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LES VOIX
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LATEST NEWS FROM THE OUTER SPACE

CONTEXT – TECHNOLOGIES – SCOPE OF APPLICATIONS – OUTLOOK

BY
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DEFINITION

What is the Universe?

By definition, the Universe is everything that exists. But not all events, not all stars are accessible to us and astrophysicists concretely define the Universe as being everything that they can observe with their instruments. This "observable universe" is necessarily finite for two reasons. Firstly, most of the information we collect on Earth reaches us in the form of light at a variety of wavelengths. We also collect a few particles and, since September 2015, gravitational waves. Light and gravitational waves propagate at the speed of light, which is finite and is approximately 300,000 kilometres per second. Secondly, since the early 20th century, we have known that the objects in the Universe, notably the stars, have not always existed. We can therefore only observe objects that are close enough for their light to have had the time to reach us since they were formed. In other words, when taken together, the finite nature of the speed of light and the finite age of the stars and galaxies mean that only a part of the Universe is directly accessible to us. Our observations are therefore limited by a horizon whose internal volume defines the observable universe the astrophysicists talk about. According to the current cosmological model, this horizon is today 45 billion light years away and the Universe is 13.8 billion years old. In the same way as the maritime horizon, the cosmological horizon depends on the position of the observer in space. It also depends on the time, because every second, information arrives from a little further away, from objects which are just appearing over our horizon.

Another consequence of the finiteness of the speed of light is that an object in the observable universe does not appear as it is at the moment it is observed, but rather as it was at the moment the light which reaches us was emitted: for example, a galaxy appears all the younger, the further away it is. The light rays that we receive weave our cone of light from the past, a set of events linked to our spacetime position – the here and now – from a messenger made of light. We thus only observe a section (our cone of light from the past) of a finite volume of the Universe (the observable universe). Moreover, some of the observable objects escape our detectors owing to their low luminosity due to their considerable spacetime distance. Finally, we only have access to a finite quantity of information, perceived from the "here and now", on the basis of which we aim to reconstruct the content, history and structure of the entire Universe. These obstacles pose the question of the exhaustiveness of this reconstruction using the partial information available and give some idea of the complexity of the task facing astrophysics.

Strangely, on the scale of cosmological time, our situation would appear to be more favourable. At present, the most coherent and robust description of the Universe is the "concordance model", which describes it as a homogeneous, isotropic, infinite space with Euclidian geometry and experiencing accelerated expansion. If this model is correct, there is a boundary beyond which events occur will remain for ever invisible to us, an event horizon limiting our future perception of the Universe. Within this framework, our sky will gradually empty of its galaxies over the course of billions of years, as the increasingly rapid expansion takes them beyond our event horizon. In a far distant future, cosmology – which is already a difficult discipline – could become nearly impossible, with no objects left to observe. The most reasonable model of the Universe will doubtless be that of an island universe consisting solely of our galaxy, which will have merged with that of Andromeda, a model which was already postulated at the very beginning of the 20th century, at the dawn of scientific cosmology! ■

"At present, the most coherent and robust description of the Universe is the "concordance model", which describes it as a homogeneous, isotropic, infinite space with Euclidian geometry and experiencing accelerated expansion."

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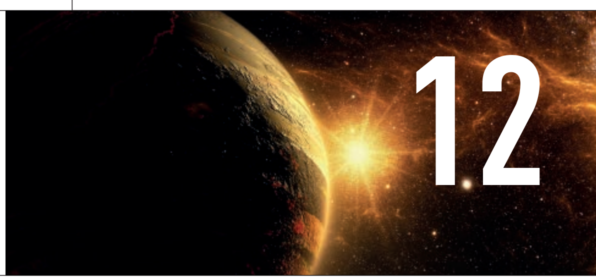

DYNAMICS OF STARS AND EXOPLANETS

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OUTLOOK

The Universe Has More Imagination than Mankind Does.

By Catherine Cesarsky,

astrophysicist and member of the Académie des Sciences

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"Continuing to progress with discoveries in astrophysics demands rigorous programming, not only at the level of a laboratory or a country, but on the scale of a continent or even of the whole world."

In the 20th century, major discoveries in astronomy often happened as a result of serendipity. Outstanding examples are: the microwave background radiation, relic from the Big Bang; quasars, extremely bright sources drawing their intense luminosity from the kinetic energy acquired by matter drawn towards a gigantic black hole; pulsars, magnetised, rotating neutron stars emitting periodic signals; binary star systems emitting strong streams of X rays; gamma ray burst sources and so on. Today, discoveries are programmed. Using extremely precise spectrometers or photometers, astrophysicists have the means of detecting the presence of planets in orbit around stars and prepare specific space missions to attempt to characterise their atmospheres. They construct space missions carrying cooled telescopes with sensors kept at temperatures close to absolute zero, able to detect in the slightest detail the emissions from the cold Universe or the cosmic microwave background. X-ray and gamma-ray sources are being tracked and examined from space, but also from the ground for the highest energy photons.

To gain a clearer understanding of how the Sun works, probes are getting closer and closer to it. Systems capable of detecting the passage of gravitational waves are developed on ground and in space. Once new cutting-edge instruments are deployed and in service, they usually obtain results close to the predictions, but as the Universe always has more imagination than humankind does, there are still many surprises. Thus, the coalescing stellar black holes perceived by the LIGO and VIRGO interferometers were more massive than expected; very massive galaxies were discovered earlier on in the life of the Universe than predicted. Astrophysicists know what they are looking for, they even produce highly detailed advance models of what they expect to find, but in the end, nature decides.

Continuing to progress with discoveries in astrophysics demands rigorous programming, not only at the level of a laboratory or a country, but on the scale of a continent or even of the whole world. Programming at CEA's Astrophysics Department (DAp) is part of this global planning process. Throughout its history, the successful research at the DAp has to a large extent been based on space missions, in partnership with the CNES, which were decided on and implemented within the European Space Agency (ESA), via its successive Horizon 2000 and Horizon 2000+ programmes. In the coming years, the missions of the next programme, Cosmic Vision, will be launched. In 2004, the community formulated a list of essential questions and the programme has been built since then to address them. Even if the DAp is dependent on the choices made by ESA, it is also highly active, first in submitting proposals and then by having researchers involved in the selection process, participating in or chairing ESA committees. Preparations for the future ESA programme, Voyage 2050, which will cover the period 2035-2050, have just begun.

In general, space and ground agency programmes over the world complement each other. For instance, in an attempt to pierce the mystery of the dominant components of the Universe, dark matter and dark energy, ESA is preparing the Euclid mission, while an international telescope, the LSST, is under construction in Chile under American leadership and NASA is studying the WFirst mission.

On ground, European astronomy is in pole position in the field of optics and near infrared, thanks to the European Southern Observatory (ESO). The DAp, which participates in building ESO instruments, is a frequent user of ESO telescopes. The era of worldwide observatories is upon us with, at very high energies, Pierre Auger for cosmic rays and the future CTA for gamma rays, while in radio astronomy, there are the ALMA millimeter and submillimeter array and the future giant SKA radio telescopes. ■


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Astrophysics, a Challenging Technological Quest

BY
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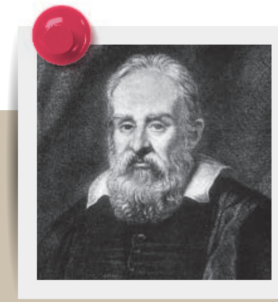
Astrophysics at the CEA developed in the 1960s at a time when space activities were being constructed at the national, European and international levels. NASA was created in 1958, the French Centre National d'Etudes Spatiales (CNES) in 1961 and the European Space Research Organisation in 1965, that led to the European Space Agency (ESA) created in 1975. It was also in 1962 that the European Southern Observatory (ESO) was set up, with the aim of providing Europe with large ground-based astronomy telescopes. France is one of the five founding States of the ESO.

The CEA thus opened the door to space applications. Its 1961 annual report mentions "applications of nuclear electronics for the study of radiation in oceanography, in the atmosphere, in the stratosphere and in astrophysics". The expertise specific to CEA's founding missions, based on radiation-resistant instrumentation (electronics, electron, X-ray and gamma-ray photon detectors), has made it possible to open up a whole range of high-energy astronomy at the CEA, in a period that was rich in discoveries. It was in 1962 that Riccardo Giacconi (United States) discovered the first X-ray source outside our solar system, Scorpius X-1. This binary system consisting of a neutron star accreting matter from its companion star is a powerful source of X-ray emission. This discovery opened up the field of X-ray astronomy (more than 500,000 sources currently identified) and, 40 years later, earned Riccardo Giacconi the Nobel prize in physics (2002). CEA, in partnership with the CNES, then used rockets and balloons to obtain the first measurements of cosmic ray electrons and protons (1963, 1964) and then, in 1965, of X-ray and gamma-ray photons from astrophysical sources. 1965



Galileo Galilei

Galileo was born in Pisa in 1564 and died in Arcetri, near Florence, on 8 January 1642. He was a 17th century Italian mathematician, engineer, physicist and astronomer.

thus marked the birth of astrophysics at CEA, whose 50th anniversary was celebrated at the Cité des sciences in Paris in 2015.

In addition to observations, the modelling and theory of these high-energy sources was developed at CEA: accretion on black holes or neutron stars in binary systems, particle acceleration at the supernova remnant shockwaves, enrichment of intergalactic gas in galaxy clusters. At the same time, technological progress and the development of infrared and submillimetre detectors at the CEA/Leti opened the door in the 1990s to the exploration and study of the cold Universe: from interstellar dust to star formation and the evolution of galaxies.

By its very nature, the observation of the Universe is a challenge. Scientific discoveries are to a large extent based on technological developments enabling our view of the world to be transformed. From Galileo's telescope in 1609 to the instruments located in extreme conditions at 5,000 m altitude in Chile, or on satellites in space, there has been a constant quest to go beyond the performance limits of existing instruments. Astronomical data are obtained by a variety of detection systems, whether in terms of the wavelengths of the electromagnetic spectrum or other messengers, of types of measurement (imaging, spectroscopy, polarisation, etc.) or of methodology (sky scanning, targeted observations, etc.). Signal processing is one of the key tools for extracting from these observations the physical quantities essential to being able to characterise the astrophysical sources.

The Universe which offers itself to our eyes and our sensors and telescopes is often highly complex. It displays, multi-scale spatial structures, multiple physical processes, a wide variety of time scales, and with often nonlinear coupling between the various scales, from the formation of planets to that of stars, from the central black hole to the evolution of host galaxies. Ambitious numerical models are required if one is to be able to understand it.

Understanding the Universe, its formation, its evolution, its composition and its physical laws, requires that theory must be confronted to observations and numerical models to the characterisation of the observed properties of the Universe. This close link between instrumentation, multiwavelength observations and modelling is the very DNA of the astrophysics carried out at Irfu and within its joint research unit, the AIM (Astrophysics, Instrumentation, Modelling). It is built around:

- R&D targeted on sensors benefiting from the CEA's areas of expertise;
- the ability to build and manage instruments or sub-systems;
- extensive expertise in astronomical observations and high-level data analysis;
- the development of innovative statistical tools, combining applied mathematics and astrophysics;
- the development of numerical simulations and ab-initio modelling;
- engaged staff and partners and a strong dynamic of exchange between the various areas of expertise.

"By its very nature, the observation of the Universe is a challenge. Scientific discoveries are to a large extent based on technological developments enabling our view of the world to be transformed."

ESA's XMM-Newton X-ray telescope is the largest space observatory ever built in Europe.

The Technological Challenges for Detection

Our knowledge of the cold Universe has progressed significantly thanks to a complementary range of space observatories launched between 1989 and 2009, covering infrared radiation down to wavelengths of one millimetre (CoBE, ISO, Spitzer, Planck and Herschel). They have revealed where and how stars are born, produced evolution models for interstellar matter over the past five billion years and the conditions prevailing when the Universe was in its infancy.

BY
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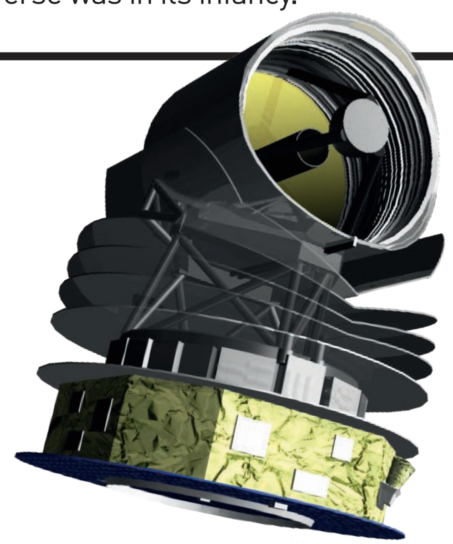
Jean-Marc Duval is head of the CEA Cryocoolers and Space Cryogenics Laboratory (Irig/DSBT).



CRYOGENICS

All these observatories share one common feature and that is they are all based on cryogenic instruments with cooled sensors, sometimes down to a fraction of a degree above absolute zero. The goal is to improve sensitivity by using sensors cooled to the lowest possible temperatures in order to measure an infinitely small variation in signal. The Low-Temperature Systems Department (DSBT) at CEA has for many years been working more particularly to develop evaporative and magnetic cooling systems in the 10 mK (-273.14°C) to 4 K range, suited to the constraints of a space environment. It provided the sub-kelvin cryogenics for the Herschel space observatory at the L2 Lagrange point 1.5 million km from Earth, and those of the instruments at the South Pole (BICEP), in Chile (APEX/ArTéMiS) and in Hawaii (Keck, MegaCam).

One challenge for future space missions is to replace cryogenic liquid tanks by mechanical cryocoolers. This disruptive technology means space and weight savings and, above all, considerably increases the lifetime of the missions. For extremely low temperatures, several systems must be cascaded (cryogenic chain) to cover the entire temperature range. This trend is underpinning developments of all aspects along the chain. This approach applies to the needs of isolated sites – ground telescopes for example – for which the availability of cryogenic fluids such as liquid nitrogen, and of course liquid helium is difficult and/or extremely costly.

The ambitious goals of future astrophysics space missions (ATHENA, SPICA or LiteBIRD) require sensors to be cooled to 50 mK or 100 mK. Building on its heritage, the DSBT has developed and qualified an innovative concept to a high level of technological readiness (TRL6) combining a cooling stage using evaporation and a miniature adiabatic demagnetisation system (Fig. 1). This combination enables temperature of about 20 mK to be achieved with a compact, lightweight system (≈ 5 kg). Other solutions based on a series of magnetic stages enable a wider temperature range to be covered with high efficiency. Work is under way to maximise the cooling power of each of the stages. A prototype has demonstrated cooling to 50 mK from an interface at 4 K and a demonstrator providing a continuous cooling power to 100 mK is currently under development. ■

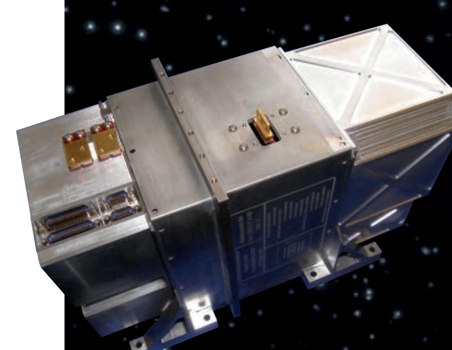


Fig. 1 : engineering model of the 50 mK cryocooler developed for the SPICA mission.

BY
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CRYOGENIC SENSORS

Cryogenic sensors, which are ultra-sensitive to temperature, were patented and developed by CEA for ESA's Herschel space observatory (2009-2013). CEA thus developed the first all-silicon sub-millimetre bolometer arrays (Irfu/DAp and Leti), operating at a temperature of 300 mK to equip the PACS instrument, which was the most extensively used on Herschel. These sensors were then used in the photometer on the CNES PILOT balloon and for the ArTéMiS submillimetre camera on the APEX telescope (Chile).

Today, a new frontier in observation is being opened up with the possibility of measuring terahertz and millimetre polarisation of light, with very high sensitivity. It will in particular give access to traces of primordial gravitational waves embedded in the cosmic microwave background and the magnetic field at work in star formation sites. To this aim, we designed and patented new sensors sensitive to polarised light and operating at 50 mK to reach a very high sensitivity. These sensors, manufactured on Leti's Silicon platform, are produced directly on top of a cryogenic read-out integrated circuit designed by the Microelectronics Laboratory at the CEA Sensors and Computers for Physics Electronics Department (DEDIP), in an above-IC (Integrated Circuit) arrangement. These new sensors are currently under development for the B-BOP instrument (for which CEA is responsible). B-BOP is one of the three instruments of the SPICA space observatory, a candidate for ESA's M5 mission, in collaboration with the Japanese space agency, for launch in 2032.

This approach to integrating instrument functions into the sensor paves the way for new functionalities and improved performance. Spectroscopy, for instance, could benefit from this approach, with the integration of a spectroscopy device very close to these high sensitivity sensors. More recently, we looked at introducing electronic cooling into the detection device using a technology similar to the Peltier effect, which would make it possible to cool only the few micrograms of sensors actually needed for observation of the Universe. These developments were considerably helped by the FOCUS Labex and the CNES. ■

BY
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Olivier Limousin is an instrumentation physicist in the Astrophysics Department (DAp-AIM) and director of cross-disciplinary program on Instrumentation and Detection at CEA.

CdTe SENSORS

At the other end of the electromagnetic spectrum, CEA is developing hard X-ray sensors (from keV to MeV) based on uncooled CdTe (cadmium telluride) semiconductors, associated with application specific integrated circuits (ASIC). These small heavy and dense crystals allow to stop each X-ray photon and to measure their energy individually. The spectral and temporal distribution of the light emitted in this energy band by the accretion disks surrounding black holes or neutron stars, by gamma ray bursts or during supernovae explosions, reveal the physical mechanisms at work in these celestial objects of the violent Universe.

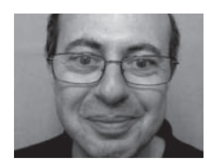
Extensively used in space on the ISGRI instrument on-board ESA's Integral mission since 2002, CdTe/ASIC technology is still the subject of research at CEA for space astrophysics, in order to optimise its performance. Over the past 15 years, thanks to the development of ultra-low-noise and radiation-resistant microelectronic read-out circuits developed at the DEDIP and the optimisation of their integration into 3D modules with finely pixelated crystals, records have been broken using the Caliste technology developed with the help of the 3D PLUS company and the support of the CNES. These small low power consumption components no larger than a cube of sugar offer exceptional modularity in the design of imaging-spectrometers with a wide spectral range and high spatial, spectral and temporal resolution. The technology is deployed in the STIX instrument on-board Solar Orbiter which, in February 2020, will be the first medium-class mission of ESA's Cosmic Vision programme to be launched into space. STIX will observe solar flares when the satellite is close to our star, at a distance of about 43 million km. It will automatically provide spectro-images between 4 and 150 keV. Together with the 9 other instruments in the payload, it will notably help shed light on the sources and acceleration mechanisms for the electrons in these flares. ■

© Getty Images

First NectarCAM being assembled at Irfu (CEA Paris-Saclay).

“Focal planes of Cherenkov telescopes are equipped with cameras with several thousand photomultipliers, able to detect the photons individually.”

BY
JEAN-FRANÇOIS GLICENSTEIN
(Fundamental Research Division)



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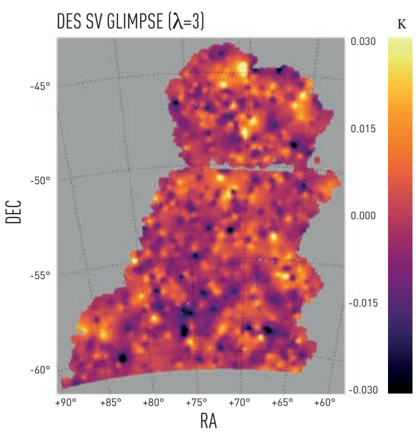
CHERENKOV DETECTORS

The photon fluxes from very high-energy gamma sources (energies larger than 50 GeV) are very small, less than one particle per km² per second. Detecting these photons and identifying their source requires large detection surface areas obtained by using arrays of telescopes on the ground. The very high-energy photons themselves do not reach the ground: they interact in the atmosphere and create particle showers. The imaging atmospheric Cherenkov telescopes capture the Cherenkov radiation from the relativistic charged particles in these showers, which reach the ground in the form of a few tens of optical photons per m². The corresponding flash of light only lasts a few tens of nanoseconds. Focal planes of Cherenkov telescopes are equipped with cameras with several thousand photomultipliers, able to detect the photons individually.

CEA is involved in designing, assembling and testing these cameras – NectarCAM – designed for the CTA very high energy observatory, in partnership with the CNRS and Spanish and German laboratories. Their dimensions are impressive: 3m x 3m x 1.5m and weighing 2 tonnes. They are equipped with 1800 photomultipliers (pixels) giving a field of view of 8 degrees for mapping extended sources such as supernova remnants. The NectarCAM can read 10,000 image sequences per second, with each sequence lasting 60 ns. The current of each pixel is continuously read in a circular buffer, the Nectar chip, designed at the DEDIP. The signal comprising groups of 37 adjacent pixels is evaluated in parallel by a trigger system, which tests for the simultaneous arrival of photons in the focal plane of the camera.

The noise due to the presence of ambient photons such as zodiacal light or stars, which only appears in a single pixel, is thus eliminated. When a signal is detected by the trigger system, the data are digitised by the Nectar chip and transferred to disk via Ethernet. The combined analysis of the shape of the images obtained in several Cherenkov telescopes for the same event enables the kinematics of the photons to be reconstructed and astronomical charts to be produced, after eliminating the atmospheric hadron showers. ■

Fig. 1: image reconstructed using the GLIMPSE method developed at CosmoStat showing the distribution of dark matter in the Universe using data from the DES (Dark Energy Survey) project. The signal-to-noise ratio of the density peaks was improved by a factor of 9 as compared with conventional methods.



The dome of the Victor M. Blanco telescope in Chile

© Reider Hahn, Fermilab

The development of innovative statistical tools

combining applied mathematics and astrophysics

BY
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(Fundamental Research Division)

Jean-Luc Starck is head of CEA's CosmoStat Laboratory (DAp-AIM).

