Royal Observatory, Edinburgh** (**ROE**), and funded by the respective national agencies.

It should be pointed out that, initially, the JWST program had made no provisions for a dedicated instrument for mid-infrared observation. In the late 1990s, only a small band of US, and European astrophysicists advocated the presence of such an instrument, in the proposed space telescope. This prescient advance guard included, in particular, astrophysicists at CEA, aware as they were of the potentialities of this type of instrument, and already heavily involved in observations of the mid-infrared – e.g. with the ISOCAM camera, sent out in space in 1995, or the VISIR (VLT Imager and Spectrometer in Infrared) instrument for the **European Southern Observatory**'s (**ESO**) Very Large Telescope (VLT), in Chile. This state of affairs resulted in SAp taking on the scientific, and technical leadership, for the MIRI imager.(2) Aside from IRFU, three other French laboratories are involved in this project – namely, the Space Research and Astrophysical Instrumentation Laboratory (**LESIA: Laboratoire d'études spatiales et d'instrumentation en astrophysique**), at the **Paris–Meudon Observatory**; the Space Astrophysics Institute (IAS: Institut d'astrophysique spatiale), at Orsay (near Paris); and the **Marseille Astrophysics Laboratory** (**LAM**). CNES – also a CEA partner for this program

NASA

Full-scale mockup of JWST.

(2) Aside from SAp, other services at IRFU are taking part in the project: the Detector Electronics and Informatics Service (SEDI); the Systems Engineering Service (SIS); and the Accelerators, Cryogenics, and Magnetism Service (SACM).

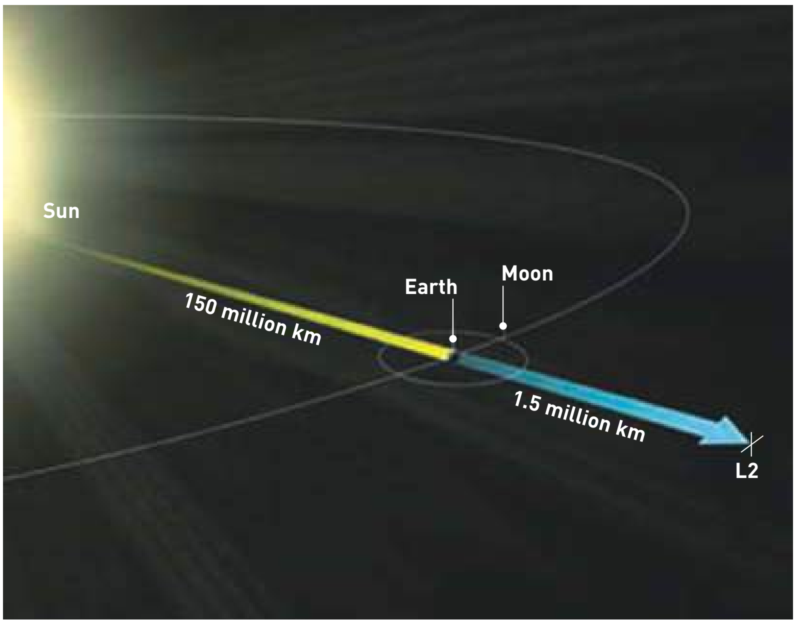


Figure 1.
Schematic showing the location of Lagrangian point L2, around which JWST will be positioned.


L. Godart/CEA

The Mid-Infrared Imager (MIRIM) camera, due to be mounted in JWST, being inspected, under ultraviolet light, to check no particulate contamination has occurred.

– is contributing 50% of program funding (including workforce costs).

Once commissioned, JWST will take its place in the range of second-generation infrared telescopes. Affording as it does a sensitivity, and angular resolution 100 times better than those featured by its forerunners, the new instrument will allow notable advances to be achieved, in various areas of astrophysics, e.g. **galaxy** assembly, the initial phases of star formation, or the search for exoplanets. With regard to the latter specific area of interest, a so-called coronagraphic observation mode has been introduced, for the MIRI imager. This involves a method making it possible to "extinguish" a star, to probe its vicinity, free from its "glare," and thus gain the ability to look for possible **planets**, "companions," dust disks… This coronagraphic observation mode required the fabrication of specific optical components, hitherto unavailable from manufacturers. LESIA designed these components, the Radiation–Matter Institute (IRAMIS: Institut rayonnement matière) at CEA constructing them.

What is the present state of advancement for this project? Technically speaking, the various models of the MIRI imager indispensable for the purposes of space qualification of the instrument have already been completed. The flight model is currently undergoing tests, at CEA's Saclay Center. Once this phase is completed, this being scheduled for December 2009, the instrument is due to be delivered to the British engineers who will assemble it with the spectrometer, prior to sending the complete device to NASA. NASA will subsequently integrate the instrument into JWST, in 2011.

Construction of the MIRI imager has enabled CEA engineers, and research scientists to gain outstanding knowledge of the device. It further secures their access to the observation time required to conduct new, yet more ambitious observation programs – assets that will enable SAp to keep, for a long time yet, to the fore of astrophysical research. This expertise, gained by CEA in the course of construction of the instrument, during tests carried out in laboratory conditions, or out in space, will prove of benefit to the European astrophysical community as a whole, by way of the setting up of an Expertise Center, based at Saclay. One further benefit of the project is that it preserves CEA's scientific, and technical expertise, in the area of mid-infrared radiation, which as ever proves to have great potential, for astronomical purposes. Indeed, a sequel is already shaping up, with, in particular, design studies for the METIS (Mid-Infrared E–ELT Imager and Spectrograph), planned for the European Extremely Large Telescope (E–ELT), a new 42-meter diameter giant, currently in the detailed study phase at ESO (see *ELT/METIS, a 42-meter giant*, p. 110).

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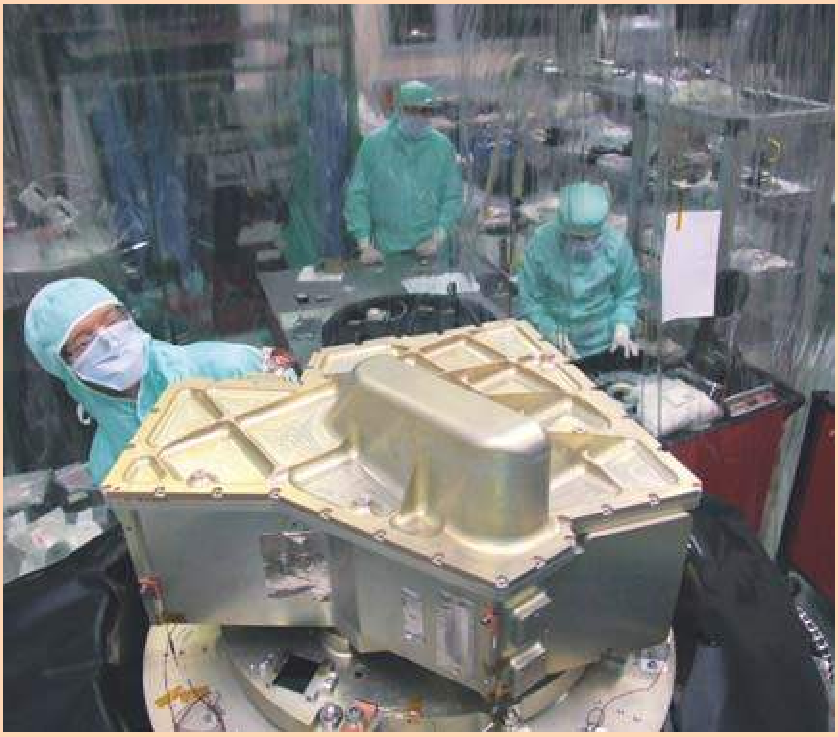
Space specifics: the learning curve to know-how

The construction of space equipment, and devices is a relatively novel area of technology, referred to the scale of astronomical science. In France, the first experiments to be carried on board sounding rockets, to collect a few minutes' worth of observations above the atmosphere, go back barely half a century. In those pioneering days, the trial and error method could meet the expectations of the scientific community. With the advent of satellites, however, there began to be a call to set in place a common, reference working approach, for the purposes of optimizing the chances of success, and ensuring feedback from experience, such as to allow risks to be minimized, for subsequent projects.
This reference approach makes it possible, by way of engineering, quality, and project management standards, to take on board, from the initial design phase, the specific constraints of space technology. The first concern, of course, is to meet stringent technical constraints: space instruments often involve technologies of marginal feasibility, in extreme application domains. The requirements stemming from space programs, however, extend far beyond functional operating specifications. Thus, specific environmental constraints – launcher vibrations at takeoff, ultravacuum, **radiations**, the impossibility of carrying out an intervention, in the event of a failure – call for a peculiarly stringent quality assurance approach.
To take the case of the JWST space telescope, for which CEA/IRFU is developing the Mid-Infrared Imager (MIRIM) camera, which will make it possible to survey the first stars in the Universe. This project will have required several billion US dollars, and called on 20 years' efforts, on either side of the Atlantic, from the initial blueprints, originating in the mid-1990s, to the launch, scheduled for 2014. From components to completed instrument, every system undergoes a qualification campaign, to demonstrate the reliability, and performance of the selected design, and concept. For instance, prior to construction of the flight model, the MIRIM camera will, over five years, have gone through four models of the complete instrument, for the purposes of checking the entire range of performance, in operational conditions, with regard, in particular, to behavior in launch conditions, by way of vibration tests, or at extreme temperatures, with cryogenic tests in a liquid-**helium**-cooled (4 K) chamber. Likewise, as regards the PACS (Photoconductor Array Camera and Spectrometer), and SPIRE (Spectral and Photometric Imaging Receiver) cameras, intended for the Herschel space telescope, 2,500 working hours will have been required, to check the 65,000 electronic components, 900 mechanical parts, and 50 electronic cards.

L. Godart/CEA

The MIRIM cryogenic test bench.
Test benches, and test campaigns may reach levels of complexity, and cost that come close, in some cases, to those involved for the instrument itself.

Thus, over time, concepts are refined, procedures improved, and anomalies (noncompliance with specifications, errors) reduced, down to the risk level deemed to be acceptable, if the project is to be successful. In a political, and international context that often proves complex, space project management calls for the careful balancing of risk management, against cost, and scheduling constraints. Canceling a test campaign may be seen as allowing savings to be made, in terms of valuable working days, however the risks associated to this may turn out to be altogether more costly, and indeed catastrophic, as shown by the Hubble example. An accurate critical-path analysis is required, if satisfactory progress is to be ensured, for projects that are protracted, uncertain, and risky.
Some of the constraints outlined in this paper do also arise in other areas of scientific instrumentation. On the other hand, the one major specific feature of space programs is the concurrence, within any one project, of all of these particular constraints, and of the methods adopted to manage these constraints.



L. Godart/CEA

The flight model of the MIRIM instrument being positioned inside the cryogenic test chamber, at SAp. The cleanliness constraints, for space instruments, require that work be carried out in a controlled environment, in this case in a class 100 environment (i.e. exhibiting fewer than 100 particles of a size larger than 0.5 µm, per cubic foot).

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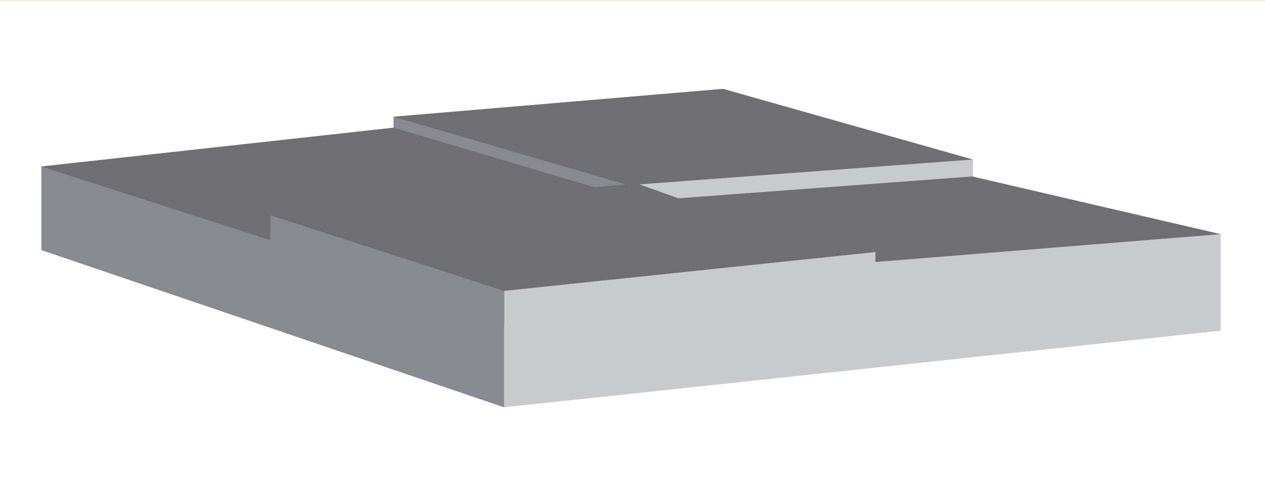
Fabricating a coronagraph mask



CEA

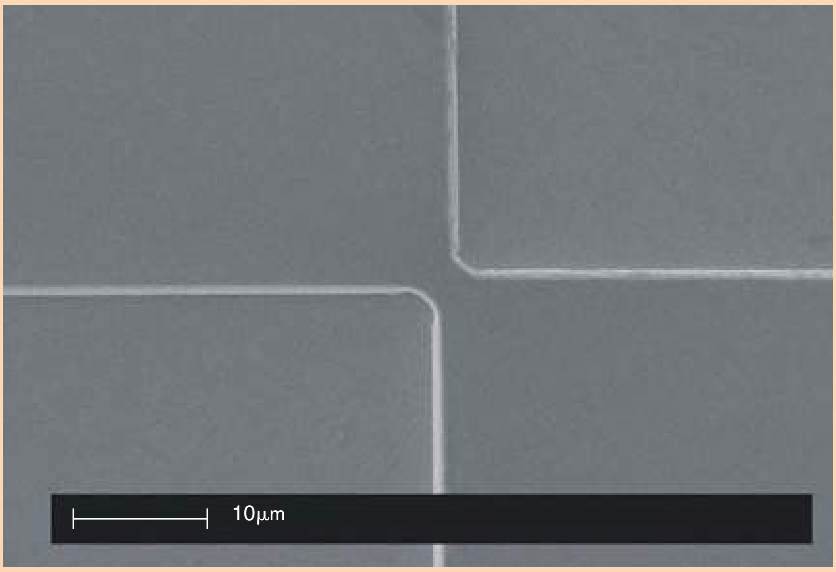
Figure 1.
Schematic of the coronagraph mask, made from a germanium single crystal (step thickness is not to scale).

Invented by French astronomer Bernard Lyot (1897–1952) in the early 1930s, coronagraphy involves mimicking a total eclipse, to observe the **solar corona**, while it is not drowned out by the Sun's luminosity. The principle involves placing an opaque spot over the image of the **Sun** formed by an astronomical telescope, to occult the solar disk, thus allowing only the light from the solar corona to be seen. Nowadays, coronagraphy is used for the purposes of making observations of other **stars** than the Sun, and there is an alternative to the use of Lyot spots, to carry out such observations: to wit, the quite recently developed four-quadrant phase masks (4QPMs), which allow better performance to be achieved. Fabricating such masks involves a thin plate, of near-perfect geometry, comprising two quadrants exhibiting a thickness differing from that of the other two quadrants – by half a wavelength, in germanium, at the observation frequency (see Figure 1).

The Mid-Infrared Instrument (MIRI), due to be mounted on the forthcoming James Webb Space Telescope (JWST), will implement this principle, targeting three observational **wave**lengths in the infrared – this entailing the development of 4QPM-type masks, in germanium, this being a material that affords the benefit of becoming transparent, in this observational region. As regards the fabrication process, the Space Research and Astrophysical Instrumentation Laboratory (**LESIA: Laboratoire d'études spatiales et d'instrumentation en astrophysique**) supplied parallelepipeds, cut from a germanium single crystal, exhibiting parallel, plane surfaces. That the required step thickness could be obtained, in germanium, is wholly owing to the high precision afforded by the microfabrication tools used in the clean room at the Solid State Physics Service (SPEC). Two techniques were used: optical lithography, to define the protected quadrants, and reactive ion etching, to etch the thinner quadrants. For the researchers involved, however, the greatest difficulty encountered, in the fabrication of such masks, was that of achieving the requisite precision:

- a step thickness set at values in the 0.8–2 **µm** range, depending on working wavelength;
- an error tolerance, with regard to the step, of less than 0.5%;
- outstanding homogeneity, notwithstanding a total surface area in excess of 1 cm^2;
- surface roughness kept at less than 30 nanometers across the entire component.

Some 60 prototypes had to be fabricated, with a whole sequence of steps needing to be carried through (resin deposition, reactive etching, cleaning, checking step thickness, etc.), before the three final masks could be obtained, that will be fitted to MIRI (see Figure 2).



Anne de Vismes/CEA

Figure 2.
Scanning electron microscopy image showing the center of the component, subsequent to etching. Scale: 10µm.

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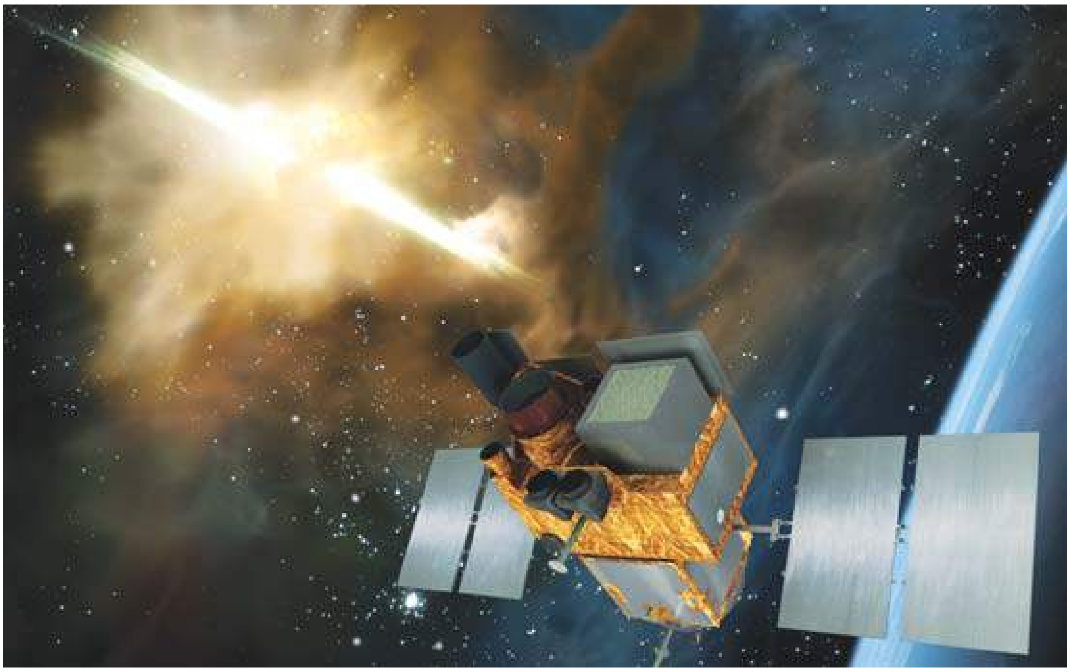
SVOM, a satellite to detect the explosions of the first stars to be formed in the Universe



Cnes

Artist's impression of the SVOM satellite.

In 2014, the Space-based Multi-band Variable Object Monitor (SVOM) satellite is due to be put in orbit, to monitor **gamma-ray bursts**, in other words to look for the most violent events in the Universe, since the **Big Bang**. The bursts' extreme brightness should make it possible to detect the first **stars** in the Universe, and to survey distances across the cosmos, by using them as astronomical standard candles. This brightness is due to their **gamma-ray** emission, which is very powerful, but equally highly ephemeral: 0.1–100 seconds. This initial emission is invariably followed by a second, much fainter one, the so-called afterglow, decreasing over time, and covering a broad band, ranging as it does from **X-radiation** to **infrared**, through **visible radiation**. The short-lived character of the gamma-ray phenomenon, together with the desire to observe the process at one and the same time across a wide spectral band, entailed that appropriate means be used. The SVOM mission was the outcome, involving as it does a panoply of telescopes, both spaceborne and ground-based, featuring sensitivities ranging from gamma radiation to the infrared. Such instrumental complementarity marks this out as a unique experiment, the world over, as regards the investigation of gamma-ray bursts, from prompt emission to afterglow. This involves a Chinese–French collaboration, set up between the **China Aerospace Science and Technology Corporation**, the Chinese Academy of Sciences, and the French National Space Research Center (**CNES**: **Centre national d'études spatiales**).

At the core of this setup stands the ECLAIRs telescope, which will set in train the entire concatenation of measurements involved in the mission. Developed at IRFU, who are acting as project leader for this, it forms the chief French contribution to the SVOM satellite's payload. ECLAIRs will have the remit of detecting the onset of a gamma burst, across a segment of the celestial canopy, determining its location with a precision of 10 minutes of arc, or better – about a hundred bursts should be detected annually. Since conventional optics proves unable to focus gamma rays, researchers opted for coded-mask imaging. As its name implies, this technique involves positioning a mask in front of a detector plane, in the knowledge that, to a given position of a particular source in the sky, there corresponds a unique mapping of the mask pattern onto the detector plane. All that remains is to make use of a mathematical tool, to reconstruct the image, allowing the source's direction to be ascertained. The coded mask consists of a tantalum plate, perforated according to a specially selected pattern, and kept taut by a titanium frame, to compensate for thermal distortions – this being a device fabricated by the **Paris Astroparticles and Cosmology Laboratory**. The mask is supported by a light, rigid carbon structure, surrounded by a multilayer shielding of lead, copper, and aluminum, having the purpose of blocking **photons** not originating in the field of view defined by the mask.

Fabricated by the Space Radiation Research Center (**Centre d'étude spatiale des rayonnements**), at **Toulouse** (southern France), the detector plane combines cadmium telluride detector crystals, and low-noise analog application-specific integrated circuits (ASICs) for readout. The assembly process involves stacking ceramic elements compactly, to form a 6,400-**pixel** detector unit, across a surface area of 1,024 cm². Cooled as it is by a high-performance system, using variable-conductance heatpipes, the

plane's overall temperature stands at –20 °C. Particular attention was paid to the value to be achieved for the low-energy detection threshold. Through stringent selection of unit detectors, and thorough control of electronics noise levels, a 4-**keV** low-energy threshold was obtained. This was a crucial outcome, with regard to the telescope, for the purposes, in particular, of detecting events lying at cosmological distances, for which photons are shifted to lower energies. The ASIC was developed by IRFU, while optimization of the detector–ASIC couple came from one of its R&D business units.
Likewise developed by IRFU, the onboard triggering and scientific processing unit (UTS) will have the remit of detecting, and locating, in real time, the onset of a gamma-ray burst in the sky, going on to analyze the data yielded by the detector plane, with regard to photons. The UTS design hinges on a space-**radiation**-tolerant onboard microprocessor. The onboard scientific **algorithm** makes use of two burst detection methods. The dedicated method for long bursts reconstructs images of the sky every 20 seconds, looking for the emergence of a new source. The second method, sensitive to shorter-lived gamma-ray bursts, scans every time interval, down to 10 ms, to detect any increase in the number of photons detected, this allowing it in turn to reconstruct the image of the sky, and thus pinpoint the source. Once the gamma-ray burst is located, the SVOM satellite realigns itself, so as to be able to observe the afterglow, by means of the onboard, narrow-field-of-view dedicated X-ray, and visible-radiation telescopes. Concurrently, the UTS unit draws up an alert message. Swiftly transmitted to the ground by way of a VHF datalink, connected to some 30 ground stations, spread out along the satellite's path, this message will trigger observation of the burst's afterglow by ground-based telescopes. From this observation, it then becomes feasible to determine the event's distance.
The deployment of high-performance, innovative solutions manifests the expertise that has been gained by the space instrumentation technical teams. Drawing on this experience, SVOM will be opening up a new window onto the Universe, bringing into view knowledge of such distant phenomena as gamma-ray bursts. For that, however, we needs must await 2015.

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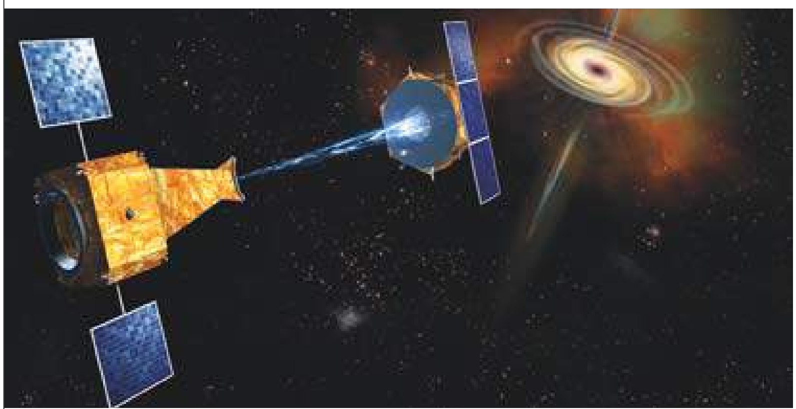
2. Seeing more precisely

SIMBOL–X, pioneering formation flying



Artist's impression of SIMBOL–X observing an active galaxy. The satellite on the right is carrying the mirror, focusing X-rays onto the detector positioned in the satellite on the left, 20 meters out.

If evidence is to be found, in the sky, of the activity manifested by the Universe's more extreme sources, it takes the form of **X-radiation**, and **gamma radiation**, originating in **plasmas**, brought to temperatures of hundreds of millions of degrees; or due to particles, accelerated to energies up to one billion times higher than those achieved by our most powerful accelerators. This accounts for the interest evinced by astrophysicists, as regards scanning the sky in this **radiation** domain. They may thus be able to provide an answer, at some point, to the fundamental queries arising in modern astrophysics – such as those relating to **black holes**, the immediate vicinity of their horizon being approached by way of the X-radiation spectrum; or regarding the origin of **cosmic rays**. As regards black holes, how many are there in the Universe? What are they? Do they have an impact on their environment? What part did they play in **galaxy** formation? Turning to the other issue, how do cosmic accelerators work? Can all cosmic radiation be accounted for?
The SIMBOL–X space telescope was designed for the purposes of seeking an answer to such queries, through the very precise observation of the sky, in its very distant reaches. The reason why no previous instrument had the ability to do this, is owing to the altogether too highly penetrating character of X-ray, and gamma-ray **photons**, precluding the use of telescopes of conventional construction, in which they might be collected, and reflected by a large mirror, to be focused onto a small detector. As is the case for human tissues, in medical X-ray examinations, such mirrors prove transparent to X-radiation. Consequently, the optics of the best X-ray, and gamma-ray imaging instruments, e.g. the IBIS (Imager on Board the INTEGRAL Satellite) imager, carried by the INTEGRAL (International Gamma-Ray Astrophysics Laboratory) satellite, consists of a coded mask, allowing true images to be obtained, with an **angular resolution** that still proves fairly low, at some 10 minutes of arc or so (i.e. one third of the size of the Moon, as seen from the Earth). However, since they do not operate by focusing light, these instruments do not benefit from the concentration effect that serves

to endow conventional telescopes with their power. Fortunately, there is indeed a way of focusing X-rays. This relies on the fact that such radiation may be reflected over very smooth surfaces, provided that it impinges on these surfaces at a near-parallel (grazing) angle. By combining several such reflecting materials, in the form of coaxial shells, nested one inside the other, in the manner of so many Russian dolls, large-area focusing optics may be constructed, along which X-rays may be "channeled through," prior to reaching the detector, positioned at the focus of the system. The maximum energy at which such optics may operate turns out to be proportional to the length of the telescope. The first X-ray focusing optics, put into space in 1978, brought about a revolution in X-ray astronomy. However, this was restricted to observation of so-called "soft," i.e. relatively low-energy X-rays. Currently, the position is unchanged. The SIMBOL–X mission involves the emerging technique of formation flying, to build up, for the first time, a very-long-focal-distance telescope. This novel, revolutionary concept involves carrying the X-ray focusing optics in one satellite, and the focal plane in a second satellite, servo-controlled to keep position relative to the leading satellite, so as to form, so to speak, a quasi-rigid, albeit tubeless, telescope. With such a configuration, the telescope may be made sensitive to so-called "hard" X-rays, i.e. X-rays exhibiting energies 10 times higher than "soft" X-rays. This new-generation focusing instrument affords performance levels from 100 to 1,000 times better than the best current instruments. The SIMBOL–X concept was put forward, as early as the end of 2001, by astrophysicists at CEA. Taken up by the French, Italian, and German scientific communities, the feasibility study phase for the project was successfully completed. This was carried out by the French, and Italian space agencies, together with some twenty French, Italian, and German laboratories, brought together under the joint leadership of CEA, and the Italian organization. The key components of SIMBOL–X include, in particular:

- the X-ray optics, coming under Italian leadership, drawing on the expertise gained with low-energy X-ray astronomy missions, in particular with the X-ray Multi-Mirror (XMM) satellite; its main characteristics concern its focal distance, of 20 meters, and outstanding angular resolution, of 20 seconds of arc;
- formation flying, this being a world first, coming under **CNES** responsibility; the challenge being that of achieving the ability to keep the "detector" satellite automatically locked into position around the focal point set by the optics, within an uncertainty of about 1 cm^3;
- the detector unit, constructed by French teams, with a contribution from German laboratories, this being intended to cover the 0.5–80 **kiloelectronvolts** range, while proving highly sensitive, and providing a finely detailed imaging capability.

In order to meet the stringent specifications set for it, the detector unit relies on the use of two superposed "imaging spectrometer" planes, of 16,384 **pixels** each, over a total area of 8 × 8 cm^2 (see Figure 1).

For every X-radiation photon (these being individually counted, at such energies), these planes measure the energy, and location on the detector. The first imaging spectrometer plane, made from silicon, and provided by a German team, serves to detect "soft" X-rays, with a readout speed 20,000 times swifter than its forerunners. As silicon is transparent to higher-energy X-rays, which prove far more penetrating, a second plane is fitted at the back, just below the first plane, to provide the ability to stop, and characterize such radiation. This second plane is fabricated by CEA, and is based on use of cadmium telluride (CdTe) crystals, a material that has already shown proven effectiveness in the INTEGRAL coded-mask imager. Since that satellite was launched, major advances have been made, as regards miniaturization (the SIMBOL–X pixels are 50 times smaller), and the reduction, to the utmost feasible, of non sensitive area, between pixels. The high-energy imager plane is built up by juxtaposing 64 X-ray minicameras, each 1 cm square, with 256 fully contiguous pixels, and each carrying all of the operations-critical electronics (see Figure 1). A compact shielding, and particle-detection system is positioned around the two imager planes. Supplied by the Paris Astroparticles and Cosmology Laboratory (**APC**: **Laboratoire astroparticules et cosmologie**), this brings down, by a factor 10, spurious noise generated by the numerous cosmic rays pervading interplanetary space. This focal plane, studies for which were conducted under IRFU leadership, further features an onboard data processing unit, this being cared for by the Space Radiation Research Center (**CESR**: **Centre d'étude spatiale des rayonnements**), at Toulouse (southern France).

As the French and Italian space agencies were unable to secure sufficient monies to fund this ambitious project, it did not prove possible to initiate the detailed study phase for it. Considering the quality of the "science to be done" with this project, and the wide research community showing an interest in it, it is bound to reemerge, in some other context.

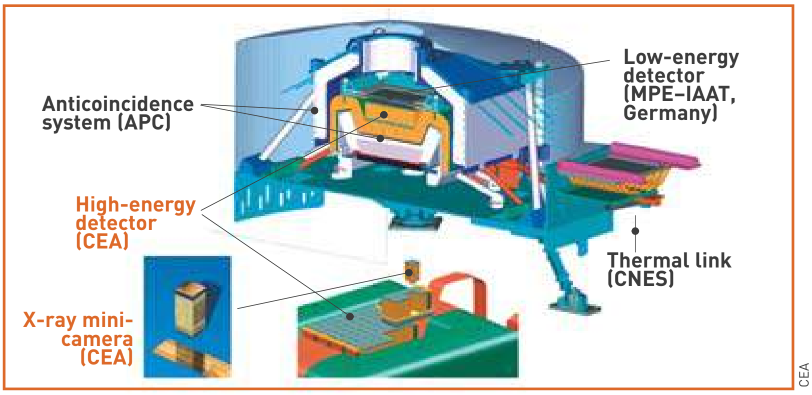


Figure 1.
The detector focal plane unit, entrusted to IRFU oversight, showing its various components, and the laboratories providing them: CEA, Astroparticles and Cosmology Laboratory (APC: Laboratoire astroparticules et cosmologie), Max-Planck-Institut für extraterrestrische Physik, Institut für Astronomie und Astrophysik–Tübingen (IAAT), CNES. The various components, and the way they operate, are detailed in the text.

