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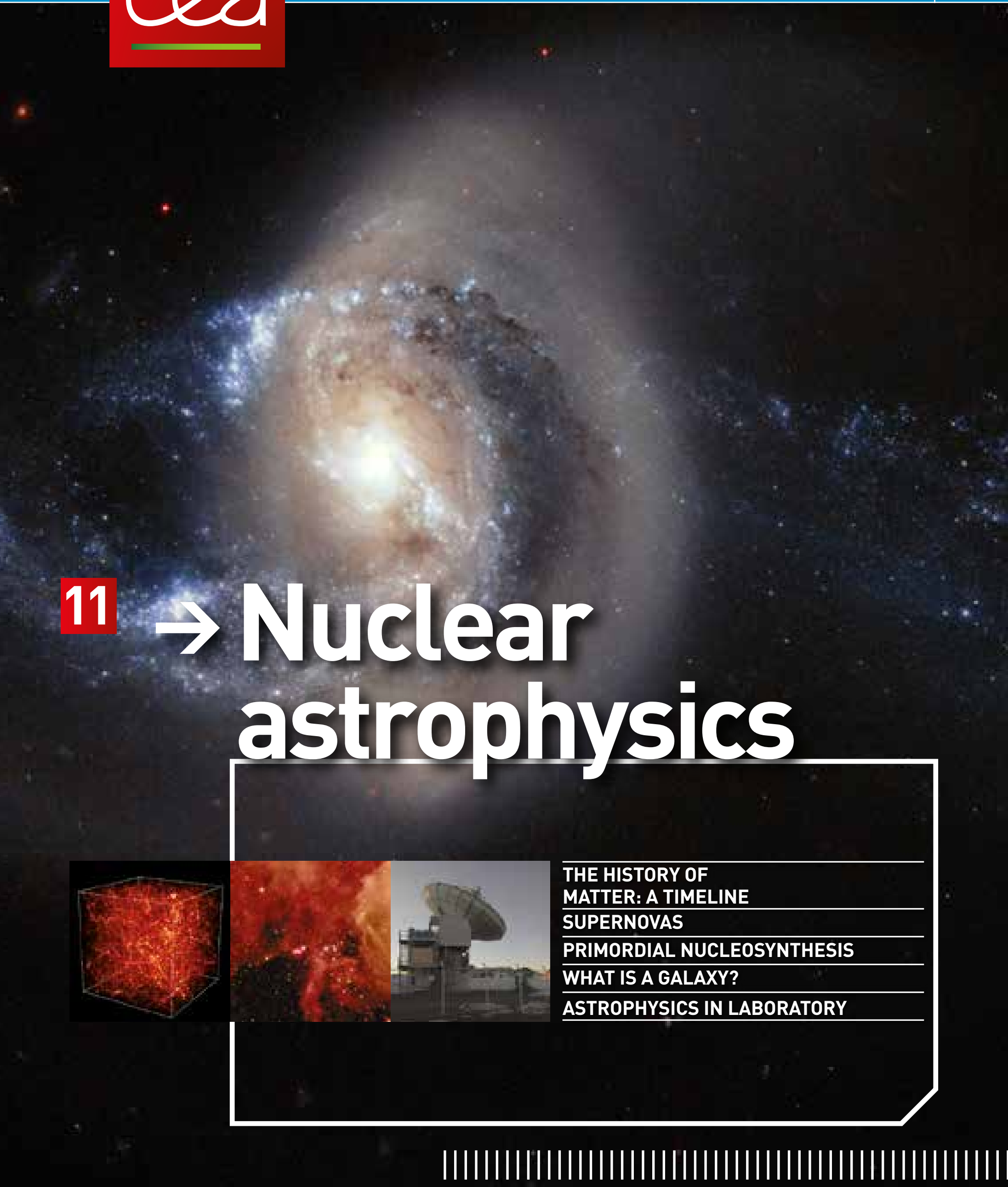

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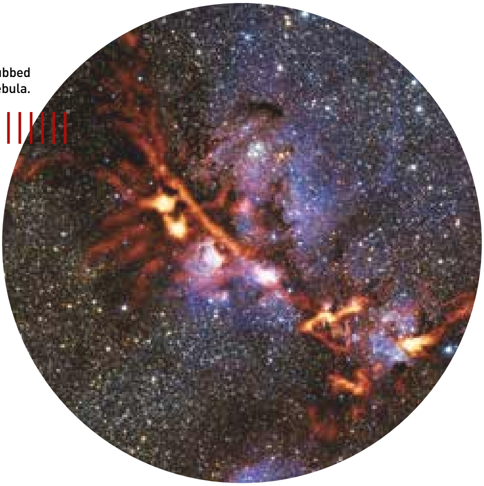
→ Nuclear astrophysics

Nuclear astrophysics

NGC 6334, dubbed the Cat's Paw Nebula.



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Cover: Spiral galaxy NGC 7714, at 100 million light-years from Earth, a seen by the Hubble space telescope

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How was the Universe made? What are all these bright spots in the night sky?

Astrophysicists use calculation and observation to attempt to find the answers.

Introduction

Astronomy is all about the observation and movement of heavenly bodies objects like Sun, Moon, planets, comets, asteroids, and stars. Astrophysics studies the physical properties of these objects: how they evolve, and how they form. It emerged as a science in the late nineteenth century.

Nuclear astrophysics is the marriage of nuclear physics, a laboratory science concerned with the infinitely small, and astrophysics, the science of what is far away and infinitely large. It sets out to explain the origin, evolution and abundance of all the chemical elements in the Universe. It was born in 1938 with the work of physicist Hans Bethe on the nuclear reactions occurring at the core of stars; reactions that produce the incredibly powerful energy that keeps stars shining for billions of years.