The technological progress related to new instruments leads to new challenges for the scientific exploitation of the acquired data. Indeed, the DES (Dark Energy Survey) project generates 2.5 terabytes (TB) of data per night of observation, the archived data for the future Euclid space telescope will contain 150 petabytes (PB) of data and the SKA (Square Kilometre Array) project will generate 2 TB per second, with 1 PB per day archived!

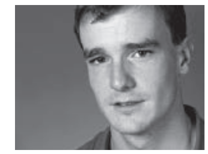
The challenge is to analyse such data sets employing algorithms capable of detecting weak signals embedded in noise, which requires to use the most advanced methodologies. The availability of such new algorithms will be a real challenge for scientists in the coming years, as it will determine the scientific returns on their involvement in the major international missions. To meet these new challenges, notably in the case of the Euclid project, an interdisciplinary laboratory called CosmoStat [1] was created at the DAp jointly with the DEDIP. Its goal is to promote new methodologies, develop new algorithms, disseminate the codes, use them for the scientific exploitation of data and train young researchers at the interface between various disciplines (cosmology, applied mathematics, statistics). The numerous methods developed at CosmoStat concern the restoration and reconstruction of images or cubes, the separation of components, or the measurement of the shapes of galaxies (Fig.1).

These methods are based on a wide variety of mathematical tools, such as learning techniques, statistical tools, optimal transport or concepts derived from harmonic analysis and which make it possible to handle complex data such as hyper-spectral, polarised data and/or data residing in non-Euclidian spaces, in other words geometrical spaces such as the surface of the Earth. The computer codes developed are not only extensively used by the other teams at the DAp but also by other CEA units such as the Technological Research Division for mass spectroscopy applications and above all, NeuroSpin, for the reconstruction of brain MRI images, potentially with a significant impact for neonatal medicine, in which the acquisition and analysis of premature infant data is extremely difficult. ■

[1] CosmoStat :
http://cosmic.cosmostat.org

Role and challenges of numerical simulations

BY
FRÉDÉRIC BOURNAUD
AND PATRICK HENNEBELLE
(Fundamental Research Division)



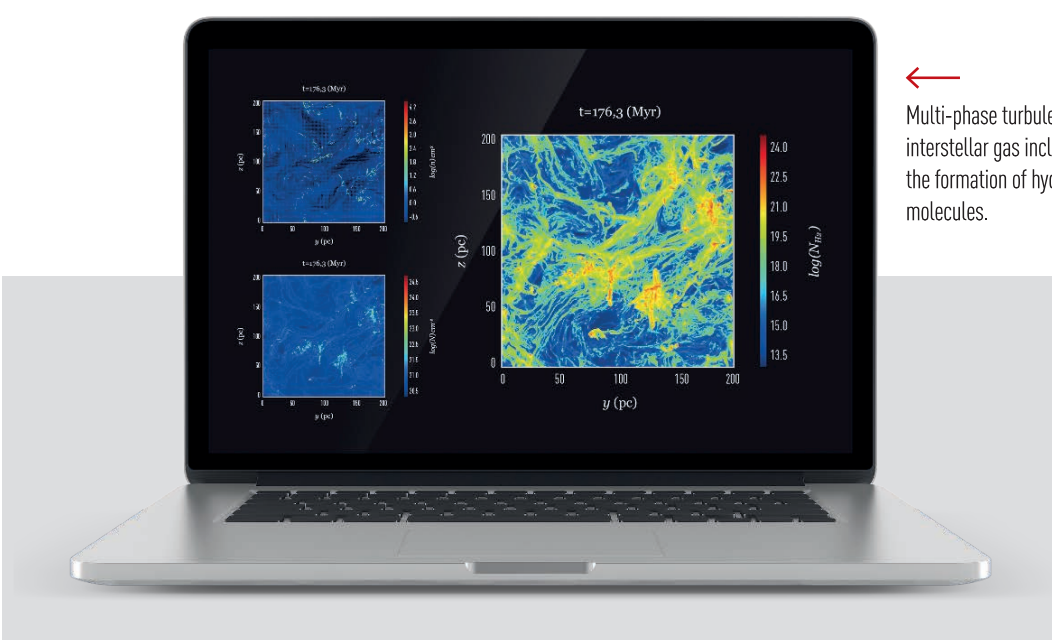
Frédéric Bournaud is an astrophysicist and head of CEA's Cosmology and Evolution of Galaxies Laboratory (DAp-AIM).

Patrick Hennebelle is an astrophysicist at CEA's Astrophysics Department (DAp-AIM).

Numerical simulations play a leading roles in number of astrophysical research programmes. On the one hand they can be used to explore the systems of coupled equations governing the evolution of astrophysical objects and are in this respect a vital tool for interpreting observations and comparing them with theoretical models. On the other, they can be used to predict the observables corresponding to the objects studied, at various wavelengths: this gives simulations an increasingly important role in the preparation of observations, in obtaining telescope time and in the design of future ground instruments and space missions.

The teams from the CEA Institute of Research into the Fundamental Laws of the Universe (Irfu) are closely involved in numerical simulation projects, ranging from cosmology and large structures in the Universe to the physics of stars and planets. Several numerical simulation codes are being developed, optimised and maintained on local computing resources. Major simulation campaigns are carried out on the national GENCI supercomputer (large national supercomputing equipment) and the European PRACE (Partnership for Advanced Computing in Europe) facilities, which includes the Joliot-Curie supercomputer installed in the TGCC (CEA's very large computing centre) and which is intensively used by astrophysicists.

The current challenge for numerical simulations is to adapt them to rapidly evolving computing architectures. The coming decade will see the advent of exascale, or supercomputers capable of performing 1 billion billion operations per second. This will make it possible to perform increasingly precise astrophysical simulations, including an increasingly complete range of physical processes. However, these new computers will not use traditional IT processors because their computing speed is bounded by the intricacy of etching the printed circuits, while the number of processors in a supercomputer (already several hundred thousand) is limited by their energy consumption. The next generations of supercomputers will therefore use new technologies such as vector computing and graphic accelerators. The teams at CEA are preparing for this future and already adapting their simulation codes to these new architectures, together with specialists in algorithms and programming techniques. ■



← Multi-phase turbulence in interstellar gas including the formation of hydrogen molecules.

"The coming decade will see the advent of exascale, or supercomputers capable of performing 1 billion billion operations per second."

DYNAMICS OF STARS AND EXOPLANETS

The Sun and its surrounding planets are no longer alone in the Universe. We know that exoplanets orbit around the vast majority of the multitude of identified stars. We thus see a convergence of interest between solar and stellar research and exoplanet research: a clear understanding of the host star enables us to better understand its planet(s) and the resulting space and habitability conditions.

Star Magnetism

Stars are dynamic, turbulent and magnetic objects. Understanding the origin of stellar magnetism and the associated turbulent state and various instabilities is essential because this intense activity (via the stellar wind and magnetic eruptions occurring at the surface of the stars) has a direct impact on the space environment around them. In the case of our Solar System, solar activity has a major impact on the Earth, its magnetosphere and its atmosphere.

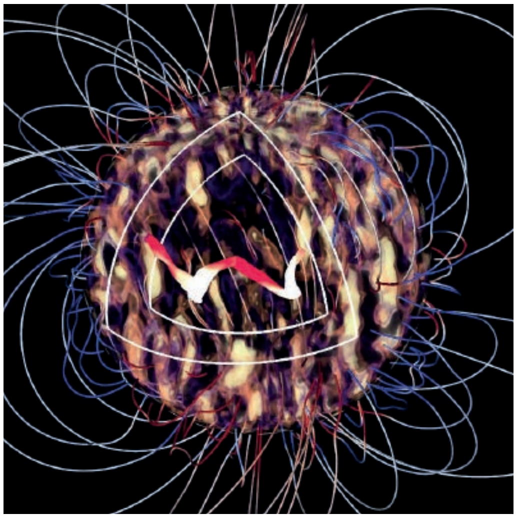
The turbulent, magnetic and time-dependent (from a few minutes to millions/billions of years) state of stars is anything but trivial to understand and explain. The magnetohydrodynamic physical mechanisms at work in the stars involve a non-linear, multi-scale space-time coupling which as yet has no simple analytical solution! This complex problem [1] therefore needs to be tackled by solving the equations of magnetised fluids in extreme parameter regimes, either to find semi-analytical solutions for them, or to achieve a numerical approximation of the solution leveraging the most powerful supercomputers.

These two complementary approaches recently enabled CEA to obtain significant results on the origin of stellar magnetism and the cycles (such as the Sun's 11-year cycle), via the dynamo effect, on the structure and amplitude of the particle wind which extends from the hot upper atmosphere of the stars and, finally, on the organisation of the magnetism and waves in the deep radiative interior of solar type stars.

Solar dynamo and origin of the 11-year cycle

Figure 1 shows a convective stellar dynamo solution with a magnetic cycle comparable to the Sun's 11 years. Over the past ten years, simulations of the magnetism of the Sun and stars have made a significant leap forwards. We have identified the parameter sets for simulations in which cyclic dynamo solutions with a ten-year period exist (Strugarek et al. 2017, 2018). We have also understood why stars have grand minimum periods, through an advanced analysis of the interaction between the various magnetic multi-poles of the stars (Derosa et al. 2012, Augustson et al. 2015). Finally, we have expanded our understanding to stars other than our Sun, with different rotation, age and/or mass. We now need to understand the role of the chemical composition on the intensity of star activity (ERC Whole Sun project – http://wholesun.eu).

Fig. 1: 3D view of turbulent (convective) movements and the magnetic field of a Sun-type star. The dynamo process allows the creation of most stellar magnetic fields and enables them to be maintained against the Joule effect.



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[1] In order to gain some idea of the complexity, it can be compared to understanding the displacement of fluid masses in the Earth's atmosphere, but with the addition of high stratification, extremely high turbulent state, and intense magnetic fields.

SUPERALFVENIC

Alfvén waves (named after Hannes Alfvén, a Swedish astrophysicist and Nobel Prize for physics in 1970) are magnetohydrodynamic waves encountered in plasmas.
A flow is said to be superalfvénic if it exceeds the Alfvén velocity at which the waves move (magnetic counterpart to supersonic for the speed of sound).

Origin of the solar wind

The magnetism of the Sun sculpts its environment: it determines the "cold" regions (known as the "coronal holes" because the magnetic field is open to the interstellar medium) and the hotter regions of the corona of our star where the magnetic field is closed in the form of loops. A high-speed particle wind escapes from the coronal holes, which accelerates as it moves away from the Sun. It quickly becomes supersonic and then superalfvénic and can reach speeds of 800 km/s when it reaches the Earth's orbit. But how is this wind accelerated?

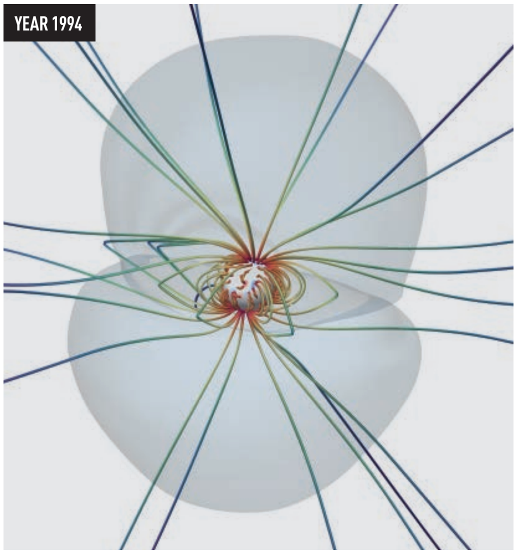


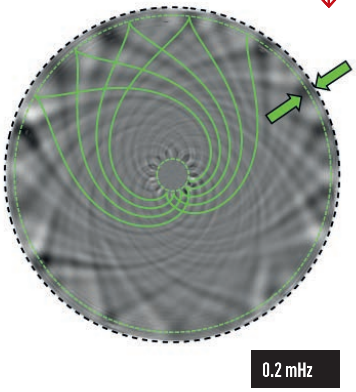
Fig. 2: simulation of the solar wind in 1994, during an activity minimum. An observed magnetic map of the Sun (orange-red sphere) is used as the calculation basis to impose a realistic magnetic topology. The solar wind opens the magnetic field lines in the interplanetary medium (orange tubes). This wind accelerates until it becomes superalfvénic when it passes through the transparent surface called the Alfvén surface.

This is one of the fundamental questions of solar physics and one that the Parker Solar Probe and Solar Orbiter missions (see box) are looking to answer. We have developed a 3D model of the solar wind (Fig. 2, Réville et Brun, 2017) in order to tackle this question head-on using an ab-initio approach based on the magnetohydrodynamic formalism.

We have shown that a wave turbulence, naturally excited at the solar photosphere by the convective granulation of our star, explains the heating of the solar corona and the observed acceleration of the wind. Many questions however still remain unanswered: how to transcribe this detailed understanding of the solar wind to other types of stars? Why does the solar wind have two populations, with different chemical compositions? Finally, how does the solar wind feedback to the dynamo itself throughout the lifetime of our star? These fascinating questions will lie at the heart of our research over the coming decade.

Transport and waves

Fig. 3 : 3D non-linear numerical simulation of the internal gravity waves (whose restoring buoyancy force is related to the Archimedes principle) propagating in the radiative core of a solar-type Sun-type star. In black and white is the radial velocity of the waves while the theoretical radius along which the wave energy propagates is superposed in green. The dotted concentric circles indicate the limits of the wave propagation cavity (Alvan et al. 2015).



Stars lose angular momentum from their formation until the final stages in their evolution through the action of stellar winds. Simultaneously, the interiors of stars are the seat of powerful mechanisms which transport angular momentum and contribute to the mixing of their chemical elements. These processes, called transport mechanisms, are the equivalent in stars of those which are at the origin of the large-scale winds and of the transport of chemical elements in Earth's atmosphere.

Their impact on the structure and evolution of stars is of primary importance, because they modify the speed of rotation and thus the magnetism and chemical composition, with significant consequences for their planetary and galactic environments. The main observational signature of these processes lies in the internal rotation profile of the stars from the surface to their core. This profile can be measured by means of helio and astero-seismology (see p. 15) in the respective cases of the Sun and the stars. For example, the Sun's convective zone rotates faster at its equator than at its pole, while its radiative core (where the energy is transported by radiation) rotates like a solid body, with the transition between these two widely differing regimes taking place at a very thin layer called the tachocline (for speed transition layer).

With CoRoT and Kepler/K2, space astero-seismology has revealed that the speed of rotation of the interiors of stars varies little from their surface to their core whereas variations of several orders of magnitude had been expected owing to the evolution of the structure of stars and the action of stellar winds.

To explain the intense exchanges in angular momentum needed to flatten internal rotation profiles in stars, we are carrying out ab-initio studies of the large-scale flows, magnetic fields and waves occurring in stellar interiors. We study in particular their instabilities and the resulting turbulence leading to angular momentum exchanges. The difficulty is to assess the impact, over the secular time-scale associated with the nuclear evolution of stars, of dynamic processes that are often non-linear and three-dimensional, taking place over short periods of time.

In recent years, considerable progress has been made in this field by DAp researchers through studies combining the most advanced theoretical methods with high-performance numerical simulation (for example, in the case of European STARS2 and SPIRE projects). For the case of internal gravity waves from solar-type Sun-type stars, an example is given in figure 3. These latter allow simultaneous sounding of the core of the stars and of the extraction of the angular momentum. ■

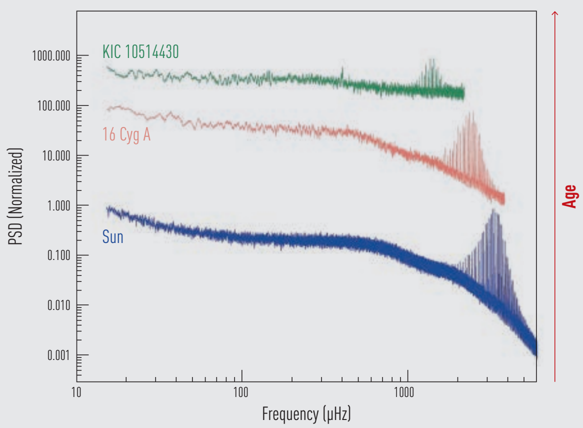


Fig. 1: spectral power density normalised according to the frequency of the Sun and two other stars observed by the Kepler mission, 16 Cyg A and KIC 10514430. The vertical lines correspond to the oscillation modes trapped in their interiors. These last two stars have a mass similar to that of the Sun, but they are older, constituting what we call an evolutionary seismic sequence for 1 solar-mass stars. As shown in the figure, the frequencies of the oscillation modes of stars with similar initial mass and chemical composition decrease with age.

BY
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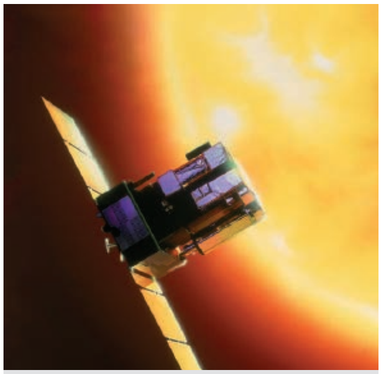
Shedding Light on the Interior of Stars

The light from the Sun and stars which illuminates us day and night is emitted by their photosphere, one of the outer layers of their atmosphere. The photons, originally produced by nuclear reactions in the core of stars like the Sun, travel the distance separating them from the surface over a period of millions of years. During this "journey", they "forget" the conditions in which they were produced as well as the properties of the layers through which they pass.

The photons which reach Earth can therefore only inform us about the properties of the photosphere of the stars. To study the entrails of these stars, the scientists must use other techniques. This is where seismology comes in: just as seismologists are capable of deciphering the entrails of the Earth by studying seismic waves with seismometers, the helio- and astero-seismologists can use waves excited in stars to reveal their most closely guarded secrets (Fig. 3 p. 14).

Stars like the Sun have a turbulent convective outer layer which excites sound waves in a manner similar to water boiling in a heated pan. The study of these waves tells us about the properties of the cavity in which they evolve and about the dynamics of the plasmas through which they pass. Thanks to the combination of waves which are trapped in various cavities, we can determine the properties of the stellar interiors with considerable precision.

The observations leading to the characterisation of these waves are supplemented by theoretical studies and numerical simulations, by means of which we gain a clearer understanding of how stars work and their history and future evolution. Nowadays, seismic studies of the Sun and stars are living a golden age. Space missions such as SoHO (ESA/NASA) or SDO (NASA) for the Sun, or CoRoT (CNES/ESA) and Kepler/K2 (NASA) for the stars, have collected data of unprecedented quality to improve the theoretical models and thus enhance our knowledge of the physical processes which control the evolution of the stars. The future looks even more promising with the TESS space mission, launched by NASA in 2018 and which is in the process of scanning virtually the entire sky with seismic observations of millions of bright stars. For the longer term, we are engaged in preparing ESA's future mission, PLATO, which will enable us to study millions of stars, including dozens of stellar systems like our own. ■



SoHO/GOLF

GOLF (Global Oscillations at Low Frequency) is one of the twelve scientific instruments carried on-board the SoHO (Solar and Heliospheric Observatory) satellite, the cornerstone of ESA's Horizon 2000 programme, launched on 2 December 1995. For more than 23 years, GOLF has been informing us about the structure and internal dynamics of the Sun, thanks to the study of global oscillation modes. In partnership with CNES, ESA and NASA, CEA was in charge of the detection subsystem and some of the electronics, the flight computer and associated software. SoHO is still in service and its mission has been extended for at least a further two years.

In the Atmosphere of Exoplanets

BY
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Are we alone in the Universe? We are not yet ready to answer this question, but we are making progress!

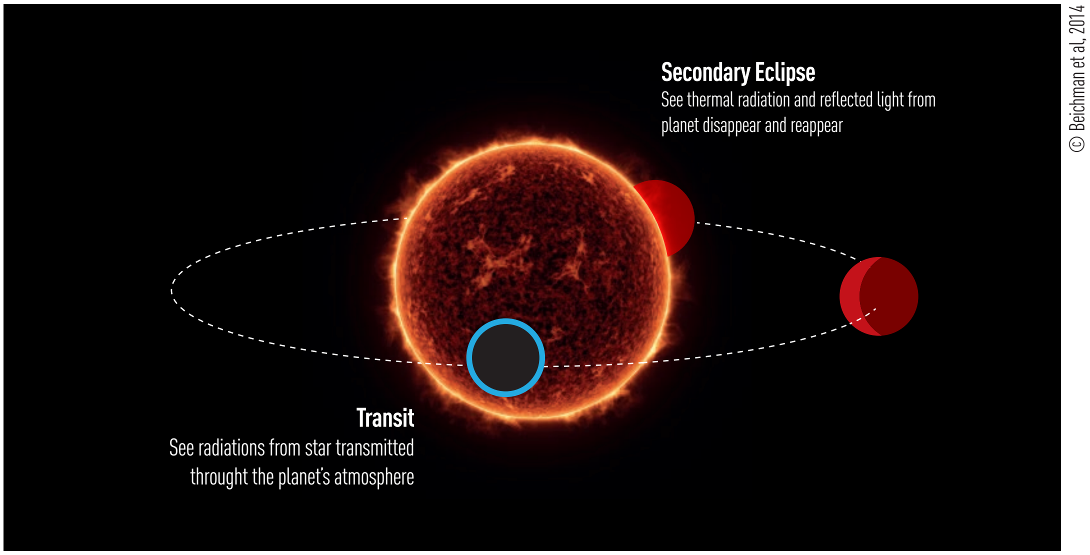

Fig. 1:

Eclipse: by differentiating between the signal observed before the eclipse, which contains emissions from the star and the planet, and the signal observed during the eclipse, which only contains the emission from the star, we can obtain the signal from the planet. This type of observation is only possible when the exoplanet, its host star and the Earth are aligned.

Transit: we can also obtain information about the atmosphere of exoplanets by observing the absorption by this atmosphere (schematically shown by the blue ring) of the light from the host star. The molecules in the atmosphere absorb the light from the star in the wavelength bands characteristic of the molecule, usually located in the infrared range. The observations are thus made with spectrographs to detect infrared light.