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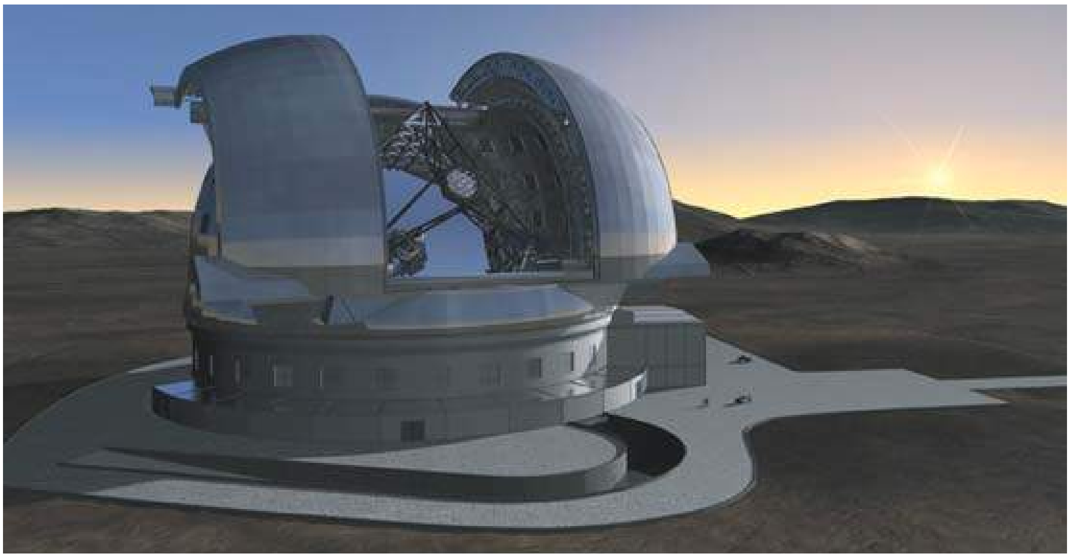
ELT/METIS, a 42-meter giant



Artist's impression of the European Extremely Large Telescope (E–ELT), a 42-meter diameter telescope being studied by ESO; to the right, in this picture, two cars may be noted, showing the scale of this giant telescope.

ESO

On the strength of the successful outcome of the Very Large Telescope (VLT) program, involving an array of four 8-meter diameter telescopes, the **European Southern Observatory** (**ESO**) has now taken up a new challenge: the construction of a telescope featuring a 42-m diameter (1,300-m²) mirror. Fabricating a mirror of such an area, and of monolithic construction is, at the present time, still altogether unfeasible. Hence the idea of segmenting the surface area into a thousand or so hexagonal tiles, each 1.4 meter wide. Weighing in at 5,000 tonnes (half the weight of the Eiffel Tower, in Paris), this giant is to be known as the European Extremely Large Telescope (E–ELT), and should come into service by 2018. The site where it is to be set up will only be revealed early in 2010: it could be in Chile, in Argentina, or yet on the Spanish island of La Palma, in the Canary Islands (in the Atlantic Ocean, off the coast of Africa). In like manner to its forerunner, VLT, E–ELT will have the remit of observing the cosmos, from the ground, in the domain ranging from the ultraviolet to the infrared, through visible radiation. Increasing the size of a telescope affords a twofold benefit. First, by allowing fainter, or more distant objects to be detected, owing to the larger collecting area. Second, in making it possible to see objects in finer detail. Indeed, in accordance with the physical phenomenon known as light diffraction, the image of a point object, as seen through a telescope, is not a point, rather it forms a spot, the so-called "diffraction spot." Consequently, the larger the telescope's diameter, the smaller that spot becomes. Thus, the diffraction spot for a star, as seen through E–ELT, will have an area 25 times smaller than that of the images yielded so far by VLT. These twin advantages, together, will allow unique programs to be carried out, in particular to investigate the disks around **stars**, in which **planets** are formed, or even to achieve direct observation of the thermal emission from giant exoplanets. Concurrently with the design studies for the construction of the E–ELT telescope, ESO sent out a number of calls for proposals to European laboratories, concerning the dedicated instruments to be mounted at the telescope's focus. Owing to its outstanding experience as regards the so-called "mid"-infrared region,(1) the Astrophysics Service at CEA (IRFU) elected to join a consortium led by **Leiden Observatory** (Netherlands), to carry out preliminary design studies on the planned Mid-infrared E–ELT Imager and Spectrometer (METIS) instrument, due to be fitted to E–ELT. Aside from studies for the cryomechanisms being developed with the Systems Engineering Service (SIS) at IRFU, SAp has taken on responsibility for the imaging of objects involving a strong intensity contrast (this being the case, e.g., for a planet lying next to a star), calling for specific observational modes, e.g. coronagraphy, or differential imaging.

The area of mid-infrared radiation has seen impressive strides being made, over the past 30 years. In the early 1990s, SAp already ranked as a pioneer, as regards imaging the cosmos from the ground, for this type of radiation, in particular through the use of detector arrays developed by CEA's Electronics and Information Technology Laboratory (LETI: Laboratoire d'électronique et de technologies de l'information) – as by-products from the major development work on detector arrays, being carried out under the aegis of the ISOCAM space camera project. At the time, images would not exceed a few thousand pixels, being yielded by a telescope only a few meters in diameter. Thirty years on, we are to achieve images of one million pixels, obtained with a telescope 100 times more powerful – involving, in other words, an advance by a factor 100,000!

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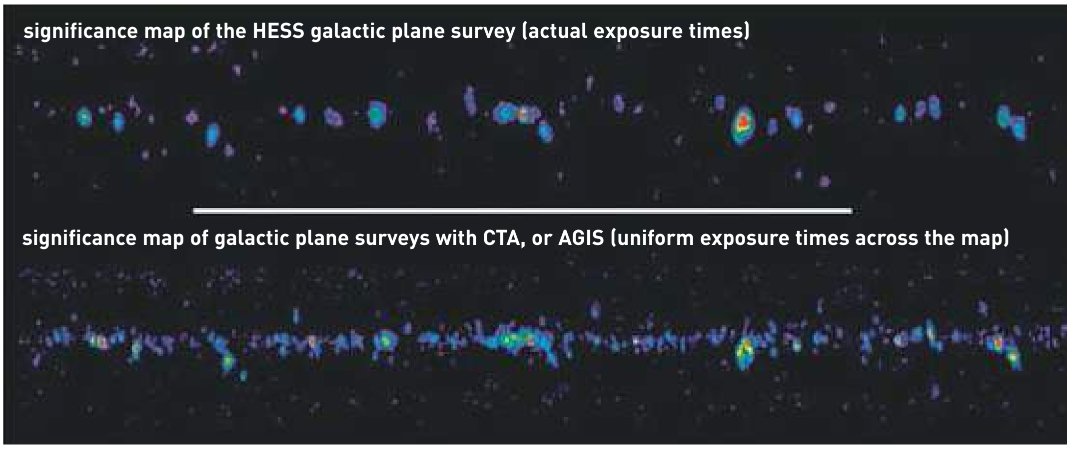
(1) This covers radiation at wavelengths in the 5–25 micrometer range.

One hundred telescopes in CTA arrays



S. Funk, J.-A. Hinton, G. Hermann, S. Digel

Figure 1
Predicted improvement for the astronomical map of the galactic plane, after going over from HESS to CTA. (AGIS is the US Advanced Gamma-ray Imaging System project.) The number of sources detected should increase by more than one order of magnitude.

Following on the European High-Energy Stereoscopic System (HESS)(1) experiment, and the successes it has achieved, in the field of very-high-energy gamma-ray astronomy, the forthcoming Cherenkov Telescope Array (CTA) is a large scale project for a European array of next-generation Cherenkov telescopes. A special feature of CTA is the location of the two arrays of atmospheric Cherenkov imagers it involves. The first array, located in the Northern Hemisphere, will carry out observations in the low-energy band, covering the 10 GeV–1 TeV range. Its twin will be located in the Southern Hemisphere, and will be dedicated to the high-energy band, in the 10 GeV–100 TeV range. The core of the CTA southern array will comprise four telescopes, featuring mirrors some 20 meters in diameter. A ring, comprising several tens of 12-meter diameter telescopes, similar to those already supplied for the HESS array, will form a first, inner circle around these instruments – this setup being complemented by a second, outer circle, comprising a further 10 telescopes or so, featuring 6-meter diameter mirrors. By way of this complex configuration, CTA will have the ability to observe radiation fluxes 10 times fainter than those currently detected by HESS. By introducing a large number of telescopes into the array, the new CTA will soon gain the ability to achieve **angular resolutions** of the order of the minute of arc.

Several research teams, mainly from Europe, are collaborating on CTA design work, and construction. As far as France is concerned, this involves CEA, by way of IRFU, and **CNRS**, through the National Institute of Nuclear Physics and Particle Physics (**IN2P3**: **Institut national de physique nucléaire et de physique des particules**), and the National Institute for the Sciences of the Universe (**INSU**: **Institut national des sciences de l'Univers**). Currently ongoing, the design and prototype construction phase should carry through to 2011–12. The CTA project is included in the roadmap of the European Strategy Forum on Research Infrastructures (ESFRI), and is a participant in two of the networks set up under the European Research Area (ERA), or ERAnets: AstroParticle ERAnet (ASPERA), and ASTRONET.

(1) The acronym commemorates Austrian physicist Victor Hess (1883–1964), who was awarded the Nobel Prize in Physics, in 1936, for his discovery of cosmic rays.

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3. Seeing wider

Euclid, mapping the extragalactic sky

The name of Greek mathematician Euclid was chosen for the forthcoming telescope, having the remit of exploring the dark side of the Universe, i.e. the part which, as yet, eludes all observation by researchers – namely, **dark energy**, and **dark matter**: in other words, close to 95% of the Universe. This study mission will use, as its data, the map it makes of the extragalactic sky. Currently at the feasibility study stage, the Euclid project has already been selected as an initial candidate by the **European Space Agency** (**ESA**), under the aegis of its Cosmic Vision 2015–2025 program. If the project is ultimately selected, launch could be scheduled for 2017.

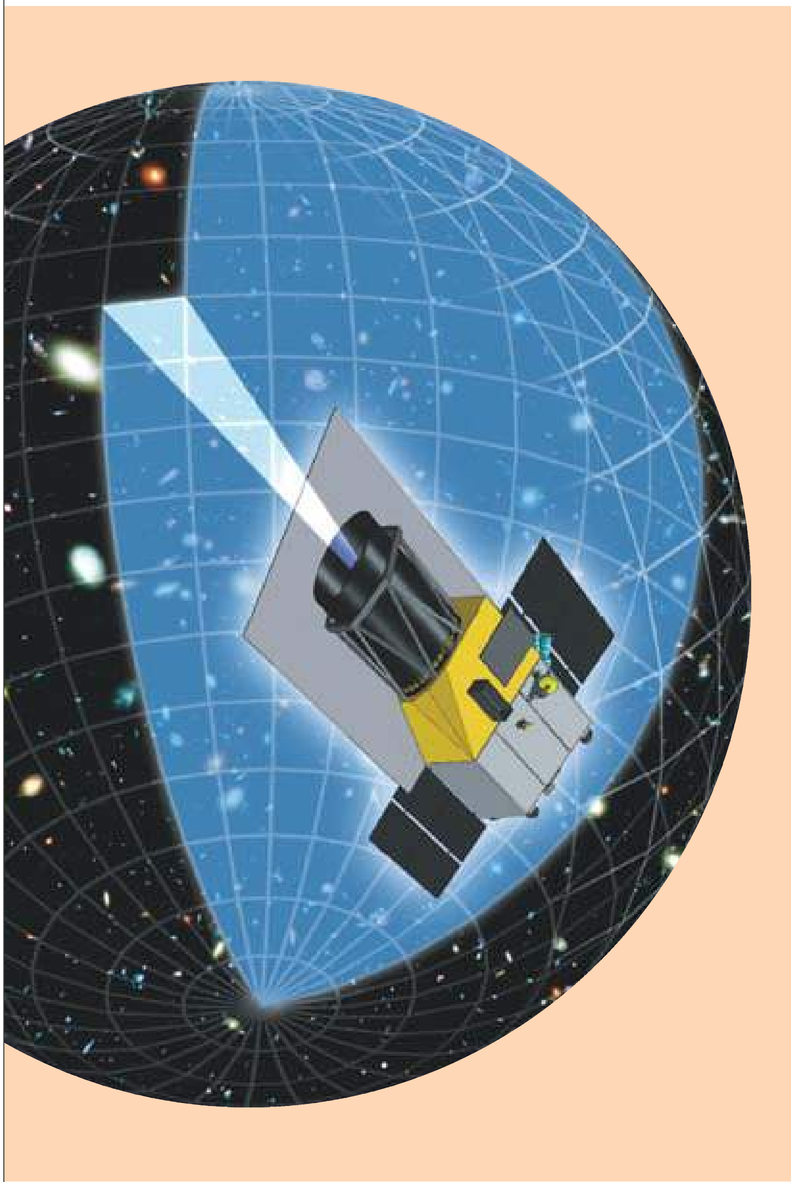
The observation program

The Euclid program stems from the following point: dark matter may be detected indirectly, through its **gravitational effects**, i.e. by way of the distortions it causes in the propagation of light. Since Albert Einstein, physicists have been aware that matter exerts a **gravitational attraction** on light, and is thus able to deflect its path. Indeed, matter (be it visible, or dark matter), lying between the observer, and the **galaxy** observed, invariably distorts the image reaching us, of this galaxy, acting somewhat like a lens. This is a well-known effect, known as "weak gravitational shear." Thus, through observation of the images of distant galaxies, and by measuring the distortions these have undergone, researchers may infer the distribution of dark matter interposed between our own Galaxy, and more distant galaxies. And, moving from one consequence to the next, from the distribution of matter may then be inferred the nature of dark energy, one of the engines for the structuration of the Universe. Finally, by applying this line of inference to galaxies at varying distances, it further becomes possible to measure the evolution of dark energy, over time.

This type of measurement has already been carried out, from space, by means of the Hubble Space Telescope, on the basis of the thousands of hours of observation it carried out. This is the largest survey of the Universe ever carried out, going by the name COSMOS (Cosmic Evolution Survey). However, that survey only covered a very small region in the sky, having an angular size of barely 2 square degrees – equivalent, nonetheless, to 9 times the apparent size of the Moon. Concurrently, MEGACAM, one of the two largest astronomical imaging cameras the world over, mounted at the focus of the ground-based Canada–France–Hawaii Telescope, carried out a similar program, covering however an area in the sky equal to some 200 square degrees. The synthesis of the information yielded by these two observatories enabled astrophysicists to determine the spatial distribution of dark matter, and visible matter, for that region in the sky, with unrivaled precision, and to an unmatched extent.

On the basis of the findings from the Hubble Space Telescope, a twofold quantitative target was set for Euclid. First, the aim will be to determine the dark energy equation-of-state parameter, to a precision of a few percent; and, second, to ascertain the variation affecting this parameter, over time, with a precision of a few tens of percentage points. Achieving such a result entails that the numbers of galaxies measured be considerably increased, to limit statistical errors. Hence the coming mission, assigned to Euclid, of subjecting 20,000 square degrees to observation, i.e. one half of the sky, with a total of some 3 billion galaxies. As for the determination of the relation between distance, and redshift, this will be based on measurement of the spectra of more than 100 million galaxies, here again across one half of the sky. The evolution of the galaxy correlation function,(1) on the basis of the redshift observed, will yield information, for researchers, as to the history of the expansion of the Universe, and, by way of consequence, as to the source of this expansion. The information sent back from the two surveys carried out, namely the mapping of dark matter, and baryonic acoustic oscillations, will make it possible to set very precise constraints on the parameters for dark energy.

(1) The galaxy correlation function involves, for every pair of galaxies, measuring their distance from one another, to reconstruct a 2D pattern of galaxy distribution.



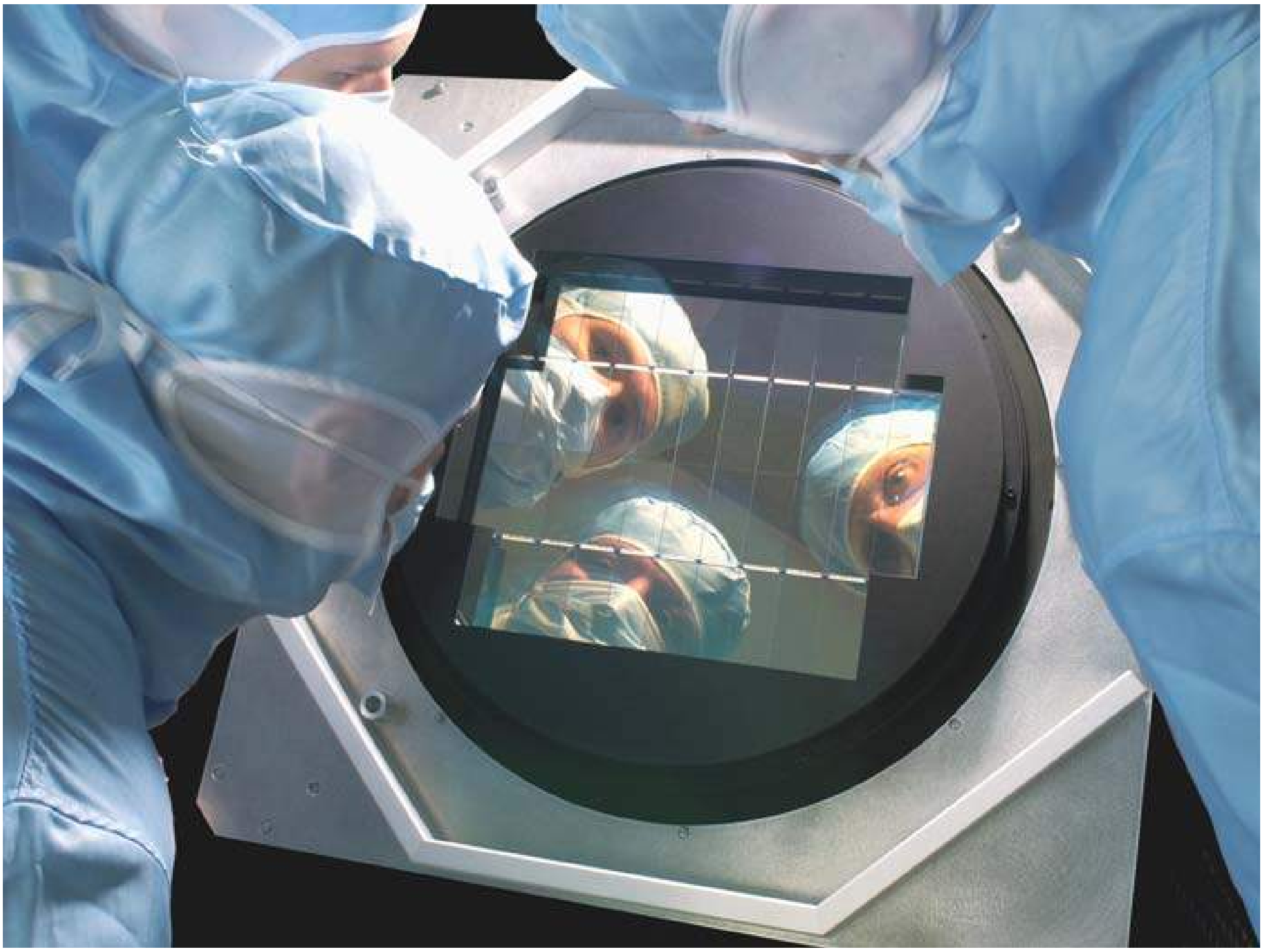
Frédéric Durillon/CEA

Artist's impression of the Euclid satellite mapping the extragalactic Universe.

The Euclid payload

To carry out this program of observation, and dark matter mapping, Euclid will make use of the so-called "wide-field imaging" technique, as already experimented with MEGACAM. This technique involves constructing instruments featuring detectors that comprise a very large number of **pixels**. Each observation thus allows a snapshot to be taken of a large area in the sky, while retaining a very good spatial resolution, this being required, if the shape of galactic images is to be measured accurately.

The Euclid satellite will carry a telescope, featuring a primary mirror 1.20 meter in diameter. At the


J.J Bigot/CEA

The MEGACAM camera: view showing the 40-CCD mosaic, at the end of assembly. This camera, constructed by IRFU, is in operation, being mounted at the focus of the Canada–France–Hawaii Telescope since 2003.

focus of this telescope will be mounted two cameras. The first camera, dedicated to **visible-light** observation, will comprise 36 detectors of the CCD (Charge-Coupled Device) type, for a total of 600 million pixels. It will carry out the measurement of galactic image shape. A second camera, operating in **infrared light**, and comprising some 50 million pixels, will carry out complementary observations, to measure the distances of the galaxies. Finally, a third instrument, operating independently from the two imager cameras, will obtain the spectra for more than 100 million galaxies, serving to measure the relation obtaining between distance, and redshift, for these objects.

The Euclid mission

The chief difficulty involved in "weak gravitational shear"-type observations is due to systematic measurement errors. There is a need, consequently, to optimize the design of the instruments, of the telescope, and of the satellite, so that instrumental errors may end up smaller than the statistical errors. For that reason, the Euclid satellite is to be placed in orbit around **Lagrangian point** L2, lying 1.5 million kilometers from the Earth, away from the **Sun**, at which location the satellite's thermal environment will remain quite stable. Researchers hope that the Euclid instruments, intended to achieve 5–6 years' observations, will yield a highly stable image quality, both spatially, across the entire field of view of the telescope, and temporally, so that data quality will prove homogeneous. The design of the payload, in turn, takes on board the degradation in detector performance, due to space **radiation**. Currently, IRFU is leading a consortium of laboratories, comprising half a dozen from European countries, and one US laboratory, for the purposes of carrying out studies for the imaging instrument charged with "weak gravitational shear" measurements. The budget earmarked for this space mission, at present, consists of 450 million euros, provided by ESA, to be complemented by contributions from the various national space agencies involved. Four other missions are currently under study, two being due to be selected early in 2010. The final selection, retaining one project, will only be known in 2011, launch not occurring before 2017.

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4. ANTARES: the neutrino, another cosmic messenger


L. Fabre/CEA

A storey, with its three "eyes," being submerged during deployment of the first ANTARES line, 40 kilometers off La Seyne-sur-Mer, near Toulon (southern France).

If there is one place where the uninitiated would not go looking for a telescope, it has to be deep down in the oceanic abyss. And yet, the ANTARES (Astronomy with a Neutrino Telescope and Abyss Environmental Research) experiment is scanning the skies, at a depth of 2,500 meters, on the bottom of the Mediterranean Sea, 40 kilometers off the port of Toulon (southern France). So positioning a downward-looking telescope, observing right across the Earth – contrariwise, therefore, to skyward pointing instruments – might seem, at first blush, incongruous. For researchers, this is a location which may allow one puzzle in astrophysics, as yet unresolved, to be unraveled: to wit, the origin of the **cosmic rays** that are constantly bombarding the Earth's atmosphere.

To understand what the ANTARES experiment is seeking to achieve, it should be borne in mind that the more energetic cosmic rays originate in such events as exchanges of matter occurring in binary **stars**, **supernova** explosions in the **Milky Way**, jets emitted by active **galactic** nuclei, or **gamma-ray** bursts in the more distant reaches of the cosmos. It should further be understood that gamma photons, involving as they do more extreme energies, allow cataclysmic phenomena to be probed only in the nearer proximity of our Galaxy. Yet another difficulty: the particles making up cosmic radiation – chiefly **protons** – are swiftly arrested, or, at lower energies, deflected by intergalactic **magnetic fields**. The solution, allowing all of these issues to be sidestepped, involves the **neutrino**. Generated as it is inside the objects within which cosmic rays are accelerated, this is a neutral elementary particle, consequently insensitive to magnetic fields – and it interacts but weakly with matter, this making the Universe transparent to it. The neutrino makes it possible to probe the core of the densest objects. This advantage, however, does involve a drawback: it does mean neutrinos are extremely hard to observe. Hence the notion of designing a detector, large enough to detect the few, scarce interactions due to these elusive particles, and submerged, to reduce the cosmic radiation flux. Such is the detector that is to go by the name ANTARES.

Submersion increases the chances of observing neutrinos, by using the Earth as a target. Indeed, a neutrino interacting with the Earth's crust yields a "**muon**," emitted along the same direction. As it reaches the marine environment, this then yields Cherenkov photons. ANTARES is able to observe these, by means of its array of 900 photodetectors, mounted on 12 vertical lines, 450 meters long, spread out at a distance of 65 meters, the mooring site covering an area equal to four football pitches (see Figure 1). Each line is kept vertical by buoys, and comprises 25 storeys, each fitted with three photomultiplier tubes, together with onboard electronics providing

L. Fabre/CEA

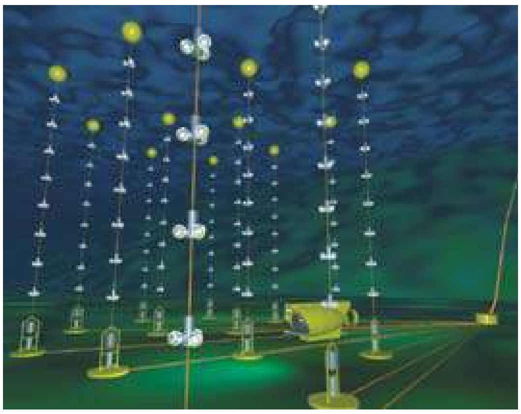
An ANTARES line, stored pending deployment.

the ability to transmit signals, in real time, to the shore. There, a "farm" of several tens of computers filters out the hundred or so photons received for every muon, from the spurious light emission due to **natural radioactivity**, and bioluminescent marine fauna.

In operation as it has been since 2006, ANTARES has made it possible to build up a vast amount of data, including, in particular, tens of millions of down-going muons, yielded by the interaction of cosmic rays with the atmosphere, notwithstanding the water shield lying above the detector. They do also include, however, upward-going muons – a much rarer phenomenon: only a few thousand annually – induced by so-called atmospheric neutrinos, these being the only particles yielded by the interaction of cosmic rays at antipodean locations having the ability to pass through the Earth. Once their direction has been ascertained, these neutrinos are found to fill uniformly the map of the sky, forming what astro-particle physicists term a "background." The discovery of a cosmic source may only arise when an abnormal buildup, of a few high-energy neutrinos, is found to occur on this map. On the other hand, the detection of such a source will provide irrefutable evidence of the presence of a cosmic ray accelerator.

Owing to the very small number of events anticipated, the development of neutrino astronomy calls for a kilometer-scale detector, i.e. one 50 times larger than ANTARES, and featuring several thousand photomultiplier tubes. Studies for such a telescope of the future have already been initiated, within the KM3NeT (km^3-scale Neutrino Telescope) consortium, bringing together 40 laboratories, from 10 European countries, funding being aided by the European Union.

Scheduled for 2012, the beginning of construction work for this instrument will give concrete shape to a multidisciplinary infrastructure that will be unique, the world over, in the area of environmental sciences (oceanography, seismology, marine zoology, climatology…). In the meantime, ANTARES keeps on scanning the sky of the Southern Hemisphere, across the Earth, looking for the origin of cosmic radiation.



F. Montanet/CNRS/IN2P3 and UFJ.

Figure 1.
Artist's impression of the ANTARES detector, an array of 900 photodetectors mounted on 12 lines, each 450 meters long, moored at a depth of 2,500 meters. These lines enclose a volume of 20 million tonnes of water, this being used to observe the Cherenkov light generated by the particles passing through it (the scale, and number of elements, are not depicted realistically).

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FOR FURTHER INFORMATION

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The new generation of **imaging spectrometers**

Contemporaneously with the International Year of Astronomy, 2009 will have seen the celebrations of the 400th anniversary of the first observations to be carried out with an astronomical telescope, by Thomas Harriot and Galileo Galilei – of the mountains on the Moon, sunspots, the phases of Venus, or the satellites of Jupiter. **Nowadays, astrophysicists are no longer content with ground-based telescopes, rather sending out their observatories into space, the better to probe the Universe**. The instruments carried on board these satellites include imaging spectrometers, affording the ability to effect, at one and the same time, spectrometry, and imaging. CEA's contribution has proved particularly effective, with regard to the design, development, construction, and qualification of such instruments, a new generation of which is now emerging.

ESO

Centaurus A, viewed in optical radiation, submillimeter waves (orange), and X-radiation (blue).

Observing the Universe in the submillimeter spectral region

On 14 May 2009, Herschel and Planck, two satellites for the European Space Agency (ESA), with a combined weight of close to 5 tonnes, were jointly put into space by an Ariane 5 launcher, from the Guiana Space Center, Kourou (French Guiana), being placed in orbit around the Sun, 1.5 million kilometers from the Earth, more precisely at Lagrangian point L2, this being deemed the best location accessible, for the purposes of observing submillimeter-, and millimeter-wavelength radiation.

CEA, with strong support from **CNES**, contributed to the development, construction, and qualification of two of the three instruments carried by the Herschel satellite. The instruments involved were PACS (Photodetector Array Camera and Spectrometer), and SPIRE (Spectral and Photometric Imaging Receiver), two medium-resolution bolometric imaging spectrometers: the former being effective in the 60–210 μm spectral range, the latter in the 200–650 μm range.

ESA

On 14 June 2009, The Herschel space telescope, then positioned more than 1 million kilometers away from the Earth, took its first look at a galaxy. This picture of the Universe, in the submillimeter infrared, featuring as it does unprecedented fine resolution, was captured by the bolometer-array camera in the PACS instrument, designed and constructed by CEA.

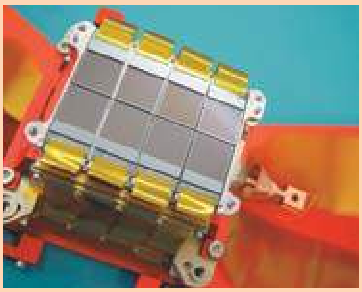
Out in the cold of the early galactic eras

Herschel, featuring as it does a 3.5-meter diameter mirror, is the largest space telescope to have been placed in orbit to date. Designed to benefit the world scientific community as a whole, the satellite carries a massive cryostat, holding 2,500 liters of **helium**, a superfluid liquid serving to cool instruments to temperatures lower than –271 °C. For astrophysicists, the aim is to minimize the **infrared**, and submillimeter emission from the new observatory, thus enhancing contrast, for the sources being observed.

The Herschel space telescope will open up a new observational window, namely one giving a view onto the cold Universe. This is where the earliest phases of **star** formation are initiated, but equally the less-well-known phases of **galactic** evolution. It should be said that, so far, the **models** available to researchers, with regard to formation, and evolution processes, are still found wanting, in terms of being matched with actual observations. The prime reason for this is that such phenomena may not be followed in **visible light**, but solely in the far infrared, and beyond. Now, these **wavelength** bands are affected by heavy **radiation absorption**, in the Earth's atmosphere. Herschel will be remedying this state of affairs, by providing temperature and matter density measurements, and ascertaining the chemical species involved, but equally by yielding information as to the dynamics of the objects investigated. The other reason that may allow the inadequacy of current detectors to be understood has to do with the atmosphere's **opacity**. Not before the early 1990s, with the emergence of the first bolometric detectors, could researchers finally avail themselves of instruments sufficiently sensitive to measure radiation in the submillimeter region.

The Herschel Space Observatory has made a strong contribution to the development of such **bolometers**, for wavelengths shorter than 1 millimeter, and to spurring on technological research in this area (see Box).

A bolometer (from the Greek *bolê*, meaning "sunbeam," "ray of light," hence "radiation," and *metron*, "measure") is a thermal detector of radiation. This involves a device having the ability to measure an incident flux of energy, whether carried by **photons**, or massive particles, and to convert it into heat. For a given quantity of energy, the lower the mass (and hence the heat capacity) of the device, the higher the rise in temperature is found to be. At very low temperatures, this phenomenon is amplified, owing to a steep drop in the heat capacity of matter.