Nuclear astrophysics is still booming as a science.

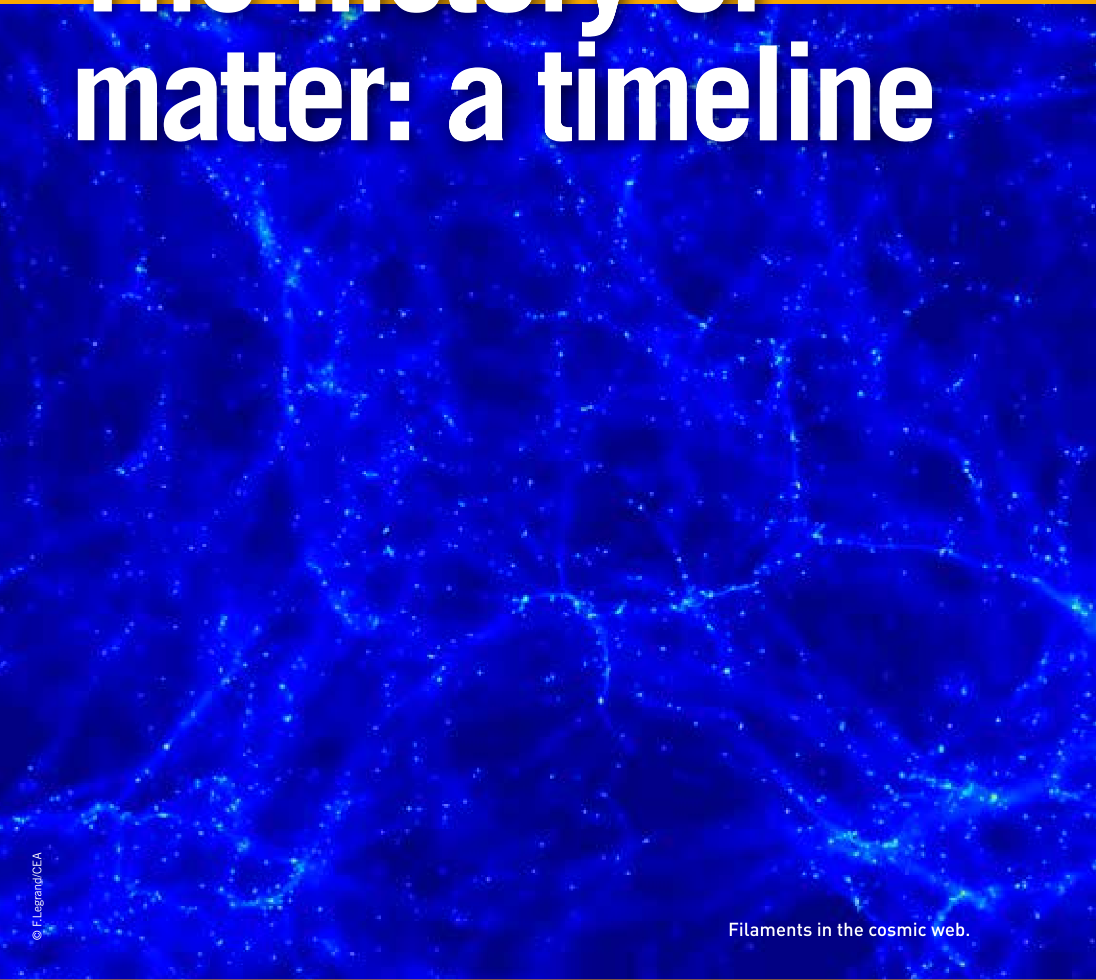
The matter all around us, and from which we are made, is made up of 92 chemical elements that can be found even in the deepest confines of the Universe. Nuclear astrophysics explains the origin of these chemical elements by nucleosynthesis, which is the synthesis of atomic nuclei in different astrophysical environments such as the core of stars.

Nuclear astrophysics provides answers to fundamental questions, like:

- How can our Sun and the stars keep shining for billions of years?
- What is the origin of elements essential to life, like carbon, oxygen, nitrogen and iron?
- How do the nuclei formed by nucleosynthesis get dispersed into space?
- How are the heaviest chemical elements formed, like gold, platinum and lead?

THERE IS A TIGHT LINK CONNECTING NUCLEUS-SYSTEM MICROCOSM TO STAR-SYSTEM MACROCOSM.

The history of matter: a timeline



Filaments in the cosmic web.

© F.Legrand/CEA

In 1610, Galileo viewed the moon through his telescope eyepiece, saw mountains, and deduced that the moon was 'earthly'. Today, we could qualify Earth as celestial, as the elements it is composed of were all formed in stars. Systematic study of the structure of nuclei, their behaviors and the reactions that mobilize them has played a pivotal role in the development of a unified theory on the origin of the chemical elements.