It was not until 1995 that a positive answer could be given to the question of whether there were planets around stars other than our Sun. This first exoplanet detected was a real surprise: it was a giant planet in an orbit ten times closer to its star than Mercury is to our Sun. Since then, "planet hunting" has been in full swing and 4,000 exoplanets have now been detected, some of which are the size of the Earth and in a so-called "habitable" orbit, where water could be found in liquid form. The TESS space mission, along with small ground telescopes, are in the process of systematically logging the planets orbiting in the habitable zone of small bright stars near us. For the planets orbiting in the habitable zone of near solar-Sun-type stars, we will have to wait for the PLATO space mission (see box p. 18).

While exoplanet discoveries are continuing apace, a new chapter in their study is being written and will develop considerably in the coming years: the characterisation of their atmosphere. Much can be learned from spectroscopic observations of an exoplanet's atmosphere: for example, the molecular composition of gas giant exoplanet atmospheres can trace the formation and evolution of the planet, while the atmosphere of rocky exoplanets can reveal gases indicating the existence of biological activity.

Major advances in the study of these atmospheres are expected with the commissioning of the James Webb Space Telescope (JWST, see p. 17). We were closely involved in the production of one of its four instruments, MIRI, which gives us access to guaranteed observation time. We will be using a large share of this time to more particularly target the retinue of seven planets orbiting the dwarf star Trappist 1. We will begin with observation of the planet closest to its star, with the same mass as Earth but slightly hotter. If detection is positive, we will attempt to observe other planets of the system located in the habitable zone. The method used to obtain the emission from the planet is that referred to as the eclipse (Fig. 1). While preparing for the observations with JWST, we are working on the next generation of space instruments. JWST is not only devoted to the observation of exoplanets and however/but the atmosphere of about only a hundred exoplanets should be studied in detail. Far more would be needed to reveal the physical and chemical phenomena at work. This will be the purpose of the ARIEL mission (see p. 17) which will study the atmosphere of about a thousand exoplanets as of 2028. The next two decades will be a fascinating time for enhancing our understanding of exoplanets! ■

On the Importance of Tides

BY
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As extra-solar systems began to be discovered, we obtained a completely different image from that we had imagined when the only known planetary system was our Solar system.

Various and unprecedented distributions of orbits were observed, in particular with far closer systems than ours, like the "hot" Jupiters gas giants which orbit very close to their star, and compact systems such as Trappist 1 whose seven planets orbit their star at a distance less than that between the Sun and Mercury. In these systems, the interactions between the host star and the retinue of planets are intense and involve gravitation, electromagnetic forces and radiation simultaneously.

In this context, the first interaction to consider is the tidal effect between the stars, planets and their natural satellites. In our Solar System, it is responsible for the synchronisation of the rotation of the Moon with its orbital movement around the Earth, the intense volcanic activity observed on the satellite of Jupiter Io, or the geysers seen at the south pole of the Saturn's moon Enceladus. Tides also play a crucial role in the evolution of the orbital architecture of planetary systems and the rotation of their component bodies, whose structure and internal dynamics are also affected.

The mechanism underpinning these phenomena is the dissipation of the energy from tidal waves, which propagate in the planets and star in a manner similar to those travelling through the atmosphere, oceans and crust of the Earth. Over the past decade, researchers at the DAp have made a significant contribution to establishing the link between the intensity of dissipation and the structure and internal dynamics of planets and stars. They thus established that the dissipation of tides in the host stars of planetary systems varied widely throughout their evolution (Mathis 2015). These variations are linked to changes in the structure of the stars in the early stages of their evolution and to the slowing down of their rotation by stellar winds during the main sequence when hydrogen is transformed into helium. They have a major impact on the orbital architecture of compact systems and the rate of survival of near planets such as the hot Jupiters (Bolmont & Mathis 2016).

At the same time, taking full advantage of the space missions to explore Jupiter and Saturn, they demonstrated the importance of the dissipation of the tides in the rock and ice cores of gas giant planets and in the regions resulting from their erosion owing to the high pressure and temperatures at the centre of these objects (Fig. 1) (Remus et al. 2012; André, Mathis & Barker 2019). The predicted dissipation rates are in line with those measured for Jupiter and Saturn thanks to the detection and evaluation of the movement of their moons, which call into question the values commonly accepted, which are now increased by one order of magnitude (Lainey et al. 2017). Finally, they developed complete models of atmospheric and oceanic tides on telluric planets such as the Earth, Venus, or even the potentially habitable super-Earths (Auclair-Desrotour et al. 2017, 18). The key objective is to understand their impact on the history of the rotation of these planets, the consequences of which are numerous and crucial for their habitability, from the evolution of their climate to the variations in their potentially protective magnetic field. ■

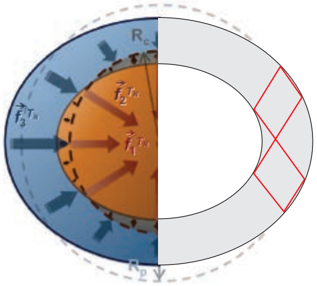

Fig. 1 : tidal dissipation mechanisms inside gas giant planets.

On the left, the dense rock and ice core is subjected to different forces as a result of the tides exerted by the moons, which are modified by the presence of the planet's deep fluid envelope. **On the right,** a schematic view of the propagation of a tidal wave driven by the planet's rotation that lead to the formation of a shear layer (in red) and to effective dissipation in the gas envelope (Guenel, Mathis & Remus, 2014).

ARIEL →

ARIEL is the M4 mission of ESA's Cosmic Vision programme. It is a 1m class telescope intended for the observation of a statistically significant sample of exoplanet atmospheres. Under an international consortium, in partnership with the CNES and in collaboration with laboratories at the CNRS, CEA is notably responsible for the mission's main instrument: the AIRS infrared spectrometer (ARIEL InfraRed Spectrometer).

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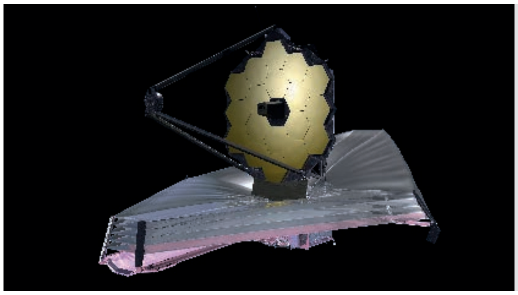

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← The James Webb Space Telescope

The James Webb Space Telescope (JWST), NASA's flagship programme, in which Europe (via ESA) and Canada are participants, is the successor to the Hubble Space Telescope (HST). The 6.5 metre diameter telescope is expected to be launched in 2021: it will then be the largest telescope ever sent into space. JWST will lead to major advances in numerous areas of astrophysics, from cosmology to exoplanets. Under an international consortium, in partnership with the CNES and in collaboration with laboratories at the CNRS, CEA has scientific and technical responsibility for the imager of the Mid InfraRed Instrument (MIRI).

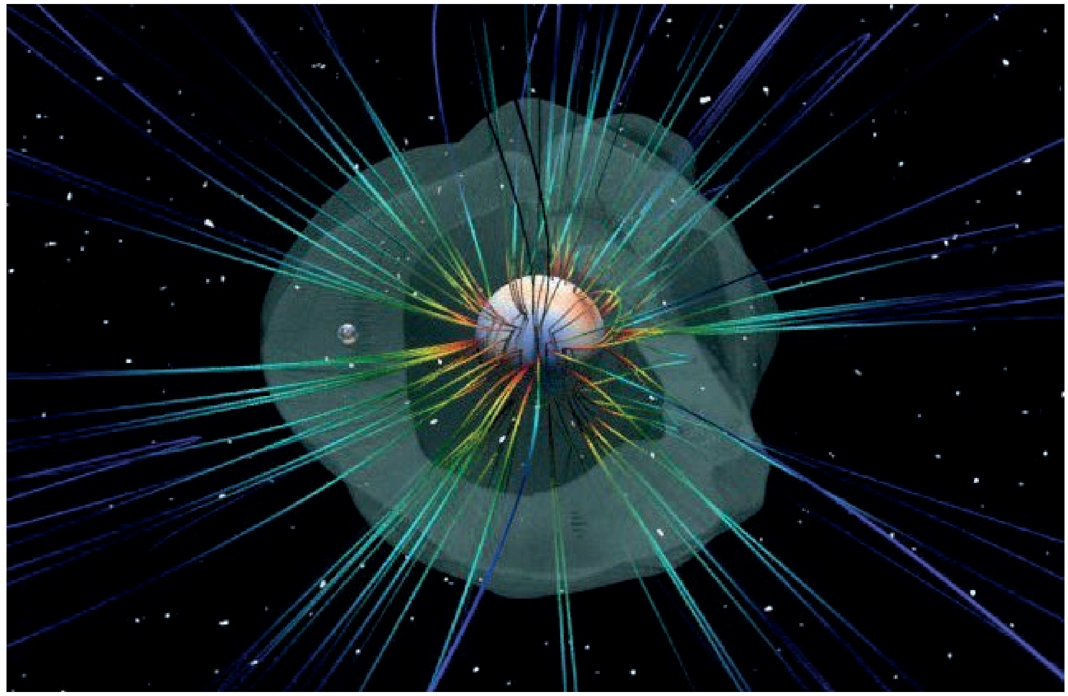

Fig.1 : model of the atmosphere of star HD 189733.

A super-Earth in close orbit around this star is pictured, to show the compactness of such star-planet system. In this particular case, the planet follows its orbit while entering/exiting the blue Alfvén surface, resulting in a complex temporal evolution of the magnetic connection between the two bodies.

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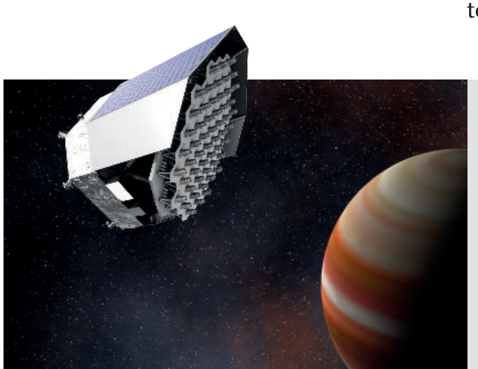
Star-planet magnetic interactions

What would life be like here on Earth without our magnetic cocoon? The commonly accepted idea today is that our magnetosphere helps Earth to retain its atmosphere, which is essential for our biosphere.

We know nothing about the magnetic field of exoplanets! This field is decisive for exoplanets in a close orbit around their star, because it partly determines their orbital migration in conjunction with the tidal forces (see p. 17). When a planet is in orbit within the Alfvén surface of its host star wind, a magnetic connection establishes between the two bodies. Energy and angular momentum, carried primarily by Alfvén waves, are then exchanged. This magnetic interaction can lead to observable traces of the magnetic properties of the exoplanets in the atmosphere of their host star.

We have developed a 3D model of these compact systems (Fig. 1) in order to quantify magnetic exchanges. Our model enable us today to identify the best orbital and rotational phases during which we can optimally observe the exoplanetary systems. They will be of considerable benefit when characterising the magnetism of exoplanets in the coming decades, enabling us to make the most of the multi-wavelength observations with the future SPIRou, JWST, PLATO instruments and of course ARIEL.



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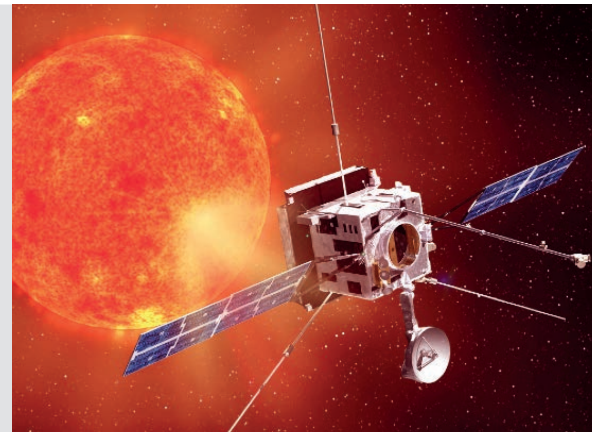
← PLATO

PLATO (Planetary Transits and Oscillations of stars) is the M3 mission of ESA's Cosmic Vision programme, selected in 2014 for a launch scheduled for 2026. Its goal is to detect and characterise exoplanetary systems, in particular those similar to the Solar System, consisting of a star similar to the Sun, with at least one Earth-type planet in orbit in the habitable zone. PLATO will therefore combine transit detection of exoplanets with astero-seismic characterisation of the host star. Several French laboratories at the CNRS and CEA, supported by the CNES, are taking part in this project (Rauer et al. 2014).

Solar Orbiter →

Solar Orbiter is the M1 mission of ESA's Cosmic Vision programme. It is an ambitious mission to study the Sun, combining numerous instruments (in-situ and remote-sensing), and which will follow an inclined elliptical orbit. This will enable it to approach the Sun closely (about 30 solar radii) and observe the poles of the Sun that we only see very partially from Earth. In collaboration with the CNES, CEA has developed the focal plane of the STIX instrument, a spectro-imager designed to study solar flares. CEA is involved in the Modelling Group (MADAWG) for developing simulations to enable the data to be interpreted, notably in collaboration with the laboratories of the CNRS and the Paris Observatory.

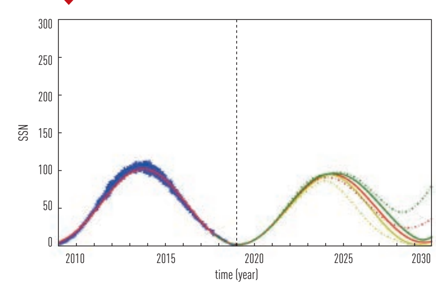


The Challenges of Space Weather

frequency range. This activity is accompanied by a wind of energetic particles in which magnetic storms can propagate and directly impact our planet and our technological society (radar signals, HF, GPS, electricity and gas grids, air passengers and flight crews, etc.).

Space Weather (SW) consists in characterising the dynamic state of the Sun-Earth pair (and by extension of star-exoplanet pairs) in order to anticipate and protect against the fury of the Sun. There is thus an operational aspect to SW: one must be able to predict the eruptive state of the Sun for both the short term (a few hours to a few days) and the medium term (the 11-year cycle). There is in effect a strong correlation between the magnetic state of the Sun (is it at the minimum or maximum of the 11-year cycle?) and the number of flares and magnetic clouds it produces. Thanks to observations, we know that on average there are three magnetic clouds per day during maximum activity, while only one every three days during minimum activity. At the DAp, we have developed innovative tools, based on the data assimilation method, in order to enhance various Sun models with observations and thus predict the state of the Sun-Earth system. Figure 2 shows the case of the prediction of cycle 25 that we expect to occur by the end of 2024 with an error of about 6 months. ■

Fig. 2: prediction of the number of sunspots, of the timing and the amplitude of the next solar cycle 25, for the period 2019-2030 (Brun et al. 2019).



Secular Evolution

The stars and their surrounding planets evolve on a time scale we refer to as secular. So what was the activity of the Sun or the orbital configuration of our Solar system four billion years ago, just after it formed, and what will it be like in one billion years? Was the Sun (its radiation, rotation, activity) the same and will it remain the same? Did the planets have the same orbits or the same atmosphere and chemical composition and will they retain them?

We know that the answer is no! To answer these questions, it is essential to understand how each body evolves over time in order to characterise the resulting star-planet coupling and the feedback loop on the habitability and stability of the system that it implies. Figure 3 represents the evolution of a close star-planet system over ten billion years. Here, we focus on the rotation of the star and try to find out whether the planet will survive or be consumed by the star. Several physical processes are taken into account: stellar wind, various tidal effects and magnetic torque linked to the direct magnetic interaction between the star and its planet. Our work on the fundamental physical mechanisms of angular momentum transport in stars, planets, and between the two celestial bodies enables us to perform precise ab-initio calculations of the torques and thus of the detailed evolution of the systems over long periods of time (Benbakoura et al. 2019). In this precise case, the planet cannot survive if all the effects are considered simultaneously: the star swallows it in 50 million years (blue peak on the star rotation curve). The planet's orbital angular momentum is transferred to the star, which means that its rotation accelerates. If the star or planet has a weaker magnetic field, then the planet disappears after a billion years (red curve peak), which gives a little breathing space! ■

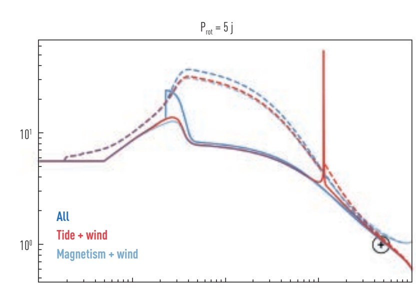


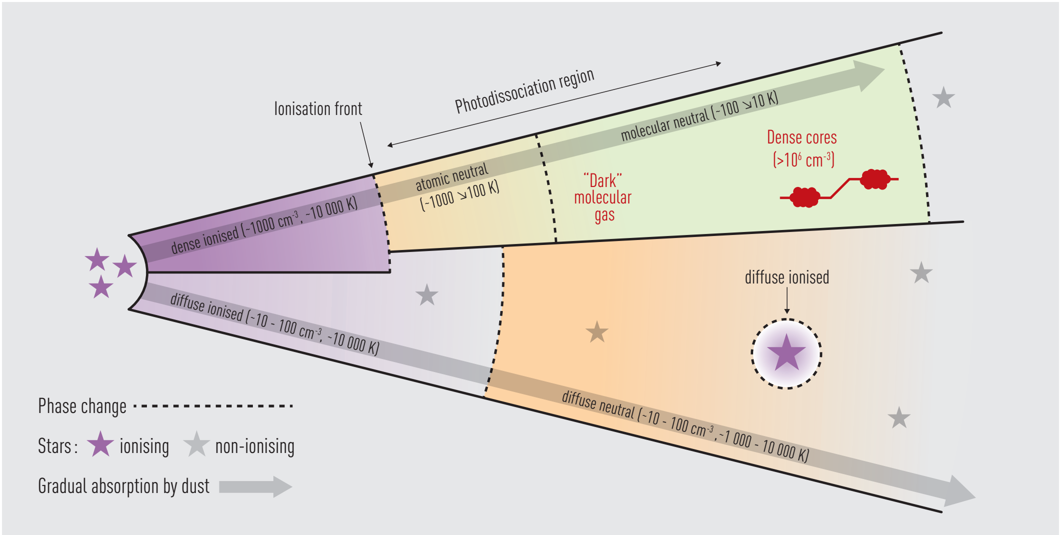
Fig. 3: evolution of rotation rate of a Sun-type star with a hot Jupiter-type planet orbiting it. Three cases are considered: in light blue, only the stellar wind is considered; in red, we add tidal effects and, in dark blue, magnetic interactions (such as Alfvén wings).

STAR FORMATION AND INTERSTELLAR MEDIUM

Stars power the main engine in the evolution of our astronomical environment, feeding the cycle of matter and energy in the galaxies. We are also closely tied to them because they are the source of the main chemical elements of which we are made. Their birth, or rather their formation, is complex and takes place in the densest clouds of gas and dust in the galaxies. By probing these dense clouds, new links between the mechanisms which regulate the star formation and those which structure the interstellar medium on large scales have been discovered, as well as the quasi-systematic presence of matter in disks around protostars. The exoplanets, which we now catalogue by the thousands form in such disks.

The Interstellar Ecosystem

As its name implies, the interstellar medium (ISM) fills the space between the stars within a galaxy and is far from empty: it represents about 20% of the mass of visible matter in the Milky Way. In general, the ISM is very sparse, with an average of one particle per cm^3 (10 billion billion times less dense than Earth's atmosphere). This medium is part of an ecosystem within which the stars – formed by gravitational collapse of molecular clouds – act in return via their radiation and their violent ejection of matter. Our understanding of the ISM has been considerably improved in recent years, notably through the observation of nearby galaxies.



A multi-phase medium...

The ISM consists of gas (atoms and molecules) and dust grains. The gas comprises about 73% hydrogen and 25% helium; the remaining 2% are the so-called "heavy" elements (O, C, N, Fe, etc.) which are produced during the stellar evolution . The grains are solid particles smaller than one micron (smaller than bacteria).

The effect of stellar radiation is to dissociate the molecules and ionise the atoms, thus producing different "phases" (Fig. 1). On the surface of molecular clouds, where hydrogen takes the form of H2, the carbon monoxide molecule CO is dissociated. For convenience, though, it is often by observing CO that we measure the mass of molecular gas. There is thus a molecular region which can easily elude the observations: this is the "dark" gas.

Stellar radiation also has the effect of heating up the ISM through energy transfer via ionisation or via the photoelectric effect on grains in the atomic regions. The gas thus heated then cools down while emitting discrete (spectral lines) or continuous radiation. The cooling of the gas and the shielding of the ionising radiation produce favourable conditions for the formation of future stars. Taking it to the extreme, elliptical galaxies, in which there is almost no ISM, have pretty much ceased to form any stars.

... And a turbulent one

Just like the Earth's atmosphere or oceans, the ISM is a turbulent fluid (in other words in perpetual evolution and subject to complex movements at all scales). This turbulence, which originates partly in the galactic gravitational interactions and partly in star explosions, plays a preponderant role in the ISM because, it is,

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←

Fig. 1: schematic view of the stratification of ISM phases. Clusters of young stars are particularly interesting because they evolve around numerous interstellar clouds, producing different gaseous phases depending how deeply the radiation penetrates into these clouds. The radiation is primarily obscured by dust. The structure shown is the result of theoretical work on the physical processes in the ISM and was confirmed by the observation of nearby regions with a high spatial resolution.

along with self-gravitation and the magnetic field, responsible for its spatial structure made up of clouds and filaments of dense gas immersed in a far sparser medium. Turbulence also plays a fundamental role in the formation of stars of different masses within these clouds.

Turbulence is a complex phenomenon which is not yet fully understood, even in simple fluids. To study it, one must first of all perform numerical simulations on massively parallel large computers. These simulations, which can comprise several billion calculation data, enable quantitative predictions to be made of the structure of the medium, which can then be combined with calculations of gas and dust emissions and compared with the observations.