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A bolometer is a kind of ultrasensitive thermometer, having the ability to detect minute variations in temperature (by a few millionths of a degree). Shown here, the bolometer-array (32 × 64-pixel) focal plane of the PACS instrument.

NASA

At right: artist's impression of the Herschel satellite, with the telescope and instrumentation positioned above a helium tank. Left: Herschel will be investigating star-forming regions in a hitherto unexplored energy range (image of Rho Ophiuchi, as viewed by the ISO satellite).

ESA

Herschel's cryostat holds 2,500 liters of helium, ensuring about 3 years' autonomy for the mission. This keeps the entire focal plane at a temperature of –271 °C. As for the telescope, it is passively cooled to –200 °C, by means of thermal shielding.

A concatenation of technological challenges

CEA's concrete contribution proved particularly significant with regard to the PACS imaging spectrometer. First, through the involvement of a number of structures, including the Nanosciences and Cryogenics Institute (INAC: Institut Nanosciences et cryogénie), and the Institute for Research on the Fundamental Laws of the Universe (IRFU) – both coming under CEA's Physical Sciences Division (DSM) – together with the Electronics and Information Technology Laboratory (LETI: Laboratoire d'électronique et de technologies de l'information), in the Technological Research Division. Second, it proved significant in that this cooperation allowed a complete camera to be constructed, including the detectors, the 0.3-**K** **cryocooler**, the mechanical and electronic systems required for control, and data acquisition purposes, along with, obviously, the bolometer arrays specifically developed for the mission.

Currently, CEA teams have achieved mastery in the fabrication of focal planes involving several thousand **pixels**, by way of collective fabrication processes, derived from the silicon microtechnology developed by LETI. This involves a technological leap forward, compared to what is on offer from other laboratories, which have to be content with a few tens, possibly hundreds of detectors. The limitations faced by these laboratories stem from the devices used to collect radiation – feed-horns positioned in front of each detector, integrating spheres – with each pixel requiring manual assembly, etc. The breakthroughs achieved at LETI benefited from the exceptional context of the 1990s, marked by the rise of microelectronics, with the advent, in particular, of chips affording the ability to hold a variety of sensors, obtained by deep, collective etching of the silicon (microaccelerometers for the airbags fitted to automobiles, methane detectors for domestic use…). This technological spurt was complemented by a more relaxed circulation of information than had prevailed in earlier years: older ideas, concerning the absorption of **electromagnetic** waves, were coming back in favor. These were tweaked to meet the issue of detection, by the teams at LETI, to be compatible with collective fabrication processes. No obstacle then remained, to the fabrication of large detector arrays.

There was yet, for researchers, another challenge to take up: ensuring that the sensitivity of the new detectors be solely limited by the fluctuations in radiation originating in the telescope's mirror (albeit cooled to close to –200 °C). Thus far, bare detectors involving a surface area not even equal to 1 mm^2 already afforded the ability to detect a source equivalent to a 100-watt lightbulb positioned 300 km away. With the Herschel telescope, the observatory is to fare much better, being able to detect a similar source – positioned this time, however, on the Moon! Achieving such a performance entails cooling every bolometer, standing as it does as a veritable thermal detector of radiation, to a far lower temperature than that of the instrument itself, i.e. to 0.3 kelvin. To achieve such a temperature out in space, researchers turned to closed-circuit helium (^{3}He) evaporation cryocoolers, developed by CEA's Low Temperatures Service (SBT: Service des basses températures). The chief issue arising with this type of system relates to the total power "budget" available across the focal plane, to wit 10 µ**W** – this power being indispensable for biasing purposes, readout, and the detectors' electrical and mechanical connections. Development of an ingenious **multiplexing** setup enabled the researchers to deploy 2,560 operational bolometers in the PACS camera, within that power "budget," whereas the SPIRE instrument, of more conventional design, even though it draws on the selfsame cryocooler, is only able to control 300 bolometers!

F. Vigouroux/CEA

Work needs must be done on the issue of cooling the detectors carried on board satellites, so that they may operate correctly for ten years at least. Cryocoolers serve to cool detectors to a few hundred millikelvins. The picture shows thermal tests with the backup cryocooler for the Herschel satellite.

These detectors are distributed across two focal planes, to cater for the 60–130 μm, and 130–210 μm ranges, respectively. Within the camera, their layout makes it possible to map one and the same region in the sky, at different wavelengths. At the shorter wavelengths, focal plane complexity stands at 64 × 32 pixels, making it possible to gain best advantage of the resolution afforded by Herschel's large mirror; on the other hand, a complexity of 32 × 16 pixels proves adequate for the longer wavelengths. Each focal plane is built up from 16 × 16-pixel modules, which may be joined end to end on three sides. And, as the detectors exhibit a wide spectral absorption band, modules may be mounted indifferently onto either of the optical channels. It is solely the optical filters positioned in front of each focal plane that determine the wavelength band detected. Every pixel in the module corresponds to a silicon bolometer, which has undergone prior hybridization, by way of an indium bump, to a readout and multiplexing circuit, of CMOS (complementary metal–oxide–semiconductor)(1) technology. The hybridization operation ensures three functionalities:

- the usual electrical interconnection of bolometer, and readout circuit;
- the setting up of an optical cavity, ensuring the efficient trapping of incident light;
- bolometer mechanical strength, and thermalization.

The size of the hybridization bumps was calculated to ensure that the resonance cavity would be tuned to the wavelength to be absorbed. This cavity comprises the bolometer array, and a reflector, positioned over the CMOS circuit: this promotes maximum absorption of the incident wave, close to unity. Absorption occurs on metal deposited onto the array, exhibiting a surface impedance matching that of the vacuum.

(1) A successor to bipolar transistor technology, CMOS technology involves fabricating electronic components featuring low power consumption, dedicated to processor design requirements.

As for the silicon bolometer array, this is suspended by way of very thin (≈ 2 μm), low-thermal-conductivity beams. This setup allows the tenuous absorbed radiation to induce a measurable rise in temperature. Finally, a doped-silicon thermometer, positioned at the center of the array, effects the measurement, making use of an exponential law, relating resistance to temperature. This exhibits a temperature coefficient close to 3,000%/K. Compared to a "solid" surface, the array affords a twofold advantage: first, that of exhibiting a lower heat capacity, ensuring a swifter thermal response rate; second, that of proving less susceptible to the ionizing cosmic particles present in the space environment. Obviously, the use of an array to absorb light may raise queries: would not such light "get through" the gaps in the array? Such is not the case, for the simple reason that light does not "detect" details smaller than its own wavelength. All that is required is to fabricate an array with a pitch smaller than the wavelength to be detected.

As regards the 16 × 16-pixel modules, every one of them was individually evaluated, during test campaigns carried out in 2003–2005. On the basis of the performance found for them, they were integrated into the focal planes, and calibrated a first time. Subsequently, once the complete camera had been integrated into the PACS instrument – including its cryocooler, and flight electronics – final calibration could be carried out, this involving two steps: the

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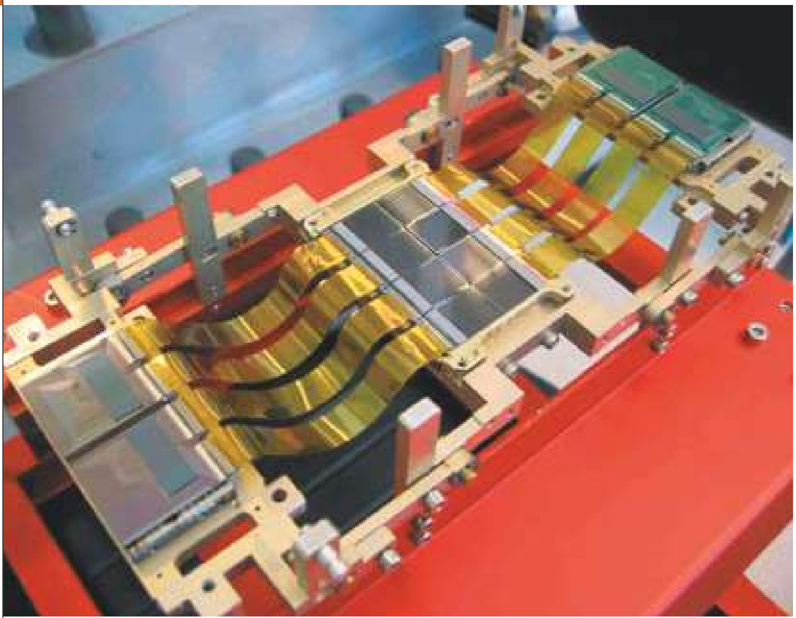
A helium-3 cooler.



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One of the bolometer-array (32 × 64-pixel) focal planes fitted to the PACS instrument.

first one carried out at CEA's Saclay Center, in 2006; the second one at Garching (Germany), the following year. Early in 2008, the PACS instrument in turn was mounted on board the Herschel satellite, alongside SPIRE, and HIFI (Heterodyne Instrument for the Far Infrared). After the final adjustments had been carried out (replacing faulty connectors, rerouting cables to preclude interference from the solar panels…), the satellite was passed as "ready for service," in December 2008.

Prospects

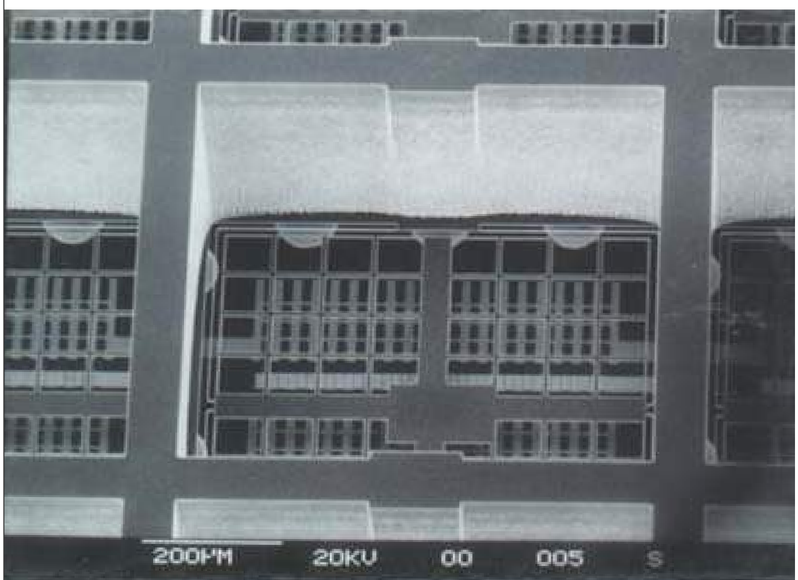
Currently, the development teams for this submillimeter camera are switching the thrust of their effort along two directions:

- The first direction involves taking the PACS bolometer arrays to longer wavelengths, in order to fit them to large ground-based telescopes. Such an operation requires that these arrays first be adjusted to cater for the various atmospheric "windows," i.e. the various narrow spectral bands for which the atmosphere (at altitude) does not prove wholly opaque (200 µm, 350 µm, 450 µm, 865 µm). The benefit accruing from this development work has less to do with measurement sensitivity (there being no way of matching spaceborne performance!) than with the use of very large telescopes (12–15 meters in diameter), affording far higher resolving power. Adjusting the arrays to the longer wavelengths will chiefly involve increasing the size of the hybridization bumps.
- The other avenue is concerned with the development of far more sensitive detectors, intended for future space missions.

Currently, two projects are already benefiting from this development work. These include ArTéMis (*Architecture de bolomètres pour les télescopes submillimétriques au sol:* Bolometer Architecture for Ground-based Submillimeter Telescopes), a 5,000-pixel bolometer-array camera intended for the Atacama Pathfinder Experiment (APEX) Telescope, sited in Chile; and PILOT (Polarized Instrument for Long-wavelength Observation of the Tenuous Interstellar Medium), an experiment featuring two focal planes, carried by balloon, to measure the polarized radiation emission from the **Milky Way**.

Finally, bolometer optimization should also prove useful to a variety of very-low-background-flux applications. Such is the case as regards SPICA (Space Infrared Telescope for Cosmology and Astrophysics), a space mission conducted by the **Japan Aerospace Exploration Agency** (**JAXA**), in collaboration with the **European Space Agency** (**ESA**), launch being scheduled for 2018. This space telescope will be using the same mirror as Herschel, cooled however to –268 °C! In order to optimize to the utmost this new configuration, researchers will need to raise detector sensitivity by a factor 100, at least. To achieve such sensitivity (background noise power of 10^{-18} watt), the silicon bolometer cooling will be enhanced, down to 0.05 kelvin.

In order to meet the challenges set by this new mission, CEA has embarked on a preliminary study phase. For instance, research scientists at SBT are already working on the design of an **adiabatic** demagnetization cryocooler for space applications. SPICA should pave the way for other exciting projects, e.g. the spaceborne FIRI (Far-Infrared Interferometry) experiment, involving use of bolometers, or the BPOL (Cosmic Microwave Background **Polarization**) experiment, at 3 K.



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Scanning electron microscopy image of a bolometer pixel.

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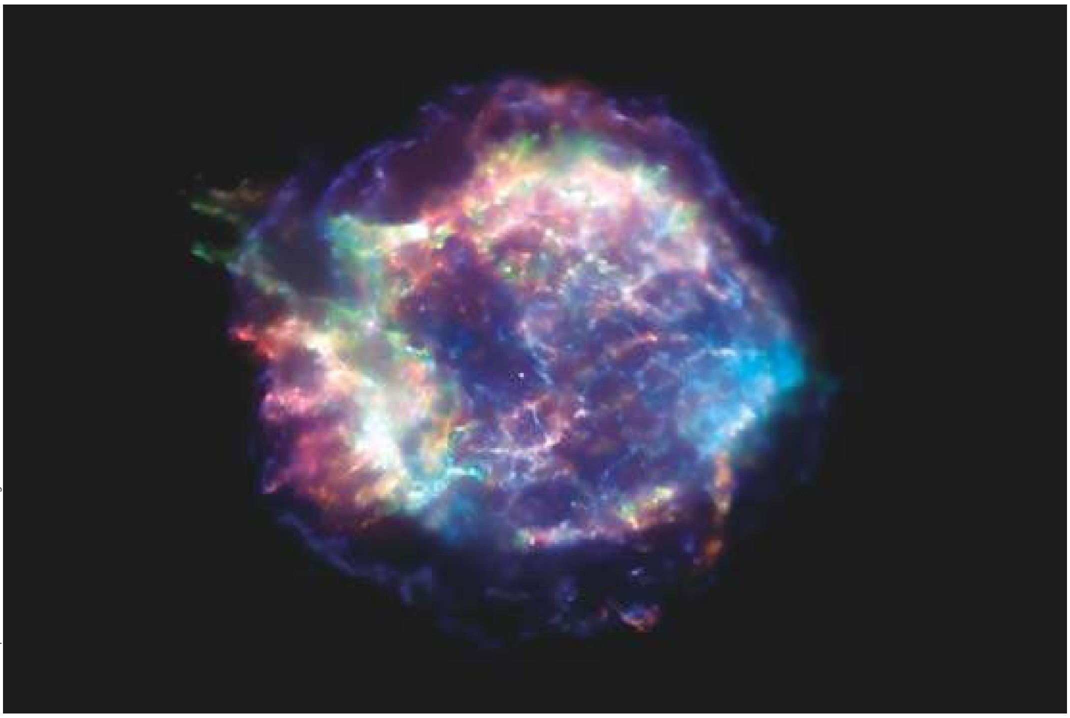
The X-ray Universe

If there were to be but one observatory, to shed light on X-ray astronomy across the Universe, it would undoubtedly have to be IXO. The interest evinced by researchers for this type of radiation is due to the fact that most astrophysical sources emit X-rays, to a greater or a lesser extent; and that such X-radiation yields a rich vein of scientific information, regarding these sources, and thus stands as an outstanding observational tool.

The chief advantage afforded by the International X-ray Observatory (IXO: see Box) is its ability to carry out observations over a very long time, in an extremely stable environment. To carry out its mission, IXO will be carrying an imaging spectrometer based on microcalorimeter arrays, exhibiting the best spectral resolution ever achieved by an energy-dispersive spectrometer, namely 2 **eV** for 6-keV X-ray photons.

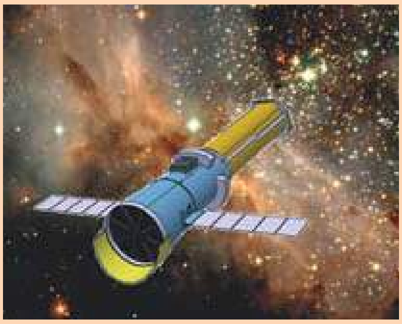


Chandra Supernova Remnants Catalog

Supernova (end-of-life star explosion) remnant Cassiopeia A. This X-ray image, obtained by the Chandra satellite, shows (in false colors) an expanding bubble of gas, at several million degrees, within an envelope of highly energetic electrons.

Under the IXO spotlight

IXO stands as the flagship program, for X-ray astronomy, at the outset of the present century. This program arose from the merging of two major projects. To wit, one US project, Constellation–X, which set out as a battery of four probes, simultaneously observing one and the same region in the sky; and one European project, XEUS (X-ray Evolving Universe Spectroscopy). The latter involved two probes, one being the "mirror," the other the "detector" probe, flying in tandem, with a precision of a few millimeters in all three dimensions. Chiefly on cost grounds, the two projects have been in the process of merging, since August 2008. The new program being considered would involve a deployable satellite. In other words, it will take off, inside the launcher's shroud, in folded configuration; once out in space, a mechanism will allow the satellite to extend, to achieve a focal distance of some 10 meters (somewhat in the manner of a ship's telescope). At the same time, the mirror for this telescope will be of an altogether revolutionary type. To date, virtually all space X-ray observatories have involved the technique of nested metal shells, exhibiting cylindrical symmetry, for their grazing-incidence mirrors. The proposed technique, for IXO's very large mirror, will be based on developments in silicon technology. The basic element for this mirror consists of a wedged, ribbed silicon plate. Each element is bonded to its neighbor, to form a structure resembling a microchannel wafer. The huge advantage afforded by this technology results from its light weight, and rigidity, making the mirror highly attractive, for a rocket launch. The observatory is to be placed in orbit around **Lagrangian point L2** of the **Sun**–Earth system, allowing observations of very long duration (virtually free from eclipses) to be carried out, in an extremely stable environment.



J.-L. Sauvageot/CEA

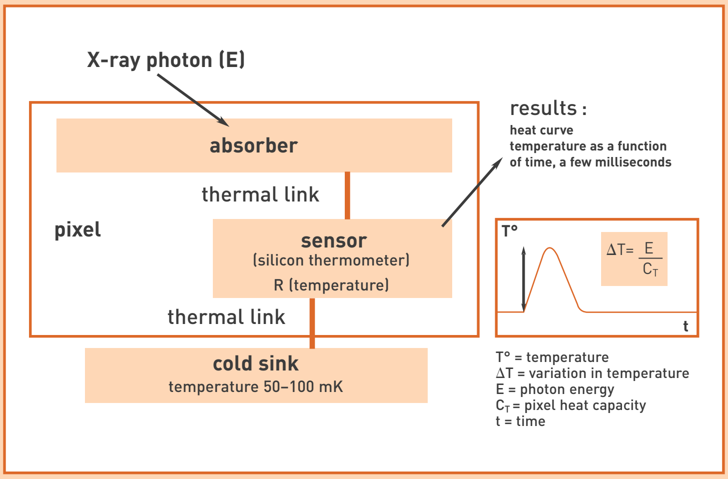
Artist's impression of IXO.

Principe of the X-ray microcalorimeter

Carrying out the calorimetric measurement of a single X-ray photon entails that two major notions be taken on board:

1. The property, exhibited by the overwhelming majority of materials, of involving a specific heat capacity that declines with temperature. This makes it possible to obtain a far from negligible rise in temperature, from the sole energy of a single X-ray photon, dissipated within a detector pixel, provided the latter be small (hence the term "microcalorimetry"), and, most importantly, kept at a low temperature (around 0.05 K);
2. The existence of sensors (thermometers) sufficiently sensitive, at such very low temperatures, to measure a rise in temperature (by a few microkelvins).

The most commonly used thermometers deliver an electrical signal, taking the form of a voltage (semiconductor sensors, in silicon or germanium), or of a current (superconducting transition-edge sensors), proportional to temperature. Measurement of the time curve (i.e. the pulse induced by energy deposition from the X-ray photon) makes it possible to determine the quantity of energy deposited, with an outstanding spectral resolution.



Structure of a microcalorimeter pixel.
A thermal impedance, inserted between absorber and sensor, promotes full thermalization of the energy within the absorber, before the corresponding heat is transmitted to the sensor. Subsequently, with the heat slowly evacuating to the cold sink, the pixel is brought to a level making it sensitive to the incident X-ray. In the meantime, a finescale measurement of the associated temperature curve is carried out by the thermometer.

X-radiation as tracer

Virtually all astrophysical sources emit X-radiation, some indeed emitting only X-radiation. At such energies (the accepted usage being to speak in terms of energy, when dealing with X-radiation), photons become penetrating, and thus prove able to carry valuable information, in particular with regard to processes that are buried inside clouds of matter. X-radiation thus stands as a tracer, both as regards matter at very high temperatures (several million degrees), and high-energy electrons, interacting with a magnetic field or low-energy photons. Matter may be brought to such high temperatures by intense gravitational potentials, within galaxy clusters, or close to massive, compact objects, or when stellar explosions occur. By collecting, and detecting X-radiation, researchers are opening up a new window, providing a view of the "tumultuous" Universe. Among the advantages afforded by X-rays, their ability to undergo reflection at grazing incidences allows telescopes involving mirrors to be used. The interaction of X-rays with the detector medium, being of relatively point like character, yields high-angular-resolution imagery. Such is not the case in the gamma-ray domain, at higher energies, where reflection optics become inoperative, the outcome being that collimators allow only low-angular-resolution imagery to be obtained. As for energy deposition from photons, chiefly occurring as this does by way of the photoelectric effect, this takes place in a pixel, located within a reasonably-sized detector array. For all of these reasons, high-quantum-efficiency energy-dispersive spectrometry is now becoming a feasible proposition, for every absorbed photon. This represents a notable advance, compared with the results achieved with wavelength-dispersive spectrometry. Obtained as it is, at longer wavelengths, by means of such optical devices as gratings, this proved to be a highly "wasteful" technique, in terms of photons used.

For astrophysicists, the observation of X-ray fluorescence lines, and of the continuum (emitted by thermal processes, or by electrons interacting with the magnetic field, or with photons) opens up a rich vein of new, hitherto inaccessible information as to the composition, density, temperature, and dynamics of matter at very high temperatures, but equally as to the local magnetic field. Provided, that is, the said astrophysicists may have the use of a spaceborne platform, mounting a high-performance imaging spectrometer, since X-rays are blocked by the Earth's atmosphere!

Virtuoso know-how

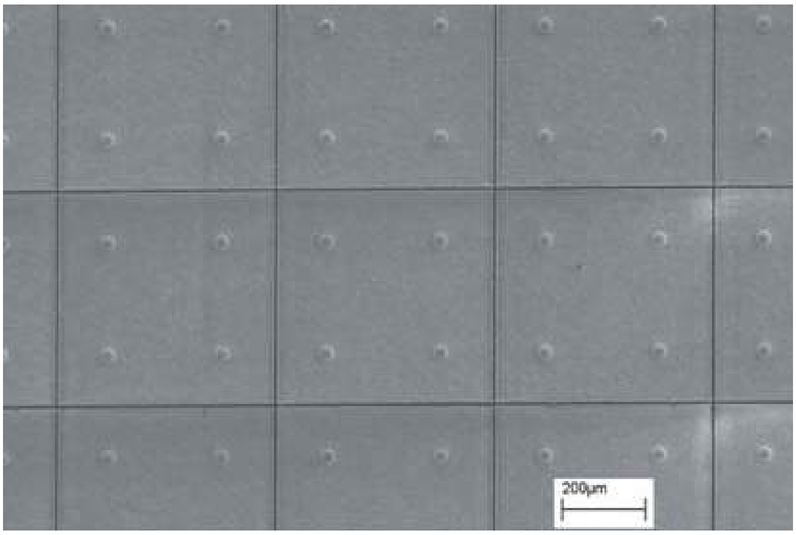
Since their launch, in 1999, two dedicated telescopes, for X-ray astronomy purposes, have been orbiting the Earth. The satellites involved are XMM–Newton (X-ray Multi-Mirror), and Chandra.(1) Both observatories are fitted with imaging spectrometers relying on CCDs (silicon Charge-Coupled Devices. Within these instruments' semiconductor detectors, the energy deposited by an X-ray photon is measured by way of the count of electron–hole pairs generated. An issue then arises, owing to the fact that the energy of that X-ray photon is also dissipated in the form of heat, which phenomenon competes with the generation of electron–hole pairs. Consequently, the quantity of energy measured will fluctuate from one absorbed X-ray photon to the next, at equal incident energies. The spectral resolution obtained may thus not prove better than a threshold value (120 eV at 6 keV). In this respect, researchers come up against a limitation that is inherent in the detector medium (in this case, silicon), and in this manner of determining energy (counting electron–hole pairs), which they cannot hope to remedy. If such fluctuations are not to hamper measurements, all of the energy must first end up in heat form, thus allowing measurement of the associated temperature to be carried out (in other words, calorimetry). A collaboration has been set up, within CEA, between the Electronics and Information

(1) Taking its name from Indian-born US astrophysicist Subrahmanyan Chandrasekhar (1910–95).

Technology Laboratory (LETI), and the Institute for Research on the Fundamental Laws of the Universe (IRFU). For these teams, the aim is to develop microcalorimeter arrays (see Box), in order to enhance spectral resolution, by one or two orders of magnitude, thus bettering semiconductor detectors. The experience gained in the **infrared** and **submillimeter** region, with micro**bolometer** arrays (in this wavelength domain, the measurement effected being that of flux), proved all the more effective, since many silicon technologies, previously used for the PACS (Photodetector Array Camera and Spectrometer) instrument, may be directly transferred to microcalorimeter arrays. This R&D effort has the purpose of fabricating large (32 × 32-pixel) arrays, involving a **pixel** design affording the ability to take on board the stringent specifications of X-ray astronomy (see Box, *Under the IXO spotlight*). Fabricating microcalorimeter pixels (500 × 500 μm^2) by micromachining from a silicon-on-insulator (SOI) wafer calls for virtuoso know-how. The outcomes allow extremely thin (less than 1.5 µm thick) sensors to be exhibited, connected to the cold sink by way of silicon beams, involving cross-sections no larger than a few square microns. All of which performance levels are compatible with requirements as regards strength, as the sensors withstand assembly by hybridization, by way of indium bumps, to absorbers, taking the form of thin strips of tantalum foil. At the same time, it took all of LETI's expertise to achieve the integration of the thermometer, into the suspended plate. Indeed, as this instrument exhibits variable resistance, depending on temperature (around 1 megohm at 50 mK), controlling high doping levels (to within a fraction of a percent) was imperative, prior to homogenization, this involving subjecting it to a high-temperature treatment. This fabrication technique allowed thermometers to be produced that exhibited, at last, the ability to achieve the performance required.

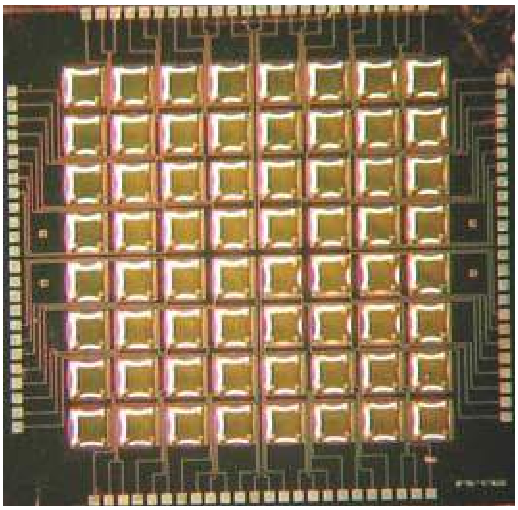
There still remained the matter of catering for large arrays. Hitherto, small arrays would be fabricated by way of manual assembly of absorbers, and sensors, an operation that was carried out under the microscope. Now, such a technique is unsuitable for large arrays. Hence the concept of a prototype array, of 64 hybridized pixels, liable to be extrapolated to larger sizes, this being produced by LETI, using a transfer technology (of the absorber onto the sensor) no longer involving manual operations, instead being collectively implemented.

Nevertheless, one major barrier still precludes constructing a focal plane from a mosaic built up from arrays of this type, namely the lack of proximity electronics operating at low temperatures. Indispensable as it is for readout and **multiplexing** purposes, this electronics must be cryogenic, if it is to be located inside the cryostat, as close to the detector as feasible, a location that affords many benefits: simplicity, reliability, operation free from noise, increased bandwidth, reduced unwanted power demand from flight cryocoolers (exhibiting necessarily limited performance). With a view to achieving this, researchers are currently exploring original avenues, e.g. high-electron-mobility transistors (HEMTs), in GaAlAs/GaAs (gallium–aluminum arsenide, and gallium arsenide); or application-specific integrated circuits (ASICs) in silicon–germanium. These advances will unquestionably be of benefit, as regards enhancing the performance of future observatories, dedicated to X-ray astronomy, with regard to effective area, or spectral resolution, in particular. Research scientists are convinced of one thing: new discoveries in astrophysics, as yet unforeseeable, will result from this.



A. Aliane/CEA

An array of tantalum absorbers.


A. Aliane/CEA

A sensor array.

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Space cryocoolers

Several constraints are associated with the space environment, such as the mechanical strength required to survive takeoff, the microgravity conditions and the most critical one, the need for reliable systems able to operate without any failure for 5–10 years. The solution to this last requirement is to develop systems without any friction or even better with no moving parts.

Setting up a flight cryocooler atop the test cryostat.

The simplest way to obtain cryogenic temperatures in space is to benefit from the natural resources available; for instance the near perfect vacuum prevailing in the Universe, and the cold "cosmic background radiation". Indeed the absence of matter (of gas, in particular) restricts heat exchanges to the sole **radiative** transfers. Consequently, from a location exposed to the deep space, radiating as it does at 2.7 **K**, it should be possible, in theory, to cool a surface down to temperatures of just a few kelvins.(1) Unfortunately, in practice, this method is only valid for specific orbits and the so-called **passive radiators** do not allow temperatures lower than 30–40 K to be achieved. Another solution involves taking a cryogenic liquid, first liquefied on Earth, and stored in a tank known as a cryostat, and then taking advantage of the vacuum in outer space to obtain cooling by way of evaporation. With this technique temperature of the order of 1.5 K can be achieved by using **helium**. To reach lower temperatures entails that other technological solutions be resorted to.

(1) The conversion from the kelvin (K) scale to the Celsius (°C) scale is straightforward: the kelvin scale has its origin at absolute zero (–273.15 °C), while an increment of 1 K is equal to one of 1 °C.

From cryostat to cryocooler

On the other hand, the current trend in space cryogenics is to suppress the cryostats, turning instead to systems, known as **cryocoolers**, designed to provide cooling power down to cryogenic temperatures (below 120 K). Indeed, while the use of cryostats is a straightforward technique featuring many advantages, it does nevertheless involve two major drawbacks: a large mass and volume, restricting mission duration owing to the tank running dry. By contrast, cryocoolers may operate for a virtually indefinite time, as their source of power is provided by means of the **photovoltaic** energy available in space, already put to advantage by almost all space missions.

CEA's Low Temperatures Service (SBT: Service des basses températures), in particular its Cryocoolers and Space Cryogenics Laboratory, has been developing for many years, cooling systems suited to the various constraints entailed by the space environment. For extreme cold conditions, the solution involves associating a number of cryocoolers, set up in cascade, to cover the entire range of temperatures. Such cryogenic chains can achieve temperatures of 20 mK (–273.13 °C). For the purpose of achieving the cooling of components for space applications to temperatures of less than 1 K (–272.15 °C), currently, three techniques are emerging:

- evaporative cooling, using a helium **isotope** (helium-3):
- magnetic cooling, by way of **adiabatic** demagnetization;
- dilution, by making use of the properties exhibited by the two isotopes of helium.