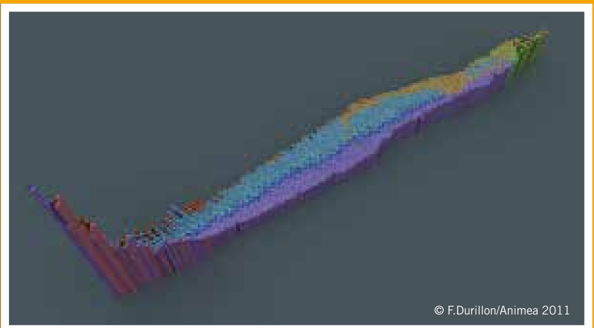
A QUICK REFRESHER ON NUCLEAR PHYSICS

The nucleus of an atom is formed of particles called nucleons (protons and neutrons) held bound together. The number of protons, Z, and the number of neutrons, N, vary from nucleus to nucleus, and there is a limit to their possible (Z, N) combinations.
Neutrons and protons are held together by the strong nuclear force, whose radius of action which is incredibly small is of the order of a millionth of a billionth of a meter (10^{-15} m). It is therefore maximal where the nucleons are in contact or practically touching. However, the nucleons located near the outer surface of the nucleus are less densely surrounded and thus less strongly bound than the nucleons deeper inside the nucleus, and it is this interaction force deficit that diminishes their binding energy.
The protons, which carry a positive electric charge, experience an electrostatic force that pushes them apart, and this repulsion further diminishes the binding energy of the nucleus. To counter this disruptive energy, the heaviest nuclei present an excess of neutrons, which have a net zero electric charge. The lead nucleus, for example, has 82 protons and 126 neutrons. However, all nuclei lighter than calcium (Z=20) contain practically as many protons and neutrons. A majority of nuclei share the common property of having an even number of protons and neutrons. You have to pore through the list of nuclides up as far as magnesium before finding one that has an odd number of nucleons.

THE NUCLIDE INVENTORY

What nuclei are found in the universe, and in what amounts?
We can get a reasonable idea by analyzing the light emitted by stars, using spectroscopy. Invented as a technique in the late nineteenth century, spectroscopy can be used to derive intrinsic characteristics of stars (such as their temperature, luminosity, or chemical composition), thus marking the birth of modern astrophysics.

VALLEY OF STABILITY



The 256 stable nuclei inventoried by nuclear physics occupy a clearly defined region called the "valley of stability".

As this valley reaches out to its boundary lines, electrostatic repulsion between protons becomes so strong that there are no stable nuclei after lead (Z=82). This is where the natural radioactive nuclei can be found, some of which, like bismuth, thorium or uranium, has life-times in excess of a billion years.

http://www-centre-saclay.cea.fr/fr/La-vallee-de-stabilite

AN EXAMPLE, THE SUN

The Sun is Earth's star. Even though it is around 150,000,000 km away, it is relatively easy to study.

The relative abundances of its constituent atoms are measured by analyzing the spectrum of its photosphere. This only gives the composition of this outer region, but scientists normally consider it as practically identical to the composition of the molecular cloud that originally formed our star, 4.56 billion years ago.

> Its light-radiating outer shell.

We can also compare the composition of the solar photosphere to the composition of meteorites, which offer a second source of information on the composition of the protosolar cloud.

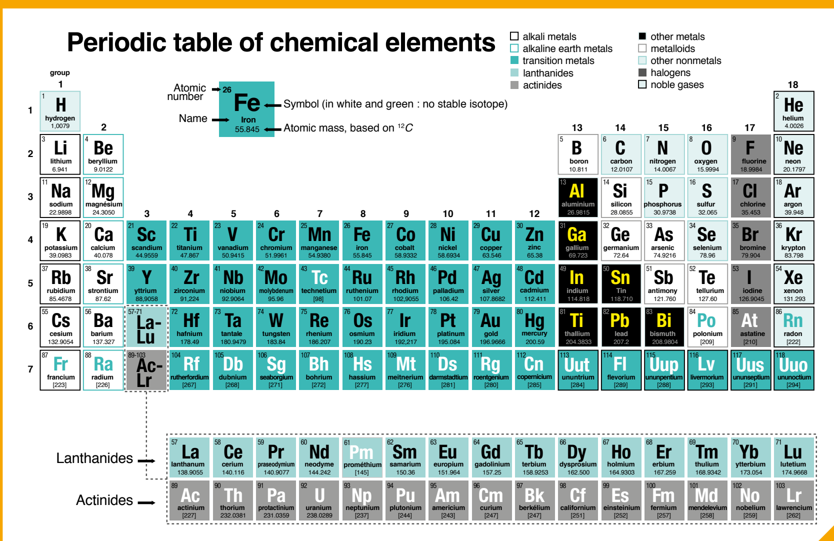
For that, we shoud take into account the most volatile elements (for example hydrogen, helium, nitrogen, oxygen and neon), some of which have managed to escape since they were first formed. In-lab analysis of meteorites can then help ascertain the isotopic composition of all matter in the solar system.

> The many isotopes of a particular chemical element are nuclei variants that differ only in number of neutrons. For example, carbon-12 (6 protons and 6 neutrons) and carbon-14 (6 protons and 8 neutrons) are two isotopes of carbon.

These complementary analyses converge to yield the relative abundance of chemical elements and isotopes in our home-universe environment, making it the bona fide Rosetta Stone of nuclear astrophysics.

MENDELEEV'S PERIODIC TABLE

Mendeleev's periodic table of the elements enables us to classify the different chemical elements discovered to date by number of protons in the nucleus, starting from 1 for hydrogen up to 92 for uranium and even higher for synthetic elements created in the lab that do not occur naturally. It arranges the chemical properties of the elements as dependent on their number of electrons. The ten most abundant elements in the universe are, in decreasing order, hydrogen and helium, then oxygen, carbon, neon, iron, nitrogen, silicon, magnesium, and sulfur.