Infrared: ideal for observing the interstellar medium

The infrared spectral range (IR) comprises most of the continuous emission from the grains and numerous gas cooling lines (Fig. 2). Spectroscopy, that is the breakdown of the radiated power into wavelengths, gives access to another, spectral, dimension which is rich in information and comes on top of the two spatial dimensions of a simple image. We can thus produce “spectral maps” and, at each point in a region, isolate the various ISM components and from there deduce the temperature, density, degree of ionisation, and chemical abundances.

The versatility of the Herschel European space telescope (2009-2013) enabled an overview of the ISM evolution in nearby galaxies beyond the Milky Way. Thanks to the new information obtained in IR, it was thus for the first time possible to construct complex models of the multiphase ISM accounting for all known physical processes. Starting in 2021, the James Webb Space Telescope (JWST) will extend this understanding to the remote universe.

Spying on our neighbours...

To fully understand the physical and chemical processes in the ISM, we need to access environments that are different from that of the Milky Way, which is on the whole relatively monotonous, with few variations in the star formation rate (about twice the mass of the Sun per year, for the entire galaxy) and in the abundance of heavy elements (about 2% of the atoms). The nearby galaxies (within a sphere of several million light-years) however offer a far greater range of conditions, sometimes extreme (active accretion around black holes, abundance of heavy elements up to 50 times lower and star formation rates up to hundreds of times higher than in the Milky Way). The most remarkable results obtained with Herschel include the confirmation of the importance of the dark gas, which dominates the molecular mass budget, and the “transparency” of the ISM, which enables the radiation to travel over long distances. With regard to the grains, the telescope showed that their emissivity had so far been significantly under-estimated, indicating that their composition is most certainly amorphous (disordered) rather than crystalline (ordered). Finally, it revealed the importance of the growth of the grains in the ISM through the accretion of gas atoms.

... To identify the ancestors of the Milky Way

Beyond our understanding of the properties of the ISM as an astrophysical object per se, the study of these properties as a function of environmental parameters provides a means to reconstruct the evolution of the galaxies. In certain nearby galaxies, the ISM appears to be primitive, if not primordial (chemical composition relatively close to that just after the Big Bang). These nearby galaxies (with the age of the current Universe) can thus be seen as laboratories to help us understand the formation of the first stars and understand the evolution of the galaxies following their formation. ■

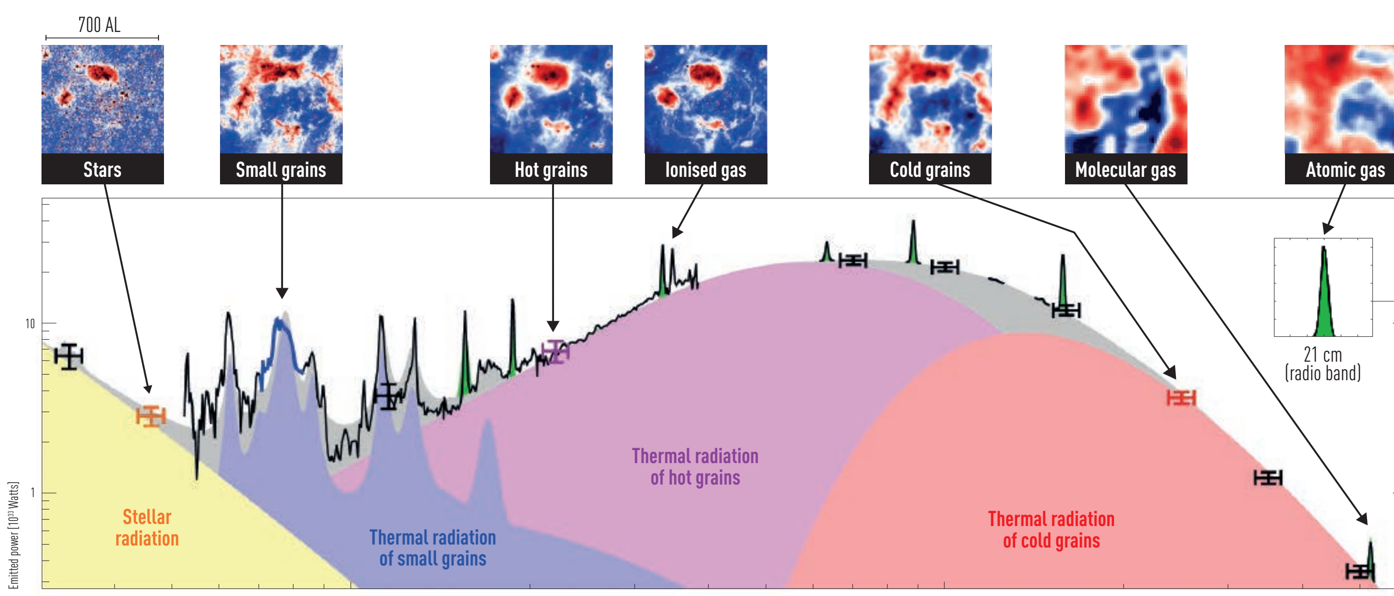

Fig. 2: top: images of the N11 giant nebula in the Large Magellanic Cloud galaxy. The red regions are brighter than the blue ones. A cluster of stars is situated in the centre of the bubble (bounded by the red regions) and several star forming regions can be found on the edge of the bubble.
Bottom: typical spectrum that can be obtained for a pixel of the above images. The spectroscopic observations (black) only cover a small fraction of the spectrum, the rest having been modelled. CEA is involved in several future missions, whose goals include filling in these gaps in the spectrum and in our knowledge.

Along Interstellar Filaments

BY
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Star formation is one of the most fundamental processes in astrophysics, but is also one of the most complex. The study of the physical mechanisms at work is important for understanding not only the origin of our own Sun, but also the formation of planetary systems on small scales and the evolution of galaxies on large scales.

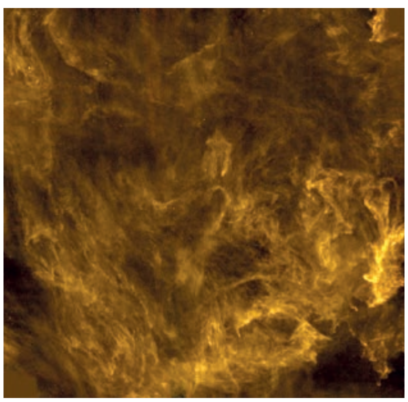

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Fig. 1:
Left, combination of images obtained at 250 µm, 350 µm and 500 µm with Herschel in the direction of the Polaris interstellar cloud, showing no star formation.
On the right, a composite Herschel image of the Orion A cloud, in which there is very active star formation and which is home to the famous "Orion nebula". The "false" colours correspond to wavelengths observed by the Herschel telescope (red = 250 µm, green = 160 µm and blue = 70 µm).

The problem involves a large number of physical effects (interplay between gravity, turbulence, interstellar magnetic fields, feedback phenomena, thermodynamics of interstellar gas) over a wide range of scales. However, the overall products of the star formation process (distribution of stellar masses at birth, star formation rate in galaxies) appears to be governed by relatively simple and quasi- universal laws.

Observations show that the star demographic curve appears to follow an immutable law with few stars or "brown dwarfs" of very low mass, few massive stars and a vast majority of solar-type stars with a mass quite close that of our Sun. Similarly, the (in) efficiency of the star formation process in dense molecular gas appears to be almost identical in all nearby star-forming regions of our galaxy on parsec scales and in external galaxies on scales of ~10 kiloparsec. Clarifying the origin of these laws and understanding how only a small fraction of cold interstellar matter is converted into stars represents one of the main challenges for contemporary astrophysics.

As star-forming interstellar clouds are cold (about 10 K), they are generally dark and completely unobservable in visible light. However, they become very bright in the far-infrared and submillimetre ranges, observable from space. The images from Herschel have revolutionised our understanding of the link between the structure of the cold interstellar medium and the star formation process and led to significant advances on these questions, closely related to the issue of the origin of solar systems in the Universe.

Universality of the filamentary structure

In all the nearby molecular clouds of our Galaxy, the Herschel images have revealed the ubiquitous presence of filaments as well as numerous dense "pre-stellar" cores along these filaments. Before 2009, observations in the infrared had already identified the presence of gigantic networks of gas filaments but their role was a mystery. Herschel showed on the one hand that interstellar filaments are far more widespread than hitherto believed and, on the other, that star formation mainly takes place in the densest of them. They now appear to be key, omnipresent components of the cold interstellar medium.

A rich network of filaments can thus be observed in all interstellar clouds, those where star formation process has not yet started (Polaris cloud, fig. 1 left) and those which have already formed a large number of stars (Orion complex, fig. 1 right). This is a first clue: the formation of filaments in the interstellar medium must precede the formation of stars.

Thanks to the angular resolution of the Herschel telescope in the far-infrared and submillimetre ranges, astrophysicists could precisely measure the sizes of interstellar filaments for the first time and show that they all have a very similar width of about ~0.1 pc or ~0.3 light-years. Nearly 600 filaments in eight nearby clouds of the Gould Belt have thus been examined. While each filament can extend over more than ~1 to ~10 pc in space, their width varies very little from an average value of ~0.1 pc.

This result provides a second clue to the origin of interstellar filaments. Their uniform diameter ~0.1 pc is reminiscent of another characteristic scale known since the early 1980s: that below which disordered motions corresponding to what is called interstellar turbulence (see p. 21) become slower than the sound speed. By comparing these observations with several theoretical models, the "Herschel Gould Belt survey" team concluded that the observed filaments are probably the direct result of large-scale turbulent compression flows in the cold interstellar medium.

The central role of interstellar filaments

The Herschel images have also made it possible to establish a direct link between the filamentary texture of molecular clouds and the formation mechanism of "pre-stellar cores" for the first time. Pre-stellar cores are dense globules or condensations of cold matter in interstellar clouds which eventually collapse onto themselves under the effect of their own weight, giving birth to protostars. One of the main goals of the "Herschel Gould Belt Survey" was precisely to identify all the pre-stellar cores and protostars in nearby clouds, in order to examine their demographic curve and try to better understand the origin of the distribution of stellar masses.

In the nearby clouds of the Gould Belt, thousands of pre-stellar cores and several hundred protostars have been identified, more than three-quarters of which are distributed along the densest filaments (Fig. 2), above a critical threshold of about 15 M⊙ per parsec expressed in filament mass per unit length. This value can be interpreted as the threshold above which filaments become gravitationally unstable and break up along their length for a gas temperature of about 10 K. The same threshold is observed in all nearby clouds harboring a large number of pre-stellar cores.

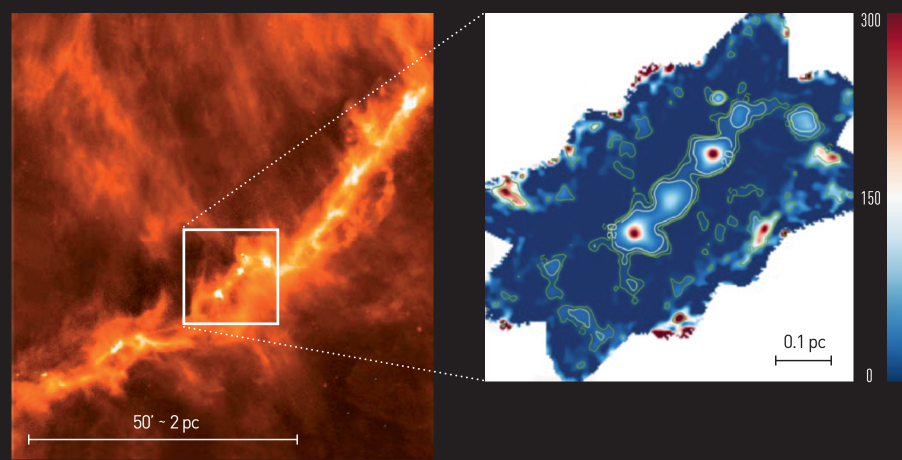

Fig. 2: Fig. 2: On the left, an image of the main filament in the Taurus cloud as observed with Herschel at 250 µm. This filament contains several pre-stellar cores and protostars, the direct progenitors of solar-type stars. On the right, a close-up of the central part of the Taurus filament taken with the IRAM 30m telescope's NIKA camera at 1.2 mm.

Interstellar turbulence alone is not therefore sufficient to form stars. An additional ingredient – the force of gravity – is needed to fragment the densest filaments and lead to the formation of pre-stellar cores and subsequently protostars.

Towards a "universal" scenario

By comparing these results with other observations and theoretical models, a two-step scenario for the formation of solar-type stars has been proposed:

- firstly, a series of multiple compressions associated with large-scale supersonic "turbulent" flows generates a complex network of filaments in each interstellar cloud;
- secondly, gravity takes over and fragments the densest filaments into pre-stellar cores, which subsequently evolve into protostars and then stars like our Sun.

Interstellar filaments and pre-stellar cores thus appear to be the "building blocks" of star birth, and the mass per unit length of filaments may be the critical parameter controlling the formation of stars on parsec scales. Even if many details are still poorly understood, this scenario is extremely promising and provides a potential explanation for the origin of the characteristic mass of stars and the remarkably uniform efficiency of star formation in the dense molecular gas of galaxies. It postulates that the characteristic stellar mass is the direct result of the characteristic fragmentation scale in filaments and that the "microphysics" of the fragmentation process plays a "universal" role in regulating the efficiency of star formation in the dense molecular gas of galaxies such as our Milky Way. ■

FUTURE PROSPECTS

New instruments should allow key progress in the coming years. By combining data from the ArTéMiS submillimetre camera, which has an angular resolution 3.5 times better than Herschel, and those obtained with the large interferometer ALMA at even higher resolution, we should be able to test the universality of this scenario beyond the nearby clouds of the Gould belt and understand the role of filaments in high-mass star formation. Regarding magnetic fields, polarization data obtained with the Planck satellite already emphasize its importance. But the angular resolution of Planck is not sufficient to probe the interior of filaments and understand the role of magnetic fields. Thanks to its high resolution and unprecedented sensitivity, B-BOP, the imaging polarimeter of the SPICA space telescope proposed as ESA's M5 mission, will make it possible.

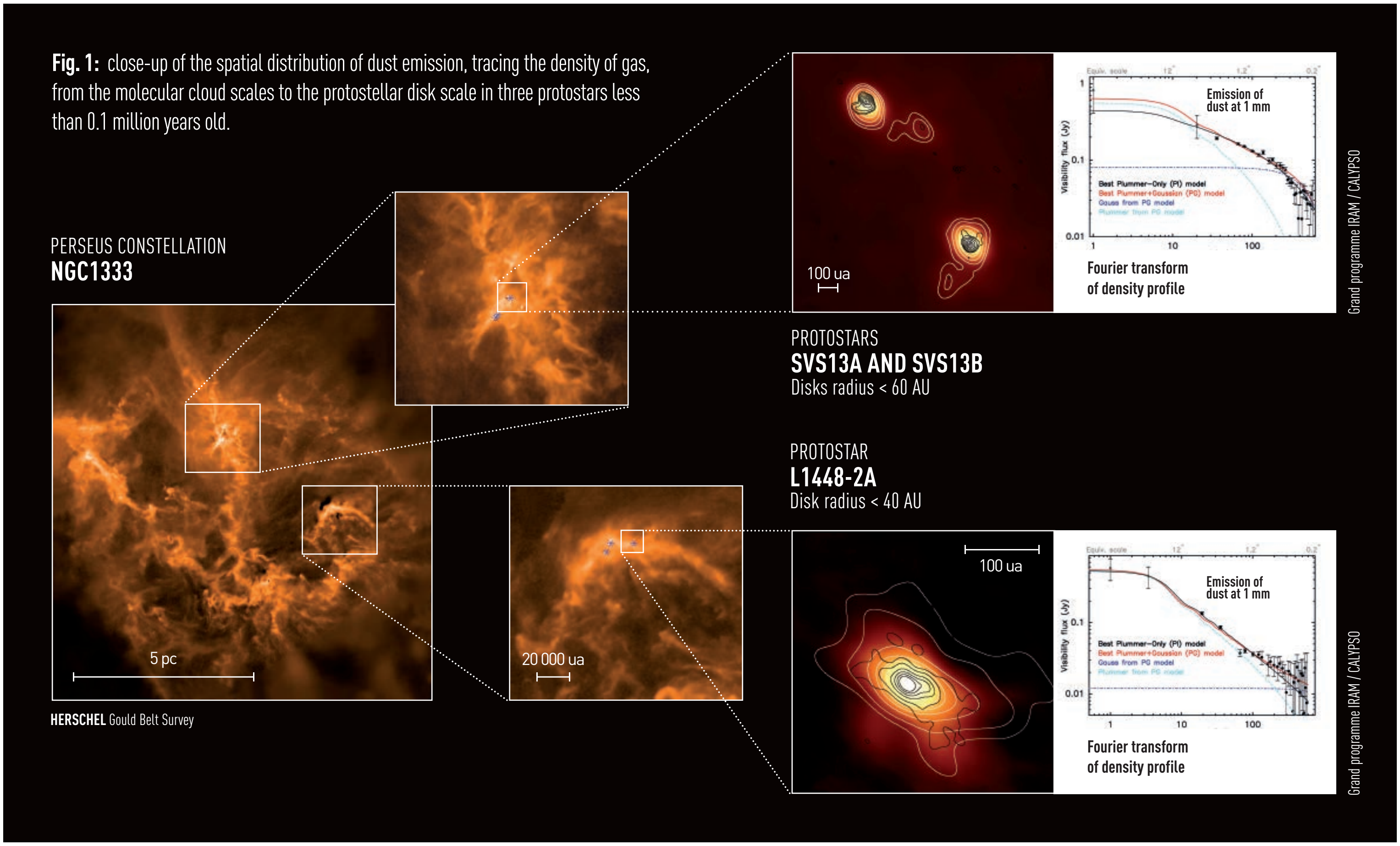

Fig. 1: close-up of the spatial distribution of dust emission, tracing the density of gas, from the molecular cloud scales to the protostellar disk scale in three protostars less than 0.1 million years old.

At The Heart of Proto-planetary Disks

For about fifteen years, the search for exoplanets has proven to be extremely fruitful (see p. 16), suggesting that most stars are accompanied by planetary corteges. These planets usually belong to a plane around their host star (plane of the ecliptic in our own solar system) leading astrophysicists to speculate that they were formed in "accretion"protoplanetary discs.

These disks are rotating structures composed of gas and dust left over from the formation of the young stars they are surrounding. To clarify the precise circumstances of their formation and their evolution, studies of the youngest stars in our galaxy, protostars, were initiated. These very young objects are key to characterize the mechanisms enabling the gas in the interstellar medium to be transformed into stars, but also for better understanding the origin of our own Solar System.

The teams at the DAp are for example analyzing both the dust thermal emission and the light emitted by molecules in the gas of circumstellar disks around the youngest protostars that are still actively growing, known as "Class 0" objects, discovered by this same department thirty years ago.

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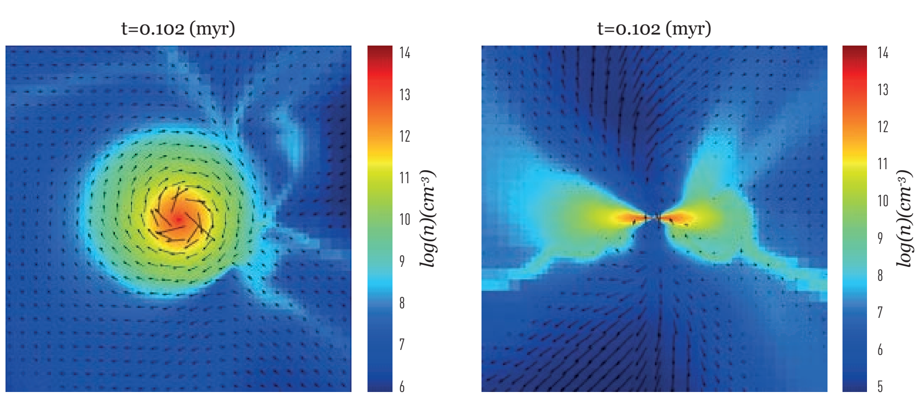
"Comparison between the observations and the numerical simulations of star formation enabled the researchers at the DAp to suggest that the effect of the magnetic field could be a key physical process in explaining the early steps in the formation of protoplanetary disks."

Demographic studies on populations of protostars (Fig. 1) carried out with ground-based telescopes and with the Herschel space telescope, have enabled the DAp researchers to demonstrate that these objects are only a few tens of thousands of years old, suggesting that they still retain the memory of the initial conditions of their formation and that they can thus inform us about the very first steps in the formation of stars and protoplanetary disks.

Owing to their very low temperature and their location immersed deep inside cocoons of matter, these protostars do not emit in visible light, but in long-wavelength radiation only observable with radio telescopes. The first phases in the formation of the disks are yet poorly understood because observing them requires being able to detect their weak radiation and to distinguish it from the signal of the surrounding envelope of circumstellar matter feeding the protostar. To reach the disk scales means being able to look at regions of about a hundred astronomical units (AU). Since the nearest protostars are about a hundred parsecs away, scientists have used the most powerful instruments currently available in these wavelengths (interferometers such as ALMA or NOEMA) to confirm the existence of embryonic protoplanetary disks around these very young protostars, suggesting that the disk is formed at the same time as the protostar itself. Nonetheless, these observations showed that these embryos appear to form at smaller scales (radius < 60 AU) than those predicted by the hydrodynamic models of protostellar core collapse. To interpret these observations, theoretical models based on the fundamental principles of physics have to be developed. Numerical simulations (Fig. 2) solving hydrodynamic equations are thus produced, incorporating a large number of physical processes such as gravity, magnetic field and radiation.

Fig. 2: Numerical simulation of a protostellar disk. The two figures represent density cross-sections, front views on the left and profile views on the right. The arrows represent the velocity field. Above and below the disk, streams of matter are ejected. This "accretion-ejection" process plays an important role in astrophysics.



Comparison between the observations and the numerical simulations of star formation enabled the researchers at the DAp to suggest that the effect of the magnetic field could be a key physical process in explaining the early steps in the formation of protoplanetary disks. There are still many challenges to better characterize these embryonic disks, within which the first planetesimals could have begun to form: new decisive constraints will be obtained in the coming decade thanks to new observational facilities such as the ALMA submillimetre interferometer and the JWST infrared space telescope.