The teams at SBT are engaged in development work on all three techniques. The first technique has earned them worldwide renown, following its implementation for the SPIRE (Spectral and Photometric Imaging Receiver) and PACS (Photodetector Array Camera and Spectrometer) instruments, on board the Herschel satellite. To understand the principle of this cryocooler, it should be borne in mind that evaporative cooling involves the same physical mechanisms as perspiration. For water, the change from the liquid to the gaseous state requires energy; however in the absence of any external source, this energy is taken directly from the thermal agitation of the liquid's **atoms**. By way of consequence, this leads to a cooling effect. This property holds for nearly all fluids and perspiration itself is based on this principle to regulate body temperature. In the case of helium-3, this allows temperature of –272.85 °C (300 mK) to be reached. However helium-3 is unable to cover alone the entire range, all the way down from ambient temperature. In the case of the Herschel mission, it is associated with helium-4 (a large tank of some 2,500 liters), this being indispensable, to achieve a temperature of around 2 K. At low temperatures, it should be emphasized that the gain should not be assessed in terms of temperature differences, but rather in terms of temperature ratios. In effect, cooling from 2 K down to 300 mK (i.e. by a ratio of 7) is practically as difficult to achieve as coming down from ambient temperature (293 K) to –230 °C (42 K).

The evaporation rate is increased by pumping on the liquid. To eliminate all moving parts and hence improve the reliability, researchers have recourse to the adsorption properties exhibited by **activated carbon**. This material exhibits a considerable specific area (≈ 1,200 m^2/g); once cooled, it "traps" the gas **molecules**, and, conversely, "releases" them when heated (a physical adsorption phenomenon, related to **van der Waals forces**). **Adsorption** and desorption temperatures depend on the nature of the gas involved. In the case of helium, heating the activated carbon to –230 °C (42 K), and subsequently cooling it down to –270 °C (3 K) makes it possible to obtain the pressures required to achieve condensation of the liquid, and then an effective pumping. In that manner, pressure, and thus temperature, may then be reduced (see Figure 1). This fully static process is highly effective in terms of pressure amplitude. In effect, it allows a compression/expansion ratio of six orders of magnitude (10^6) to be obtained, a performance unmatched by mechanical systems.

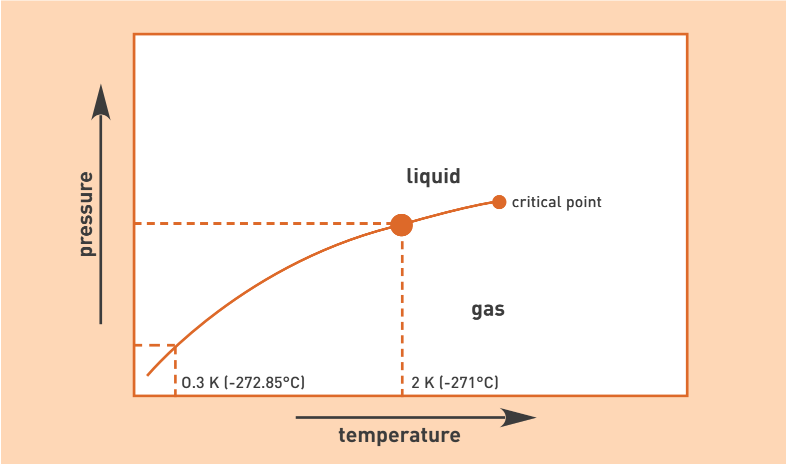


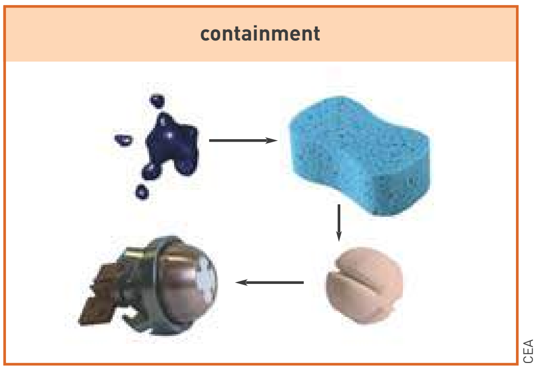
Figure 1.
Phase diagram for helium-3, showing the extreme point in the cycle for the liquid phase.

A liquid in zero-gravity

Sending instruments out in space further entails that the issue of microgravity be resolved if necessary. In the present case liquid is confined by capillary attraction within a porous material, acting as a sponge. Consisting of an alumina foam, this material exhibits an open porosity, in other words every tiny cavity communicates with its neighbors, allowing the liquid to move around, and making it possible for gas to be pumped. The **thermodynamic** cycle involved requires that the thermal gradients be controlled across the system, in other words that the temperature distribution is controlled. Here again, a technique without any moving parts is used, to wit the gas-gap heat switch technology using an exchange gas. These thermal switches are equivalent to electrical switches: they allow to create a thermal contact between two components (resulting in a heat flow), or, on the contrary, insulating them from one another. Switching from the closed ("on") to the open ("off") position is effected by the presence or absence of gas in the gap between two concentric parts. The gas management is achieved by means of a miniature adsorption pump, featuring no moving parts.

Takeoff and mechanical strength

Finally, the constraints ultimately entailed, if instruments are to be sent out into space – last, but indeed not least – further include ensuring the thermal isola-



Principle of capillary containment.
The evaporator (the titanium half-sphere, which may be seen in the photograph) holds a porous material, acting as a sponge.

Vibration tests at the Liège Space Center (Belgium). A flight model is positioned on the vibration table.

L. Duband/CEA

tion required, if very low temperatures are to be obtained, and the requisite mechanical strength to withstand launcher takeoff, using e.g. an Ariane 5 rocket. To meet these conflicting constraints, researchers use **Kevlar** suspensions. This material affords the twofold advantage of low thermal conductivity, and very high mechanical strength (double the strength of a steel wire of the same diameter). In principle the lifetime of this type of cryocooler is unlimited, a direct result – at first blush – of the absence of moving parts. In fact several systems have been operating, in laboratory conditions, for more than 20 years, without experiencing any degradation in performance. Indeed, although using liquid helium for the purposes of low-temperature operation, these systems, kept sealed, can be recycled indefinitely, once the final drop of liquid has evaporated. The only limit is set by the upper-stage availability. Thus, in the case of Herschel, the main tank is expected to dry out after three and a half years' of operation.

The forthcoming SPICA (Space Infrared Telescope for Cosmology and Astrophysics) and IXO (International X-ray Observatory) missions will call for cooling resources targeted at achieving yet lower temperatures (50 mK). The know-how gained on the 300-mK helium-evaporative systems is feeding into the ongoing development of an original architecture, combining a Herschel-type system with one or more adiabatic demagnetization (magnetic cooling) stages. Such a combination should result in significantly limiting the overall cryocooler mass, consequently allowing additional "on board science". For both of these coming missions, the cryogenic chain will solely involve mechanical cryocoolers: this making for a possible extension of the mission lifetimes, together with optimization of the "payload" carried. Researchers will still need to meet a number of technological challenges. The first one concerns the association of a system of the Herschel type – generating peak power during the recycling phases – with mechanical upper stages – these, on the other hand, proving intolerant to large peak powers. The goal will thus be to devise, and design a thermal architecture making for an optimized distribution of heat releases.

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After takeoff, the satellite reaches the vacuum of outer space, exposed to heat from the Sun. Such conditions may be tested for, in a white room, on test models.

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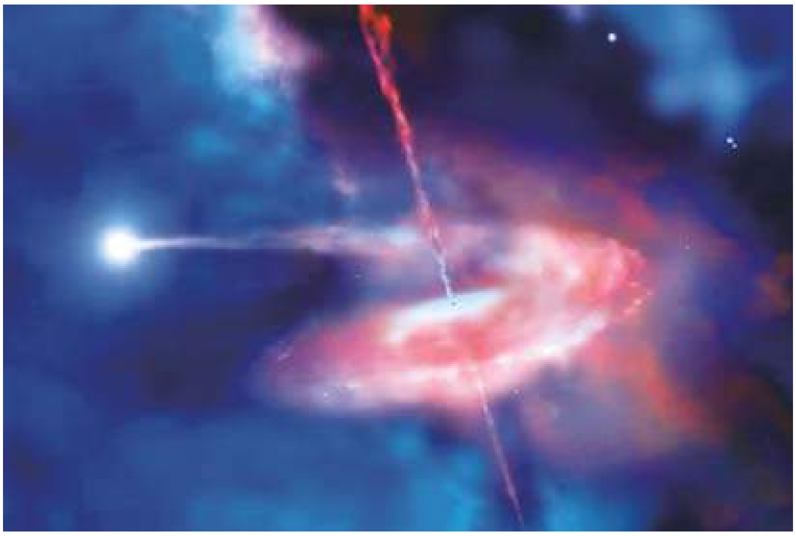
Out in the extreme, tumultuous Universe

There is a part of the Universe that still holds its secrets, namely that where black holes, and sites of cosmic-ray particle acceleration make their presence felt. Gaining some knowledge of such phenomena, ranking amongst the most energetic in the Universe, entails the exploration of a specific region of cosmic radiation: that of hard X-rays, and gamma rays (1 keV–1 MeV).

With regard to the **hard X-ray**, and **gamma-ray** spectrum, the exploration of the sky has only just begun. One thing is certain, however: in that range of energies, the Earth's atmosphere interposes a definite barrier to the propagation of **photons**. The idea, therefore, is to launch a space telescope, to carry out observations outward of this boundary, and one fitted with an imaging spectrometer. The latter instrument answers the purpose of detecting gamma photons, measuring the direction they come from, and their energy, and determining their time of arrival (to a precision of one millionth of a second), and, if possible, their **polarization**. Often proving faint, in some cases distant, and elusive, the sources that are looked for entail, if they are to be studied, that the largest possible number of photons be taken in by the survey. Thus, the very few grains of light coming from such sources, drowned as they are in an intense background noise, call for instruments exhibiting very high sensitivity, and the highest possible detection efficiency, if they are to be observed. While the combination of high-performance, innovative detectors, and space technologies has allowed spectacular advances to be achieved, the fact remains that the detection – individually – of gamma photons in space stands as one of the major challenges set to astrophysicists.

A revolution in high-energy astronomy

It was a full 20 years ago, already, that astrophysicists carrying out observations in the hard X-ray and gamma-ray spectrum gave up their scintillators, switching to more sensitive, more complex semiconductor-based detectors, in silicon and germanium, and subsequently – most commonly – in cadmium telluride (CdTe), this proving to be an outstanding material, for the purposes of gamma photon detection. As regards high-energy astronomy, this brought about a revolution. Indeed, owing to the **pixelization** they involve, these instruments, acting as true satellite onboard digital cameras for gamma-ray photography, afford hitherto unmatched levels of image detail, timing precision, and energy measurement, for every photon. CEA has played a major part in designing this new generation of semiconductor imaging spectrometers, and in optimizing their performance. The degree of precision achieved is the outcome of the determined effort made by researchers, to ensure their detectors, increasingly miniaturized, and pixelized as they were, would be shielded against background noise, be it of physical (cosmic rays), or electronic origin.
The first large camera to benefit from the technological performance afforded by the use of cadmium telluride (CdTe)-based detectors was the INTEGRAL



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Artist's impression of a black hole accreting matter from its companion star, in a binary system.

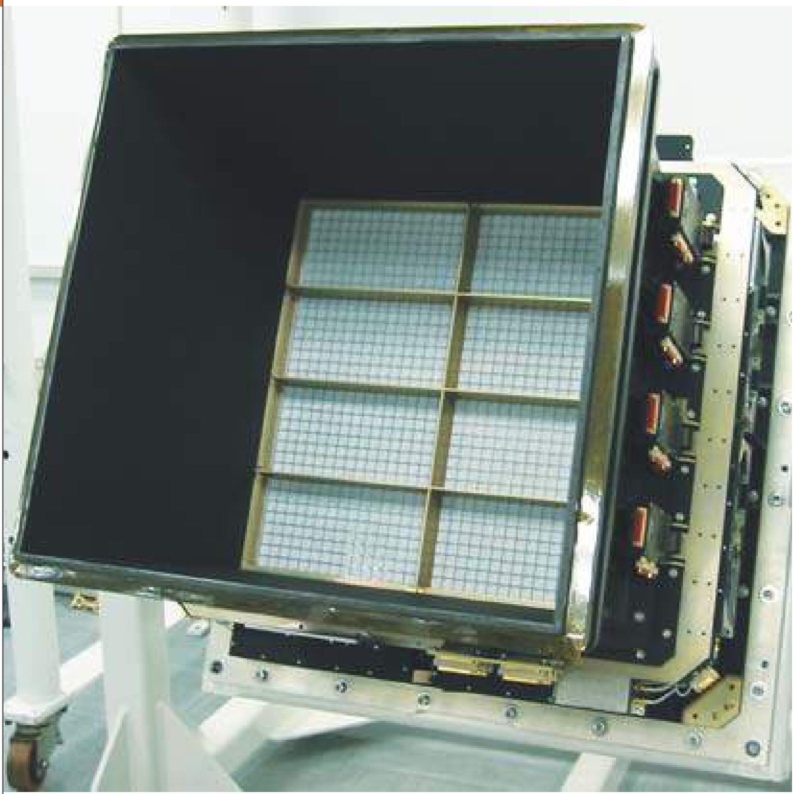
Soft-Gamma-Ray Imager (ISGRI), featuring a detection surface area of fully one fourth of a square meter. Carried on board the INTEGRAL (International Gamma-Ray Astrophysics Laboratory) satellite, this is a mission set up by the **European Space Agency** (**ESA**), launched in 2002. CdTe stands as one of the most effective materials, for the purposes of gamma photon detection. This successful venture by CEA gave a new impulse to the development of further new miniature "technological gems," exhibiting ever improved performance levels. Thus, the joint R&D efforts conducted by CEA, and **CNES**, subsequent to ISGRI (INTEGRAL Soft-Gamma-Ray Imager), can now ensure the required scientific performance for the forthcoming ECLAIRs space telescope, dedicated to gamma-ray burst detection, or next-generation high-energy telescopes, as typified by SIMBOL–X.

New smart instruments

By way of an extended metaphor, new-generation dedicated detectors, for the purposes of hard X-ray, and gamma-ray space astronomy, may be portrayed in terms of the following four features:

- Their mind, and smartness, is provided by a detection system, comprising a CdTe sensor, and its associated electronics, inserted within a complex, "space-grade"-capable miniature detection module, optimized for scientific purposes (a gamma-ray camera being made up of a mosaic of such modules).

(1) Fabrication of a Schottky electrode involves a metal–semiconductor contact, forming a reverse-biased diode.



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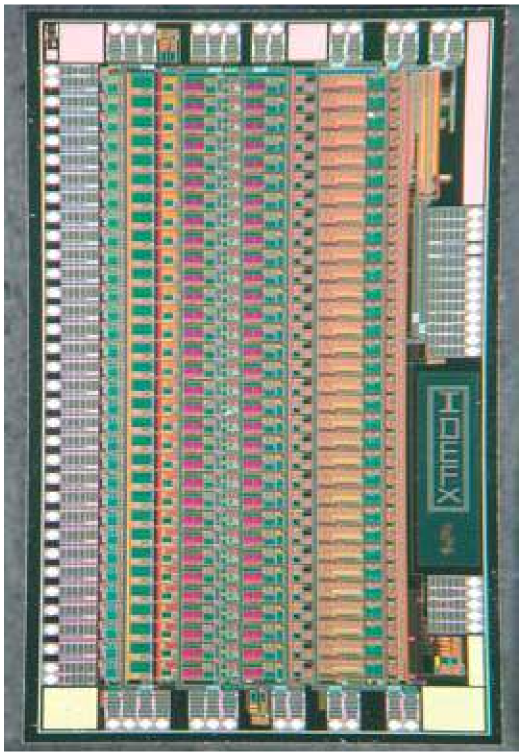
By means of its camera, comprising an array of cadmium telluride (CdTe) semiconductors, of 128 × 128 pixels, the IBIS (Imager on Board the INTEGRAL Satellite) telescope carries out observation of the sky with an angular resolution of around 10 minutes of arc. The ISGRI camera was constructed by CEA, with support from CNES (photograph taken in 2001 at Laben Spa, Milan, during integration of the instrument).

Advances in space gamma-ray detection thus result from efforts concerning sensors (CdTe, featuring a highly segmented Schottky electrode),(1) their readout electronics, of the ASIC/CMOS (application-specific integrated circuit/complementary metal–oxide–semiconductor) type, and their assembly, to obtain "hybrid" components. To complicate matters further, the various objects must be compatible with the space environment (thermal conditions, radiation, reliability…), and able to withstand a rocket launch. The past few years have witnessed, at the same time, notable advances in imaging, through **pixel** miniaturization (500 µm square), as in spectral performance. This twin breakthrough has promoted the extension of the spectral range covered, to lower energies, together with enhanced precision in the energy measurement carried out for every photon. The extension to lower energies has proved decisive, with regard to gamma-ray astronomy. Indeed, it is through the simultaneous study of low-energy (a few k**eV**), and high-energy photons that certain objects ultimately show their true nature: **black holes**, or otherwise, in what state…

• Their heartbeat comes from CdTe, a material exhibiting now generally recognized qualities for **spectrometry** purposes, at temperatures close to ambient conditions (ranging from –40 °C to +20 °C). This is a heavy (mean atomic number Z equal to 50), dense (≈ 6) crystal, making it able to act as an effective blocker of gamma photons of up to several hundred keV, whereas these, as a rule, pass through matter without undergoing any interaction. Thus, when a gamma photon interacts with an **electron** in the crystal, this electron, as it is stripped away, takes with it virtually all of the energy shed by the photon. As for the electron, its advance across the crystal comes to an end by yielding «**electron–hole**» **pairs**, in numbers that are proportional to the quantity of energy deposited by the incoming photon. An electric field, applied to the crystal, serves to accelerate these pairs. The setting in motion of these free carriers induces a transient current, this providing a valuable signal that has to be "sensed" and processed. It should be noted that these carriers do not all migrate at the same velocity, this depending on whether they are electrons, or holes. The discrepancy is so large, indeed (by a factor 10 or so), that the slower carriers are subject to a trapping phenomenon, resulting in "charge loss". This phenomenon, which is particularly exacerbated in CdTe, entails that specific signal processing be provided for. Finally, as CdTe crystallogenesis still stands as a highly complex process, fabrication of this semiconductor remains a difficult operation, restricting crystal size to a few square centimeters in area, for a thickness of a few millimeters. Currently, the advances achieved by manufacturers, as regards crystal fabrication, the setting up of metal–semiconductor contacts, and sensor stability have made it possible to overcome these limitations, and come close to the ultimate performance possible for this material. In particular, the most recent single crystals, fitted with segmented electrodes, exhibit **leakage currents** (a source limiting electronic noise) 1,000 times weaker than 10 years ago. It now proves feasible to accelerate carriers, so as to limit trapping, this making for more straightforward signal processing. Signal processing is effected by IDeF–X (Imaging Detector Front-end–X-ray) circuits.



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IDeF–X V2 microcircuit, for ECLAIRs. The 32 parallel structures visible in this picture are the independent spectrometry lines, featuring a separation of a mere 170 µm. This low-noise, low-consumption circuit is able to withstand the radiation prevailing in a space environment.

• The microelectronics may be seen as playing the part of the central nervous system, involving as this does circuits adapted to the specific signals from CdTe detectors, and to the constraints arising from their integration into a modular hybrid component. Nowadays, production of IDeF–X circuits is carried out using standard, affordable CMOS technology. Designed as they are with particular care, these circuits are able to withstand the **radiative** environment, with regard to two modes: either in terms of cumulated dose, this having the effect of altering transistor properties, and impairing circuit performance; or with regard to individual **cosmic radiation** events, having effects that may go as far as the destruction of the circuit. Even though involving an area no larger than 20 square millimeters or so, IDeF–X chips allow 16 or 32 independent detection lines to be integrated, depending on the version used. Their role is to collect the charges delivered by the detector, carry out signal amplification, and shaping, and consign data to memory. These chips afford the advantage of generating but very low noise levels: barely equivalent to 30 RMS (root mean-square) electrons or so, when the chip is isolated. Once the circuit is connected to a detector, the noise from the unit as a whole stays below 60 RMS electrons or so, i.e. 5 times less than for the circuit fitted to the ISGRI camera. These circuits, typically associated to good-quality CdTe crystals, allow photons to be detected in the 1.5–250 keV range. Their low threshold, at the lower boundary for the detection range, stands about two and a half times lower than in the best similar circuits extant, the world over. Such performance affords a prime advantage for the future ECLAIRs, and SIMBOL–X missions.

• The 3D hybrid components, and packaging may be deemed to flesh out the bodily envelope. Readying an imager, together with its CdTe detectors, and associated IDeF–X circuits, entails that the latter be assembled into a hybrid component. The densest such component is dubbed Caliste 256. It is fitted with a 1-square-centimeter CdTe crystal, pixelized at a pitch of 580 µm, every pixel being connected to an IDeF–X line. 8 IDeF–X circuits are operated simultaneously, to extract the 256 signals yielded by a single Caliste.

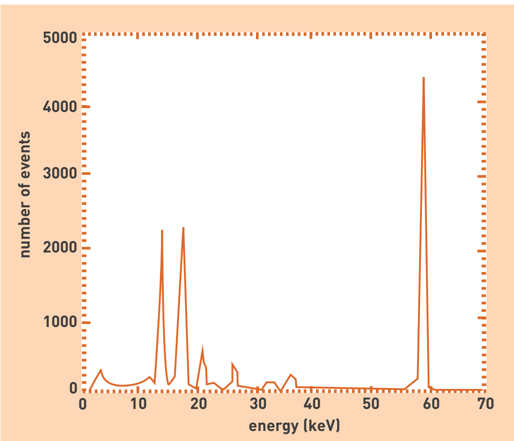
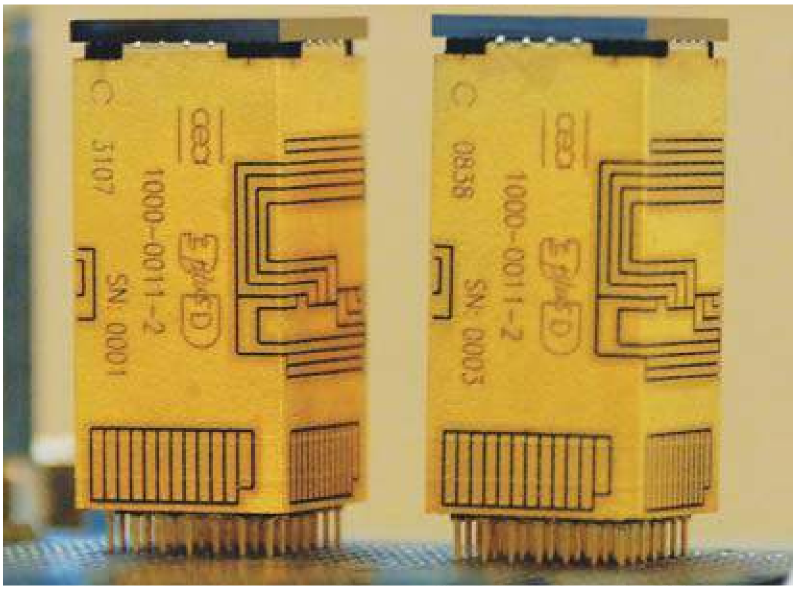


Figure 1.
An instance of a spectrum recorded using Caliste 64.
The figure shows the energy distribution of photons emitted by an americium-241 source. This spectrum is built up from the sum of the responses from 64 independent pixels, calibrated in terms of energy. Spectral resolution stands at about 900 eV FWHM at 60 keV. The detection threshold stands at about 1.5 keV.



Caliste 256 modules. Each of these two prototypes is a miniature imaging spectrometer, about 1 cm square, and 2 cm high. A CdTe crystal is positioned above an electronic component (gold), inside which eight IDeF–X circuits are stacked vertically.

Specified as it is for the purposes of wide-field observation, the large area featured by the imager has a layout involving a mosaic of Caliste components, every one of these being joinable end to end on all four sides, to preclude any dead area (see Figure 1). This entails that all eight IDeF–X find a place below the limited CdTe area. To achieve this, the solution found involves stacking the circuits one above the other, positioned perpendicularly to the crystal surface. This technological feat was carried out by French company 3D Plus. For space applications, these unit detection modules afford guaranteed reliability, considerably reducing the risks of failure, for an imaging spectrometer. It should be mentioned that this component was designed to withstand the mechanical, thermal, and radiative stresses inherent in going into orbit.
Presently, researchers can only find one word, as being fit to describe this new-generation detector: impressive! Its performance stands as evidence of this:

• spectral resolution, standing lower than 900 eV FWHM (full width at half maximum), at 60 keV, involves a sixfold enhancement in precision, compared with ISGRI;
• the low threshold is brought down to 1.5 keV, as against 15 keV for ISGRI;
• pixels are 100 times smaller.

Once it is mounted at the focus of a telescope of the SIMBOL–X type, this CdTe gamma-ray imager model will yield, undoubtedly, an extraordinary wealth of scientific findings.

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CEA Saclay Center

Probing the sun with GOLF–NG

Over the past four hundred years – at least – the Sun has shown highly variable activity, exhibiting, in recurrent fashion, dark spots across its surface. The impact of such variability on the Earth's atmosphere still remains poorly understood, in spite of the startling correlations found with past climate. Through the invention of innovative techniques, a thorough understanding of the processes generating this variability might be gained. And some prediction of the coming solar activity could become feasible for the coming century.

Photo Link

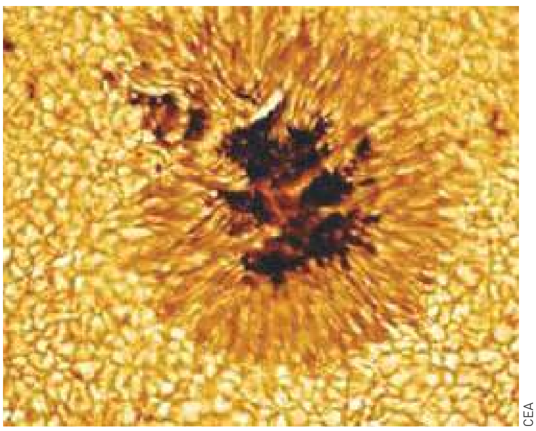
CEA, involved as it is with issues relating to the terrestrial environment, is constructing a new multichannel **resonant spectrometer**, called GOLF–NG (Global Oscillations at Low Frequency–New Generation). The two goals will be to ascertain the roles played, respectively, by the solar core, and the transition region between the photosphere and the chromosphere, from which darker regions emerge, known as "sunspots," together with brighter ones, known as "faculae" (see Figure 1).
For more than a decade, the Solar and Heliospheric Observatory (SoHO) satellite has been probing the internal and external regions of the Sun, on a continuous basis, by means of a dozen instruments having

the ability to record all of the manifestations of solar activity – this being the outcome of a collaboration between **ESA**, and **NASA**. Thus, SoHO is constantly monitoring solar coronal mass ejections, the emission of particles known as the "**solar wind**," or the dark spots that regularly appear on the solar surface, migrating, over time, from the higher latitudes to the solar equator. Astrophysicists have a good understanding of the cause of this phenomenon, occasioned by a cooler local temperature, associated with an increase in **magnetic field** strength. It is to the credit of the SoHO satellite that it evidenced the internal origin of that magnetic activity, by measuring permanent standing **waves**, excited by convection. It has thus been monitoring new indicators of activity for more than 15 years now.

The principle of solar seismic measurements

The best way of determining the internal waves that penetrate down to the Sun's core is to measure the variation, over time, found in the **Sun**'s "**Doppler velocity**," relative to the observer, and extract, from this, the frequency spectrum for the internal modes. This velocity, standing as it does at about 1 km/s, is evaluated on the basis of the shift in wavelength found for well-known spectral lines, e.g. the sodium, or nickel lines. These **absorption** lines arise in the Sun's atmosphere, which is agitated by **turbulence**. The sodium line is used by GOLF, the nickel line by the Michelson Doppler Imager (MDI), two instruments carried by the SoHO observation satellite. It is the analysis of the light from the absorption lines for these elements, in the solar atmosphere, that yields these velocities.

The GOLF instrument provides astrophysicists with a resonant spectrometer concept affording extremely high performance levels. It operates by way of successive steps. The first step involves filtering solar **photons**, over a wavelength range matching the sodium line. Subsequently, the photons thus absorbed are captured in a cell containing pure sodium vapor, and then reemitted in a narrow wavelength band, on either wing of the line. Owing to its atomic reference, this is a method affording unique precision. It makes it possible, in particular, to measure constructive interference between modes, generating a **stochastic signal**, with a velocity of around 1 m/s. As this signal is superimposed on the global solar displacement velocity, its measurement over time yields the frequency spectrum for the modes. To improve detection quality, with regard to individual signals that are very faint, GOLF–NG will extract this signal at eight points, on the Na D1 sodium line (see Figure 2).



Close-up of a sunspot, showing how surface granulation gives way to matter dominated by magnetic field influences.

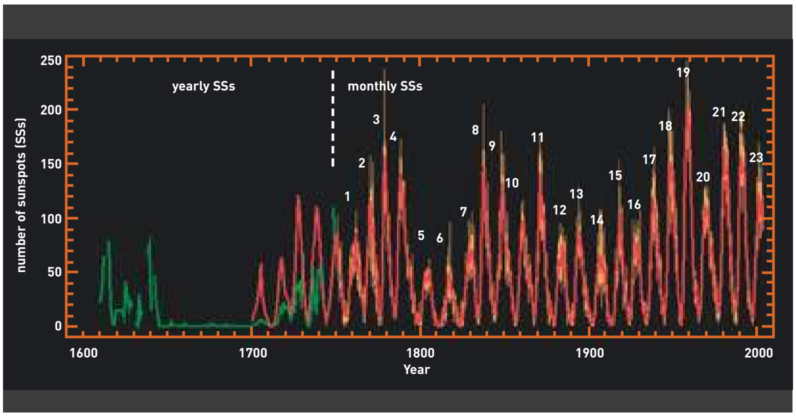


Figure 1.
Since the first observations made by Galileo, the number of sunspots appearing on the Sun's surface has varied, following an 11-year cycle, with an amplitude, however, that is as yet unexplained.

Exceedingly faint signals from a highly turbulent Sun

For over 10 years, a succession of space probes has been planned: SoHO (in observation up to 2012 at least) is now accompagnied by the Picard(1) (a **CNES** microsatellite), and Solar Dynamics Observatory (SDO) satellites, both launched in 2010. With these

(1) Taking its name from French astronomer Jean Picard (1620–82), who made the first precise measurements of the solar diameter, in the 17th century.

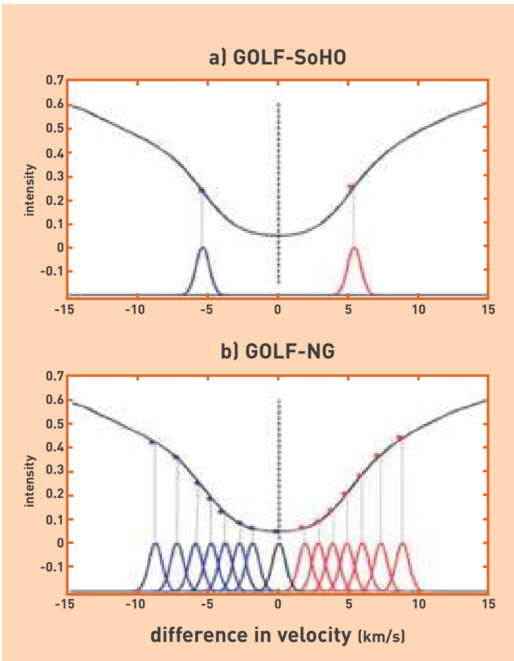


Figure 2.
Principle of the measurement by multichannel resonant spectrometer: the eight blue measurements are carried out simultaneously, as the cell, filled with sodium vapor, is positioned in a varying-field magnet; the alternative of blue-, and red-wing measurements is ensured by a liquid-crystal polarizer.

S. Turck-Chièze/CEA

The SoHO satellite (seen here during the final integration tests) was put into space by an Atlas–Centaur launcher, and is scanning the Sun, from a position 1.5 million km from the Earth. This satellite, launched in 1995, is still carrying out observations, with instruments studying the Sun, from core to corona. The GOLF instrument may be seen on the left, in the picture.

instruments, advances in knowledge will be secured – not that all issues, however, will be settled. Indeed, it should be kept in mind that acoustic modes displace the atmospheric layers, individually, to a maximum velocity of 20 cm/s, with a periodicity of a few minutes. **Gravity modes** – these providing the indispensable probes of the core dynamics, have periods of a few hours and velocities no higher than 1 mm/s, involving displacements by 18 meters, at the surface of a highly turbulent Sun. This challenge has already been met, to some extent, by the GOLF instrument, by effecting measurements 400 kilometers above the **solar photosphere** – in a calmer, transparent region. GOLF has already detected the first manifestations of gravity modes. This instrument has convinced the teams at CEA that GOLF–NG might contribute to write the concluding pages.