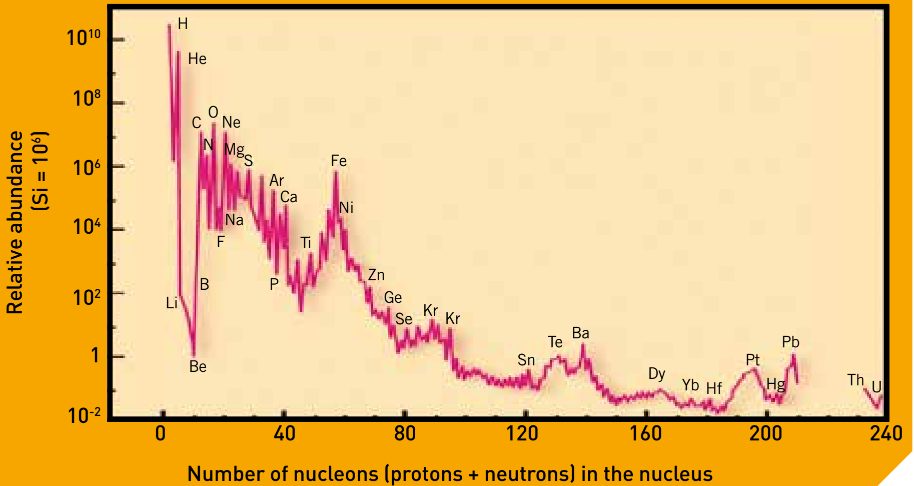
THE ABUNDANCE CHART

The abundance chart gives each element in the periodic table with the amount found in the solar system. It is composed from measurements and observations, and is a precious cornerstone of astrophysicists' work. On this scale, silicon, taken as the arbitrary benchmark, is worth a million.

For a million silicon nuclei, there are ten billion hydrogen nuclei, and the most simple elemental nuclei—hydrogen and helium—alone account for 98% of the mass of the Sun.

After carbon, nitrogen and oxygen, the nuclei start to get increasingly rare—with the notable exception of iron, which has the most robust nucleus found in nature.

If there is so little lithium, beryllium and boron (Z = 3, 4 and 5), it is because their nuclei are so fragile. They are not produced by thermonuclear fusion but by nuclear breakup of interstellar nuclei, as carbon, nitrogen and oxygen, due to collisions with high energy cosmic rays.



STELLAR ALCHEMY

It took until the early twentieth century and the development of nuclear physics for astrophysicists, who were primarily looking to understand the mechanism that keeps a star shining, to be able to answer the big question: where do the nuclear reactions that produce nuclei happen?

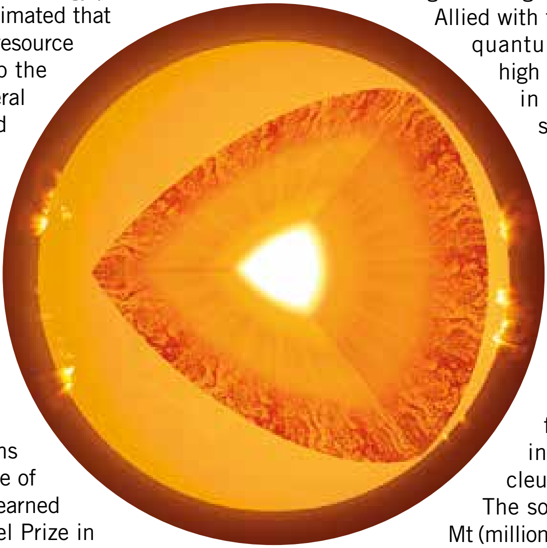
A star is a sphere of hot gas held together by gravitational attraction, which tends to pull its particles as closely as possible together. The star does not collapse under its own gravity, as its internal gas pressure counteracts the gravitational contraction. For this balance to stay stable, the internal pressure has to increase steadily along a gradient with depth into the star, such that each shell of inward-pressing material is counterbalanced on either side between a more compressive and a less compressive shell. As a compressed gas releases heat, the stellar material gets hotter with increasing depth and with increasing pressure. Working in from a few thousand degrees at the outer surface, the temperature can, depending on the mass of the star, reach tens or even hundreds of millions of degrees in its central-core regions. This temperature gradient between inner core and outer surface generates an energy transfer that takes excess thermal energy from the hot inner region and gives it out to the cooler outer region. At the star's surface, this energy flux escapes before diluting as radiation this makes the star shine, and it can only keep shining if there is an internal source of energy to compensate for the radiation emitted at the surface.

“ A star can live with its loss of radiant energy by digging into its nuclear energy resources.”

Betelgeuse is a red supergiant, in the constellation of Orion. It is one if the biggest stars in the observable universe.

STARS, NATURE'S NUCLEAR REACTORS

With the state of science at the end of the nineteenth century, there was no known source of energy (gravitational or chemical) capable of explaining how the Sun had been able to shine for over a billion years - the age geologists had given Earth - at the power level observed. The solution to the riddle came in 1921 by French physicist Jean Perrin, followed by English physicist Arthur Eddington, who first proposed nuclear reactions between atomic nuclei as the source of energy production in stars. He estimated that this nuclear energy resource was enough to keep the Sun shining for several billion years a period compatible with the age of Earth as determined by contemporary geologists. This idea was taken up and developed a few years later by American physicist Hans Bethe, who first elucidated the nuclear reactions occurring at the core of the Sun, work that earned him the 1967 Nobel Prize in physics.