The grains in these protostellar disks become larger as the disk ages: observations suggest that after about a million years, when they enter the protoplanetary (or class II) phase, the first small embryonic planetesimals are already formed. The most recent results tend to indicate that the most massive planets could already have been formed at this stage or could have at least entered the final phases of their formation.

During the protoplanetary phase which lasts about 10 million years, the dust grains and planetesimals will migrate through the disk. This migration is imposed by the gas which, as it rotates slightly slower than the dust around the star, slows the grains down by viscous friction. The larger the grains (i.e., 1 µm and above), the faster they will sink from the surface layers towards the median plane (sedimentation) and then migrate radially onto the star. The numerical models show that this physical phenomenon is very fast, much faster than the formation of planets. But then how can this migration be slowed down or halted, so that planetary formation has time to proceed? Several hypotheses are being examined, including the promising theory of "back-projection", i.e., the constitution of such a large concentration of dust that the physics of friction is "reversed".

In the 1990s, the infrared spectra of several protoplanetary disks were shown to be atypical, with an emission shortfall between 2 and 20 µm. This shortfall was first interpreted as being due to the presence of cavities in the central regions, which were then confirmed with angular high-resolution imagery. These cavities have variable sizes of from a few AU to up to a hundred AU. This type of disk was called a "transition disk" (Fig. 3): they represent the transition between the continuous primordial disks and the most evolved disks, they have lost a large part of their mass and they are also better structured. The physical reason for the appearance of the internal cavities as the system ages so far remains unknown. Several theories are put forward to explain this: gradual photo-evaporation (erosion by the energy radiated from the star) of the disk; accumulation of the matter into planets which are undetectable because they are too small; trapping of the dust particles during their radial migration in the density maxima created by the planets.

A more detailed study showed that at ages ranging between 6 and 8 million years, 20% of the protoplanetary disks are of the transitional type. Even though this phase only lasts ~100.000 years, it is assumed nowadays that this is part of the natural evolution of a typical disk and constitutes the first phases of what we call the dissipation of the disk.

The internal cavities are far from being the only structures present in the disks, as shown by the very high resolution angular imaging, for example with the VLT/SPHERE instrument (Fig. 4). Spiral structures, density waves and azimuthal overdensities are a plethora: there are virtually no disks without a radial or azimuthal structure!

Fig. 3:
sketch of a transitional disk (bottom), and a primordial full disk (top).

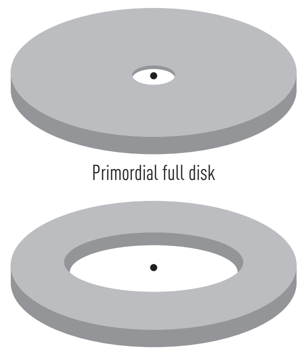
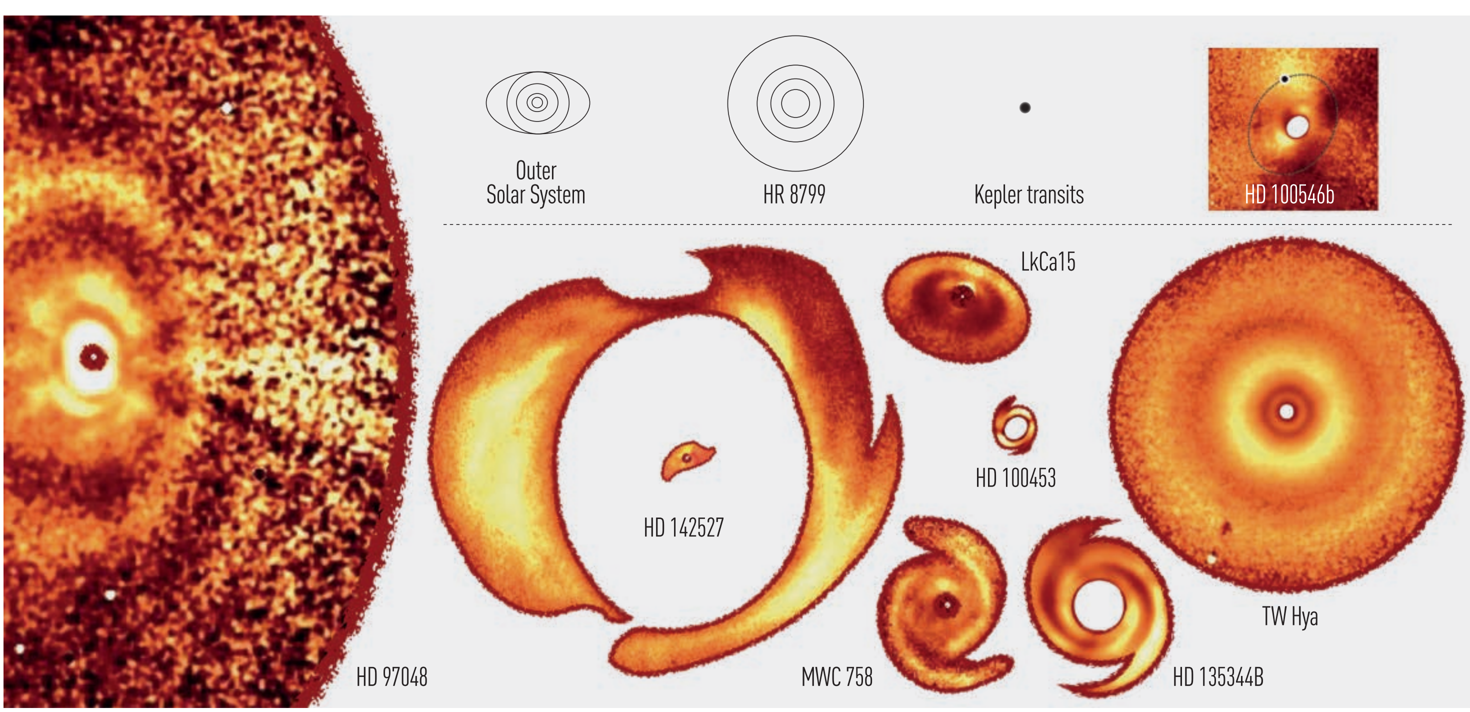


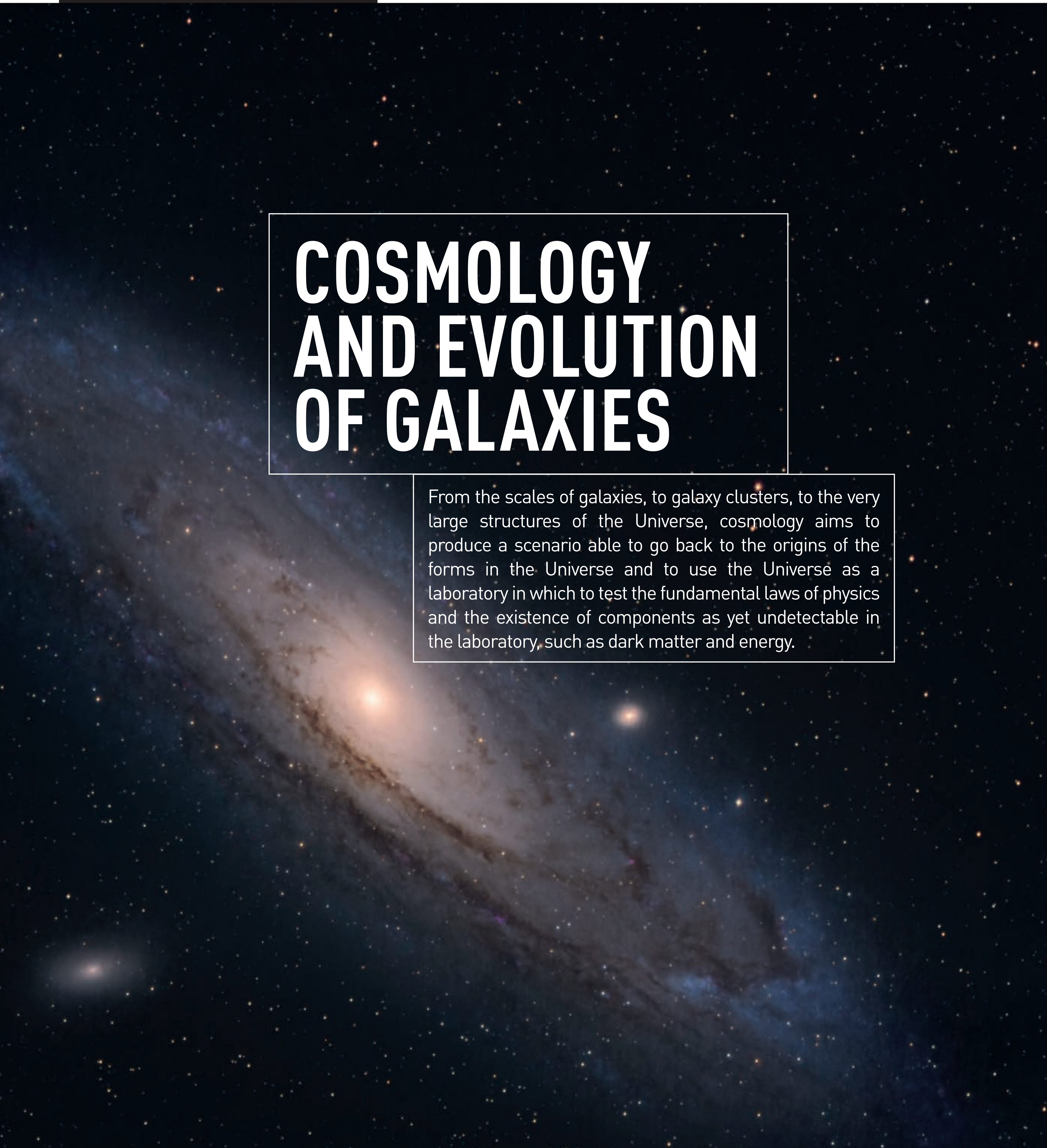
Fig. 4:
dseveral protoplanetary disks, observed at near-infrared wavelengths with very high resolution angular imaging using adaptive optics (VLT/SPHERE various types of structures are evidenced: inner cavities, density waves, spirals. To give some idea of scale, the physical sizes of our Solar System and the planetary system around HR8799 are shown.

The origin of these structures is still widely debated, even though the hypothesis of a massive planet distorting the disk through gravitation and mechanical resonances remains the most likely explanation. Moreover, although this has yet to be confirmed, it seems that the youngest disks preferentially harbour density wave type structures, while spiral structures appear later on, after 8 million years.

But when and how do the planets form in these disks? To answer this question, a relatively large number of planets must be detected and their characteristics studied. Despite the considerable efforts devoted to this area, so far only two to three planets, needing confirmation observations, have been detected in protoplanetary disks. Why is it so hard to detect planets just being formed, when we can detect so many around older stars? The mystery remains!

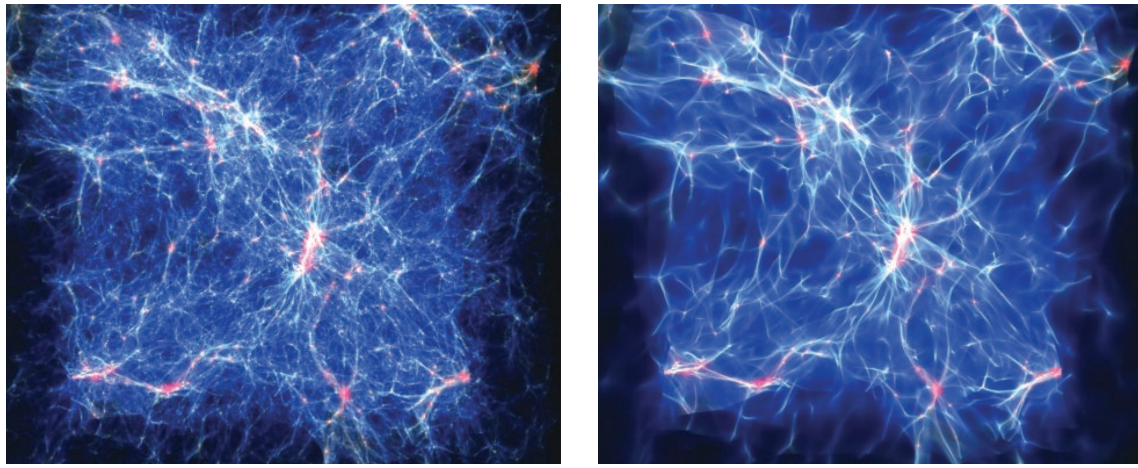
CEA has been a major player in the study of protoplanetary disks. It will continue its contribution with the JWST/MIRI instruments for the 2021 time-frame and E-ELT/METIS in 2027. Given its performance in terms of sensitivity and angular resolution, METIS will in particular be in perfect synergy with the observations obtained with ALMA. ■





COSMOLOGY AND EVOLUTION OF GALAXIES

From the scales of galaxies, to galaxy clusters, to the very large structures of the Universe, cosmology aims to produce a scenario able to go back to the origins of the forms in the Universe and to use the Universe as a laboratory in which to test the fundamental laws of physics and the existence of components as yet undetectable in the laboratory, such as dark matter and energy.



→ **Fig. 1:** distribution of intergalactic hydrogen, taken from simulations at the TGCC for a standard dark matter (left) or one consisting of sterile neutrinos (right). The smoothing of the small structures is clearly apparent in this second case.

Cosmological Implications of Large Galactic Surveys

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Cosmology has recently made considerable progress thanks to the large surveys of galaxies or of the sparse filaments of hydrogen omnipresent in intergalactic space, carried out on scales of hundreds of millions of light years.

These surveys have gradually refined our knowledge of the evolution of the Universe, the nature of dark matter or the mass of neutrinos and are even beginning to provide constraints on the possible modifications of the laws of gravity described hitherto by Einstein's general relativity model. CEA has made a significant contribution to this process and is continuing to play a leading role in this field on the international stage.

The 3D map of matter is the keystone of these discoveries. It is obtained by the spectroscopic survey of millions of galaxies and quasars through the BOSS, eBOSS and soon the DESI projects. The two coordinates of each object in the sky are supplemented with a third dimension by measuring its spectral redshift, which increases the more remote the object. The purpose of this map is to identify the imprint left in the distribution of matter by the recombination of protons and electrons in the Universe when it was 380,000 years old. This translates into an excess of probability, called baryon acoustic oscillations (BAO), of finding two galaxies separated by a characteristic distance of 450 million light years. At high redshift, quasars are used as cosmic beacons to illuminate the intergalactic medium. The neutral hydrogen gas that it contains imprints a series of absorption lines, called the Lyman-alpha forest, in the spectra of these quasars. Their study enabled CEA to obtain the first measurement, still the most precise to date, of the expansion rate of the Universe about 11 billion years ago and showed the need for the existence of dark energy, independently of the constraints imposed by the microwave background radiation and supernovæ. From the very first data, this analysis also confirmed that, on the scale of a few billion light years, the uniformity of the distribution of galaxies is in line with the postulated Copernican principle on which all of cosmology rests.

The Lyman-alpha forests also provide vital information on the impact of the light particles in the Universe, as we demonstrated thanks to nearly 15 million hours of calculations in the CEA's Very Large Computing Centre at Bruyères-le-Châtel (Fig. 1): neutrinos and particles of warm dark matter tend to smooth the structures on the scale of a few megaparsecs. Obtained by comparison between data and simulations, the upper limit of 0.12 eV on the mass of active neutrinos and the constraints on the mass of sterile neutrinos or axions are among the strongest obtained to date.

Today, the probes are diversifying; after the observation of quasars and galaxies, that of young galaxies enables us to explore time-scales as yet unexploited in the history of the Universe. Increasing numbers of approaches are also being used. Whereas the measurement of the BAO was the main goal of the large surveys for nearly a decade, that of the effects of gravitational distortion due to the collapse of matter on the densest structures enables new questions to be examined. Galaxy redshift indeed comprises two components: the cosmological redshift and a component from the galaxy peculiar velocity. These distortions carry the mark of the formation of the structures and thus depend on the laws of gravity. Their precise measurement can thus test general relativity and constrain modified gravity models. ■

"Today, the probes are diversifying; after the observation of quasars and galaxies, that of young galaxies enables us to explore time-scales as yet unexploited in the history of the Universe."

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"CEA plays a major role in galaxy surveys that measure WL, from the instrumentation development, to the image reconstruction of galaxy shapes, to the data interpretation."

The Origin of Cosmic Acceleration: New Energy or New Physics?

Determining what causes cosmic acceleration is a big challenge in cosmology: is it a constant (ΛCDM) or a new fluid (dark energy, DE)? Is there a new force that modifies gravity as described by Einstein (Modified Gravity, MG)?

CEA researchers lead the analysis of DE and MG within Planck, a ESA space mission which measured the cosmic microwave background (CMB) radiation, light emitted 380,000 years after the big bang. In the final data release [1], we updated [2] and tested different scenarios, combining Planck with other datasets (Fig.1).

Light coming from a faraway galaxy is deflected by the presence of dark matter along the way: this causes a distortion (shear) of the galaxy image we observe. Shear measurement can be used to reconstruct dark matter, i.e. the lens that deflects light. This effect is called gravitational lensing and is studied statistically, as the deflection is typically tiny (weak lensing, WL). DE and MG change, in turn, the lens and its lensing potential. WL is therefore also a powerful probe to test DE and MG.

CEA plays a major role in galaxy surveys that measure WL, from the instrumentation development, to the image reconstruction of galaxy shapes, to the data interpretation. CEA participated to the Canada-France Hawaii Telescope (CFHT) with MegaCam, a camera built at CEA and allowed to determine the fraction of dark matter and DE up to 8.8 billion years ago [3,4]. We are key contributors to the Euclid ESA space telescope to be launched in 2022, from technological development and scientific exploitation of data. Combining WL with other probes, such as galaxy clustering and CMB, is also a

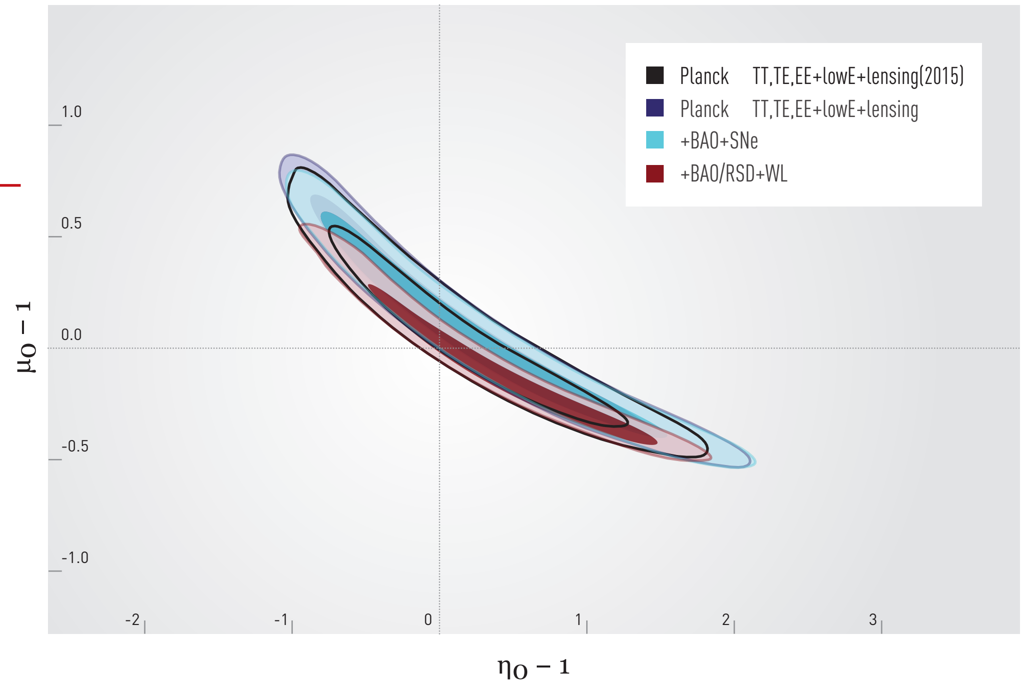

Fig. 1: [1], fig.31 result from Planck final analysis testing μ,η functions: both are 1 in ΛCDM (where dash lines cross). Any detection of a deviation from 1 would indicate a deviation from the standard theory of gravity. Colored contours identify 95% probability of the values of the parameters to agree with the corresponding data set. Results are consistent with ΛCDM.

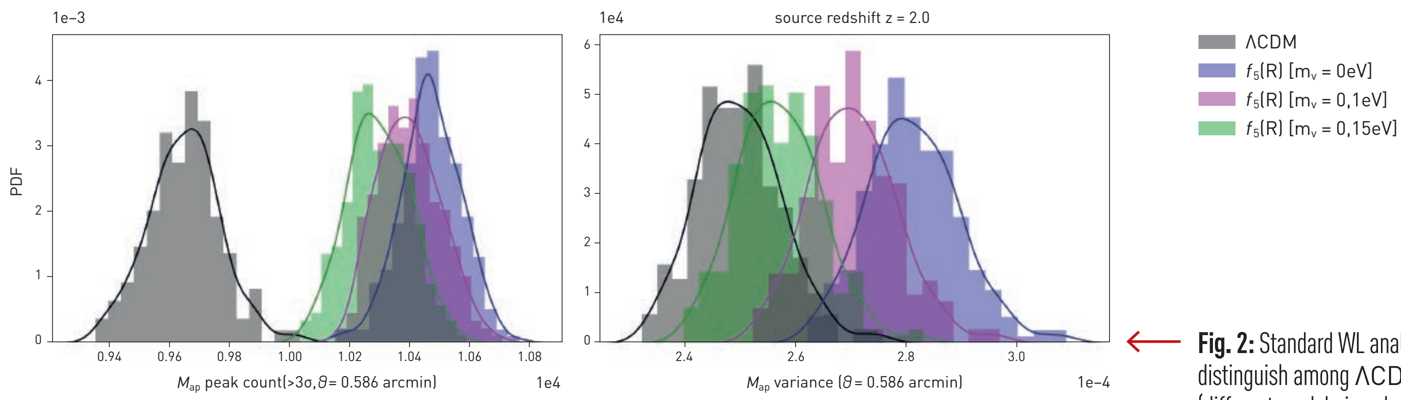

Fig. 2: Standard WL analysis (left) cannot distinguish among ΛCDM (grey) and MG (different models in color). We have identified in [6] (right panel) a different WL observable (peak counts) that can do the job.

challenge: to this end, CEA researchers are leading the taskforce in charge of such combination for the Euclid mission.