GOLF–NG, a multichannel resonant spectrometer

This new instrument, entirely constructed at IRFU, will measure, simultaneously, the spectrum of solar oscillation modes at eight positions in the atmosphere (see Figure 3), at altitudes ranging from 200 to 800 kilometers above the **photosphere**. For astrophysicists, this particular spectrometer affords a number of advantages. First, it delivers improved detection of acoustic signals, owing to their amplitude increasing exponentially with height, in the solar atmosphere. Second, the instrument enhances detection of gravity modes, as a result of the reduction of **solar granulation effects**. Finally, GOLF–NG effects the measurement, on a continuous basis, of the atmosphere's global behavior, in the region between the photosphere and the **chromosphere**, this being the region of magnetic flux emergence.

The magnetic field required to sample eight points on sodium line D1, is an axial field, this being linearly varied, over a 0–12 **kilogauss** range. This is obtained by means of a permanent magnet, built up from neodymium–iron–boron magnets, and small iron–cobalt pole pieces ($20 \times 15 \times 10$ cm^3). Transverse homogeneity of the field, along its axis, is better than 2%, along a 10-mm diameter cylindrical volume. This property guarantees a uniform response, in terms of wavelength, across the entire resonance volume of the vapor cell. Constructed in high-temperature Pyrex borosilicate glass, this cell comprises two regions : the pure sodium is held, in

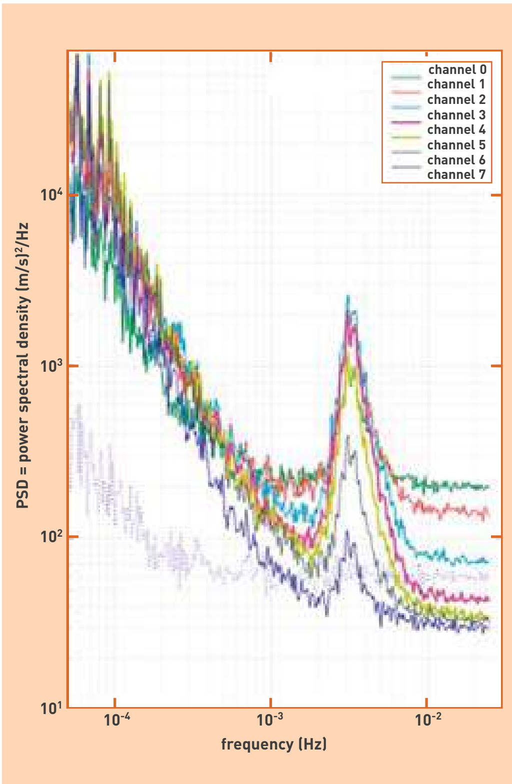


Figure 3.
First light from a prototype of the GOLF–NG multichannel resonant spectrometer. This figure shows the spectrum for acoustic modes, as measured simultaneously at eight different heights in the atmosphere. The next step will involve improving low-frequency detection, to refine the detection of solar gravity modes.

solid form, in the lower region, known as the pip, when the cell is cold; as the cell is heated, the sodium rises into the upper flask, positioned along the axis of the increasing magnetic field, this being the locus for the resonance processes (see Figure 4). The glass flask leaves 31 apertures open for reemitted photons, in an optical mask containing the heating elements. Operating temperatures reach 190 °C in the upper region, 175 °C in the lower region to preclude any condensation over these windows. The electric power required to heat the cell to these temperatures is no more than 2 watts. No regulating device was fitted – the aim being to preclude any periodic noise, whether of thermal or electrical origin, in the frequency range where the modes are subject to detection (i.e. down to about 50 microhertz). The stability of this device, its thermal homogeneity, and low consumption are due to two features: first, thermal isolation ensured by cylindrical aluminum shields, positioned around the cell; second, the fabrication of the suspensions, involving chromium–cobalt, i.e. materials exhibiting very low thermal conductivity.
The entire unit is inserted into a high-precision mechanical part, fabricated in nonmagnetic stainless steel, positioned in the gap of the magnet, with no direct contact. This component also ensures the positioning, and support of the optical elements making up the 31 measurement channels, for the 8 channels of the spectrophotometer. These optical elements are in fact optical lenses, subjected to an antireflection treatment, they have been dimensioned to be able to operate at temperatures of up to 80 °C. These lenses collect as much resonant light as feasible from the inside of the cell, and, by way of a coupling to a silica optical fiber, guide it onto the photodetector array.
Upstream from the magnet, a compact subunit carries out three functions: processing the incident solar beam, ensuring uniform insolation inside the cell, and switching the **polarization** state. This latter step entails the use of a beam splitter cube, of high purity, and of a phase retarder, involving a liquid crystal plate. It is this phase change that induces the switch in beam circular polarization, at a rate which may be faster than 1 per second, with switching times shorter than 10 milliseconds or so. This liquid-crystal device, developed by researchers at the **Canary Islands Institute of Astrophysics**, allows a polarization purity of up to 99.99% to be obtained.
Having reached functional status since 2008, GOLF–NG remains the sole solar spectrometer having the ability to effect the acquisition, in fast, simultaneous manner, of Doppler velocity at eight different heights in the solar atmosphere. An initial campaign of observations has already been conducted, in the summer of 2008, in Tenerife (Spain), this allowing qualification of the principle of this new spectrometer to be achieved. Optimization of the instrument in using a CCD camera as the detector has been demonstrated in 2010. The GOLF-NG prototype has achieved the requisite performance for space missions, and ensure its reliability. His use on ground is now studied.
For astrophysicists, GOLF–NG already stands as the indispensable instrument to understand the internal manifestations of solar activity, in the **radiative** zone. It will initially be monitoring solar activity from the ground, however its purpose is to be included in a coming solar space mission. A major space project has also been investigated, with French manufacturer **Thales**, for the forthcoming ESA missions. This project seeks to carry out global, and local observation of solar activity, together with effecting the study of the lower corona. Monitoring solar dynamics, on a short-, and medium-term (at the decade, or century scale) basis, along with its impact on the Earth's atmosphere will be one of the major challenge set, for the coming decades.

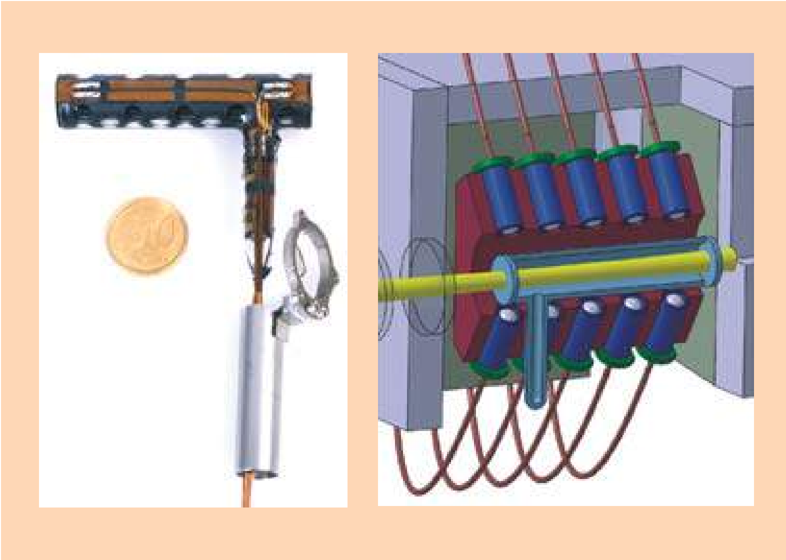
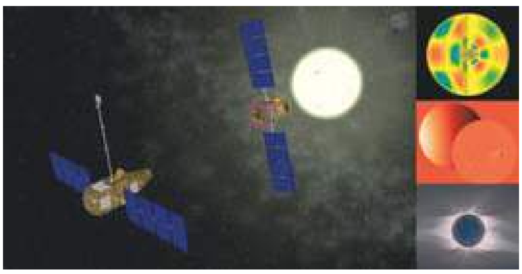


Figure 4.
The vapor cell, and 3D cutaway schematic of its positioning inside the magnet.



NASA

As a successor to the observatory designed in collaboration by the European Space Agency (ESA) and NASA, a formation-flying mission is being proposed, for the purposes of obtaining a full description, on a continuous basis, of the impact of solar activity on the terrestrial environment.

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FOCUS B

From light to imagery

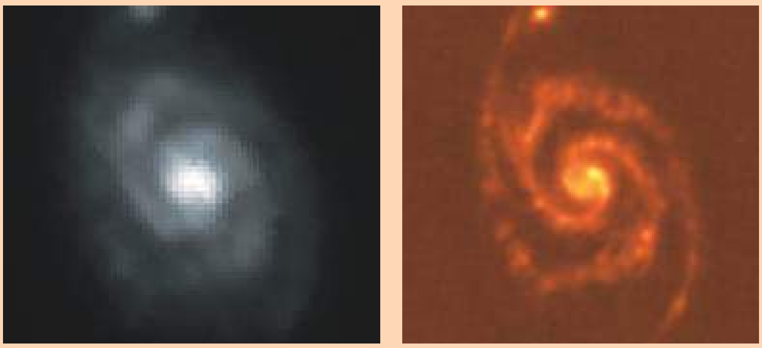
We are bathed in light. It is all around us, seemingly self-evident, and familiar to everyone. However, the human eye is only sensitive to a minute part of the light spectrum, to wit the region extending between 400 µm and 700 µm, approximately. Thus, alongside visible light, there is also nonvisible light, forming the larger part, overwhelmingly, of the electromagnetic spectrum (see *Focus A*). In order to gain knowledge of the Universe, and explore it, as fully as possible, astrophysicists must collect all of that nonvisible light, to produce images of the "invisible" sky. To date, this kind of imagery has, in many cases, made it possible to highlight an unexpected Universe, e.g. a Universe varying at the scale of a few hours, in the γ-ray region of the light spectrum.

How does one set about representing objects emitting nonvisible light, on visible maps? This query raises the issue of the relationship between astrophysics, and imagery. By definition, an image is the representation – be it analog, or digital – in two, or even three dimensions, of a reality that is ascertained by way of the measurement of a physical quantity. A picture of the nonvisible is thus the image of a reality that is not amenable to observation with the naked eye. Translating it into an image that is visible to our eyes entails going through a number of successive steps. The first step involves using a detector, i.e. an instrument having the ability to capture the nonvisible light emitted by a light source, and subsequently to convert the light received into a measurable electric current – the detector acting as the interface between that light, and the signal. By way of comparison, this is a process similar to that involved in the conversion of sunlight into electricity, by means of photovoltaic cells. However, there are many other means of converting light into a signal. For instance, **bolometers**, designed for the purposes of scanning the sky in the submillimeter **infrared radiation** region, convert light into a variation in temperature, in a material absorbent for that light. This small rise in temperature induces a variation in the electrical resistance exhibited by that material; measuring this variation then allows the incident light flux to be ascertained.


ESA & The PACS Consortium

An image of galaxy M51 (the Whirlpool Galaxy), viewed in the far infrared, in three colors: red, green, blue, corresponding to three wavelengths: 160 µm, 100 µm, 70 µm (Photodetector Array Camera and Spectrometer [PACS]).

The second step, digitization, involves translating this signal into a digital, i.e. numerical, form, to make it amenable to processing by way of computer techniques. The higher the intensity of the light source, the stronger the signal the instrument will yield, as its "output." The digital images thus obtained consist of thousands, or millions of squares, which must be as small as feasible, if a finely detailed image is to be obtained. The image thus consists of a mosaic of numbers, each one standing for the amount of light information received by one element. In the parlance of computer science, these tiny squares are known as **pixels** (abbreviated as "px"), a term coined from the contraction of "pix" (pictures), and "element," to signify a "picture element." A pixel is thus the smallest unit of area serving as the basis of a digital image. Such a picture is thus – no more, no less – a two-dimensional array, or grid, every cell being a pixel. To yield an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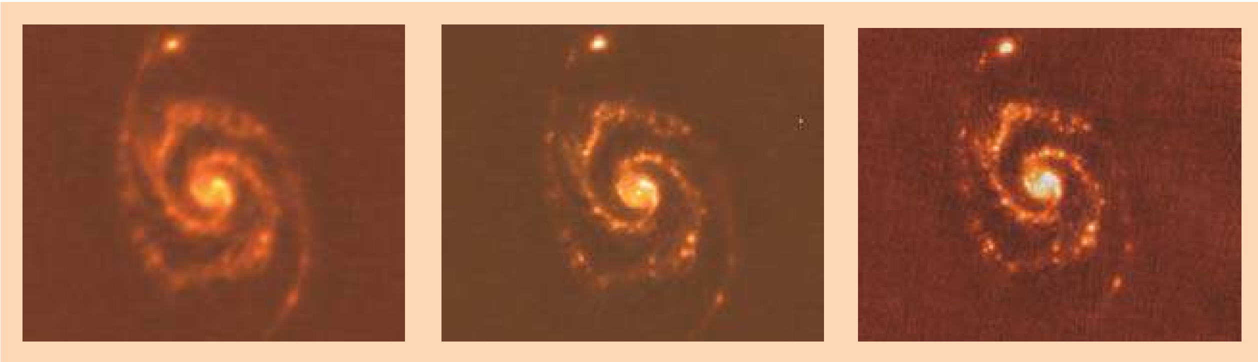
Spiral galaxy M51 (the Whirlpool Galaxy), viewed in the far infrared (160 µm), as imaged by Spitzer/MIPS (left), and Herschel/PACS (right). Owing to its 3.5-m mirror, as compared to Spitzer's 0.8-m mirror, Herschel allows images of far higher resolution to be obtained.



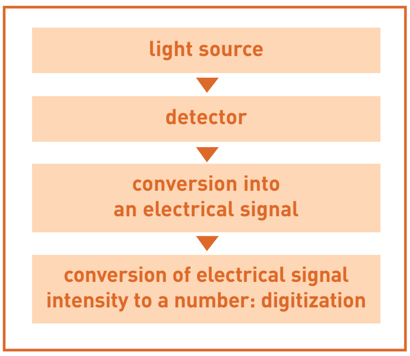
ESA & The PACS Consortium

Images of spiral galaxy M51 (the Whirlpool Galaxy), as yielded by Herschel/PACS at three wavelengths: 160 µm (left), 100 µm (middle), 70 µm (right). It will be seen, from these images, that resolution improves, as wavelengths get shorter.

image by computational means, all that is required is thus to draw up a grid of pixels, with every cell holding a numerical value. The quality of an image is directly dependent on the definition achieved for it, i.e. the number of pixels recorded to make up its height (along the vertical axis), and width (along the horizontal axis). Specialists speak of the "pixel dimensions" of the image, i.e. the product of the number of pixel columns, by the number of pixel lines. The size of the range of numbers that may be assigned to a pixel is also important, as it expresses the light dynamics the sensor will be able to capture. The value stored in a pixel is coded by way of a certain number of bits, specifying the color, or intensity of the pixel. The final step in the process thus involves specifying this code. In all communications-related fields, be they concerned with words, or pictures, a code is defined as a rule serving to convert information into some other form of representation. A code embodies an idea, a concept. For astrophysicists seeking to draw up maps of the Universe, on the basis of a range of energies, as detected by their instruments, the aim will be to specify a color convention. Every discipline implements its own such convention: for instance, in air navigation charts, the color red serves to indicate the presence of storms; while, for agricultural purposes, green indicates a cultivated area. Once the color code has been specified, a continuum of intensity must further be specified, relative to the basic unit: for instance, keeping to the agricultural example, a range of greens, from intensive cultivation to desert, through various percentages of deforestation. This range, or gamut, may be defined as a kind of false rainbow. In astrophysics, the gamut of colors serving to code for light sources often ranges from red to indigo: signifying, in this discipline, from colder to hotter, but equally from less energetic to more energetic…

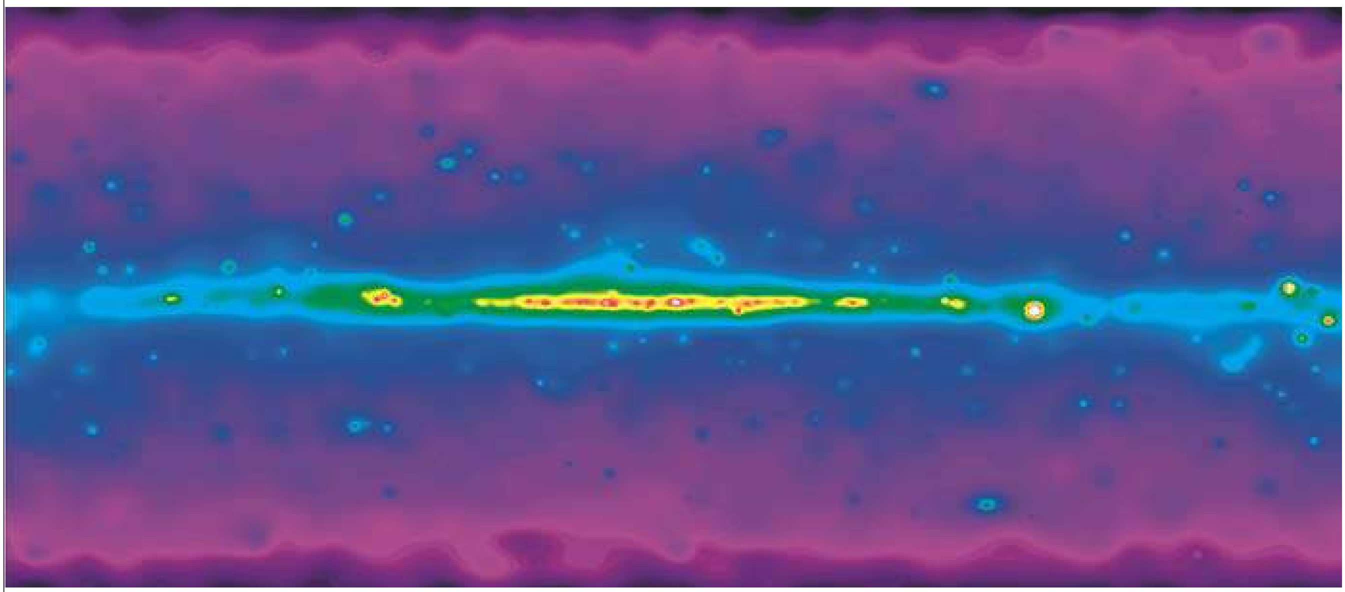
Once the image has been digitized, and coded, this does not mean all issues are thereby resolved. For the astrophysicist, there remains the issue of angular resolution, this being equal to the ratio of the wavelength at which the observation is carried out, over the size of the telescope mirror collecting the light used. Angular resolution is a measure of the angular size of the smallest details perceptible, using that telescope, this being expressed in degrees, minutes, or even seconds of arc. Thus, for the same mirror size, the shorter the wavelength of the light captured, the more finely detailed the image proves to be. Another solution, to enhance image detail, is to increase the diameter of the mirror. What happens, if two sources are observed, that lie in angular proximity to one another? Two cases are possible. If the separation between the two sources is larger than the angular resolution, the telescope will show two distinct sources. Should the contrary be the case, these two sources will appear to form but a single source. Even assuming the telescope does have the requisite power to separate these two sources, the choice of detector has to be the right one! Indeed, if the images of the two sources both map onto one and the same pixel in the detector, then the image obtained will show just a single source. Consequently, for a given wavelength, image detail is dependent both on the diameter of the telescope (which should be as large as feasible), and pixel size (this must be as small as found to be necessary).

As a result, it will be understood why astrophysicists are forever designing, and constructing telescopes of ever increasing size: thus, from the time of Galileo, who was looking at stars with a telescope featuring a lens no larger than 6 cm in diameter, to the Hubble Space Telescope, fitted as it is with a 2.4-m diameter mirror, astrophysicists have gained in angular resolution by a factor 40 (2.4 m/6 cm = 40). Another example is that of Herschel, the largest telescope to have been sent out into space, its diameter now reaching 3.5 meters. From this instrument, built for the purposes of detecting infrared, and submillimeter radiation, researchers expect highly precise information, regarding solar systems in the process of formation, or physical processes resulting in the birth of stars, and galaxies. On the other hand, however sophisticated it may be, and however high its performance, at these wavelengths, the sharpness of the resolution afforded by this telescope will be no better than that of Galileo's telescope. On the other hand, Herschel will achieve the feat of carrying out observations in nonvisible light, in the infrared and submillimeter radiation region, shedding light on the buried worlds of the Universe. Astrophysicists are convinced of one thing: they are living through a veritable revolution.



Data analysis in astrophysics

For an astrophysicist, a signal carries information sent out by a source, which he must then interpret. With the rise of computer resources, signal processing has seen, over the past decade, spectacular developments, enabling astrophysicists to validate, refine, or question our understanding of the Universe.



Simulation of six days' data from the Gamma-ray Large-Area Space Telescope (GLAST), subsequently renamed Fermi Gamma-ray Space Telescope. This covers the energy band in the 0.1–1 GeV range, filtered by means of the wavelet-based algorithm Mr-filter.

As a result of the evolution undergone by detectors, impinging as it does on all wavelength regions, data analysis has taken on an increasingly dominant place in astronomy.

The data flow

Whereas, in 1980, charge-coupled devices (CCDs) would exhibit sizes of some 320 × 512 **pixels**, astronomers, nowadays, can avail themselves of veritable CCD mosaics, involving sizes equal to 1,600 × 1,600 pixels. The methods used have forged ahead, to such an extent that the human, and financial resources involved, for the purposes of processing the data yielded by an instrument, may prove comparable to those required for the construction of the instrument itself. For instance, the ISOCAM camera, fitted to the **Infrared Space Observatory** (**ISO**), called for software packages to be compiled, for control purposes, and for real-time, and delayed-time analysis: this taking 70 man·years, whereas 200 man·years had proved adequate, for the construction of the camera. The resources taken up by the Planck program have proved larger still. Moreover, the quantity of results obtained – running, in some cases, to several hundred **terabytes** – calls for the use of databases, and development of sophisticated tools (see Figure 1).
The knowledge gained raises new issues, the resolution of which will entail observing an object, or a region in the sky. Data analysis is involved in the process of calibrating the resulting data, extracting information from them, or using the databases. Statistical studies likewise allow further knowledge to be gained: such is the case, e.g., as regards studies of the number of **galaxies** exhibiting a given **luminosity**, per unit volume. By "knowledge" is meant, here, the ensemble of theories relating to astronomy (**star** formation, galaxy formation, cosmology…), databases of objects, or of images, and catalogs, i.e. lists of objects detected using one particular instrument in a region in the sky. Such knowledge, be it in the form of scientific papers or databases, is usually accessible on the Internet.
Depending on the instrument, the data may come in the form of images, spectra, or **photometric** measurements. As a rule, astronomers can draw on an ensemble of data regarding any particular region, or object investigated – a number of images taken at different **wavelengths**, for instance. Placing instruments in orbit (Hubble, ROSAT, ISO, SoHO…) affords the benefit of bypassing atmospheric constraints. The analysis process involves a number of steps.
First comes the calibration phase, this being indispensable to correct for instrumental effects in the data, by way of a number of operations:
- dark-current correction: in the absence of any **light**, the values sent out by the detector never come down to zero, owing to electronic effects, and the "dark" level must thus be subtracted from the data;
- flat-fielding correction: at equal light exposure levels, detector response varies, from pixel to pixel; as a result,

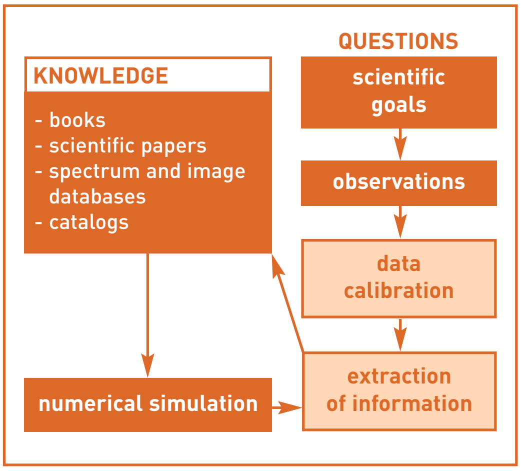


Figure 1.
The information flow determines the areas in which data analysis is involved. This makes it possible to gain a better understanding of the points where such data analysis occurs. On the basis of the knowledge gained, new questions arise, making it necessary to carry out observations of an object, or a region in the sky. The data thus acquired will first have to be calibrated, after which the information of use, for the purposes of achieving the scientific goal that has been set, must be extracted. Data analysis is involved in the process of calibration, extraction of information, and database usage. It should also be noted that statistical studies of databases (as, e.g., studies of the number of galaxies exhibiting a given luminosity, per unit volume) make it possible to gain further knowledge. By "knowledge" is meant, here, the ensemble of theories relating to astronomy (star formation, galaxy formation, cosmology...), object databases, or image databases, and catalogs (i.e. lists of objects detected using one particular instrument in a region in the sky). Such knowledge is, nowadays, usually accessible on the Internet (be it scientific papers, or databases).

the data have to be normalized, by dividing them by the detector response; detector parameters must be fully ascertained, failing which errors in terms of precision will impact on measurements.
Further effects may likewise be corrected for, in this first phase: e.g. deglitching, i.e. suppressing readings due to cosmic rays; or correcting for persistence effects in the detector; all of which tasks prove complicated, to a greater or a lesser extent (see Figure 2).
Once the data are calibrated, the analysis phase proper may begin. Depending on the goals set, a number of measurements may then be carried out, with regard to, e.g., detection of stars, and galaxies, or measuring their intensities, their position, or various morphological parameters: these findings must subsequently be compared with those found in existing catalogs. It proves quite impossible to go into all of the operations that may need to be carried out on an astronomical image; we have thus mentioned only the most common operations. Successfully extracting such information entails that such obstacles as noise,[1] or "instrument response"[2] be catered for. Once the useful information has been extracted, it must be compared with extant knowledge. This step results in validating, refining, or calling into question our understanding of the Universe. The ultimate outcome of this process of reconsideration is embodied in scientific papers, published in specialist journals.
The volume of knowledge is thus growing fast, calling for high-performance tools if it is to be put to use. These tools act as search engines, helping to draw together the latest published papers, leading-edge imaging methods, or algorithms matching objects detected in an image with a database (bearing in mind that choices have to be made, when several "candidates" are turned up). The difficulty lies, in particular, in the sheer volume of the databases. SIMBAD, a set of identifiers, measurements, and literature lists for astronomical data, developed by the Strasbourg Astronomical Data Center (**CDS: Centre de données astronomiques de Strasbourg**), brings together information on several million objects, corresponding to millions of observational measurements, with millions of literature references. The size of the images yielded by new-generation instruments results in any networked access to image archives proving virtually impossible, unless the images have first been compressed.
Mastering databases, and database usage thus stand as major challenges, for the future. Statistical analysis of catalogs further results in constraints being set, for the parameters in cosmological models, thereby increasing knowledge. For instance, the statistical study of galaxies, every one of them being individually different, shows the existence of three main families (**spiral**, **elliptical**, **irregular galaxies**), somewhat in the manner of grains of sands, which, though all different, do form a homogeneous strand.

Compressed sensing theory and the Herschel space project

In the context of some space programs, it may prove unfeasible, in some instances, to transfer back to the ground station considerable volumes of data, unless they are subjected to prior compression. This is the case for the PACS (Photodetector Array Camera and Spectrometer) instrument, carried on Herschel, which calls for compression by a factor 8, with only very limited computational power available. Standard

(1) Noise is a random fluctuation in intensity, superimposed on data; it arises, in part, in the detector, and, for another part, in the data themselves. Aside from the errors noise may occasion in measurements, it stands as a considerable nuisance, with regard to the detection of objects, and may be responsible for many false detections.

(2) The image of a star is not a point, rather it is a spot. This spread, related as it is to the instrument, is referred to as "instrument response." Its chief effect involves a loss of resolution, as objects lying close to one another tend to merge.

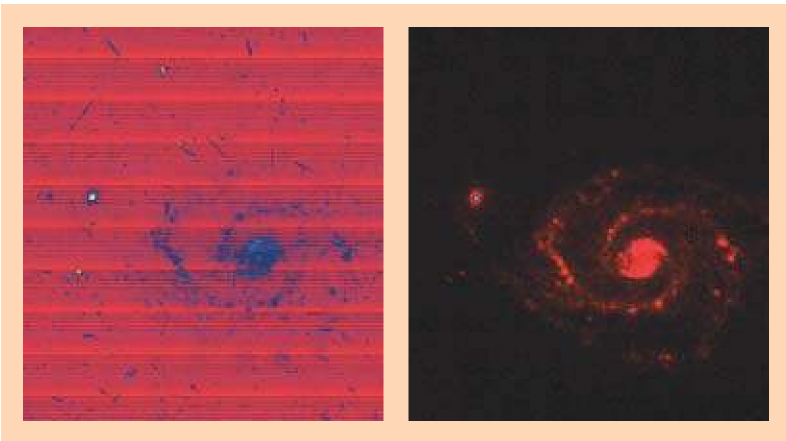

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Figure 2.
Galaxy M51, as viewed by ISO, before, and after calibration.

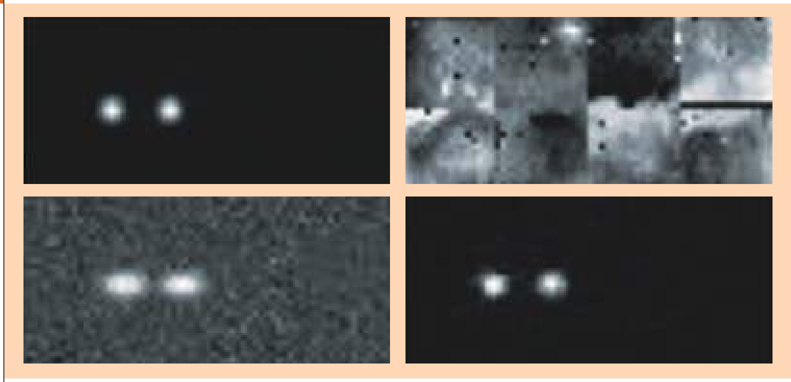

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Figure 3.
Top, simulation of an image containing two sources; and the same image, as viewed by Herschel. At bottom left, the image has been calibrated, subsequent to a conventional compression process; bottom right, the outcome yielded by the compressed sensing technique.

image compression methods – e.g. JPEG – prove unsuitable. Fortunately, over the past 10 years or so, major development in the field of harmonic analysis have emerged, that now allow images to be represented in terms of a basis of functions suitable for certain types of objects. For instance, wavelets prove ideal, for the purposes of detecting patterns, while the **ridgelet transform** is optimally suited to looking for lines, and curvelets yield a good representation of contours, or filaments present in an image. More generally, using a "sparse" representation of the data results in improved performance, for applications as varied as data compression, image restoration, or object detection. A new theory, compressed sensing theory, now explicitly relates, in a formal manner, the number of non-zero coefficients, in a given basis, and the number of samples required to effect accurate recovery of a signal. This recently developed concept shows that the constraint on sampling interval, as set by the Shannon **sampling** theorem, may be greatly reduced, provided the observed signal complies with a "sparsity criterion," in other words if a basis may be found in which the signal exhibits a small number of non-zero coefficients. A preliminary investigation has shown that this approach would provide an excellent alternative to the data transfer systems currently used for the Herschel satellite, and that, at an equal compression ratio, a 30% gain in terms of resolution would be obtained, in decompressed images (see Figure 3).

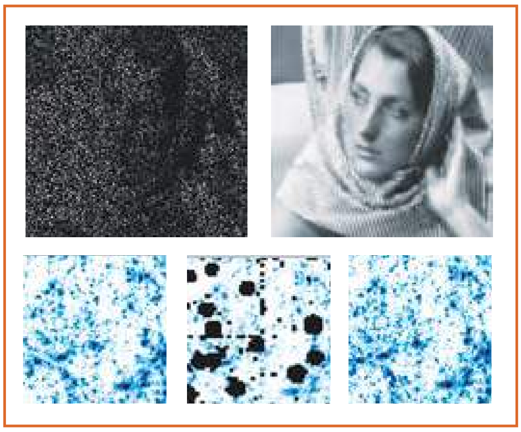

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Figure 4.
Top left: the image features 80% missing pixels; at right: the restored image.
Bottom left: simulation of a map of dark matter; middle: the same image, now involving missing regions; right: the image after reconstruction.
It has been shown that the error on the power spectrum, and on the bispectrum of the map restored by inpainting is of the order of a few percent. This original method has applications well beyond astrophysics, and it has been transferred to industry by way of a CIFRE contract,[3] passed with French company SAGEM.