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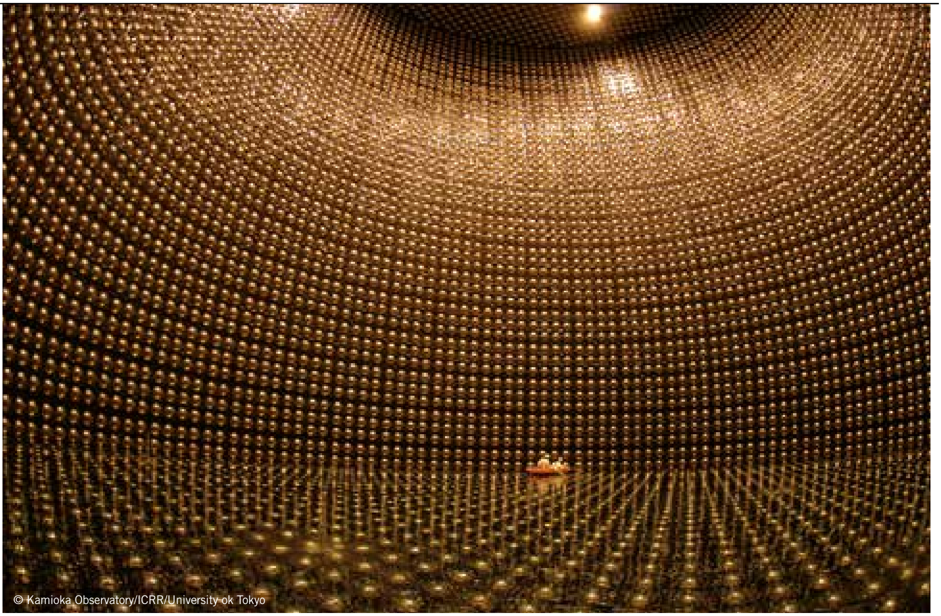
Fusion is the elementary mechanism driving nuclear construction processes that ultimately produce all the elements. If two light nuclei, such as hydrogen and helium, fuse to form another heavier nuclei, the process will release energy. This reaction is inhibited by the electrostatic repulsion between nuclei, which gets stronger with higher electrical charges. Allied with the tunnel effect of quantum mechanics, the high temperatures found in the core region of stars can overcome this repulsion. The Sun's core is the only region where temperature and pressure reach high enough levels to make these reactions possible. These reactions transform four hydrogen nuclei into one helium nucleus, releasing energy. The solar core fuses 619 Mt (million tons) of hydrogen to form 614.7 Mt helium every second, with the difference (around 0.7% of the initial mass) being transformed into energy, thus compensating for the energy that escapes out through the solar surface.

Ultimately, throughout the majority of its lifetime, a star can live with its loss of radiant energy by digging into its nuclear energy resources.



The Super-Kamiokande experiment was constructed with 13,000 photomultipliers mounted on a steel tank that is 39 meters in diameter and 42 meters tall.

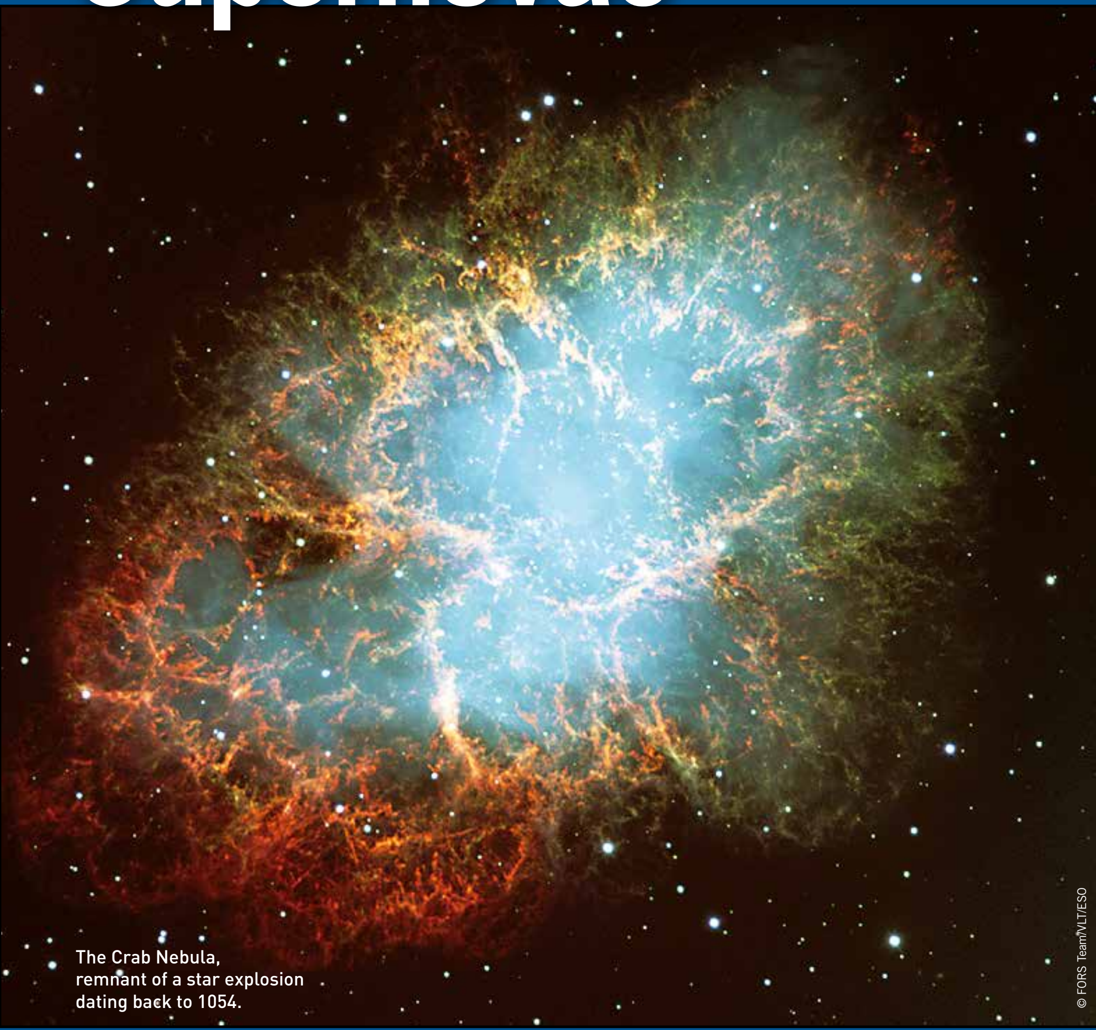
THE PROOF BY THE NEUTRINOS

Nuclear reactions long remained just hypothetic theory to explain why stars keep shining—all proof was indirect.