In particular, researchers at CEA have extracted information from WL data, hidden to traditional analyses. We highlight here a few examples. In [5] we used a new algorithm, made publicly available, to resolve a potential conflict between the observation of the Abell 520 cluster and collisionless dark matter hypothesis, finding no evidence of a dark clump claimed in previous analysis. In [6] we addressed the following challenge: given WL maps, are we able to distinguish whether they correspond to a cosmological constant or to MG? To this end, CEA researchers have compared different WL observables and identified the one that helps the most in distinguishing different theoretical models (the winner being peak count statistics, Fig.2). We have further shown that Convolutional Neural Networks improve our ability to distinguish a cosmological constant from MG theories, highlighting a new application of machine learning in cosmology [7].

These results demonstrate how the choice of the right statistical observable plays a crucial role in data interpretation and can decide whether, with the same data, we make a discovery or not. Finally, CEA is co-leading the Canada-France Imaging Survey (CFIS) program, started in 2017, necessary to derive photometric redshifts in Euclid, i.e. determine the distance of the observed galaxies and reconstruct the expansion of the universe. ■

[1] https://arxiv.org/abs/1807.06209
[2] https://arxiv.org/abs/1502.01590
[3] https://arxiv.org/abs/1708.06356
[4] https://academic.oup.com/mnras/article/430/3/2200/981767
[5] https://arxiv.org/abs/1708.00269
[6] https://arxiv.org/abs/1805.05146
[7] https://arxiv.org/abs/1810.11030

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Galaxy Clusters as Physics Laboratories

When the matter density in a given region of the Universe becomes sufficiently high, it decouples from the expansion and starts to undergo gravitational collapse. This process is hierarchical, leading to the formation of stars, galaxies, groups of galaxies, and ultimately the first galaxy clusters at a redshift [1] around 2, when the Universe was only about a quarter of its present age.

Since then, clusters have grown by continual accretion of material along the filaments that trace the foam-like structure of the "cosmic web". Located at the nodes of these filaments, they are the most recent manifestation of the hierarchical formation of structure.

Clusters can contain thousands of galaxies, measure millions of light-years across, and have total masses up to one thousand million million (10^{15}) times that of the Sun. Their composition reflects that of the Universe: 85% of their mass is composed of dark matter, which can be detected only indirectly, and only the remaining 15% of the mass is visible. The galaxies represent less than 3% of the total mass of a cluster: the visible mass dominated by a rarefied plasma that fills the space between the galaxies. This intra-cluster medium (ICM) is exceptionally hot (more than 10 million degrees), and cools by emission of X-ray photons. Interaction of Cosmic Microwave Background (CMB) photons with the ICM leads to the Sunyaev-Zeldovich effect (a spectral distortion of the CMB in the direction of a cluster).

X-ray satellite observatories such as XMM-Newton and Chandra can image the X-ray emission, yielding precise maps of the gas density distribution. Moreover, the X-ray spectrum can be measured, allowing determination of the gas temperature across the cluster extent. In a cluster in equilibrium, the gravitational force due to the dark matter is counterbalanced by the pressure of the gas. Using this fact, CEA teams have obtained precise measurements of the distribution of dark matter in clusters at a redshift of 1, or about 8 billion years ago. These dark matter profiles are highly cusped, as predicted in cosmological numerical simulations, and are strikingly similar to those seen in present-day objects. In parallel, a large campaign of numerical simulations by the CEA teams has shown the remarkable stability of the dark matter distribution over cosmic time (see Fig 1).

Most of the accretion that drives cluster growth is "quiet", but occasional mergers occur between objects of similar mass. This cluster coalescence converts kinetic energy into thermal energy, leading to the most energetic events in the Universe since the Big Bang. Thousand-light-year-long shockwaves travelling at thousands of kilometres per second are driven into the ICM plasma, heating the gas and generating bulk and turbulent motions that can last for more than a billion years.

High-resolution X-ray spectroscopy offers the possibility of direct detection of the bulk and turbulent motions in the ICM plasma through measurement of the shifting and broadening of emission lines. In the future, we hope to be able to measure these quantities precisely with the high-resolution micro-calorimeters that are being developed for the X-Integral Field Unit (X-IFU) on board ESA's next-generation X-ray mission Athena, in which the CEA plays a key role. The thousands of detectors in the X-IFU will allow mapping of the line-of-sight bulk and turbulent velocity field of the ICM plasma in many merging galaxy clusters on unprecedented spatial scales, inside and beyond the core. It will allow us to link these bulk and turbulent motions to the assembly of the "cosmic web", and give unparalleled insights into the physics of the ICM plasma during these extreme events. ■

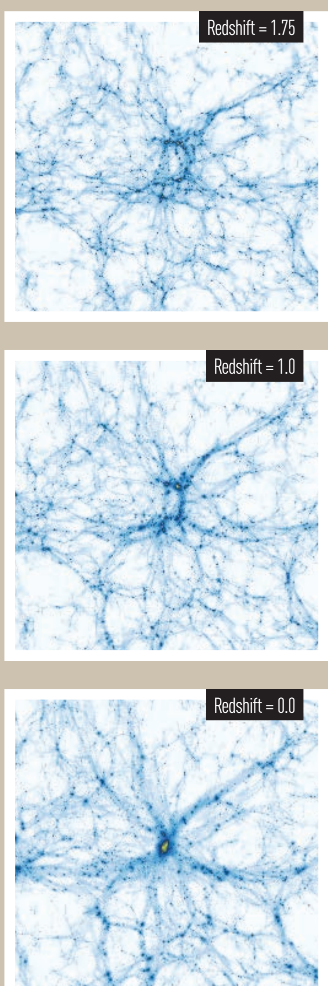

Fig. 1 : in these images taken from a CEA research programme on the GENCI supercomputers, we see the dark matter distribution of a massive galaxy cluster slowly collapsing under the influence of gravity. Redshifts 1.75 and 1.0 correspond to 10 and 8 billion years ago, respectively, while redshift is the present day.

[1] In an expanding Universe, objects move away from the observer, causing their spectrum to move to progressively lower energies the further away they are. The redshift of an object is a measure of this spectral shift. It can be directly related to the age of the emitting object.

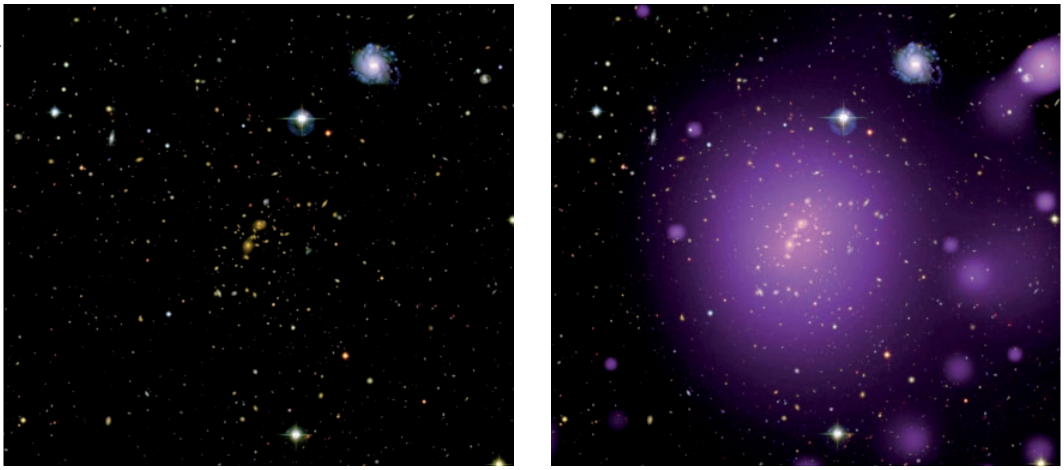

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Fig. 1: visible light image (left) and X-ray image (right) of cluster XLSSC006, situated at a distance of about 4.5 billion light-years from Earth. The pink halo of light (false colour) represents the intensity of the X-ray radiation emitted by the hot gas in the cluster.

Large Surveys of Galaxy Clusters and Cosmology

BY
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Galaxy clusters are concentrations comprising several tens to several thousand galaxies. Paradoxically, galaxies only represent a few percent of the mass of these clusters.

A diffuse gas occupies the space between the galaxies: it is heated to temperatures of several tens of millions of degrees and emits X-rays (Fig. 1). The study of galaxy motions in clusters implies the existence of a third component – the famous "dark matter" – but as it emits no light, we have no precise knowledge of its nature, hence its name. It constitutes 80% of the mass of the clusters, as against 15% for the X-ray gas and 5% for the galaxies.

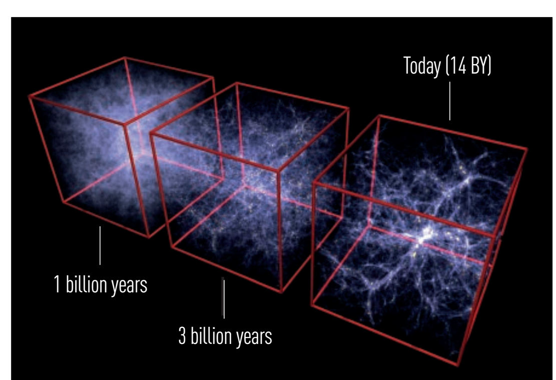
Galaxy clusters are the largest cosmic entities. They are formed under the combined action of gravity and the expansion of the Universe (Fig. 2). The first clusters appear about 3 billion years after the Big Bang, at a time when the acceleration of expansion becomes predominant. A comparison of the cluster properties at different cosmic epochs thus enables us to test the cosmological models: depending on whether the Universe is more or less dense and its expansion faster or slower, we will find clusters that are more or less massive at a given epoch. Therefore, galaxy clusters enable us to test the theories of gravitation, the properties of dark matter and the geometry of the Universe. The aim is therefore to survey the population of clusters as a function of time and, hence, of their distance.

We can undertake surveys of a large part of the sky in the visible or infrared bands, in order to detect galaxy concentrations. However, the operation is rendered more complex by the superposition of the cluster galaxies with the other galaxies in the celestial sphere, which confuses the information from the regions situated at different distances. We therefore prefer surveys in the X-ray band, because an extended source provides a univocal signal of the presence of a cluster of galaxies: large quantities of hot gas are only to be found in the clusters, which significantly reduces the superposition effects.

To be able to compare observations with the predictions of the cosmological models, the X-ray luminosity of the clusters must be tied to their mass, with an estimate of how it evolves over time. If we detect more clusters than expected, this does not necessarily mean that they are more numerous, but perhaps just because they are more luminous than expected! Numerical simulations make it possible to jointly model the formation of clusters and the evolution of the gas (see p. 32). Initial results from a cosmological analysis of galaxy clusters detected by ESA's XMM observatory were obtained with the DAp's XXL project [1]. ■

[1] http://irfu.cea.fr/xxl

Fig. 2: evolution of the structure of the Universe. Numerical simulation of the gas component in a cube of 300 million light-years on a side. The density contrast increases over time and the first clusters appear at the intersection of the filaments at about 3 billion years. Today, some clusters are extremely massive (10^{15} solar masses, in the centre of the cube).



Simulation: V. Springel (MPA)

© Hubble Space Telescope WFT3 Camera (Strazzullo et al., ApJ, 2016)

Fig. 1: RGB image from the Hubble space telescope of one of the most distant clusters known (CL~1449; Gobat et al 2011). Cluster galaxies, mostly in the left-bottom quarter of the image, can be distinguished by their reddest colors.

Observing the Formation and Evolution of the First Generation of Galaxy Clusters

BY
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L'identification des amas de galaxies les plus lointains est un sujet de recherche très actif dans le monde entier et au CEA (Fig. 1) pour étudier les processus physiques clés de la formation des galaxies et de la cosmologie.

The identification of the most distant galaxy clusters is a very active topic of current research worldwide and at CEA (see an example in Fig.1), providing an opportunity to investigate key physical processes in both galaxy formation and cosmology. Around 3-4 billion years after the Big Bang, star formation and black hole growth reach their peak activity (e.g., Madau & Dickinson 2014). This is also the time when the most intensively active galaxies occupy the centers of large-scale structures, while in the local Universe they actually avoid them (e.g., Elbaz et al 2007). Those large-scale structures are not easily separated between genuine clusters, which are gravitationally bound within a single massive dark matter halo (see discussion in Diener et al. 2015) and proto-clusters, million light-years looser over-densities that host multiple dark matter halos (Chiang et al. 2013; Muldrew et al. 2015). Although apparently trivial, this distinction is extremely difficult in the very distant Universe. Indeed, only two genuine clusters are known in the early universe thanks to a clear signpost of gravitational collapse ("virialization") detected in the form of a hot intergalactic X-ray emitting gas. Both were discovered by CEA groups, including the most distant cluster presently known, CL 1001, observed only 2.5 billion years after the Big Bang (Wang et al 2016). This situation will dramatically change in a decade when the ESA mission, Athena, to be launched in 2034 will detect this signpost in the first structures.

Meanwhile, we are exploring within CEA the possibility to use the Atacama Large Millimeter array (ALMA) to detect the hot gas via its impact on the cosmic microwave background (inverse Compton effect) through the so-called Sunyaev-Zel'dovich effect. The first promising results are in hand and being studied.

The first generation of clusters are key to test structure growth theories, hence our cosmological framework, and study the formation sites of the most massive galaxies, such as the local ellipticals whose origin remain controversial. To become ellipticals, galaxies must have experienced a transformation during which they lost their disk and became spheroidal, and stopped forming stars, and it is unclear whether this happened before or after entering cluster cores. Furthermore, high-redshift clusters are interesting laboratories to study two exciting and still mysterious phenomena (Fig.2). First, we know that some energy was injected in the intergalactic medium during the formation of present-day clusters but its origin remains unclear. We now start to have the chance to investigate this process in action. Second, cluster formation should present evidence of cold gas accretion, the fuel for galaxy growth, from the wider large-scale environment. This phenomenon predicted by theory remains unobserved yet and is crucial to understand galaxy formation.

This age of the first heroic exploratory efforts will soon end when the Euclid mission will unveil large samples of the first generation of clusters; the Square Kilometer Array (SKA) will trace the distribution and concentration of the activity in galaxies, future facilities at the VLT; and ELT will provide large number of spectra, and of course ATHENA will measure their X-ray emission. A revolution in this field is set to begin in the next 5-10 years. ■

"This age of the first heroic exploratory efforts will soon end. A revolution in this field is set to begin in the next 5-10 years."

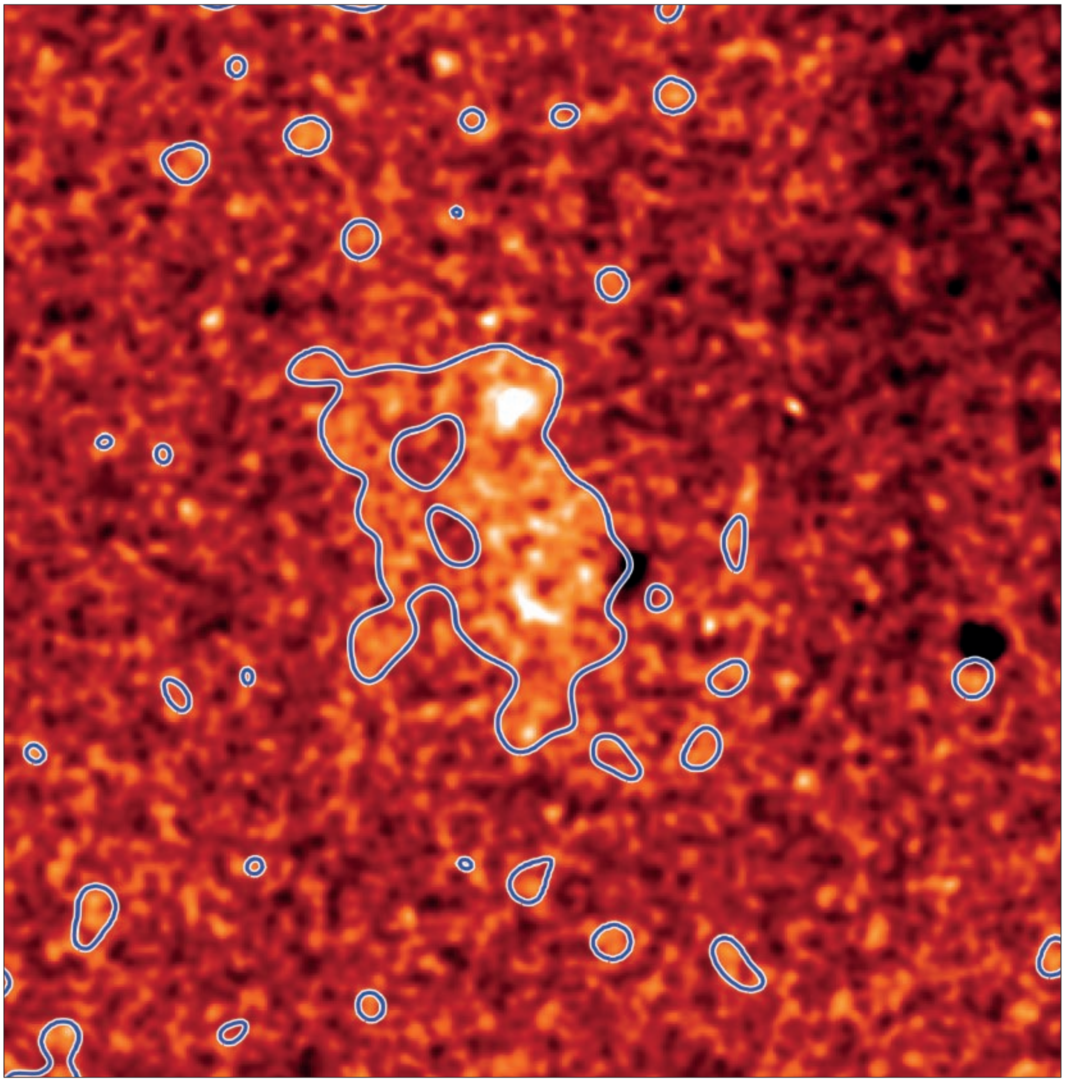

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Fig.2: a map of Hydrogen Ly-α emission in the same structure of Fig.1, a surprising discovery of diffuse cold gas from our CEA work (Valentino et al. 2016) that we continue to investigate, probably related to the two mysterious phenomena mentioned in the text (energy injection and cold gas accretion).

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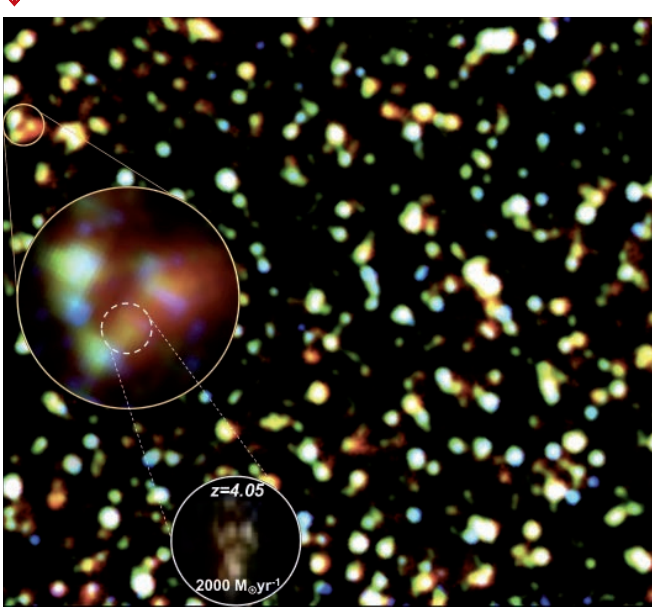
The Enigmatic Formation of Massive Galaxies

The most massive galaxies in the Universe have no longer been forming stars for several billion years. These dead galaxies – if we determine a galaxy's vitality by the intensity with which it forms new stars – pose many questions: what are their ancestors? When and how did these "elliptical" galaxies change shape and lose their disk to become spheroids? Why do they no longer form stars and how did they give birth to so many stars shortly after the Big Bang?