Inpainting to recover missing data

Missing data are a recurrent issue in astronomy, this being due to defective pixels, or regions that may be contaminated by other emissions, and which it is desired should be masked out, when image analysis is carried out. Such masked out areas occasion difficulties, in subsequent processing work, in particular with regard to extracting statistical information, e.g. the power spectrum, or the bispectrum. Inpainting is the procedure whereby these regions may be filled in. Recent work shows that the missing regions may be reconstructed, by searching for a sparse solution, in a dictionary of predefined waveforms. Through use of a shrewdly selected dictionary, stupendous results may be obtained (see Figure 4).

Planck and the extraction of the cosmic microwave background

The Planck space mission, launched on 14 May 2009 by the **European Space Agency** (**ESA**), concurrently with the Herschel mission, has the remit of mapping spatial fluctuations in intensity, and **polarization**, in the millimeter emission from the sky, for the purposes, in particular, of characterizing the statistical properties exhibited by the **anisotropies** in the fossil cosmic **radiation** background. These measurements will make it possible to set strong constraints on cosmological **models**, and, in particular, to test the standard Big Bang model, while determining, with unrivaled precision, the cosmological parameters describing the Universe as a whole. Planck affords the best prospects, as regards achieving an understanding of this model, from the primordial Universe (inflation) to the astrophysics of galactic emissions, through structure formation, **galaxy clusters**, **dark matter** and **dark energy**, or the topology of the Universe. Two instruments are being operated, the Low-Frequency Instrument (LFI), and the High-Frequency Instrument (HFI), to obtain 9 full-sky maps, at frequencies ranging from 30 **GHz** to 1,000 GHz. These maps will feature the cosmic microwave background, but equally other components, related to galactic emissions (dust particles), or intergalactic emissions (galaxies, clusters…). These are likewise of the highest interest. Since each map shows a mix of these various components (**cosmic microwave background**, galactic dust…), the issue is thus one of recovering the

(3) Industrial Training through Research Agreements (CIFRE: Conventions industrielles de formation par la recherche): these contracts are drawn up, and managed by the French National Association for Technological Research (ANRT: Association nationale de la recherche technique), on behalf of the French Ministry for Higher Education and Research; they make it possible for a company to receive a yearly, fixed subsidy, to make good the costs incurred in employing a young postgraduate, taken on for a period of three years.

"sky" components from these maps. This operation is known as "source separation" (see Figure 5). In practice, instrumental effects (noise…) must also be taken into account, these further compounding the complexity of achieving such separation. A data restoration problem is thus superimposed on the source separation problem. Using a method known as generalized morphological component analysis (GMCA), based on the **wavelet transform**, it becomes feasible to reconstruct the diffuse cosmic background. The principle involved relies on the fact that the mix of components makes the images more complex, and that, by using a regularization criterion based on the "simplicity of the solution" for the separation problem, the sought-for components may be recovered. With this approach, a "simple" image can be represented, in terms of wavelets, with a small number of coefficients; this is a so-called sparse solution (see Figure 6).

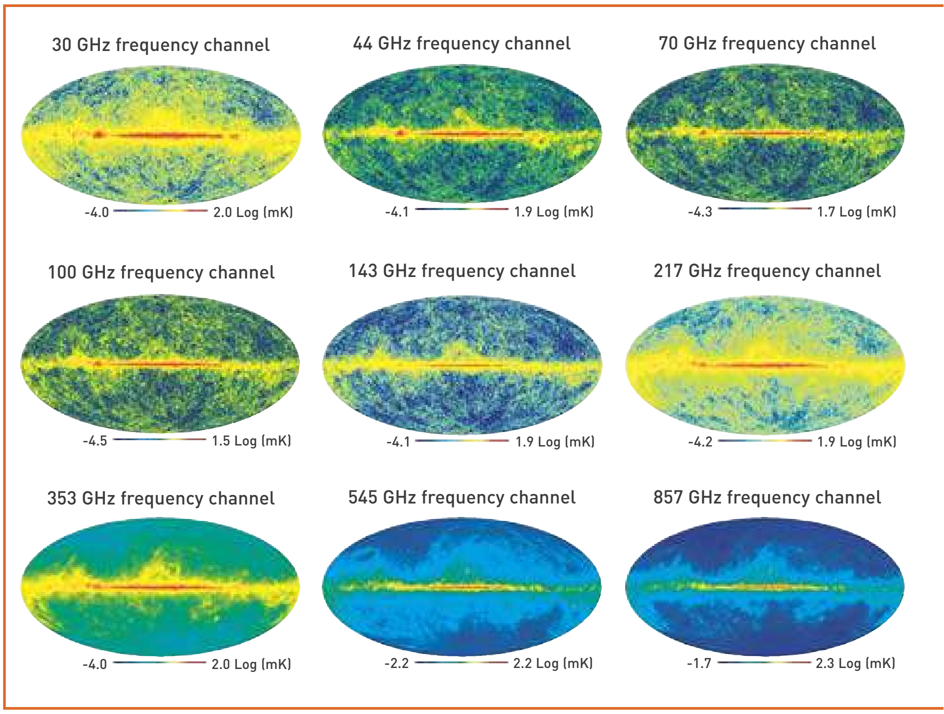

Figure 5.
Simulation of the nine Planck maps. By way of example, in order to obtain the cosmic microwave background, the contribution from the other observational components must be subtracted.
Value scale: these are temperature maps, drawn up in millikelvins (mK), to achieve sufficient contrast; the logarithmic scales for the maps are shown.

Statistical tests on the cosmic microwave background

Some applications call for elaborate statistical tools, for the purposes of evidencing exceedingly faint signals, drowned in noise. Interesting instances of this include the detection of **non-Gaussian sources** in the cosmic **microwave** background (CMB). The CMB is the outcome of the decoupling of matter, and **radiation**, occurring at a cosmological redshift of 1,000. This stands as a "relic" from the first moments of the Universe, helping to understand how structures formed, and evolved, by way of amplification of the initial fluctuations. The statistical properties exhibited by the temperature anisotropies in the CMB thus yield information as to the physics of the **primordial Universe**. Indeed, while their distribution is Gaussian, they arise by way of simple inflation models. Failing which, they may be yielded by topological defects, such as cosmic strings. Anisotropies may also arise from the interaction of CMB photons with free **electrons** in intracluster hot gas: this is the **Sunyaev–Zeldovich effect** (see Figure 7). In order to identify very faint non-Gaussian signatures, highly sensitive statistical tests are required. These could be derived from the statistical study of the distribution of coefficients yielded by multiscale methods. Wavelets are well suited to the analysis of spatially **isotropic** structures, and contribute to the detection of the Sunyaev–Zeldovich effect, while curvelet functions prove optimal, for the purposes of looking for spatially anisotropic structures. Combining these two multiscale transforms makes it possible not just to detect, in optimal fashion, the anisotropies arising in the CMB, but equally for their origin to be determined, a result that would be impossible, using conventional methods.

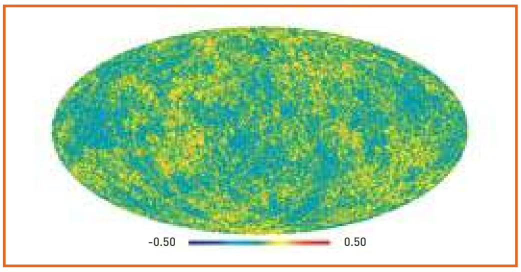

Figure 6.
Map of the cosmic microwave background, obtained through use of GMCA from the nine maps shown in Figure 5.

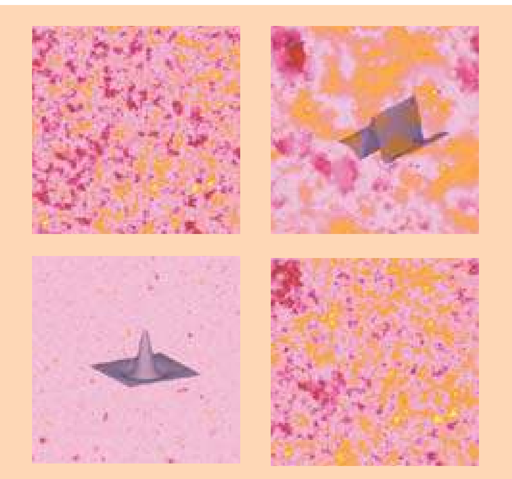

Figure 7.
Of these four maps, the first three are simulations of the CMB, of the Sunyaev–Zeldovich effect (top right), and of cosmic strings (bottom left). The fourth map shows a mix of these three components (bottom right), this being the type of data that might be delivered by the Planck mission. The wavelet function is shown overprinted, top right; likewise, the curvelet function is overprinted bottom left.

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Numerical simulation in astrophysics

The one-on-one dialog between theory and observation has given way, for some years now, to the triptych theory–simulation–observation. Between theoretical models that are ever more complex, and observation, which yet stands as the ultimate test, for the purposes of validating theories, numerical simulation now stands as a bridging link.

Information technology and theoretical predictions in astrophysics

For the most part, physical theories are grounded in complex, nonlinear equations. They further involve dynamic systems that are liable to promote chaotic behavior, and unpredictability. Should information technology support be lacking, it would prove virtually impossible to compute predictions for a theory, particularly in astrophysics.

A Bull supercomputer at CEA's Research and Technology Computation Center (CCRT: *Centre de calcul recherche et technologie*).

CEA

Whereas physical sciences, for the most part, are able to simplify, to the utmost, their experimental setups, and apparatus, so as to stay with just the one elementary process being investigated, no such ability arises, in the field of astronomical observation. The reason for this situation stems from the impossibility faced by researchers, of acting on the subject of their investigation: as a rule, they are only able to arrive at partial measurements, made on complex objects, standing in a variety of – usually unverifiable – dynamic states. This accounts for the fundamental role played by **simulation** (see Box), in providing the link between theory, and observation. Simulation further makes it possible to explore some of the properties in the models, by carrying out numerical experiments: the aim, in such cases, is not so much that of comparing theory, and experiment, rather it is one of exploring the consequences entailed by this or that model. In astrophysics, **gravity**, hydrodynamics, **radiation**, and the **magnetic field** stand as the four main models calling for description.

Gravity

Gravity is the main force involved in the formation of cosmic structures, irrespective of scale. Ranking among the largest such structures are **galaxy clusters**, dominated by **dark matter**, for which gravity is the sole interaction force. The inventory of smaller structures includes, in particular, **stars**, and **planets** in the process of formation. In the latter cases, conventional,

Processing units working with symphonic precision for the purposes of numerical simulation

Operating as a highly technical tool, numerical simulation starts with the translation, in the form of algorithms, of the set of model equations describing the theory subject to validation. As these algorithms only provide a computational approximation of the model equations, stable, accurate algorithms must then be developed, yielding a solution that comes close to physical reality. This operation comes under the realm of applied mathematics, which alone provides the ability to devise, and validate such algorithms. In astrophysics, the chief physical phenomena for which a description is sought are the following four: gravity, hydrodynamics, radiation, and the magnetic field. In these particular domains, it is often the case that algorithms must be developed, that have no counterpart in other realms of physics (particularly so as regards gravity), even though it does occasionally prove possible to make use of work carried out for industry (on fluid mechanics, for instance). Numerical simulation further entails that perfect mastery be achieved, with respect to the computing tool, supercomputers in particular. In astrophysics, models require ever larger amounts of memory, and computing power, if they are to achieve sufficient realism. This has spurred the development of complex applications, executing our algorithms over parallel architectures, for which purpose several thousand processing units work together, with symphonic precision. The development, and use of these complex applications puts one in mind of the challenges set by space instrumentation. Keeping to this metaphor, supercomputers may be seen as the new launchers, the applications developed as the new detectors. At the present time, simulation has still got no further than the pioneering stage, however, one may be confident the coming years will see accelerating growth.

so-called **baryonic** matter is dominant, with regard to mass. **Gravity** still stands as the fundamental force governing structure formation, however all of the hydrodynamic, and magnetic processes, along with processes of coupling with radiation are now also involved. **Modeling** gravity thus concerns all of astrophysics.

For the purposes of representing a mass distribution, the classical method involves the use of numerical "particles," every one of which is assigned its own mass, position, velocity, and constitution: dark matter, star, gas cloud, planet… Depending on the problem, and the computers involved, the number N of such particles may run into millions, or even billions, in modern, state-of-the-art simulations. As such simulations are broken down into successive **time steps**, one issue commonly arises, to wit that of computing, as accurately as possible, the gravitational force a particle is subjected to, this force being exerted by the $N-1$ remaining particles. The most straightforward – and most accurate – technique involves computing that force for every possible pair of particles, and then adding up the results. However, this method calls for $N(N-1)$ distance calculations, this entailing a prohibitive computation time, should the simulation involve a large number of particles. For that reason, it is only used for certain specific cases.

Most simulation codes actually compute gravity by means of faster methods, which, by way of slight approximations, allow greater numbers of particles to be taken in, thus making for higher resolution. The two main techniques, treecodes, and "particle-in-cell codes," make it possible to speed up the computation of gravitational forces, by only requiring $N(\log N)$ distance calculations.

- Treecodes, designed in adaptive fashion, prove all the more helpful, in resolving interactions, the closer particles are to one another. Figure 1 shows the

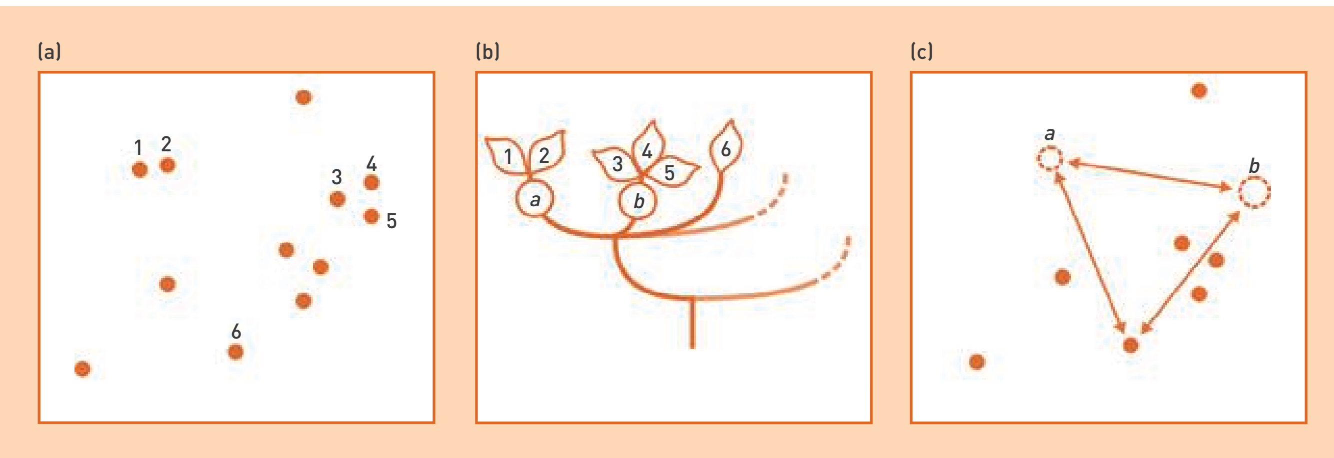

Figure 1.
Particles representing a distribution of massive objects (e.g. stars) are brought together into groups of closest neighbors, at the tip of the branching tree structure of a treecode, which is detailed here as regards particles 1–6. Close-neighbor interactions are computed exactly; these particles are then subsumed into pseudoparticles (a, and b, in this case), to compute interactions at longer ranges.

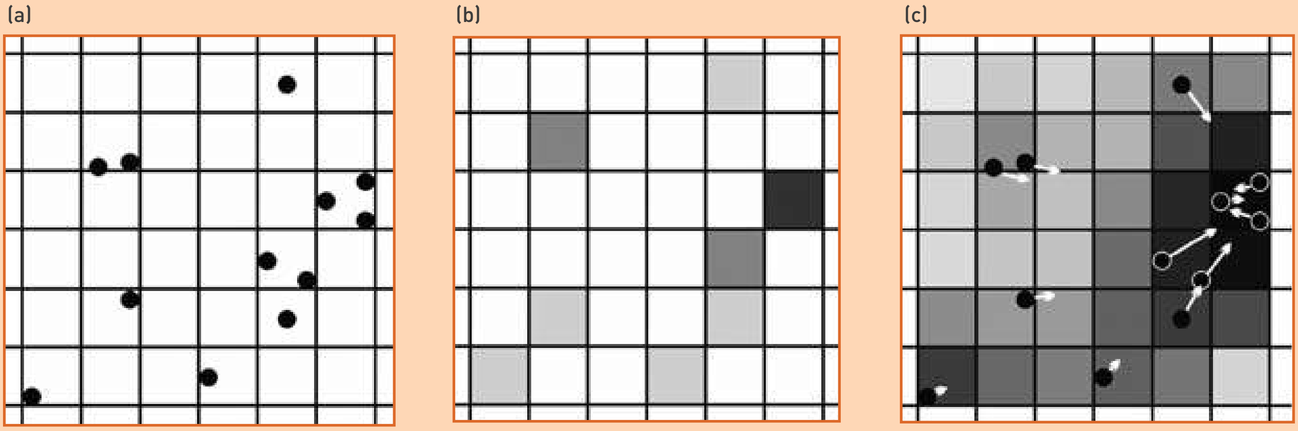

Figure 2.
The same particle distribution, now addressed by way of a particle-in-cell code (a). The operation merging particles across the grid yields a computation of mass density (b: shown in grayscale levels). Solving the Poisson equation allows the gravitational potential to be computed (grid c), on the basis of density; the gravitational force acting on each particle is then computed, on the basis of the particles' positions on the potential grid.

spatial distribution of a few numerical particles. A branching "tree" structure is built up in the computer's memory, bringing together the "closest neighbors." In this figure, two leaves, lying on the same branch in the tree, represent particles 1, and 2. Their gravitational interaction is computed exactly (allowing for computational rounding off), i.e. as being proportional to their masses, and inversely proportional to the square of their distance. The interaction arising between particles 3, 4, and 5 is likewise computed exactly. On the other hand, for particles that are more distant from one another, the estimate of the interaction involved is simplified, to speed up computation. Going down one level on the tree, particles 1 and 2 are substituted for by a single particle *a*, with a mass equal to the sum of the two masses, located at the center of gravity. Distant particle 6 is subjected to a single force, namely that exerted by pseudoparticle *a*, rather than the two forces separately exerted by particles 1, and 2. Likewise, the group formed by particles 3, 4, and 5 is substituted for by another pseudoparticle, *b*, lying at the same level as *a* on the tree. It thus proves sufficient to compute a single force, exerted by particle *a* on particle *b*, rather than the six forces individually exerted by each one of particles 3, 4, and 5 on particles 1, and 2.

Grouping particles together, depending on the various levels on the tree, does not necessarily result in any degradation in terms of precision. Admittedly, the gravitational interaction prevailing between pseudoparticles *a*, and *b* does stand as an approximation of reality, however it does remain reliable, when applied to sufficiently distant particles. Most crucially, on the other hand, the gain in terms of computation time allows a larger number of particles to be taken in by the simulation, thus making for enhanced model precision. Thus, a spiral **galaxy** may contain 100 billion stars, within a disk of 10 **kilparsecs** radius. Exact computation of all of the interactions involved would restrict the number of particles to 10,000 or so, and model **resolution** (i.e. the distance between neighboring particles) would come down to 200 parsecs. Using a treecode makes it possible, for an equal computation time, to model the **disk** by way of 1–10 million particles, making for spatial resolutions of the order of 10 parsecs or so.

The greatest advantage afforded by treecodes is their adaptive design. As computation of interactions becomes more detailed at short distances, resolution becomes optimal, for the purposes of monitoring dense, massive structures. On the other hand, such codes are not ranked among the best performers, when modeling the formation of new structures, in regions that are not already dense. For that reason, structure formation simulations frequently turn to another type of code, so-called "particle-in-cell codes."

• So-called "particle-in-cell" codes partition the region of space being simulated by means of a grid (see Figure 2). In its simplest version, this takes the form of a Cartesian grid, featuring a uniform resolution, i.e. all cells are cubic, and of the same size. As particles are merged across this grid, the first step in the operation involves counting the number of particles present in each cell – in effect, particles positioned close to the edge of a cell are partly assigned to neighboring cells, to enhance computation precision. Once that step is completed, the grid yields the mass density, across the region of space subject to simulation. Solving the **Poisson**(1) **equation** makes it apparent that the gravitational potential may be obtained by way of the convolution of that mass density with the universal function $1/r$, where r stands for the distance from one cell to the next. A number of different computations of that convolution may be carried out, depending on grid shape. For a Cartesian grid, the fastest technique involves effecting the **Fourier**(2) **transform** of the mass density: within the transform space, the convolution

(1) Siméon-Denis Poisson (1781–1840), French mathematician, geometer and physicist; he produced major work on electricity, and magnetism, a discipline of which he was one of the founding fathers. As regards astronomy, he chiefly investigated planetary attraction.

(2) Joseph Fourier (1768–1830), French mathematician and physicist, renowned for his work on the expansion of periodic functions into convergent trigonometric series, known as Fourier series.

reduces down to a conventional product, and the inverse transform then yields the value for the gravitational potential, in every grid cell. The gravitational potential having been ascertained, at this stage, across the entire grid, the code computes the gravitational force acting on each particle, deriving from this the particles' progression, for every time step. The spatial resolution of such a simulation relates to cell size. With sophisticated **algorithms**, the grid may be "refined," by partitioning the cells of greatest interest into smaller units. "Refining" the denser regions is achieved by proceeding as for a tree-code, but equally in accordance with any other criterion related to the issue being investigated (colder regions, presence of **shock-waves**…).
Particle-in-cell codes afford one further advantage, that of allowing a diffuse gas component to be included, e.g. interstellar gas in a galaxy. Such a component conforms to the laws of hydrodynamics, and is no longer represented by way of particles, but by a diffuse mass, contained in every cell. Gravity, as computed across the grid, is applied to this mass, while a variety of techniques are used to solve the hydrodynamic equations. By way of example, the formation of the largest structures in the Universe (galaxy clusters, cosmic filaments) is being successfully investigated by means of particle-in-cell codes (see Figure 3). Cosmological simulations make use of the density fluctuations arising in the **primordial** Universe, as observed in the fossil 3 K background radiation. These simulations compute the amplification undergone by such fluctuations, due to the effects of their own gravity, and the expansion of the Universe. Thus, for the purposes of testing the standard cosmological model, the statistical properties exhibited by galaxies (spatial distribution, mass) are compared with observations.

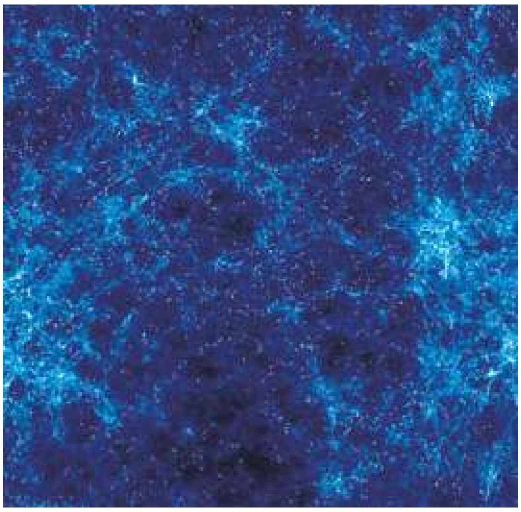
R. Teyssier/CEA

Figure 3.
Cosmological simulation of the formation of large-scale structures in the Universe. The simulation shows the state of the Universe, after some 3 billion years of evolution, in a box extending 50 megaparsecs along each side. At that scale, dark matter is largely predominant, as regards the mass of the Universe. The interaction of this dark matter, purely gravitational as it is, is modeled by means of a "particle-in-cell" code, using a refined grid, making it possible to follow the formation of cosmic filaments, and galaxy clusters. The smallest structures visible in the picture correspond to dark-matter halos, each containing a galaxy.

Particles and collisions

Interactions between particles, in the Universe, are chiefly governed by gravity. As regards **dark matter**, this is indeed the sole interaction possible. It is thought no other (short-range) force exists that could account for the paths followed by these strange particles. This dark matter stands as a "noncollisional" fluid, just like the **stars** in a **galaxy**, which are so distant from one another (related to their size) that they virtually never collide. **Modeling** entails using the **Vlasov–Poisson equation**. On the other hand, certain systems, e.g. the gas clouds (**nebulae**) in a galaxy, or the **planetesimals** in a protoplanetary **disk**, exhibit individual dimensions that are no longer negligible, compared with their separation. Such objects come into collision with one another to an extent that alters the path of each of the objects involved. Thereafter, their fates differ. Within a galaxy, interstellar clouds rebound against one another, by way of inelastic collisions, which dissipate part of their kinetic energy; planetesimals within a protoplanetary disk aggregate to form objects of increasing sizes. The numerical simulation of Saturn's rings (see Figure 4) shows the evolution of a system of gravitating, collisional objects. The numerical particles serve to model the planetesimals making up the rings. They interact through gravity, and may aggregate by way of collisions. Such collisions may equally fragment a large body into a number of smaller ones. Gravity forms so-called **Jeans waves**, which propagate across the rings, generating a filamentary morphology. The observable properties of the rings are altered thereby, which can be predicted by such numerical simulations.


S. Charnoz/CEA/Paris-VII (Paris Diderot) University and F. Durillon/Animea

Figure 4.
Simulation of the structure of Saturn's rings, at the scale of a few tens of meters. The numerical particles interact through gravity, and by way of collisions with one another.

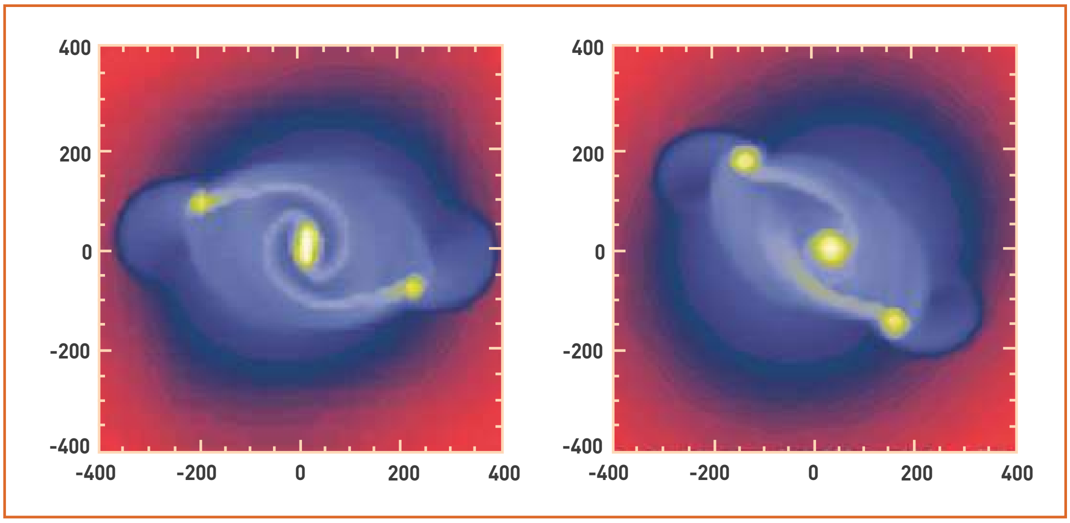

Figure 5.
The formation of a protostellar system within a molecular cloud, using an AMR code on the left, an SPH code on the right. (Distances are given in astronomical units: 1 astronomical unit is equal to the distance from the Earth to the Sun, i.e. 150 million kilometers.)

Hydrodynamics

Ordinary matter (accounting for some 15% of total mass in the Universe) has the specific characteristic of being strongly collisional, while short-range interactions are dominant, in the dynamics of **hydrogen**, and **helium** atoms. Collisions are so numerous, in that medium, that a **plasma** arises, reaching a local thermodynamic equilibrium. Nowadays, researchers are able to describe such a system by way of the **Euler**(3)**–Poisson equations**, which are valid for media governed by collisions, and fluid mechanics. These are the selfsame model equations used by aerospace engineers when studying fluid flows around airplanes, or by climatologists to investigate the physics of the atmosphere. Astrophysicists, in turn, have taken the procedure further, putting forward an original technique, known as smooth-particle hydrodynamics (SPH), having the ability to simulate fluid mechanics, by way of particles. Its advantage stems from its "**Lagrangian**" character, i.e. the sampling points, for the fluid, are particles moving along with the flow.
At the same time, the presence of gravity, in ordinary matter, results in it being concentrated, in many cases, into small, very dense volumes. To investigate such situations, astrophysicists still use the classical techniques serving in hydrodynamics, even though the meshing resolution such techniques involve does not allow very small scales to be accessed. Since the early 1990s, however, a new technique has brought about a revolution in the discipline. This is adaptive mesh refining (AMR), which allows the computation grid to adapt dynamically to cater for flow properties, by adding mesh cells at strategic locations, for computational purposes, with regard particularly to dense regions, covered at small scales. AMR thus combines two advantages: the adaptability of the SPH method, together with the precision, and stability afforded by grid methods. Recent investigations have indeed shown that the SPH method, in the form commonly used, is unable to provide a correct description of such hydrodynamic processes as the **Kelvin–Helmholtz**(4) **instability**. Grid-based methods, e.g. AMR codes, are free from such limitations. On the other hand, with regard to the cool, rotating flows found, in particular, in galaxies, the SPH method may prove more effective than AMR codes. The appropriate strategy thus involves using both methods, and comparing them, in as many cases as feasible. When the results are in agreement, the credibility of the model, obviously, is thereby reinforced. Such was the case, recently, as regards the observation of the collapse of a molecular cloud (see Figure 5). Conversely, such credibility becomes less persuasive, should other physical processes be added in – e.g. magnetized fluids, and radiative hydrodynamics.

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(3) Leonhard Paul Euler (1707–83), Swiss mathematician and physicist; he made major discoveries in the areas of calculus, graph theory, and in mechanics and fluid dynamics, with regard to astronomy.

(4) William Thomson, better known as Lord Kelvin (1824–1907), British physicist, renowned for his work on thermodynamics; Hermann Ludwig Ferdinand von Helmholtz (1821–94), German physiologist and acoustician, and physicist; he became professor of anatomy and physiology in Heidelberg, and subsequently professor of physics, in Berlin.

FOR FURTHER INFORMATION

R. Teyssier ; S. Fromang ; E. Dormy, "Kinematic dynamos using constrained transport with high order Godunov schemes and adaptive mesh refinement", *Journal of Computational Physics* 218, 2006, pp. 44–67.

Radiation

Radiative transfer is that area of physics concerned with describing the propagation of photons, and their interactions with matter. As virtually all of the information we receive from heavenly bodies reaches us in the form of light, the astrophysical community is heavily involved in investigating radiative transfer, to gain an understanding of photon emission, and how these photons propagate to reach us. Radiation thus provides a powerful tool, affording the ability to serve as a diagnostic of the physical conditions (density, pressure, temperature, chemical composition) prevailing in these bodies' interior. This must not be taken as meaning that **radiation** is merely to be seen as a passive element, for diagnostic purposes. Radiation also stands as a major dynamic agent, which must be taken into account, if the formation, and evolution of astrophysical systems is to be reproduced. Currently, with the increasing power afforded by computers, new methods are emerging, making it possible to modelise the dynamical coupling of radiative transfer and hydrodynamics. The present paper sets out an outline overview of the numerical methods relating to radiative transfer.

Owing to the numbers involved, it is as yet unfeasible to describe photons individually. One needs must operate by way of a photon distribution function: $I(x,t,n,\upsilon)$. In this expression, I stands for the number of photons per unit volume at point x, at time t, traveling along direction of propagation n, with frequency υ. The radiative transfer equation determines the evolution, over time and across space, of the distribution function: in the absence of matter, photons propagate in a straight line; however, should they encounter matter, they may be absorbed, or scattered in a different direction, while that matter then emits new photons. The transfer equation then shows that the variation in the number of photons propagating along a given direction is equal to the number of photons emitted, or scattered by matter in that direction, less the number of photons absorbed, or scattered in a different direction.