However, since the 1960s, we have instruments capable of directly detecting some of the elementary particles produced in nuclear reactions taking place in the core of stars.
These elementary particles, known as neutrinos, belong to the same family as the electron. They have a very small mass, no electric charge, and can carry energy. They have been detected from Earth by experimental facilities built underground—Gallex in Europe, Super-Kamiokande in Japan, SNO in Canada, Borexino in Italy. The measurements of solar neutrino flux brought direct conformation of the existence of nuclear fusion reactions.

THESE SPECTACULAR BUT RARE EVENTS ARE CATACLYSMIC EXPLOSIONS OF THE MOST MASSIVE STARS.

Supernovas



The Crab Nebula, remnant of a star explosion dating back to 1054.

© FORS Team/VLT/ESO

For the new elements that are synthesized in the star's core to enrich the universe, there has to be a way for them to scatter into the interstellar medium.

FROM STARS...

Stars whose mass is about ten times that of the Sun first evolve by fusing hydrogen to helium for a few million years. At the end of this period, as they start to run out of hydrogen, their core starts to contract gravitationally until the temperature gets high enough to ignite helium fusion to carbon and oxygen, while hydrogen fusion continues in a shell enveloping the core. After about a million years, the star starts running out of helium this time, and further contraction of its core enables the fusion of carbon to neon and sodium, which goes on for about ten thousand years. Next comes the fusion of neon to oxygen and magnesium (which lasts about ten years), followed by the fusion of oxygen to silicon and sulfur (for another few years).

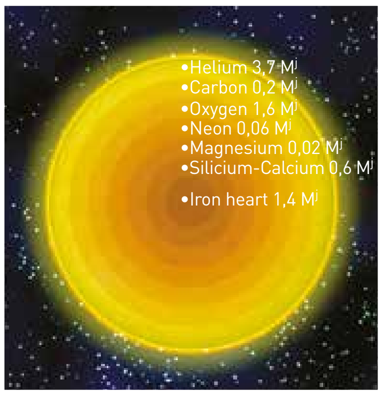
Finally, it takes just a week to transform the silicon into iron. The appearance of iron marks the start of a process that will ultimately cause the star to self-destruct.

As the iron nucleus is the most tightly bound (its binding energy is the strongest), iron burning is unable to produce the same amount of energy that inexorably radiates out from the star's surface. Once the star has exhausted its silicon and formed iron, the core begins contracting again, but this time the temperature is so extremely high that the photons can break up the iron nuclei. The disappearance of a share of the star's radiant light energy decreases the pressure at the star's center and sparks the collapse of the core, fueled by electron capture by the nuclei transforming protons into neutrons. This nuclear reaction proceeds with an emission of neutrinos, which carry with them a phenomenal amount of the gravitational potential energy released by the contraction process.

Within the space of a fraction of a second, the matter achieves an incredible density of a million tons per cubic centimeter—the equivalent of an oil rig packed into the size of a thimble!

CROSS-SECTION OF A LATE-STAGE-EVOLUTION STAR

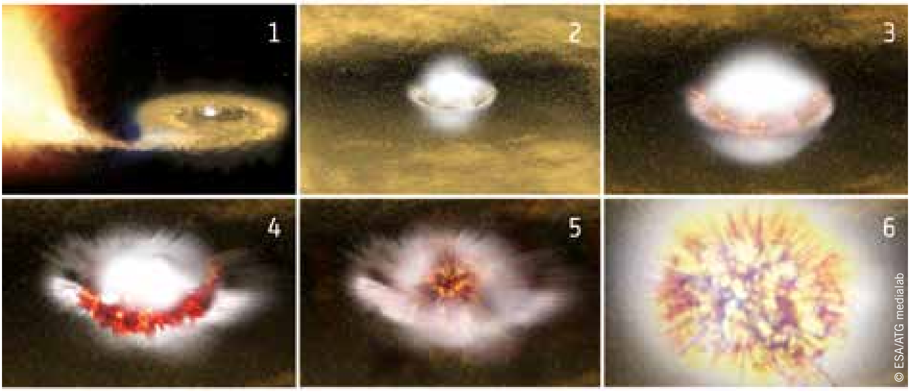
Cross-section of the central region of a star, with a mass 25 times greater than the mass of the Sun (25 M^j), about to explode (borrowed from American physicist S. Woosley).



... TO SUPERNOVAS

The star's core, now composed of neutrons, shrinks down to a small ball measuring just a few dozen kilometers in diameter; a neutron star has just formed, with the rest of the star collapsing inwards on itself and crashing into the hard core. The violent compression of the impact rebounds and produces a shock wave that travels up and out through the star's outer layers. The passage of the shock wave heats the matter to temperatures greater than a billion degrees and sparks the fusion reactions that produce heavy elements, chiefly radioactive nickel and cobalt. When the shock wave hits the surface, the temperature climbs in a violent burst and the whole star explodes, ejecting its constituent elements out into space at speeds of up to several thousand kilometers per second. The event, called supernova, landmarks the death of a massive star.