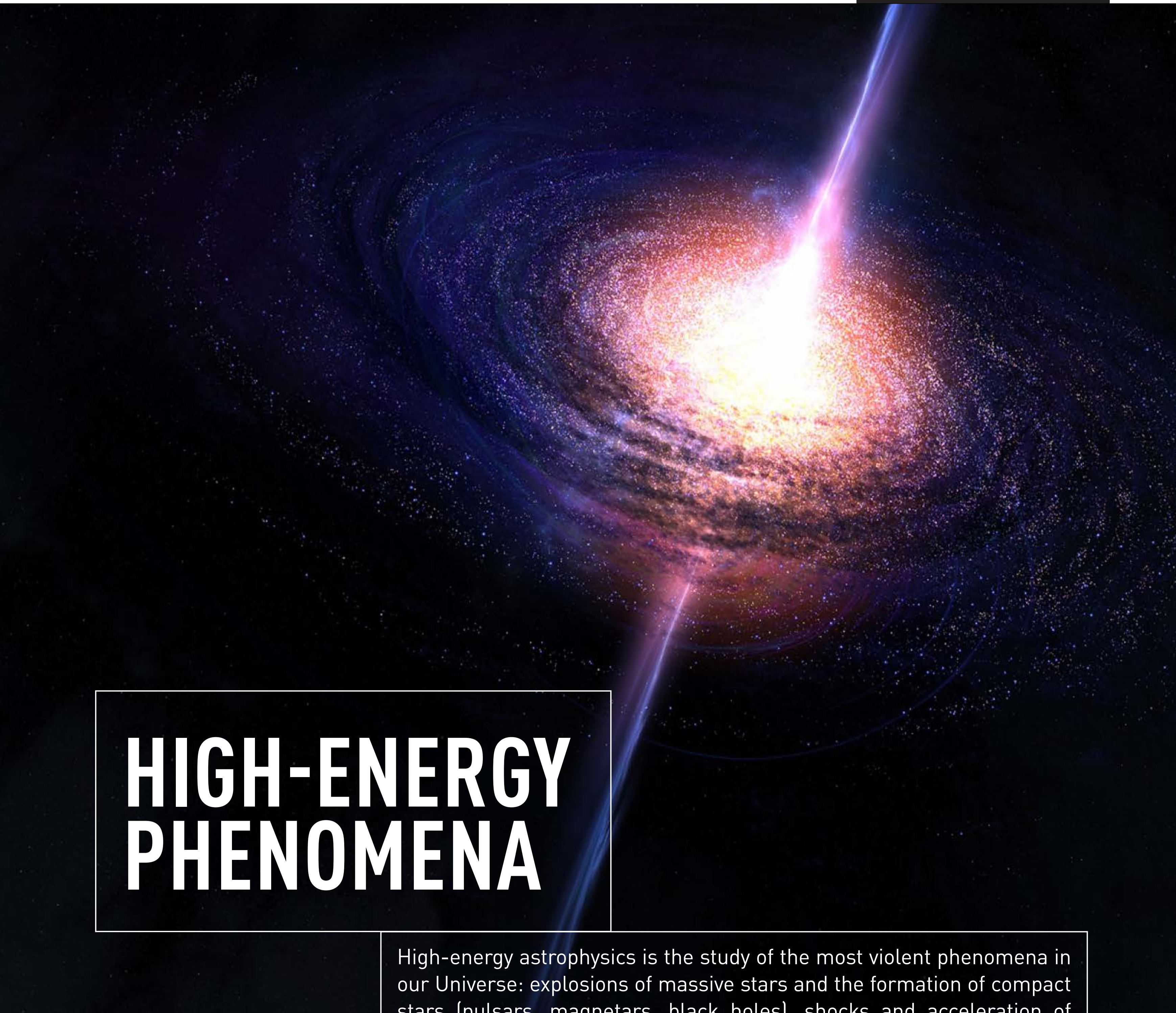
Image from the Herschel satellite presenting a host of bright spots which are all galaxies, some of which form 100 to 1000 times more stars per year than the Milky Way, such as the galaxy situated with a redshift of z = 4.05 and from which we receive the light emitted 1.5 billion years after the Big Bang. This galaxy forms 2,000 suns per year, or one sun every 4 hours. The close-up image from the Hubble satellite looks like a footprint, the footprint of a galactic dinosaur...



As the most massive galaxies are no more forming stars in the present-day Universe, we initially thought that massive dead galaxies came from the merging of smaller dead galaxies. ESA's Herschel satellite, more specifically its camera PACS, built under CEA project leadership, turned this theory on its head by discovering a profusion of remote massive galaxies forming stars at the rate of several hundred solar masses per year. Just like archaeologists, we found remains which we had attributed to the accumulation of several known animals, whereas we were in the presence of the skeleton of an animal which no longer exists, a sort of galactic dinosaur.

A few extreme cases were already known, but the observations by Herschel showed that there was a time in the history of the Universe when the dinosaur galaxies dominated the star production process. These ancestors of massive elliptical galaxies had been missed, even in the deepest images from the Hubble satellite, owing to the large quantity of interstellar dust which absorbs the light of the recently born stars. By chance, this dust radiates in the far infrared – the observation spectrum of Herschel – revealing new generations of stars. The massive elliptical galaxies were thus born about 10 billion years ago and were monsters spawning stars at a prodigious rate.

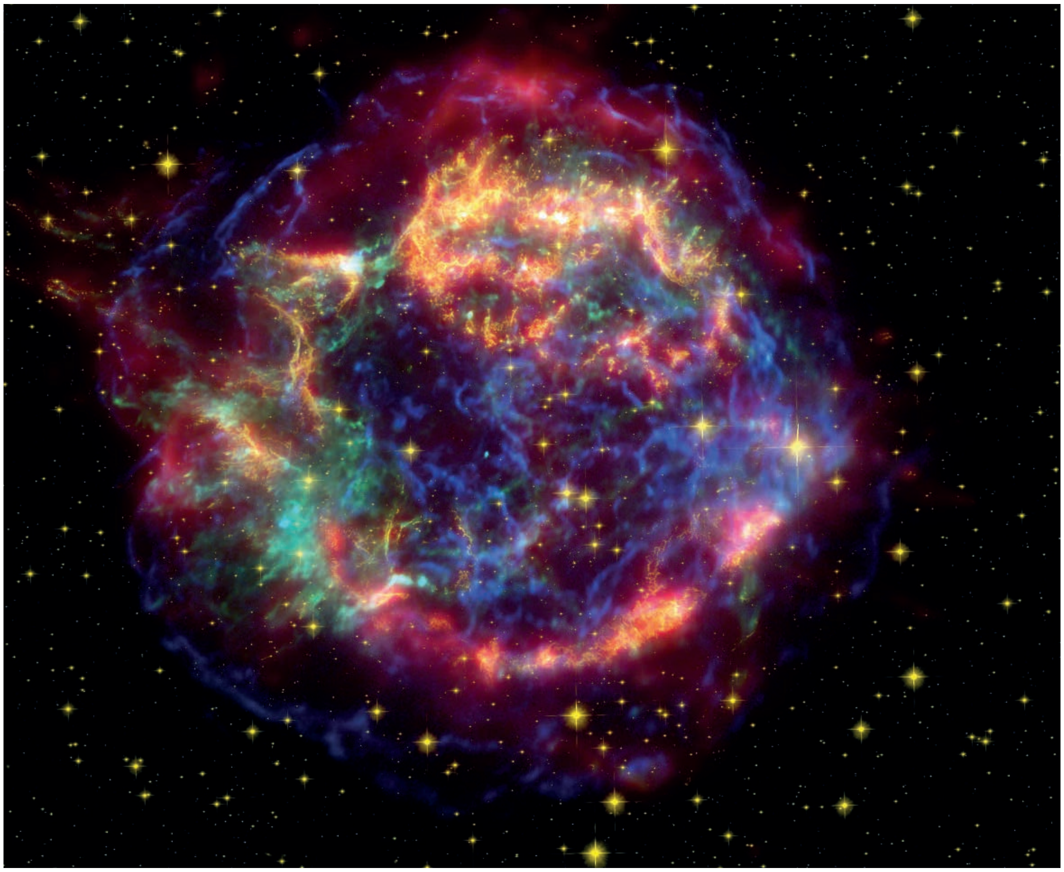
ALMA (Atacama Large Millimetre Array) and the observatory of the Institute of Millimetre Radio Astronomy (IRAM) confirmed this hypothesis by measuring the evolution of the quantity of dust and interstellar matter contained in galaxies during the history of the Universe. These reservoirs only enable the galaxies to form stars at such rates for about 500 to 600 million years. However, several billion years would be needed to explain the universal nature of the star formation discovered by the CEA teams with the "main sequence of star formation" in galaxies (the tight correlation between the intensity of star formation and the mass of a galaxy). There is only one possible explanation: galaxies must permanently receive intergalactic matter, a sort of manna from space. Numerical simulations had precisely just shown that filaments of intergalactic matter must have continuously fed galaxies. This theory also offered a natural explanation for the death of galaxies: by falling into the more massive galaxies, the matter released an energy so great that it heated the surrounding matter, causing the infall of matter to cease. Then some 500 million years later, the galaxy had exhausted its reserves. ■



HIGH-ENERGY PHENOMENA

High-energy astrophysics is the study of the most violent phenomena in our Universe: explosions of massive stars and the formation of compact stars (pulsars, magnetars, black holes), shocks and acceleration of cosmic rays, accretion and relativistic ejections by compact stars. These objects are laboratories for the physics of the extreme: the compactness, magnetic and gravitational fields, shocks, acceleration and speed involved are the most intense permitted by contemporary physics. These phenomena are being studied at CEA using theoretical, numerical and experimental approaches.

Fig.1: Remnants of supernova Cassiopeia A



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BY
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(Fundamental Research Division)

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Supernovæ: Understanding the Explosion of Massive Stars

The explosion of massive stars, known as supernovæ, is a key process in astrophysics for disseminating the heavy nuclei formed by the nuclear fusion reactions and for giving birth to compact objects such as neutron stars and black holes.

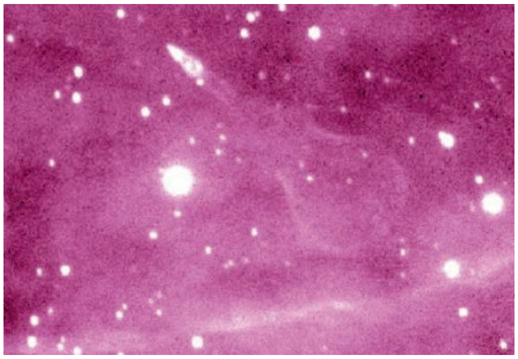
"Black holes are the result of failed explosions, when the mass of the neutron star reaches a critical threshold of about 2-3 times the mass of the Sun."

The explosive death of a massive star begins with the collapse of its core, when the mass of iron synthesised in its core approaches the critical threshold of 1.4 times the mass of the Sun.

The main challenge in supernova theory is to understand the mechanism which transforms the collapse into an explosion. The explosion threshold depends on the absorption of neutrinos in the dense region of 150 kilometres surrounding the forming neutron star. Black holes are the result of failed explosions, when the mass of the neutron star reaches a critical threshold of about 2-3 times the mass of the Sun.

At the Department of Astrophysics (DAp), the Astrophysical Plasma Modelling Laboratory (LMPA) uses analytical, numerical and experimental tools to characterise the hydrodynamic instabilities which develop in the centre of the star. This key ingredient is responsible for a deformation of the dense post-shock region (Fig.1) which leads to a preferential direction for the absorption of neutrinos and for setting the shockwave in motion. The asymmetrical movements in the dense neighbourhood of the neutron star generate gravitational waves and

Fig. 2: the guitar nebula is a shockwave produced by the movement of a neutron star at more than 1000 km/s.



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fluctuations in the neutrino emission. Several hours are needed for the shockwave to travel through the gigantic stellar envelope and produce the explosion of light called a supernova.

The supernova fountain invented at the DAp reveals the asymmetrical dynamics of the last second preceding the expansion of the shockwave, at the decisive moment when the core of the star collapses into a neutron protostar. This experiment shows that the appearance of transverse motions is the natural consequence of the laws of fluid mechanics. As a result of this dynamic, neutron stars are propelled at several hundred kilometres per second and driven in rotation at up to more than ten revolutions per second (Fig. 2).

The astrophysical connection is based on the analogy between the surface waves in the fountain and the acoustic waves in the star. The researchers at the LMPA are using this experiment to build-up their physical intuition about shockwave instabilities. The simplicity of the experiment also enables the public to grasp the physics of supernovæ and the formation of neutron stars and black holes. The supernova fountain has been part of the permanent collection at the Palais de la Découverte science museum in Paris since 2015 (Fig. 3).

In the experiment, the shockwave is represented by a sudden change in the height of the free flow surface, called the hydraulic jump. This jump is similar to the circular jump in the kitchen that occurs when the water from the tap encounters the horizontal surface of the sink and flow radially outwards. The main difference in the experiment is that the water is injected radially towards the centre.

The universal laws of fluid mechanics are responsible for the same phenomenon in the core of a star and in the fountain, although on a scale a million times smaller. The scaling laws guarantee that the dynamics of the experiment are a hundred times slower than in the core of the star. The most interesting phenomenon in the experiment is the unstable evolution of the flow. Although the water injection is steady-state and uniform, the transverse movements appear with increasingly large amplitudes. They transform the circular jump into an oscillating movement (Fig. 4) which ends up turning in a random direction while the internal regions turn in the opposite direction.

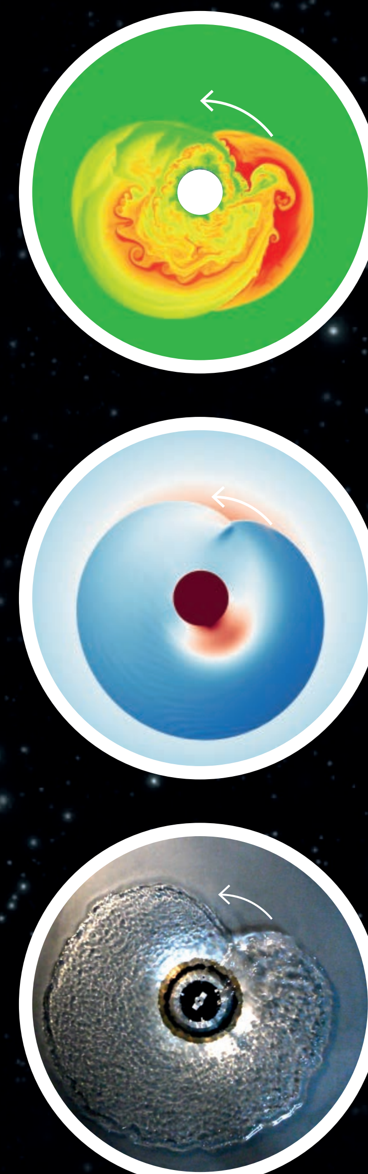
Even if the physical ingredients of the fountain are far simpler than in a stellar core, the most advanced 3D numerical simulations suggest that this simple experiment captures several key processes of supernova theory. In addition to the numerical simulations, it tells us that a spherical collapse can lead to a transverse explosion and the birth of a moving, rotating neutron star.

The next challenge is to understand how the diversity of star structures leads to a diversity of hydrodynamic instabilities and to different explosion scenarios that can be differentiated by their neutrino and gravitational wave signatures, by the properties of the residual compact object and by the heterogeneous composition of the ejecta.

Two dozen neutrinos were observed in 1987 originating from supernova SN1987A in the Large Magellanic Cloud close to our galaxy. Today's neutrino and gravitational wave detectors are ready to observe the next galactic supernova. ■

Fig. 3: the supernova fountain in the Palais de la Découverte.

Fig.4: the deformation of the hydraulic jump in the supernova fountain and in its numerical simulation is similar to that ofwthe shockwave in the numerical simulation of a star's collapse.



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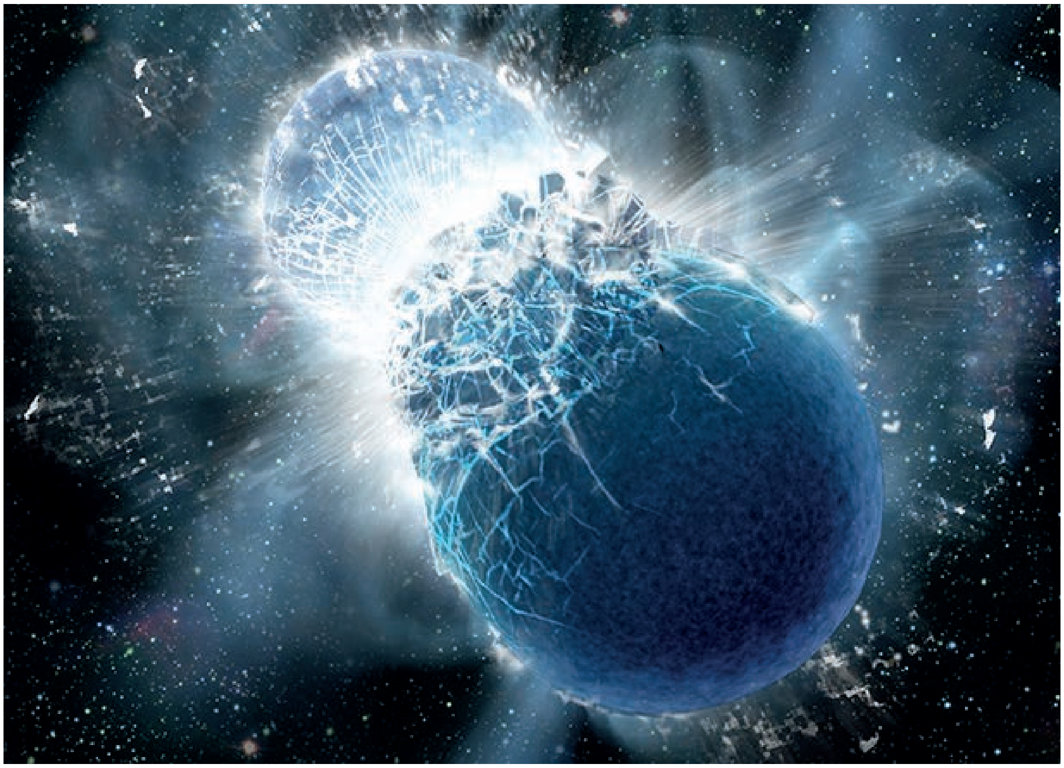
Artist's impression of the coalescence of two neutron stars.



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"Another class of even shorter gamma-ray bursts (lasting less than two seconds) corresponds not to the explosion of a conventional massive star, but to the coalescence of two neutron stars."

Extreme explosions

Some supernova explosions stand out owing to their extraordinary power. For example, the class of superluminous supernovæ emits one hundred times more light than a usual supernova. Others, called hypernovæ, stand out in their kinetic energy and their association with the emission of a gamma-ray flash of several tens of seconds, called a gamma-ray burst.

During their short span, gamma-ray bursts are the most luminous objects in the Universe and can be observed at cosmological distances. They act as beacons for probing the evolution of the galaxies in the remote Universe when it was still up to 10 times smaller than it is today.

Another class of even shorter gamma-ray bursts (lasting less than two seconds) corresponds not to the explosion of a conventional massive star, but to the coalescence of two neutron stars (a neutron star is an extremely dense star comprising between one and a half and two times the mass of the Sun within a radius of 10 km). It was only recently, in August 2017, that a coalescence of this type was directly observed for the first time, through the detection of gravitational waves by the LIGO and VIRGO interferometers. The observation of the corresponding gamma ray burst and afterglow at other wavelengths of the electromagnetic spectrum marked the beginning of a new era for exploration of the Universe, called multi-messenger.

These various extreme explosive phenomena require both a phenomenal reservoir of energy and a process capable of extracting this energy over a sufficiently short period of time. For the energy source, one of the most popular scenarios considers the kinetic energy of a neutron star which can exceed 10^{52} erg when it rotates with a period of a few milliseconds. An extremely intense magnetic field of 10^{15} G would then enable this energy to be extracted efficiently and transmit it to the explosion. There is a class of neutron stars called magnetars, the observation of which indicates a magnetic field of this intensity, making them the most powerful magnets known in the Universe. These observations militate in favour of the theoretical scenario of the "millisecond magnetar", but the link between their birth and the extreme explosions has not yet been fully established, notably owing to the lack of predictive theoretical models and any direct observational signature.

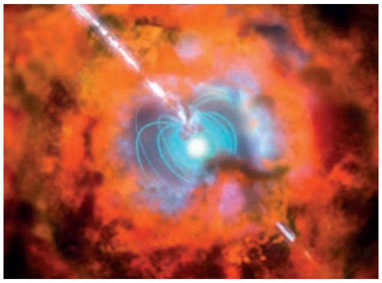
The major challenge for the theoretical models is to explain the origin of the magnetic field. At the Department of Astrophysics, the Astrophysical Plasmas Modelling Laboratory (LMPA) is developing 3D numerical simulations of the evolution of the magnetic field in the first moments following the birth of a neutron star.

As part of an ERC Starting Grant called MagBURST, which began in 2017, the first simulations showing the generation of a magnetic field compatible with that of a magnetar have just been obtained.

The magnetic field is generated by the movements of the fluid making up the interior of the neutron star. As this is a very good conductor of electricity, it can generate the currents at the origin of the magnetic field, by means of a dynamo mechanism. This dynamo could be caused by convective movements similar to those in the Sun or of the liquid iron core on Earth (see p. 13). The first simulations of a convective dynamo in a nascent neutron star showed the appearance of a new branch giving birth to extremely intense magnetic fields of 10^{15} to 10^{16} G if the rotation is fast enough (Fig. 1).

In the outermost zones of the neutron star, another mechanism, due to the magneto-rotational instability similar to that occurring in accretion disks, can also develop. The next theoretical challenge will be to determine the interaction between the two dynamo mechanisms and their impact on the properties of the corresponding supernova explosion.

In parallel with this numerical work, the LMPA and the Laboratory for the Study of High Energy Cosmic Phenomena (LEPCHE) are collaborating on the observational signatures of this scenario, more particularly if the magnetar is born from the coalescence of two neutron stars. The Franco-Chinese SVOM satellite (see below) will allow observation of these objects in several wavelengths of the electromagnetic spectrum and will thus be a valuable addition to the gravitational wave observatories. The observation of X-rays a few hours to a few days after the detection of gravitational waves could thus give the first direct proof of the formation of a magnetar. ■



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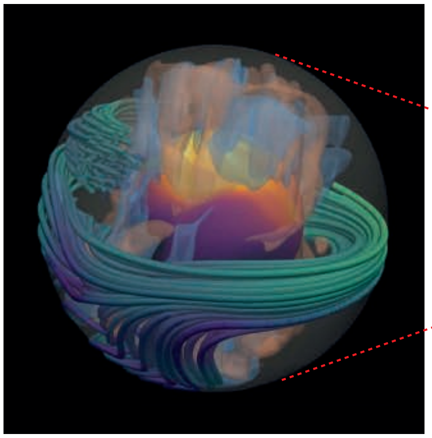
Artist's impression of a gamma ray burst caused by the birth of a magnetar.