In theory, following the evolution of the distribution function raises no particular difficulty. In practice, however, this is a problem that is truly fraught with difficulties, and resource-intensive, in terms of computation time. Indeed, aside from the time component, the distribution function is determined by way of further parameters: three for position x, two to set direction n, and a further one for frequency υ. Sampling each parameter, over N points, thus entails that the simulation grid feature N^6 elements, which quickly becomes unmanageable, for "reasonable" values of N. By way of comparison, for a hydrodynamics simulation, only N^3 elements are required, to sample every variable.

In the face of such difficulties, however, inherent as they are in the resolution of the transfer equation, many simplifying approaches are being developed. The simplest such approach involves the assumption of a fully transparent medium – this being the case for many astrophysical systems, in which gas density turns out to be very low. By this assumption, a photon, once emitted, escapes from the system without undergoing any interaction with matter. Ascertaining, or computing its path is thus of no consequence, since all that is needed is to take into account the corresponding loss of energy undergone by the gas. In such a case, researchers tend to speak of cooling, rather than radiative transfer. In technical terms, a term must be inserted, in the equation for the gas energy, to take into account all of the emission processes in the gas, causing that loss of energy. When molecules exhibiting numerous emission lines are found, the processes involved may be complex. Figure 1 shows a density map, yielded by a simulation of the interstellar medium. The small, dense structures (lightest in color) are due to more intense cooling, bringing down internal energy, and thus pressure, in these regions, which are subsequently compressed by the outside medium. This fragmentation process, through thermal instability, stands as an important stage in the formation of protostellar cores, in particular as it determines their mass.

On the other hand, as matter becomes denser, it becomes opaque to radiation, which precludes taking the assumption of a transparent medium as a basis for simulation – this would be a very poor approximation. There is a solution, allowing the method outlined above to be extended, to cover regions that are optically thick: this involves suppressing radiative cooling, above a certain density threshold. This is what happens, in particular, when a **barotropic equation of state**

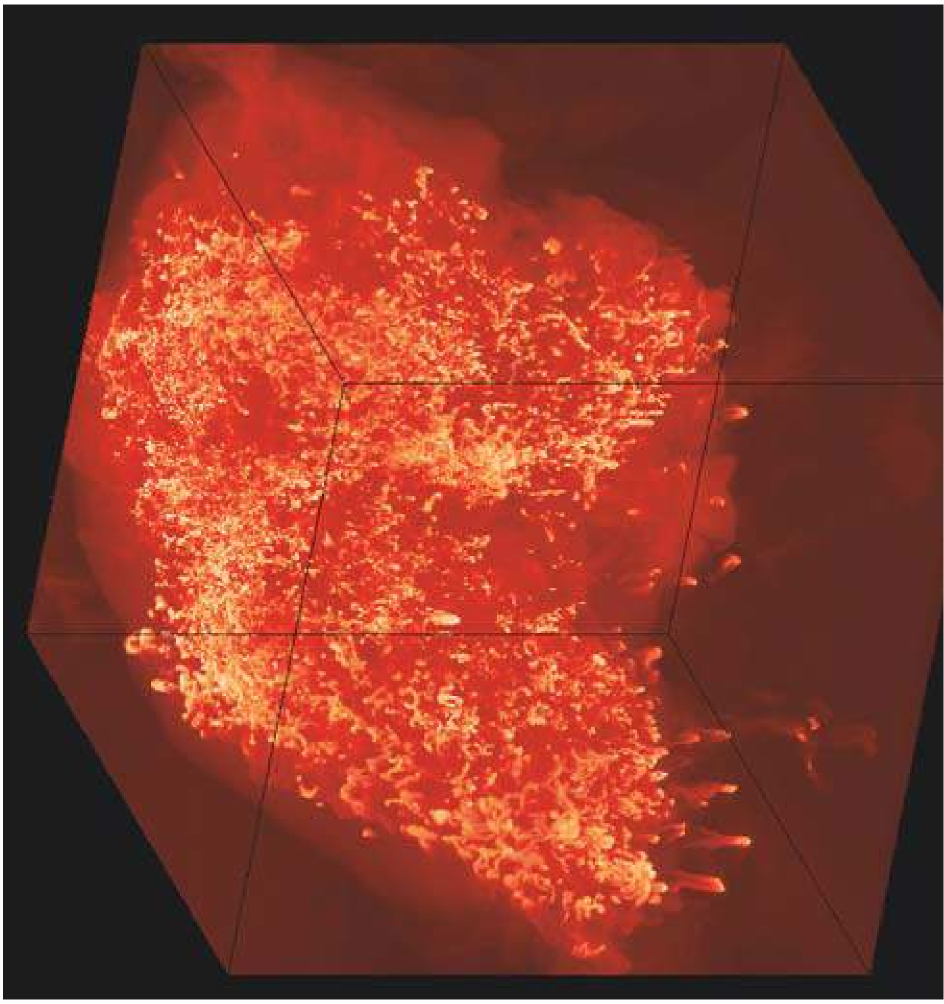

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Figure 1.
Density map from a simulation of the interstellar medium. The simulation domain has an extension of about 50 light-years. The small, dense structures (lightest in color) formed through thermal instability, due to cooling. These are the dense cores, inside which stars are formed.

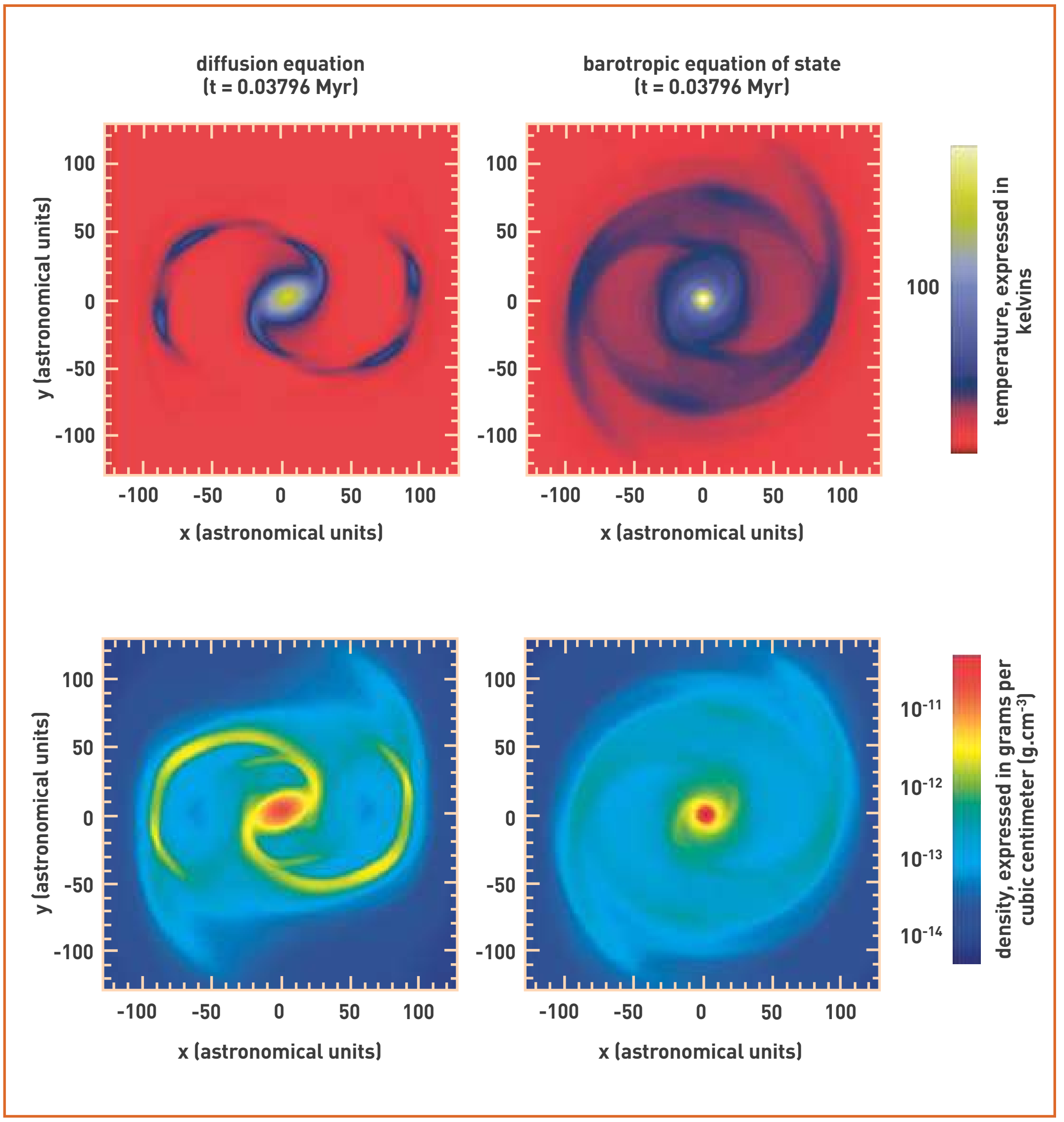

Figure 2.
Simulation of the formation, and fragmentation of a dense protostellar core. The two figures on the left were obtained by using, for radiative transfer, the diffusion approximation; whereas, for the figures on the right, a barotropic equation of state was used. The two figures at the top show temperature maps, while the bottom figures show density maps.
1 astronomical unit is equal to the distance from the Earth to the Sun (150 million km), while t = 0.037 96 million years.

is used, specifying a gas which is isothermal at low density, becoming **adiabatic** above a given "density threshold." As a rule, this threshold is calculated by determining, in one-dimensional simulations involving radiative transfer, the density above which the structure becomes opaque, this being dependent on numerous parameters. The images featured in Figure 2 (right-hand column) illustrate a simulation of the fragmentation of a **protostellar disk**, carried out using a barotropic equation of state.

While they do afford the benefit of simplicity, the approaches outlined above do however fall short in one respect: they involve no transport of energy; while energy may be radiated out of the system investigated, there is no way for it to be transported from one region to another. Recovering this major aspect of radiative transfer entails going for more complex methods, keeping closer to the transfer equation. To avoid using the full transfer equation, which would prove too unwieldy, for numerical purposes, the solution involves using angular averages of the **photon** distribution function, known as "distribution function moments." The zeroth-order angular moment corresponds to radiative energy density, while the first-order moment is radiative flux, the second-order moment radiation pressure, and so on. Starting from the radiative transfer equation, it then becomes possible to set out the equations governing the evolution of these moments. These equations, close to those serving in hydrodynamics, relate the time derivative of the moment of order n to the divergence of the moment of order $n + 1$. It thus proves impossible to achieve a direct integration of this hierarchy of **moment equations**, since, to determine the evolution over time of any particular moment, the subsequent moment must be known. It thus becomes indispensable to work out physical approximations, and introduce a closure relation, whereby one moment is related to lower-order moments. The simplest such model involves retaining just the radiative energy equation (i.e. the

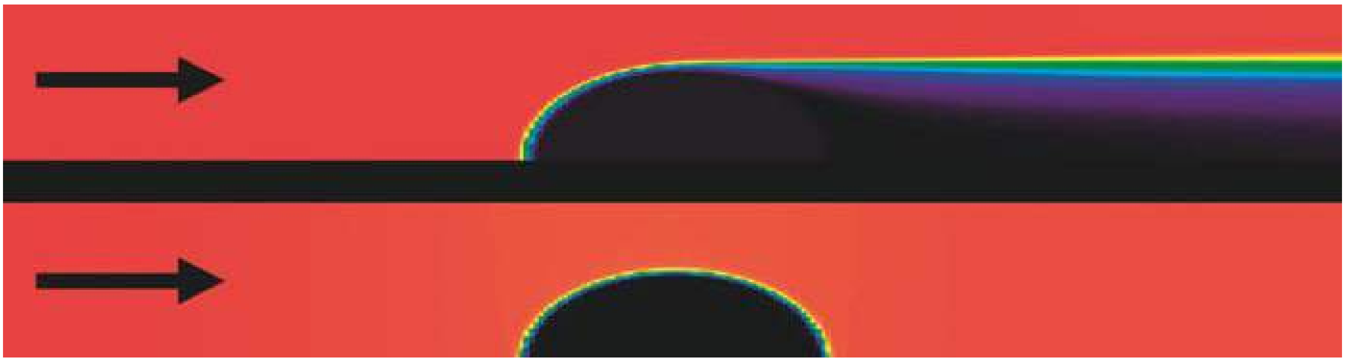

Figure 3.
Simulation of a transparent channel, inside which radiation arrives from the left (arrow), and encounters an opaque obstacle (black oval shape). At the top, using the M_1 model, the shadow behind the obstacle is adequately conserved. By contrast, at bottom, using the diffusion approximation, radiation, propagating along the temperature gradients, now fills the region in shadow.

zeroth-order moment). The closure relation is then obtained by making the assumption that the time derivative of radiative flux is uniformly equal to zero. Operating in this manner makes it possible to obtain just one equation, for radiative energy. This model, which is an exact one for optically thick media, is known as the diffusion approximation. According to this model, radiative energy is transported, from one point to another, along temperature gradients. The two images featured in Figure 2 (left-hand column) illustrate a simulation of the fragmentation of a protostellar disk, involving the use of this diffusion approximation. This yields results notably different to those obtained by way of a barotropic equation of state: for instance, the spiral arms are more sharply delineated. The diffusion approximation thus stands as a considerable advance, compared to the barotropic equation of state.

Nevertheless, it may prove useful to go for slightly more complex models, by retaining two moment equations (for radiative energy, and flux), rather than just one. For models of this type, a closure relation is required that will allow radiation pressure to be calculated, as a function of radiative energy, and flux. Such is the case, e.g., of the so-called M1 model, which calculates radiation pressure by minimizing radiation entropy. The chief advantage afforded by the M1 model is that radiative flux is no longer systematically aligned with the temperature gradient, thus conserving shadows (see Figure 3).

By simplifying, to a considerable extent, the radiative transfer equation, these moment models come down to a system of equations close to that used in hydrodynamics. On the other hand, the fact that the speed of light is high (when related, in particular, to the velocity of the fluids investigated) does mean that the characteristic times relating to radiation are extremely short. There is thus a requirement to integrate – implicitly over time – radiative transfer. This is an operation that entails solving a linear system, coupling all of the points involved in the **numerical simulation**. Aside from being highly computer-intensive, such a solution calls for dedicated, sophisticated **algorithms**, proving effective with "massively parallel" computer systems.

Finally, as and when required (and if it proves feasible!), the transfer equation should be solved by way of as few physical approximations as possible. Such is the case, in particular, when the aim is to effect detailed comparisons with certain observations. Figure 4 corresponds to a computation of radiative transfer inside a dust disk, around a binary **star**. In order to solve the transfer equation exactly, while keeping within acceptable costs, in terms of numerical

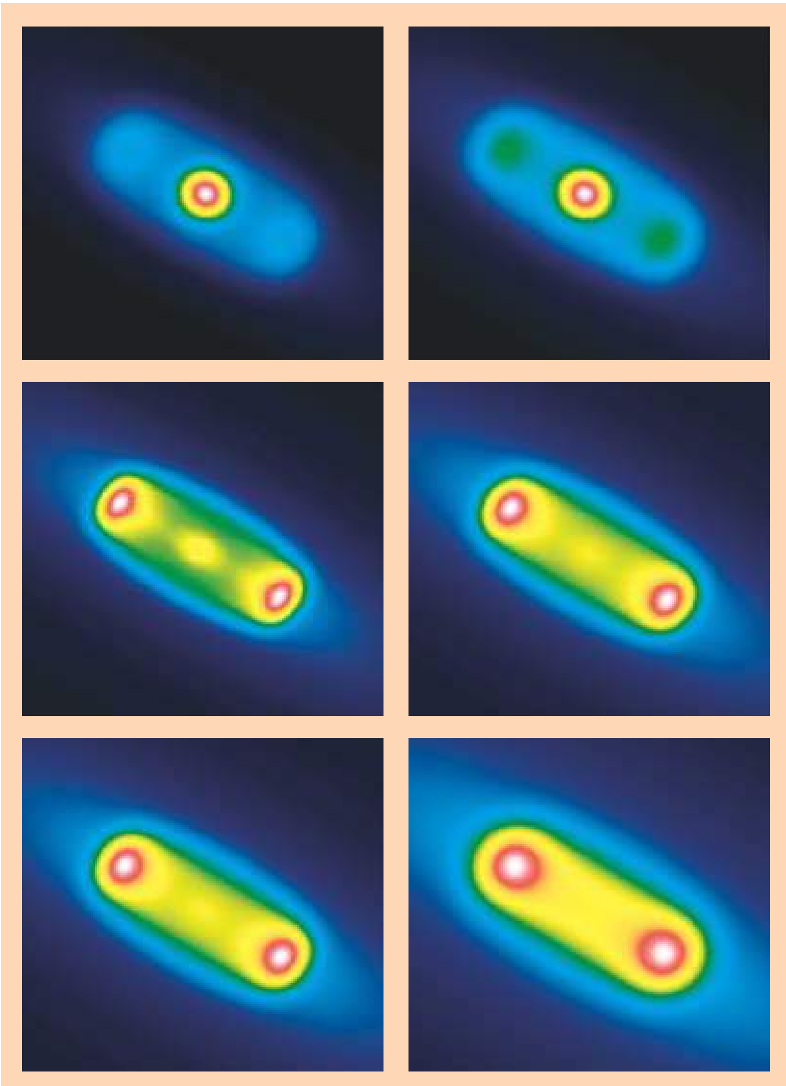

Figure 4.
Simulated images, at various wavelengths, of a dust disk surrounding a binary star. These images may then be directly compared with observations.

computation, the assumption was made that the **disk** exhibited a **cylindrical symmetry**. By way of this geometrical approximation, it proved feasible to compute radiative transfer within the disk, while taking into account, in particular, the complex radiative properties of its constituent dust particles.
Be they simple, or complex, many methods are thus available, for the purposes of **modeling** radiative transfer. The physicist's remit is then to ascertain, as best may be achieved, those physical properties that prove essential, and that are required for the investigation of the problem at hand, in order, ultimately, to strike up the best compromise, between the technical, and numerical constraints, and the physical requirements.

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Magnetism

Across the Universe, the **magnetic field** is present everywhere. In order to gain an understanding of how it arises, and of its influence on the evolution of celestial objects, researchers at CEA are developing high-performance numerical codes affording the ability to monitor the evolution, and the generation of the magnetic field, in such widely different objects as **stars**, **accretion disks**, or **galaxies**. This is one of the major challenges facing astrophysics, in the 21st century.
As the Universe is mainly made of ionized gas (in other words, of plasma, this being the fourth state of matter), the effects of the magnetic field make themselves felt in most celestial objects, since electric currents are able to circulate freely across them. For instance, on Earth, the geomagnetic field acts on compass needles, aligning them with the geographic North, which, as it turns out, is in fact the magnetic South Pole. In the **Sun**, on the other hand, where it is found to be 1,000 times more intense than on Earth, the magnetic field takes on the form, alternately, of bright spots, of sunspots, or of prominences. In galaxies, an ambient field may likewise be observed, of a few micro**gauss**, predominantly along spiral arm. Finally, the interaction set up between two magnetized cosmic structures also proves highly informative, as regards the role played by the magnetic field in the Universe – in the case, e.g., of a star–**planet** system, or of a central object, involving a disk of matter orbiting that object. This prompted this opening remark by Eugene Parker,[(1)] in his book on *Cosmic Magnetic Fields*: "Magnetic fields are commonplace in the laboratory, and even in the home, where their properties are well known. At the large scales involved in the Universe, however, the magnetic field plays a special part, somewhat different from the one it plays in the laboratory. Out in the Universe, the magnetic field behaves like an 'organism,' feeding on the motions generated by stars and galaxies." Thus, it is due to the huge characteristic size exhibited by cosmic conductors[(2)] that the electric currents they hold are determined by the motions of plasma, rather than by electric conductivity. The **Lorentz force** associated to the ambient magnetic field directly acts on the motions of this plasma. The effect of this force can be decomposed into a component related to a magnetic pressure gradient, perpendicular to magnetic field lines, and a second component, linked to the magnetic tension of the field lines along which **Alfven waves** propagate. Owing to the extended cosmic timescales involved, the Lorentz force, though small, when compared with **gravity**, at such large scales, causes systematic, and considerable effects.

• How magnetism arises: the Biermann battery, the dynamo effect.

The Universe is pervaded by an infinitesimal magnetic field. This arises as a result of the existence of unaligned electron density and pressure gradients, the association of which sets up seed magnetic fields: this is the

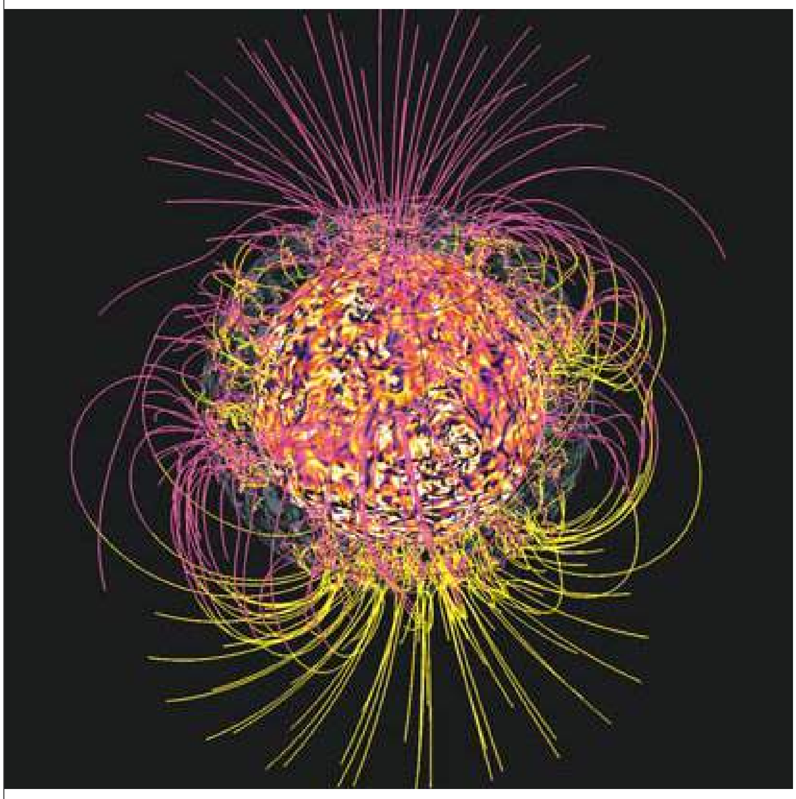

Figure 1.
Magnetic field lines inside, and outside the solar convection zone. Shown in purple are regions heading sunward, in yellow those heading toward the observer.

(1) Eugene Parker (born 1927), US astrophysicist; he developed the theory of the solar wind, and predicted the spiral shape of the magnetic field across the Solar System; he showed that the solar corona consists of a multiplicity of solar nano/micro flares, covering the entire surface of the Sun.

(2) Their magnetic Reynolds number ($R_m = VL/\eta$) is huge (meaning that the plasma is highly turbulent). In this equation, V and L stand for the system's characteristic velocity, and length, while η is the magnetic diffusivity (this being inversely proportional to the plasma's conductivity).

so-called Biermann[3] battery phenomenon. If the magnetic field is to be amplified to higher intensities (from a few microgauss to several hundred billion gauss, as in compact objects), it must either be compressed (owing to the conservation of magnetic flux, field amplitude increases as system size diminishes), or amplified through the action of a fluid dynamo. Let's for instance consider a dynamo on a bicycle. Such device converts mechanical energy provided by the person pedaling (riding) the bicycle into electric energy, in order to power the headlamp. For celestial objects, a similar physical principle is operating, converting kinetic energy into magnetic energy. This principle is dependent on the motions arising in the plasma making up these objects. This has been termed the "fluid dynamo." In all likelihood, this is what has given rise to the magnetism of the Earth, of Jupiter, of the Sun, of some stars, and of galaxies.

• Numerical methods, and the magnetic flux conservation constraint.

Investigating the magnetism exhibited by cosmic objects requires using a dynamic equation, describing the evolution of the magnetic field: this is the induction equation.[4] Analytic solutions are available, to solve this equation for certain simple magnetic configurations. However, most of the problems relating to cosmic magnetism require to the development of multi-D numerical programs, to solve this equation, and resolve its complex behavior. Over the past few years, researchers at CEA have thus developed numerical programs to achieve that goal by way of numerical approximation. This involves coupling nonlinearly the induction equation with the equation of fluid mechanics spectral elements.

• Such is the case for RAMSES, HERACLES, ASH (Anelastic Spherical Harmonics). Many numerical techniques are available, to arrive at a numerical approximation for a partial differential equation (PDE) system: for instance, finite differences, spectral methods, finite elements, or spectral components.

Moreover, two further difficulties arise, as one seeks to model a magnetized plasma, and to understand the evolution of the magnetic field it exhibits: the first difficulty stems from the conservation of the magnetic flux, this being a direct consequence of the Maxwell[5] equations; while the second one is due to the presence of specific types of waves, e.g. incompressible transverse Alfvén waves. The Astrophysics Service (SAp) at

(3) Ludwig Biermann (1907–86), German astrophysicist; he investigated comet tails, and their interactions with the solar wind. He also made contributions to plasma physics, in particular through the investigation of the chromosphere, and the solar corona.

(4) This equation derives from Maxwell's equations, and Ohm's law. As is the case for the latter relations, this is a vectorial partial differential equation:
$\delta B/\delta t = \mathrm{curl}\ (u \times B) - \mathrm{curl}\ (\eta\ \mathrm{curl}\ B)$. The first term represents magnetic field advection, shear, and compression due to motions in the plasma; the second term represents its dissipation by Joule effect ("*B*" stands for the magnetic field, "u" for the velocity field, "curl" denotes the curl [or rotational] of a vector, while "x" is the cross product [vector product], and " δ/δt " is the partial derivative with respect to time).

(5) James Clerk Maxwell (1831–79), British physicist and mathematician, renowned for his unification, into a single set of equations – Maxwell's equations – of electricity, magnetism, and induction, this involving a major modification to Ampere's theorem.

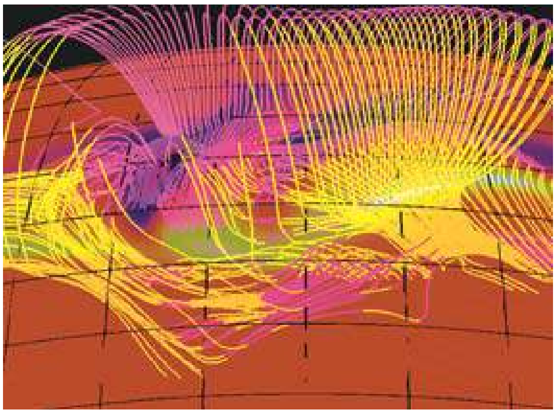

Figure 2.
Emergence of a magnetic flux tube at the surface, in a simulation of solar magnetism, illustrating how sunspots arise. The connectivity exhibited by magnetic field lines may be noted, between the interior, and the lower corona – the surface being materialized by the semi-transparent grid (when shown in yellow, lines are directed toward the reader, in mauve starward).

CEA has made use of finite difference grid methods, and spectral methods, to solve numerically, as precisely as possible, the equations of **magnetohydrodynamics** (MHD). Grid methods afford the advantage of being straightforward to implement, since the equations are directly mapped onto the computation grid. Moreover, such methods prove flexible, as it is always possible to add new grid points, as evolution proceeds (hence the term "adaptive grid"), to enhance numerical precision for the computation, thus allowing to capture shockwaves. On the other hand, they do yield limited precision, depending on the order of the expansion used to estimate derivatives, gradients and suchlike, occurring in MHD PDE systems. By contrast, the advantage afforded by the second approach, involving so-called spectral methods, is its precision: in this case, spatial derivatives reduce to products in the spectral space, rather than variations. These spectral methods rely on direct (forward) and indirect (back-

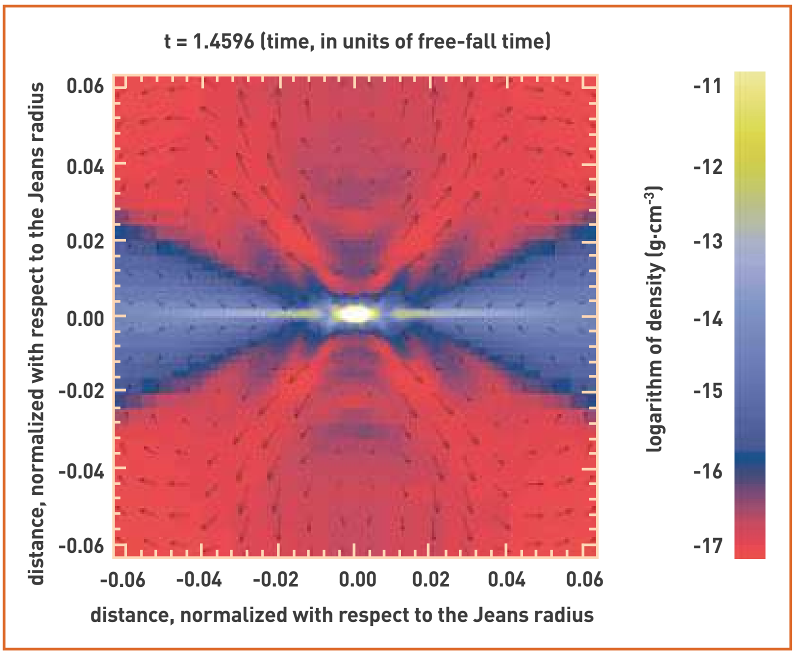

Figure 3.
Formation of a circumstellar disk by the gravitational collapse of a cloud of ionized gas, pervaded by a magnetic field.

ward) transformations, mapping from the physical (actual) space to the spectral space, and inversely. If nonlinear terms are to be estimate it is easier to compute them in physical space and to transform them back to spectral space in order to avoid evaluating costly convolution integrals. For most of these transformations, **algorithms** are available, involving **Fourier transforms**, this making them highly effective, and fast, for numerical purposes (fast Fourier transform [FFT]). On the other hand, spectral methods prove less effective if shockwaves are to be captured, as discontinuities are not readily described by way of trigonometric functions (they give rise to the so-called Gibbs ringing phenomenon).(6) To comply with the magnetic flux conservation constraints, researchers may choose between two strategies, either using the so-called "toroidal-poloidal field decomposition" method; or the so-called "constrained flux" method. The former approach involves introducing the constraint directly into the equations, this resulting in an increased order for the system of equations that must be solved: as a result, the evaluation is no longer concerned with the magnetic field, rather it addresses the magnetic potentials from which that field derives. This strategy proves particularly suitable for spectral methods, in which successive derivatives remain precise. On the other hand, a so-called "constrained flow" method is best used, with grids serving to capture shockwaves – e.g. the so-called Godunov method, or the piecewise parabolic method (PPM); these are numerical methods that make a specific treatment of discontinuities, reducing the amount of smoothing of the shockwaves, that more conventional methods usually impose.