EXPLOSION OF SUPERNOVA SN2014J



Supernova SN2014J is a type Ia supernova that exploded in 2014. Observations recorded by the ESA's Integral satellite, which detected gamma rays from the radioactive elements synthesized during the explosion, gave astrophysicists the proof that this type of supernova is effectively progenitored by a white dwarf accreting matter from a companion star.

This series of artist's impressions depicts the different stages involved. Image 1 shows a white dwarf, a star with a mass near that of the Sun but squeezed into a volume near that of the earth, leeching matter from a companion star.

Measurements from the Integral satellite suggest a belt of gas building up around the equator of the white dwarf (Image 2). This belt of gas detonates (Image 3) and triggers the internal explosion that becomes the supernova (Image 4). Material from the explosion expands so fast (Image 5) that it eventually becomes transparent to gamma rays (Image 6).

ENRICH THE UNIVERSE

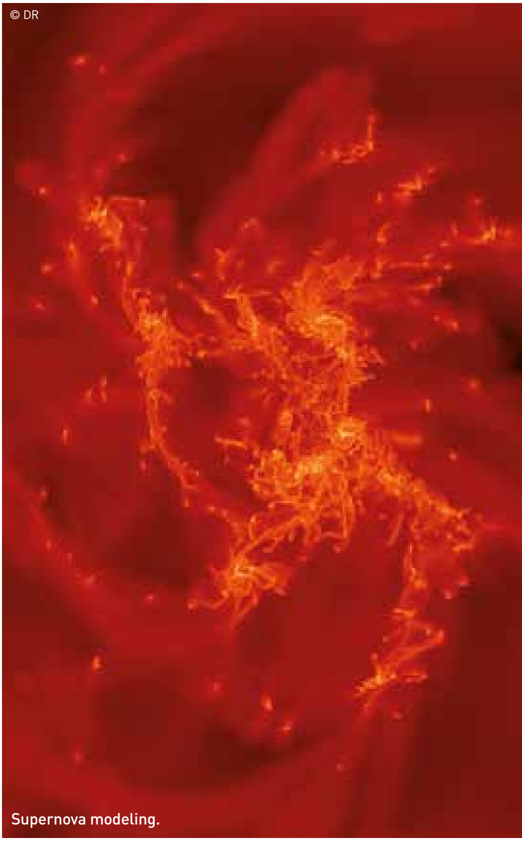
The influence of supernovas on the interstellar medium will be felt for millions of years, because this explosion throws out all the nuclei synthesized over the star's lifetime plus the nuclei that were produced when the shock wave swept through it.

Little by little, supernovas progressively enrich the interstellar medium with new nuclei, which will ultimately be recycled into future stars and any planets that may form.
These heavy nuclei, which were not present at the beginning of the universe, still represent only 2% of all atomic matter today. Practically all the nuclei found on Earth are derived from stellar nucleosynthesis, and all iron is only provided by supernovas.

It was long thought that supernovas offered the right conditions to form nuclei heavier than iron as they explode, when the heavier nuclei are exposed to a hugely intense neutron flux. Depending on the initial mass of the star, the implosion of the iron core leaves a remnant compact object called a neutron star.

Models developed in the past decade suggest that the formation of heavier elements, like gold, requires a collision in which two neutron stars meet and form a black hole. This event manifests as a flare of gamma radiation lasting a fraction of a second a "gamma-ray burst" so powerful that it is observable over cosmological distances.

The formation of gold, and more generally any nuclides heavier than iron, thus requires the evolution of stars far more massive than the Sun that explode to form neutron stars, followed by the explosive coalescence of these neutron stars into a black hole. This is why gold is so expensive - it is rare, and the universe really had to work to produce it!


© DR
Supernova modeling.

Coalescence: Phenomenon in which two identical substances, even if widely dispersed, tend to merge.

“We are all made up of star dust.”

THE DIFFERENT TYPES OF SUPERNOVAS

The traditional spectroscopic classification (presence or absence of a hydrogen line in the spectrum) has recently been refined with a physical distinction characterizing the ignition mechanism as either thermonuclear or gravitational.

Thermonuclear supernovas

When two stars cohabit in space, they orbit around their common center of mass in a binary system. Thermonuclear supernovas occur in binary star systems formed of a later-evolution red giant and a white dwarf.
Matter can fall from the red giant onto its companion white dwarf, and if it takes the white dwarf’s mass to 1.4 times solar mass, the white dwarf becomes unstable and can collapse and explode.
All the matter ejected gets dispersed into space, leaving nothing at the center of the supernova.

Gravitational supernovas

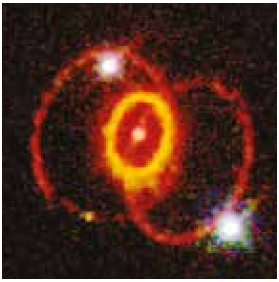
A gravitational supernova occurs when a massive star late in its evolution explodes. The implosion of its core, made unstable by process of silicon burning to iron, swiftly leads to an outward deflagration that expels its outer shell. This gravitational core collapse releases a titanic amount of energy (billions of times greater than the luminosity of the Sun!), essentially in the form of neutrinos. Only one ten thousandth of the total energy released is cast out as visible light.

These two types of supernovas do not produce elements in the same proportions, and do not occur at the same rate (one thermonuclear supernova for every five gravitational supernovas).
Gravitational supernovas produce the bulk of the elements between carbon and calcium, oxygen being the most abundant, whereas thermonuclear supernovas provide the iron and the elements neighboring the iron peak.