MAGNETAR



HYPERNOVA

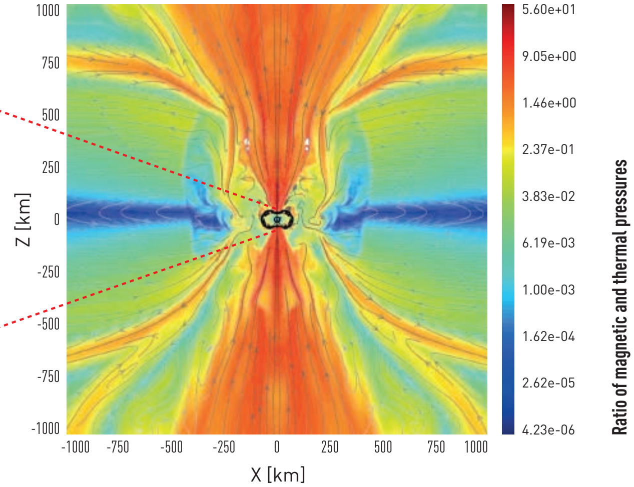
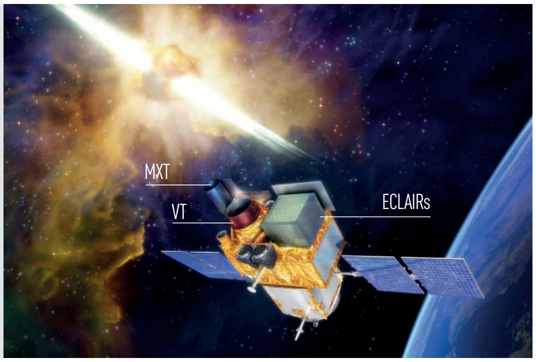


Fig. 1: numerical simulations, on the left of the convective dynamo in the interior of a magnetar being formed (Raynaud et al. under preparation) and **on the right** of the explosion of a magnetorotational supernova resulting from its birth (Bugli et al. under preparation).

SVOM

Starting in 2021, the Franco-Chinese SVOM mission will be observing gamma ray bursts produced by certain massive star collapses or the coalescence of neutron stars. Its ECLAIRs telescope will detect the prompt emission of gamma rays and localize the event in the sky in real-time using the scientific software produced by CEA. It will ask the satellite to be reoriented to observe the afterglow of the burst with the on-board telescopes, in the visible spectrum for the Chinese VT and in the X-ray spectrum for the French MXT, whose focal plane is built at the DAp. The French ground segment, coordinated by the CEA, will process the data from the French instruments and will receive burst alerts for distribution to the dedicated telescopes and to the global community, in order to ensure complete monitoring of these enigmatic events.



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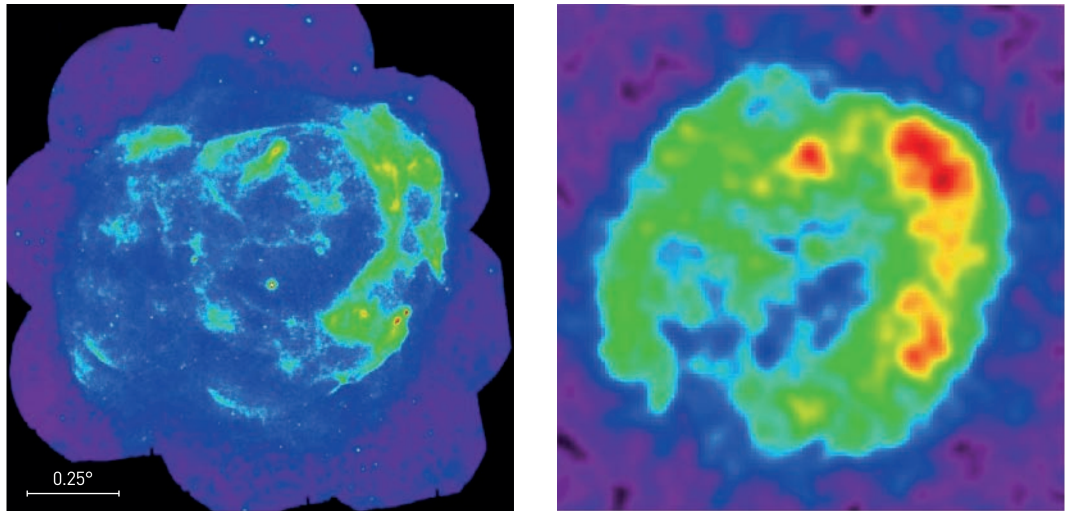
François Brun is a researcher at CEA's Particle Physics Department (Institute of Research into the Fundamental Laws of the Universe).

Fig. 1: example of SNR RX J1713.7-3946 seen with X-rays (left) and TeV gamma-rays (right). The images are on the same scale.



XMM-Newton **H.E.S.S.**

Supernovae Remnants and Cosmic Radiation:

The Gamma-ray Sky Sheds Light on the Question

Cosmic-rays, or CR, are high-energy particles, mainly protons and nuclei, but also a few electrons, which strike the Earth isotropically and continuously. Since they were discovered in 1912, the astrophysical sources from which they come have remained hard to determine.

Being charged, these CR become diverted during their propagation by interstellar and intergalactic magnetic fields. The energy spectrum of the CR, which ranges from a few hundred MeV to more than 10^{20} eV, shows a slight dip at 10^{15} eV (PeV), the energy below which the RC would appear to be accelerated within our galaxy. The strong shockwaves associated with the highly energetic explosion accompanying the death of massive stars (called supernovae remnants, or SNR) are good candidates for the acceleration of hadrons, up to PeV energy levels.

The energy from these explosions, combined with the rate of supernovæ in the galaxy (2-3 per century) would enable the stream of CR to be maintained if only about 10% of this energy were to be used for acceleration. Moreover, the diffusive shock acceleration models predict power law spectra that are relatively compatible with the observations.

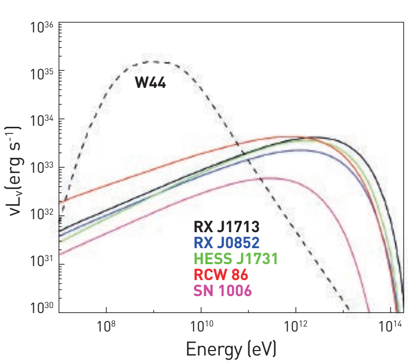
To validate this hypothesis, we examine the radiation from the particles accelerated within SNR, by means of X-ray and gamma-ray observations in order to sound out their properties (Fig. 1).

In the GeV range, the LAT on-board the Fermi satellite performed a survey of the entire sky and produced catalogues of gamma-ray photon sources, in particular an SNR catalogue. At higher energy, H.E.S.S. performed a survey in the TeV range of the innermost regions of our galaxy. In addition to listing the known SNR, H.E.S.S. revealed new candidates and carried out a population survey by comparing TeV data with that from the radio spectrum.

Fermi-LAT has been able to identify certain remnants such as hadron accelerators, which confirms that SNRs can accelerate the main component of the RC. However, this spectral signature was only observed in the middle-aged remnants ($T > 10^4$ years) where the speed of the shock has significantly dropped and the maximum energy reached by the particles cannot explain the CR streams at the highest energy levels (break in the spectrum at around 10 GeV).

The joint GeV/TeV surveys revealed two main

Fig. 2: comparison of luminosity spectral energy distributions for young SNRs in which the spectrum dips at about 10^{12} eV and for an older SNR in which emission dips at around 10^9 eV.



categories of remnants emitting gamma-rays. On the one hand, SNR that are often young (T < 5000 years) in which the gamma spectrum is dominated by lepton emission and the shockwave of which evolves in a relatively low-density medium ($n \sim 0.1\ cm^{-3}$) and on the other remnants interacting with a dense medium ($n > 1\ cm^{-3}$) in which the spectrum is dominated by a hadron process (such as W44 in fig. 2). The SNR's environment thus plays a role in its emission at high energy that is just as important as the age of the object. There are thus observational limitations with measuring the properties of the hadrons in the young remnants because the low density of the medium (i.e. the density of the targets for the hadron process) leads to a low gamma-ray emission level by comparison with the lepton channel. H.E.S.S. was in fact unable to reveal any "PeVatron" SNR (hadron acceleration to PeV).

To conclude, our observations show that for the time being, while still being excellent candidates, SNR do not as yet meet all the conditions needed to be the main source of galactic CR.

The Fermi and H.E.S.S. surveys nonetheless provided a wealth of important results, more particularly by revealing other types of sources which could contribute to the cosmic radiation spectrum. For example, a PeVatron was identified in the centre of the galaxy by H.E.S.S. (potentially linked to the activity of black hole Sgr A*). CR acceleration could also be the result of collective effects within star formation regions such as the Cygnus cocoon.

The sensitivity of the H.E.S.S. was unable to do so, but the next generation of instruments, embodied by the CTA, will be able to survey the SNR population throughout the galaxy and up to energy levels able to provide a univocal identification of the CR accelerators. Furthermore, the detection of new SNR and the characterisation of the environment of the sources, which is vital to being able to model the emission of gamma photons, will be significantly enhanced with the forthcoming ATHENA X-ray satellite. ■

Relativistic jets in microquasars

In 1962, using Geiger counters carried on an Aerobee rocket, R. Giacconi's team discovered Scorpius X-1, the first X-ray binary in history. Thirty years later, F. Mirabel (CEA) used radio to observe relativistic jets in X-ray binaries and thus discovered microquasars. A look back at some of the recent advances regarding these fascinating objects.

BY
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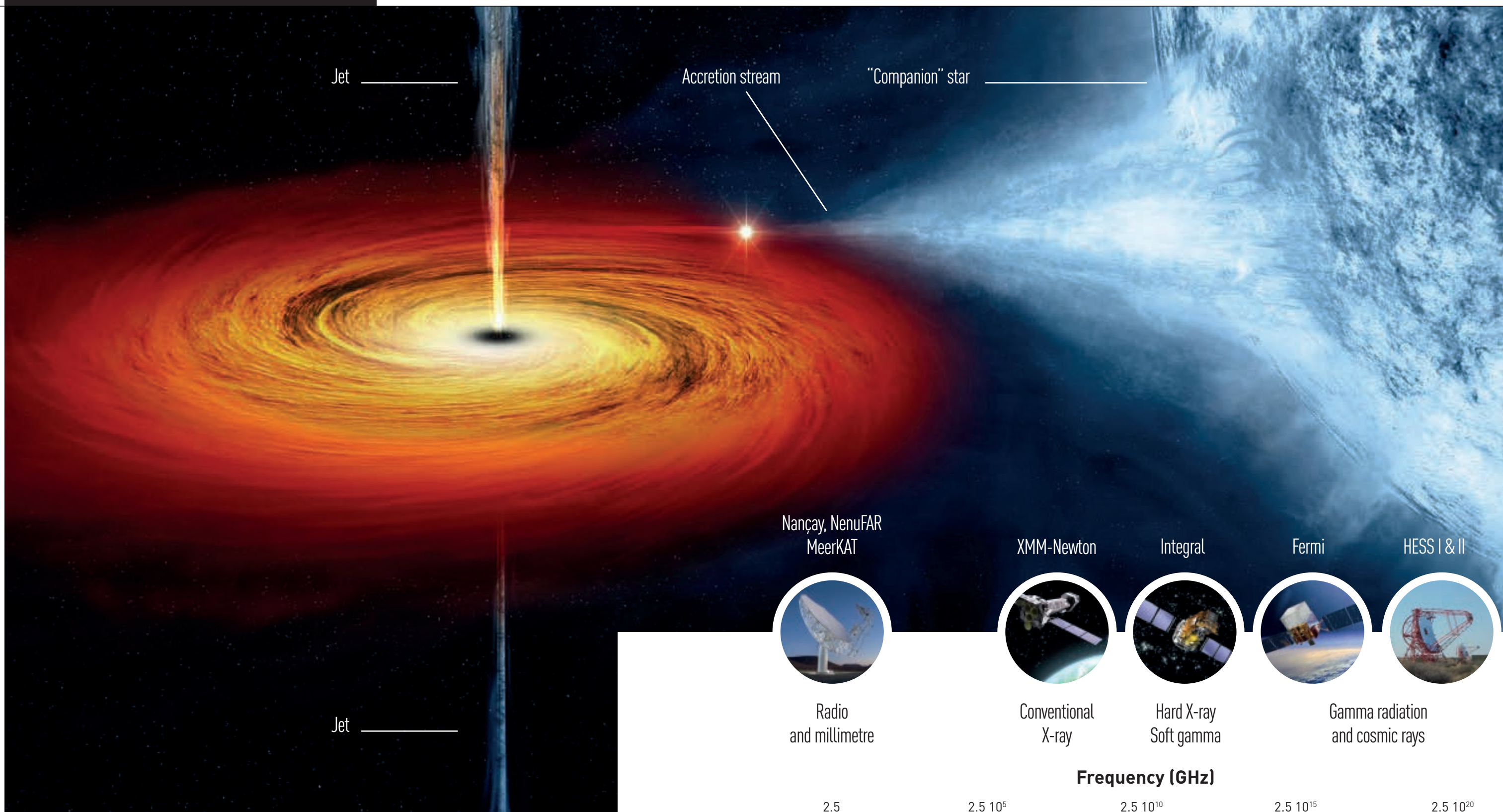
An "X-ray binary" is a system consisting of a compact object (black hole or pulsar) and a companion star. The accretion of matter from the companion and violent jets are the energy engines for the microquasars. The luminosity due to accretion is $L \propto \dot{M} \times \frac{M}{R}$ ($\dot{M}$ accretion rate, M/R compactness of the accretor) and is typically [1] $L \sim 10^{13}$ W for 1g of accreted matter (~20 times the fusion of 1g of deuterium-tritium). Accretion occurs via a disk of plasma (Fig. 1 next page) with a (thermal) emission peak at 1 keV.

The jets emit by synchrotron radiation and dominate as of the radio band. The regions closest to the black hole are the site of intense processes and matter-energy exchanges which are as yet poorly understood (Fig. 1). Accretion-ejections are omnipresent in the Universe (star formation, formation of compact bodies, galaxy cores, etc.) and can be easily studied in microquasars owing to their brightness and their relatively short evolution period (day-month).

CEA and "multi-wavelength" expertise

The origin, composition, acceleration processes of jets, their links to accretion and their feedback on the interstellar medium are some of the questions being studied by the astrophysicists at CEA.

Based on simultaneous observations on the ground and in space [2], they first of all made a major contribution to the discovery of different types of jets: short and ultra-relativistic jets ($v \geq 0.9c$) as opposed to continuous compact low-velocity jets ($v \leq 0.1c$). In the last decade, we have been able to associate discrete ejections with sudden surges in accretion indicating the very origin of the ejected matter. The compacts jets are associated with states in which accretion is more regular and relatively inefficient: the gravitational energy is here redistributed in the jets rather than in radiative form.



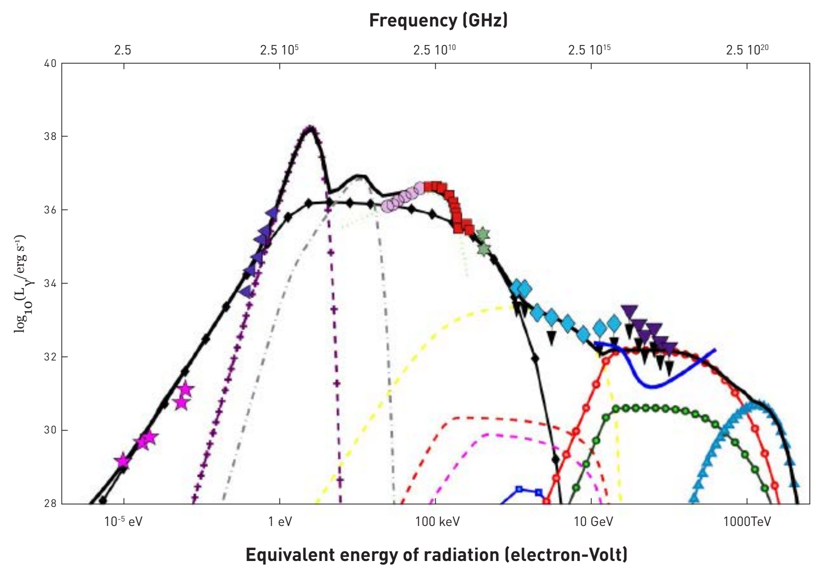


Fig. 1: broad-band spectrum of the Cyg X-1 microquasar (Pepe et al. 2016). The jets, companion star and accretion stream can be seen. The jet produces Synchrotron radiation dominating the radio range, the star produces thermal radiation in the visible and the accretion disk produces conventional soft X-ray thermal radiation. The origin of the spectrum at higher energy is widely debated: the hard X-rays would appear to be reverse-Compton radiation, with a potential MeV synchrotron component, probably stemming from the jet and, as applicable, significantly constraining the composition and energy of the jets. The solid lines are the predicted emissions of these various media in this model. The upper strip shows the instruments.

[1] M=10 M⊙, R=30 km.

[2] Notably with the XMM-Newton and INTEGRAL (ESA), and Fermi (NASA) satellites and the H.E.S.S very high energy telescope array, all with a significant investment by CEA.

[3] The Compton effect diffuses polarised radiation in a direction perpendicular to its angle of polarisation. Here, the 1st detector plane is used as a diffuser, while the second is able to establish the angular histogram of the radiation.

Even if the theoretical and numerical work carried out by the collaborators from the Astroparticles and Cosmology Laboratory (Paris), the Planetology and Astrophysics Institute of Grenoble and the Astrophysics and Planetology Research Institute (Toulouse) seems to indicate the fundamental role of magnetic instabilities in the dynamic evolution of the disk-jet, we cannot at present discriminate between the various competing models on the basis of spectral analyses alone.

An innovative means of partly lifting the veil was to use the double detection plane of the IBIS telescope on-board INTEGRAL as a polarimeter [3]. The high rate of polarisation thus detected in the microquasar Cygnus X-1 indicates the emission of compact jet electrons by synchrotron effect up to the MeV. This is confirmed by the detection of GeV radiation with the Fermi observatory in Cygnus X-1, X-3 and V404 Cygni, a sign of the interaction of these electrons with the surrounding radiation field.

The future observatories such as SVOM, CTA (gamma) and SKA (radio) will soon be actively participating in the search for these signatures in a larger number of sources. As a key player in the era of "real-time" astronomy over the coming decade, multi-wavelength monitoring of the sky will bring us new information through observations of the little-known activity phases of black holes. TeV detection with CTA will, for example, be the signature of hadron matter in the jets, with major consequences for their total energy budget. With this in mind, the purpose of the SGSO project co-sponsored by researchers at CEA will be to survey the transient very high energy sky in about 2025+. ■

Towards new discoveries!

BY
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(Fundamental Research Division)

Anne Decourchelle is Director of the AIM Joint Research Unit (UMR) and head of the CEA's Astrophysics Department (Institute of Research into the Fundamental Laws of the Universe).

Combining observations, signal processing and modelling, the scientific results obtained at CEA reflect the evolution of our knowledge in numerous astrophysical themes from the solar cycle, to the formation of stars and galaxies, the first galaxy clusters and cosmological constraints. They illustrate the indisputable progress made in our understanding of the Universe over the past ten years and highlight the open questions raised and the challenges to be addressed.

One of the main challenges in all the fields covered is the need to take account of the interplay of multiple physical processes – coupling, feedback – on a wide range of spatial scales. What is the link between the internal dynamics of the Sun and solar flares? What is the impact of the properties of the host star and its activity on (exo) planets and their habitability? What processes are responsible for structuring the interstellar medium and the formation of stars? What about the final stages in star evolution (supernovæ, compact objects) and their impact on the interstellar medium and the galaxies? What is the nature of dark energy? The numerical era, artificial intelligence and the upcoming transition to exascale in high performance computing, all offer new opportunities for astrophysics.

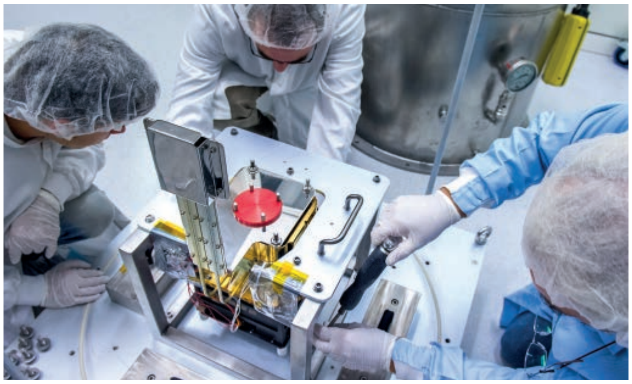
A new era of observatories on the ground and in space, to which CEA is actively contributing, will soon enable the Universe to be explored with instruments opening up new horizons through their innovative technologies affording high collecting area , high-resolution imaging and spectroscopy, temporal variability or polarisation.

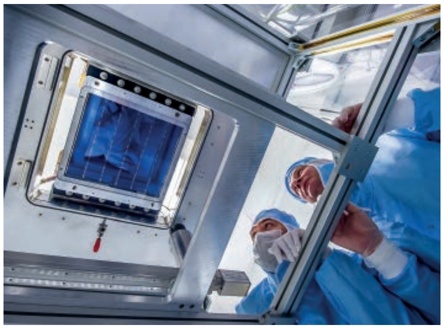
From the ground, the CTA observatory will track very high energy gamma rays and particle acceleration in the Universe. ESO's ELT (Extremely Large Telescope), to which CEA contributed the METIS infrared instrument (2026), will use its diameter of 39m to observe the first galaxies and exoplanets. The next decade of space missions is under preparation with CNES, NASA and ESA's *Cosmic Vision 2015-2035* programme: from Solar Orbiter (2020) to the JWST infrared observatory (2021), from the transient sky with SVOM (late 2021) to cosmology with Euclid (2022), from missions dedicated to exoplanets with PLATO (2026) and ARIEL (2028) to the ambitious ESA missions with the ATHENA X-ray observatory (2031) and the LISA gravitational wave space observatory (2034).

Whether observational or theoretical, the coming years will see a wealth of discoveries. These ambitious programmes are the fruit of long-term developments. At the same time, the community is already making preparations for the next steps. The THESEUS and SPICA missions are candidates for launch in 2032. Beyond 2035, thought is already being given to the definition of the next ESA programme - *Voyage 2050*! ■

"The numerical era, artificial intelligence and the upcoming transition to exascale in high performance computing, all offer new opportunities for astrophysics."

As a scientific cooperation between the Chinese (CNSA) and French (CNES) space agencies, the SVOM mission (Space based multi-band astronomical Variable Objects Monitor) is dedicated to detecting and studying gamma ray bursts.





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Inspection of CCD sensors on the focal plane of the VIS instrument for the Euclid space mission by engineers in the CEA's Astrophysics Department.

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