The so-called "constrained flow" method is based on the fact that the integral of the divergence of the magnetic field, over the volume element, reduces down to the surface integral of the magnetic flux, determined at the center of the surface. Now, using the induction equation in its ideal approximation (i.e. disregarding the effects related to the plasma's finite electric conductivity), this surface integral of the magnetic flux may be related to the calculation of the circulation of an electromotive force (emf).(7) A straightforward summation of the contributions from the various electromotive forces, arising along the various segments making up the contour (e.g. the four sides of a square), shows these contributions cancel each other out, in pairs, leaving the magnetic flux unchanged. Consequently, if a simulation is initiated with zero magnetic flux, it will retain that value, within the precision allowed by the machine. In MHD simulations, the number of waves types properly taken into account depends on the basic assumptions made to model the evolution of the plasma : whether it is incompressible, anelastic or fully compressive. For instance, in the ASH code, Alfven waves and slow magneto-acoustic waves are adequately taken into account, whereas it is not the case for purely compressible waves. By contrast, with the RAMSES code, all waves are taken on board, even compressional waves, or shockwaves. This code uses an ideal MHD approach in which dissipation is purely numerical in order to stabilize the numerical scheme. **Modeling** cosmic magnetism requires the development of codes designed for massively parallel infrastructures, having the ability to complete computations in a matter of days, or weeks, where personal computers would take decades. Such machines are to be found, in particular, at the Research and Technology Computation Center (CCRT: **Centre de calcul recherche et technologie**), one of the components in CEA's science computation complex, sited at Bruyères-le-Châtel (DAM–Île-de-France Center), near Paris, or at France's National Large-scale Intensive Computation Facility (GENCI: Grand Équipement national de calcul intensif).(8) Here again, SAp has developed several strategies: parallelism by way of a decomposition of domains (with subdomains distributed across processors), or parallelism in the spectral space (wave numbers being distributed). Depending on the choice of astrophysical problem, the numerical methods used to solve the MHD system of equation may be highly diverse, even though the initial physical equations are similar. Figures 1, 2, 3, and 4

celestial body	**amplitude** of magnetic field *B* in gauss (G)	**field characteristic size (*L*)** or shape (topology)
intergalactic field	10^{-9}	
galaxy	$2 \cdot 10^{-6}$	B regular, L ~ several kiloparsecs
interstellar cloud	10^{-5}	10 parsecs
maser, dense cold cloud	10^{-2}–10^{-3}	< 10^{16} cm
quasar (radiogalaxy)	100	~ 1 parsec
Sun		
poloidal field	1–10	0.1–1 solar radius (dipole, and quadrupole)
toroidal field	> 10^3	5,000–50,000 km
coronal field	10^{-5}	several solar radii
Ap stars	10^4	oblique dipole, starpole
white dwarfs	10^6–10^8	dipole
pulsar (neutron star)	10^{12} (magnetar: 10^{15})	dipole
X-ray binary (black hole type)	10^{-9}	3–100 gravitational radii (R)
planets		
Earth	0.5–1	several Earth radii
Jupiter	4	several Jupiter radii
Saturn	0.2–0.4	several Saturn radii
Mercury	$5 \cdot 10^{-3}$	1–2 Mercury radii
Mars	< $3 \cdot 10^{-4}$	relic, in the crust

Cosmic magnetism properties, as exhibited by a variety of celestial objects. Listed here are typical magnetic field amplitude, in gauss (10^4 G = 1 tesla), and characteristic size (*L*). Observational methods, for the magnetic field, essentially rely on three approaches: the polarization of light passing through the magnetic field of the object being observed (Hanle effect, Faraday rotation); or the alteration of the energy levels in atoms immersed in a magnetic field (Zeeman effect); or the cyclotron, or synchrotron emission from electrons following a gyrating motion along the object's field lines.

(6) This is a form of numerical noise, characterized by concentric rings appearing around the more abrupt structures.

(7) emf = *u x B* ("*u*" standing for the plasma's velocity, "*B*" for the magnetic field, while "*x*" denotes the cross product [vector product]).

(8) Set up as a French nontrading private-sector company (*société civile*), 50% of its equity being held by the French state, represented by the Ministry of Research and Higher Education, 20% by CEA, 20% by CNRS, and 10% by French universities.

show 3-D MHD simulations illustrating results recently obtained by SAp, regarding cosmic magnetism. The computation of the dynamo effect, and solar magnetic activity, using ASH (see Figure 1), exhibits how effective turbulent convection can be to generate and sustain magnetic field at all spatial scales (including at scales larger than that of the flow involved: the so-called large-scale dynamo effect). It also made it possible to highlight the role played by the **tachocline**, at the base of this convection region, in organizing the field in the form of "ribbons," and contributing to the setting up of an 11-year cycle; and to arrive at a quantitative estimate of the feedback from the Lorentz force on mean flow, and on the emergence of a magnetic flux at the surface of the Sun (see Figure 2). Finally, through the computations carried out with RAMSES, it further proved possible to model the ambipolar diffusion, and the regulating role played by the magnetic field, in star formation, promoting collapse along field lines, rather than perpendicular to them, and the formation of jets along the axis of rotation of the central body (see Figure 3); or the organization of the magnetic field along the spiral arms of galaxies (see Figure 4).

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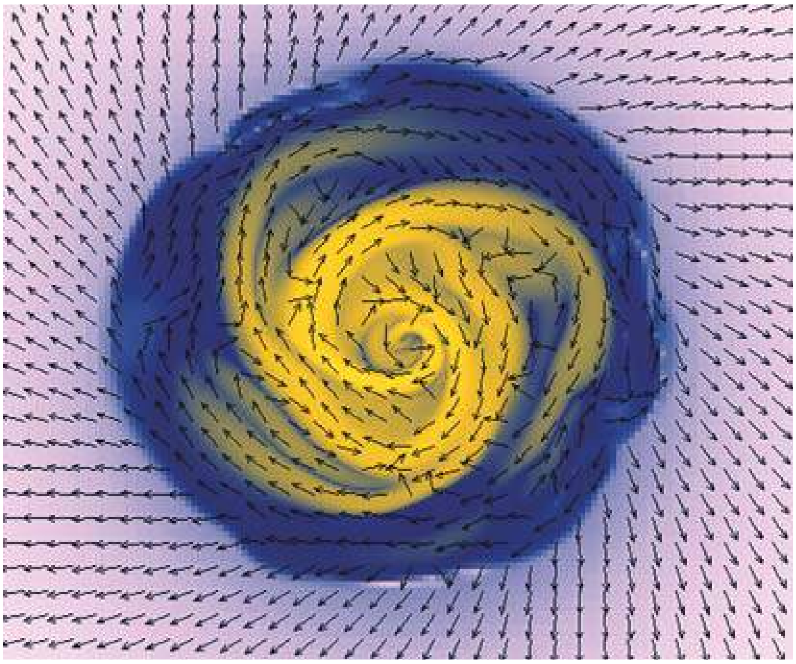


Figure 4.
A galactic disk, seen from above, showing the logarithm of density (the galaxy's spiral arms may be noted), and the way the magnetic field is organized (arrows) along the arms.

FOR FURTHER INFORMATION

A. S. Brun, M. Miesch, J. Toomre, Global-Scale Turbulent Convection and Magnetic Dynamo Action in the Solar Envelope, *Astrophysical Journal* 614, 2004, pp. 1073–1098.

Supercomputers for a better understanding of the Universe

The spread of parallelism throughout the pyramid of information technology, and the taking on board of a multiplicity of constraints, e.g. data management, or the hierarchical architecture implemented by supercomputers, have plunged scientific computation specialists in turmoil. Indeed, the setting up, the use, and administration of their new computing resources are now implemented in the manner of very large facilities, and the user community needs must, therefore, learn to organize into multidisciplinary teams around these resources.

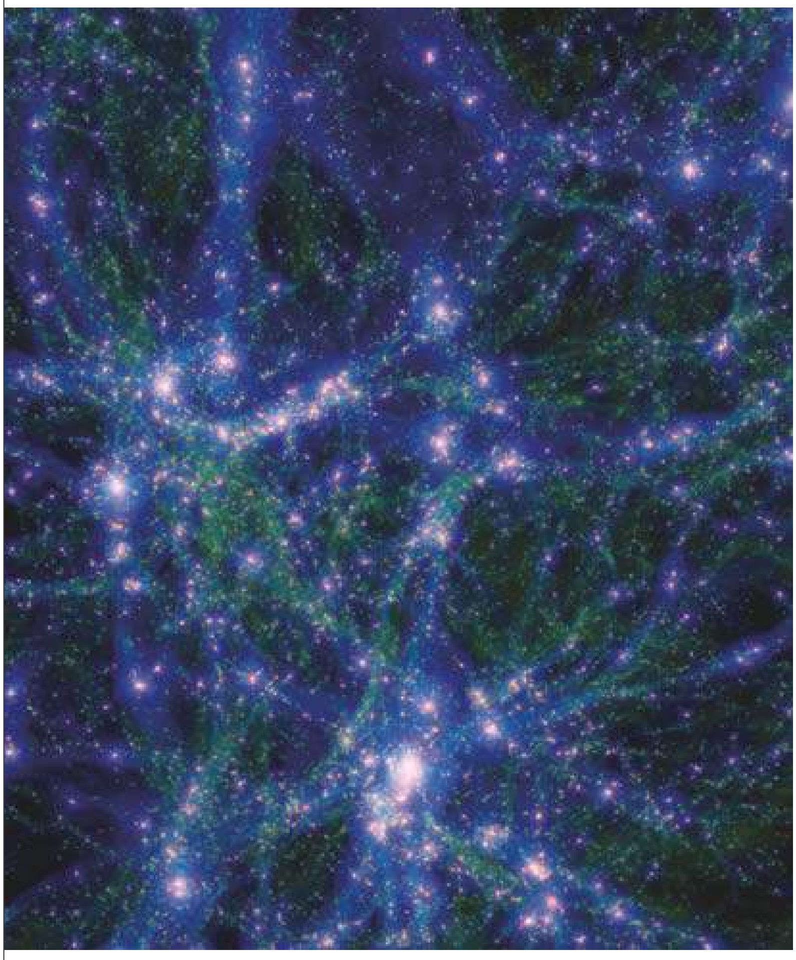
CEA

A Bull hybrid supercomputer, set up at CCRT in 2009.

Thus, if they are to carry through, successfully, the switches in scale brought about by the advances experienced in the field of high-performance computing (HPC), researchers at work in fundamental, and applied sciences needs must have access to computing resources, possibly to the extent of having full use of an entire computer, for limited intervals at any rate. There is a favorable time, lending itself to usage for so-called "grand challenge" purposes. This is the period during which the machine is being put on stream, this extending some 3–6 months subsequent to the computer passing its acceptance tests. There is a very good reason for this, since this is a privileged time, during which the teams working at the computing center (systems engineers, applications specialists), along with the experts from the computer company, are brought together, on call at the site to iron out any issue that may arise, related to the instrument's startup. Researchers are then able to benefit from this close collaboration, set up between specialists, to optimize their simulation software, with the hope of achieving further progress, and new stages, on their way to carrying out very-large-scale simulations. Thus, simulations involving several thousand processors, which, not so long ago, would still have been something of a technical challenge, are now quite commonplace.

In astrophysics, grand challenges have the purpose of achieving improved consideration of the cross-scale couplings inherent in most of the phenomena encountered, by means of enhanced spatial, and/or temporal resolution. The very large amounts of memory available in supercomputers, combined with innovative numerical techniques, favor the achievement of ever higher spatial precisions. The goal remains that of getting close to the dissipation scales involved in **turbulent** flows, of resolving protostellar cores, when simulating a molecular cloud, or of achieving the finescale simulation of **galaxies**, in a cosmological context. This latter issue gave rise, in 2007, to the RAMSES code, developed by SAp, for the purposes of investigating large structure formation, and galaxy formation. This is a code drawn up under the aegis of the Horizon project, which has the purpose of bringing together numerical simulation activities around one program, aimed at studying galaxy formation. This appraisal was carried through during the period when the Bull Platine computer was starting up, at CEA's Research and Technology Computation Center (CCRT: Centre de calcul recherche et technologie), with the target being set of simulating one half of the observable Universe. For the first time in the history of scientific computing, it proved feasible to describe a galaxy such as the **Milky Way**, by way of more than one hundred particles, while covering half of the observable Universe. In order to simulate such a volume, in so much detail, the protagonists in the Horizon project made use of 6,144 of the Intel Itanium–2® processors in the Bull Platine computer, to activate the RAMSES code at its full capacity. This simulation software package makes use of an adaptive grid, allowing hitherto unequaled spatial detail to be achieved. Involving as it does close to 70 billion particles, and more than 140 billion grid cells, this grand challenge stands as the absolute record, as regards computer modeling of N-body systems.

This example stands as good evidence that, with regard to simulation, the advances heralded by high-power computers may be achieved only if mastery is gained of the complexity involved – complexity with regard, equally, to the physical models, numerical methods and **algorithms**, and programming and parallel optimization methodologies, and techniques. Further, the requirement to keep down power consumption has promoted the emergence of a new type of supercomputer, having the ability to combine a very large number of general-purpose processors with specialized processors (graphics processing units, reconfigurable processors, vector processors…). By summer 2009, the French scientific community was able to gain access to such hybrid supercomputers, with the Bull machine set up at CCRT. Featuring as it does more than 2,100 new-generation Intel processors, associated to 48 NVIDIA graphics servers, this is the first supercomputer of this type to be set up in Europe.



CEA

The RAMSES code makes it possible to investigate the large-scale structures of the Universe, and galaxy formation. The largest simulation to be carried out of such structures was completed under the aegis of the Horizon project, with support from the French National Agency for Research (ANR: Agence nationale pour la recherche).

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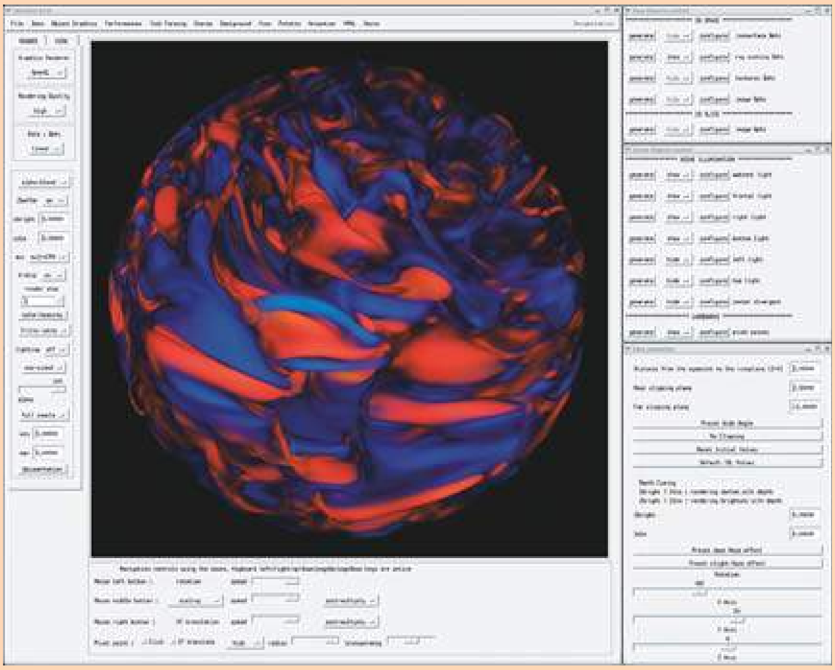
Visualization of astrophysial simulations

Numerical simulations of astrophysical plasmas generate massive and complex data. To understand and interpret these data, astrophysicists use dedicated visualization tools. The SDvision "Saclay Data Visualization" software, developed at Irfu, enables interactive visualization of simulations produced on massively parallel computers, using thousands of processors, producing data with sizes exceeding the terabyte (Figure 1). The complexity of the simulations lies essentially in the implementation of space and time meshes with a resolution that varies as a function of a number of physical criteria. The adaptive mesh refinement technique provides a mean to focus computing time and memory on areas where significant phenomena are developing, as for instance in the case of the formation of galaxy clusters (Figure 2), while much more modest resources are employed in areas with very low densities. The visualization and the analysis of such data structures is a challenge, which has led to the development of the specific algorithms provided in SDvision. This software is suited to different methods of visualization on different media, including local interactive platforms benefitting from hardware acceleration of modern graphics cards, or remote rendering on graphics clusters with important resources. An instrument for data exploration, the SDvision tool allows navigating interactively in immersion inside the simulated volume. This benefits to a wide spectrum of research areas covering multiple scales, such as the formation of large-scale cosmological structures, galaxy formation and interactions, turbulences in the interstellar medium that participate in the creation of the dense protostellar cores where stars are born and nurtured, dynamics of protoplanetary rings, magnetohydrodynamics of the solar convection zone, ... Through the use of the stereoscopic display system at Service d'Astrophysique (Irfu/SAp), the astrophysicists gain a better understanding of the three-dimensional structures of the simulated astrophysical objects and their interactions. These developments, though mainly targeted at the fundamental research in astrophysics, are also benefitting to other areas of research and technology where numerical simulations are employed: for instance, to explore simulations of the turbulent transport in the plasma of the future International Thermonuclear Experimental Reactor (ITER) which is being built in the CEA Cadarache Center, as part of a joint project with the Institut de Recherche sur la Fusion Magnétique (DSM/Irfm).

The increasing computing resources offered by the national computing centers will lead to ever increasingly massive and complex simulations, and new challenges in terms of visualization.



COAST Project

Figure 1.
The SDvision interactive visualization software package, being used, in this instance, to visualize the magnetic field obtained in a simulation of the solar convection zone.

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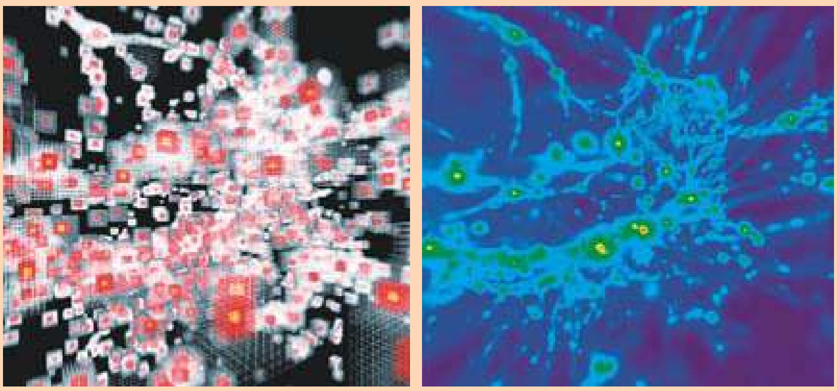

COAST Project

Figure 2
Visualization of a cosmological simulation.
Left: the adaptive-resolution grid used for the simulation, shown here featuring its highest-resolution mesh cells.
Right: matter density distribution, as computed across this grid.

Godunov, a numerical platform for education and research

It has become indispensable to provide tuition in the techniques and methodologies used in modeling, and numerical simulation, to students, graduates and postgraduates, and likewise to researchers and engineers, be they involved in astrophysics or otherwise, seeking to further enhance their education in this field. This was the reason behind the setting up of the Godunov platform in 2007 for training and research (named after Russian mathematician Sergei Konstantinovich Godunov – born 1929 – who developed a classic method of resolution, for the equations used in hydrodynamics). This platform was set up as a collaboration between CEA's Astrophysics Service (SAp), the Materials and Simulation Science Teaching Unit (UESMS: Unité d'enseignement en sciences de la matière et de simulation) at the French National Institute of Nuclear Sciences and Technologies (INSTN), and Paris-VII–Denis-Diderot University.

(1) A technique making it possible to map the distribution of dark matter across the Universe, and to characterize the properties of dark energy.

Sited at CEA's Saclay Center, near Paris, this platform is composed by 20 workstations, connected via fast data link to a computer cluster, to wit a parallel computer featuring 240 computation cores. While the platform is also intended to serve for research purposes, educational activities remain its priority. Thus, during teaching sessions, the cluster stays wholly dedicated to meeting the students' requirements, to allow them to be inducted in high-performance computing, by means of what is at the same time a high-performance tool, and an available one, before going on to pit themselves against larger computers.
Courses are pitched at the postdoctoral level, chiefly in the context of the Astrophysics Doctoral School, but equally as part of master's degree courses, in which the CEA is involved through the INSTN: e.g. Astronomy and Astrophysics, Modeling and Simulation (M2S), Structural and Energy Materials (MSE), Climate–Environment Interaction (ICE). These courses are complemented by two vocational training schemes. One of these, conducted jointly by INSTN and SAp, covers Monte-Carlo methods, and parallel programming methods (MPI library); the other course being dedicated to meeting the needs of the users of CEA's computing center (CCRT).
Aside from its educational remit, the Godunov platform is used for astrophysical data processing purposes. For instance, to fine-tune the data processing algorithms to be used for data yielded by the Gamma-ray Large-Area Telescope (GLAST) satellite – now renamed Fermi Gamma-ray Space Telescope – or to compile the catalog of sources. Other experiments – e.g. weak lensing[1] – can likewise draw on this platform for their computing requirements, which may be large, if of short duration, for image processing purposes.

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CEA/L. Godart

A study session in the computation room of the Godunov platform: plasma simulation.

Institutions and **organizations**: Who does what?

Boeing (the Boeing Company): one of the largest aviation and space manufacturers in the world; its headquarters are located in Chicago, Illinois (USA).

Bologna Observatory: a research instrument for the Italian National Institute of Astrophysics (INAF: Istituto Nazionale di Astrofisica), under the oversight of the Italian Ministry of Research; its researchers are active in various areas of astrophysics, e.g. stars, galaxy structures, and evolution, simulation... in collaboration with many local, and international organizations.

Bull: a French company specializing in professional information technology, including high-performance computers (HPCs).

Centre d'étude spatiale des rayonnements (CESR): the Space Radiation Research Center, a space astrophysics laboratory based in Toulouse (France); a joint research unit, run by **CNRS** and Toulouse-III University, specializing in four main areas: space plasmas, planetary science, the high-energy (X-ray, gamma-ray) Universe, and the cold (infrared, submillimeter) Universe.

Centre de calcul recherche et technologie (CCRT): the Research and Technology Computing Center, a component in CEA's scientific computing complex, sited at Bruyères-le-Châtel (DAM–Île-de-France Center); it was commissioned to meet the requirements of CEA, and its partners, in terms of large-scale numerical simulations, and to promote scientific exchanges, and collaborations, in a context where access to high-performance numerical simulation has become one of the strategic considerations, with regard to competitiveness, for companies, and research organizations.

Centre de données astronomiques de Strasbourg (CDS): the Strasbourg Astronomical Data Center, which collects, and disseminates astronomical data; it hosts the world reference database serving for the identification of astronomical objects.

Centre national d'études spatiales (CNES): the French National Space Research Center, set up as a public-sector establishment of industrial and commercial character (EPIC), charged with defining French space policy within the European Union, as submitted to national government, and with its implementation. To that end, it "invents" the space systems of the future, ensures mastery of the entire range of space technologies, and guarantees France's independent access to space.

Centre national de la recherche scientifique (CNRS): a public-sector establishment of scientific and technological character, carrying out its research activity in all fields of knowledge. The National Institute for the Sciences of the Universe (**INSU**: **Institut national des sciences de l'Univers**) has the remit of defining, developing, and steering research efforts at the national, and international scale, in the fields of astronomy, Earth and ocean science, and space science, carried out within CNRS, and in public-sector educational establishments.

CERN: the European Organization for Nuclear Research, the acronym standing for the name of the initial provisional institution (Conseil européen pour la recherche nucléaire: European Council for Nuclear Research); based at the Franco–Swiss border, this is the largest particle physics center, the world over.

China Aerospace Science and Technology Corporation (CASTC): the Chinese national space agency, set up in 1968 as the China Aerospace Corporation (CASC); it operates under the China National Space Administration (CNSA), and the Commission of Science, Technology and Industry for National Defense (COSTIND), and is involved in the Center for Space Science and Applied Research (CSSAR) of the Chinese Academy of Sciences.

European Southern Observatory (ESO): set up, in 1962, to establish an astronomical observatory in the Southern Hemisphere, this has become the chief protagonist in European observational astronomy, with a fleet of 20 instruments or so (allowing observations to be made in terms of imaging, photometry, spectroscopy, interferometry, at virtually all wavelengths, ranging from the near ultraviolet to the thermal infrared), and three observation sites, in Chile.

European Space Agency (ESA): the organization charged with the development of European space capabilities, and coordinating funding resources from its member states, to undertake programs, and activities beyond the abilities of any one of these states acting individually, with regard to knowledge of the Earth, of the Solar System, and of the Universe; and to develop technologies and satellite services, and promote European industry.

Horizon Project: springing from the coming together of 5 teams, from various French institutes, the Horizon collaborative project aims to use a massively parallel architecture, for the purposes of investigating galaxy formation, in a cosmological context, on the basis of numerical simulations. The aim is to make use of extant centralized computing resources in France (CEA's **CCRT**; Institut du développement et des ressources en informatique scientifique [IDRIS] at **CNRS**; Centre informatique national de l'enseignement supérieur [CINES]), under the aegis of France's National Programs on Cosmology and Galaxies.

Institut d'astrophysique spatiale (IAS): the Institute of Space Astrophysics, a joint research unit run by **CNRS** and Paris-XI (Paris–Sud) University, Orsay, focusing on investigation of the Sun, planets in the Solar System and exoplanets, extraterrestrial and interstellar matter, galaxies and cosmology, space instrumentation, experimental astrochemistry, with reference to extraterrestrial and interstellar solid matter, and the detection of dark matter, using massive bolometers.

Institut für Astronomie und Astrophysik–Tübingen (IAAT): the Tübingen Institute for Astronomy and Astrophysics (Germany): see **Max-Planck-Institut**.

Institut national de physique nucléaire et de physique des particules (IN2P3): the National Institute of Nuclear Physics and Particle Physics, coming under **CNRS**, charged with promoting, and bringing together research activities in the fields of nuclear physics, and high-energy physics; it steers programs concerned with these areas, on behalf of CNRS and French universities, in partnership with CEA; these research activities have the purpose of exploring elementary-particle physics, the fundamental interactions arising between such particles, along with their assembly to form atomic nuclei, and investigating these nuclei.

Instituto de Astrofísica de Canarias (IAC): the Canary Islands Institute of Astrophysics, set up in 1975 at La Laguna university, Tenerife, Canary Islands (Spain).

Japan Aerospace Exploration Agency (JAXA): set up in 2003, as a result of the merger of the Institute of Space and Aeronautical Science (ISAS), dedicated to space and planetary research; the National Aerospace laboratory (NAL), carrying out research and development activities with regard to next-generation aircraft; and the National Space Development Agency (NASDA), charged with development of large-capacity launch vehicles, e.g. the H–2A launcher, and of a number of satellites, together with components of the International Space Station.

Jet Propulsion Laboratory (JPL): a laboratory jointly run by **NASA**, and the California Institute of Technology (CalTech), charged with construction work for, and oversight of, NASA's unmanned space missions.

Laboratoire Astroparticule et cosmologie (APC): the Astroparticle and Cosmology Laboratory, bringing together **CNRS**, CEA, Paris-VII University, the **Observatoire de Paris**, and the Kavli Institute for Particle Astrophysics and Cosmology at Stanford University (USA); it has made possible the setting up of a transatlantic axis, to bolster collaborations, and project coordination in the field of astroparticles (dark energy and dark matter, high-energy gamma-rays and gamma-ray bursts, gravitational waves, theoretical physics, data processing, numerical simulation).

Laboratoire d'astrophysique de Marseille (LAM): the Marseille Astrophysics Laboratory, a joint research unit, run by **CNRS** and Aix–Marseille-I University, combining fundamental research in astrophysics, and technological research in the area of instrumentation; it conducts major programs in the fields of cosmology, of the physics of galaxies, and galaxy evolution, of the interstellar medium, star and planetary formation, the Solar System, and astronomical optics.

Laboratoire d'études spatiales et d'instrumentation en astrophysique (LESIA): the Space Research and Astrophysical Instrumentation Laboratory, one of the five scientific departments at the **Observatoire de Paris–Meudon**, and a **CNRS** laboratory associated to Paris-VI and Paris-VII Universities.

Laboratoire de photonique et de nanostructures: the Photonics and Nanostructures Laboratory, a **CNRS** laboratory set up for the purpose of ensuring the coordinated advancement of fundamental, and applied research, by drawing on, and developing its own areas of technological expertise.

Leiden Observatory: founded in 1633 by Leiden University (Netherlands), to house the quadrant built by Snellius, this is one of the oldest observatories in continued operation. Its astronomy department, the largest in the Netherlands, has gained worldwide recognition for its research work in various areas in astronomy.

Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. (MPG): the Max Planck Society for the Advancement of Science is a German independent, nonprofit public-sector organization, which promotes, and supports the research activities carried out by its own institutes. Set up on 26 February 1948, its activities complement those undertaken by German academia (bringing greater resources, and a truly interdisciplinary character), or work in collaboration with it. MPG thus plays a role similar to that of **CNRS** in France, in supporting fundamental research at an international level. The Society currently has 80 institutes, with a combined staff of 13,000.

Max-Planck-Institut für Astrophysik (MPA): one of the 80 research institutes in **MPG**. Set up in 1958, the **Max-Planck-Institut für Physik und Astrophysik** was split, in 1991, into several institutes: MPA, **MPE**, and the Max-Planck-Institut für Physik (MPP). Based in Garching (Germany) – next door to **ESO** headquarters – MPA addresses many issues in theoretical astrophysics, from stellar evolution to cosmology. It has a staff of 120, including 46 permanent research scientists. Since 1996, MPA is a member of the European Association for Research in Astronomy (EARA), the membership of which includes **IAC**, and the Paris Astrophysics Institute (IAP).

Max-Planck-Institut für extraterrestrische Physik (MPE): one of the 80 research institutes in **MPG**. Set up in 1963, as part of the then **Max-Planck-Institut für Physik und Astrophysik**, MPE became an independent institute in 1991. Based in Garching (Germany), MPE includes, among its main research topics, astronomical observations in those spectral regions that are only accessible from space (far infrared, X-rays, gamma rays), and the physics of cosmic plasmas.

Max-Planck-Institut für Radioastronomie (MPIfR): one of the 80 research institutes in **MPG**. Set up in 1966, from the Institute for Radioastronomy at Bonn University, which went back to the 1950s, MPIfR focuses on searching for astronomical objects in the radio, and infrared regions. The Institute operates a 100-meter diameter radiotelescope, at Effelsberg, commissioned in 1972. MPIfR runs, with **ESO** and **OSO**, the APEX radiotelescope, sited in Chile.

National Aeronautics and Space Administration (NASA): set up on 29 July 1958, on the basis of the erstwhile National Advisory Committee for Aeronautics (NACA), NASA acts as the US space agency, running most civilian space activities in the United States, along with collaborations with agencies in other countries. NASA covers 18 research centers, including the Ames Research Center, at Moffett Field, Mountain View (California), or the **Jet Propulsion Laboratory**, Pasadena (California).

NVIDIA Corporation: a fabless US company (i.e. with a design, but no manufacturing capability), one of the leading suppliers of graphics processing units and cards, chipsets, game consoles...

Observatoire de Paris: set up in 1667, the Paris Observatory is now a "major establishment" under French law, coming under the French Ministry for Higher Education and Research. Its official status is that of a university, and it includes 7 laboratories, operating as joint research units, with **CNRS** and major scientific universities in the Paris area. This national astronomical research center is established at three sites: **Paris**, **Meudon**, and **Nançay** (radiotelescope).

Observatoire des sciences de l'Univers de Grenoble (OSUG): the Grenoble Observatory for the Sciences of the Universe, bringing together 6 laboratories (including the **Astrophysics Laboratory**), and 3 research teams, from Joseph-Fourier University (Grenoble, France), in partnership with **CNRS/INSU**. OSUG focuses on three main topics: the Universe, the dynamics of the Earth, and major natural cycles.

Office national d'études et de recherches aérospatiales (ONERA): the National Aerospace Design and Research Bureau, the prime French player in the field of aeronautical, space, and defense R&T; its remits being to steer and lead aerospace research; support commercial applications for such research, for both French and European industry; set up and operate the associated experimental facilities; provide industry with high-level expert analyses, and other services; carry out in-depth examinations for government services; and train researchers, and engineers.

Onsala Space Observatory (OSO): a Swedish radioastronomy observatory, founded in 1949, coming under the Chalmers University of Technology, this being a private foundation; OSO is partly funded by the Swedish Ministry of Research. This facility operates two radiotelescopes (20-meter, and 25-meter diameter), and is a participant in many international projects, in particular APEX, ALMA, Herschel...

Royal Observatory, Edinburgh (ROE): home to one of the centers of astronomical research in the United Kingdom, which has contributed to the construction of a number of instruments, used in ground-based observatories, or carried on satellites. ROE houses the Crawford Library, one of the most comprehensive astronomical libraries the world over.

SAGEM: a French high-technology manufacturer, a world leader for solutions, and services in optronics, avionics, electronics, and critical software packages, for both civilian and defense markets.

Thales (formerly Thomson–CSF): a French electronics company, specializing in aerospace, defense, information technology, currently a world leader with regard to critical information systems, in the aviation and space, defense, and security markets.

United Nations Educational, Scientific and Cultural Organization (UNESCO): set up in 1945, to promote peace in the minds of men, through education, science, culture, and communication.

Glossary

A

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

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

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

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

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

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

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

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

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

angström (Å): 1 Å = 10^{-10} meter.

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

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

anisotropy: see **isotropy**.

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

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

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

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

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

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

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

B

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

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

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

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

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

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

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

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

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

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

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

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

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

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

C

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

D

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

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

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

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

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

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

E

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

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

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

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

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

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

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

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

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

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

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

F

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

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

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

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

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

G

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

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

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

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

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

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

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

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

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

H

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

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

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

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

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

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

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

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

I

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

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

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

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

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

J

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

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

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

K

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

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

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

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

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

L

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

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

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

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

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

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

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

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

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

M

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

N

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

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

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

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

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

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

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

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

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

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

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

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

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

O

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

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

P

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Q

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

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

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

R

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

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

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

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

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

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

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

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

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

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

S

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

T

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

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

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

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

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

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

V

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

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

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

W

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

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

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

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

Z

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