THE LATEST SUPERNOVAS STUDIED

A supernova can be visible to the naked eye, from Earth, if it explodes within the perimeter of our own galaxy or its observable satellite galaxies. As soon as it is discovered, observatories and satellites all over the world immediately point their instruments and detectors in its direction.

This is what happened in February 1987, when the supernova named **SN1987A**, appeared in the Large Magellan Cloud.



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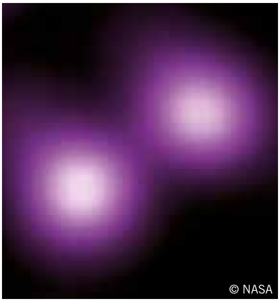
It was so close that it enabled scientists to collect a vast array of results and observe several types of radiation it emitted: visible light, radio waves, ultraviolet and infrared. It provided the first chance to detect and measure a flux of neutrinos. SN1987A was a gravitational (core-collapse) supernova.

In September 2006, supernova **SN2006gy**, in galaxy NGC 1260 of the constellation Perseus, caused quite a stir when it burst onto the skyscape.

Its peak luminosity made it a hundred times more powerful than the typical supernova explosion, and did not wane for over three months.
The star that exploded may have had a mass 100 times bigger than that of the Sun.



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Supernova **SN2014J** detected in January 2014 was thrown out by a star explosion in the Cigar galaxy, at just 11.5 million light-years from Earth.

The study of SN2014J will serve to refine the current computer models we have.

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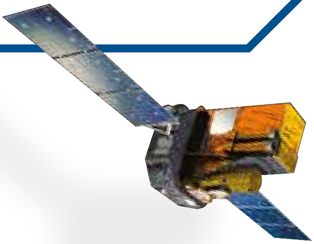
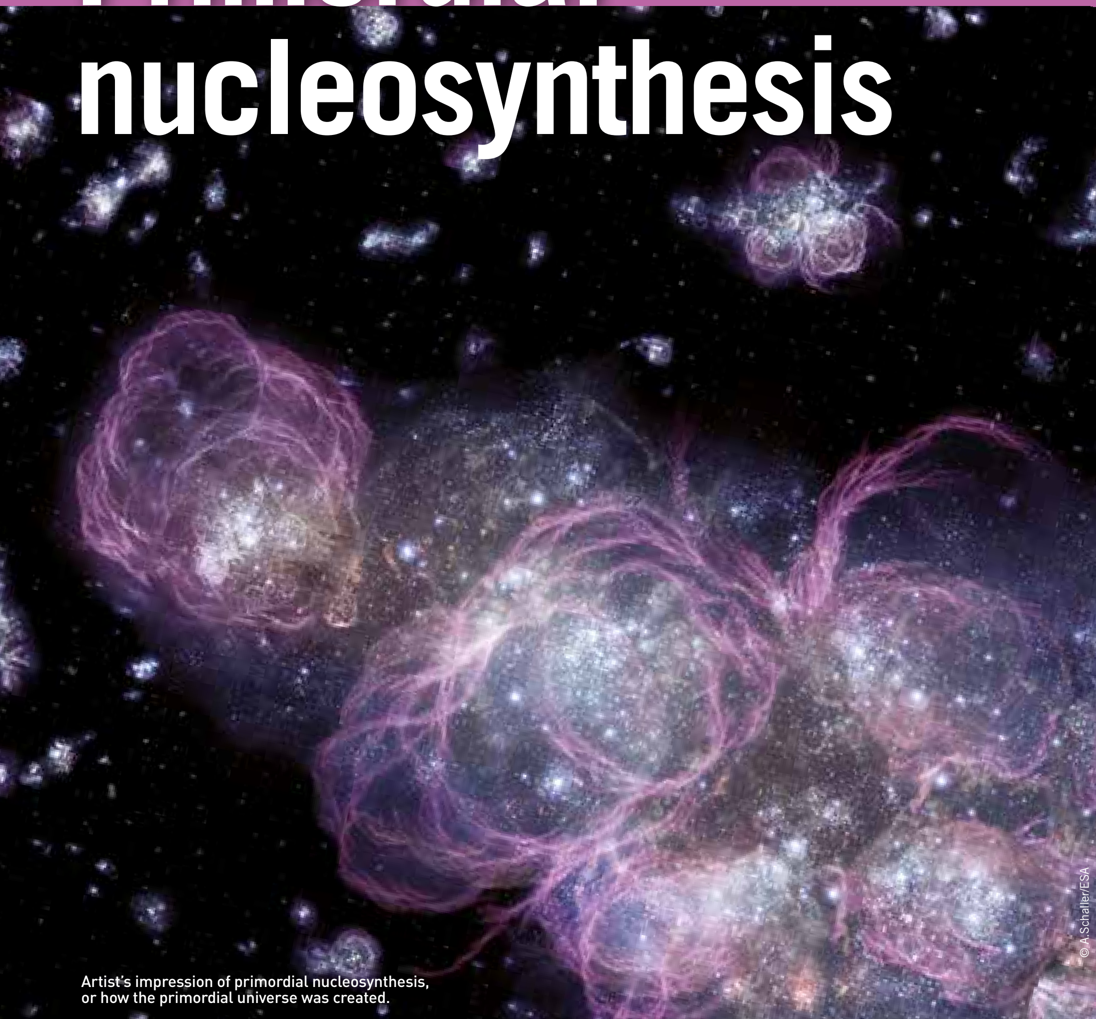


HOW WERE THE FIRST NUCLEI FORMED? STUDY OF THE "PRIMEVAL NUCLEI" HAS PROVIDED THE ANSWERS.

Primordial nucleosynthesis



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Artist's impression of primordial nucleosynthesis, or how the primordial universe was created.

PRIMORDIAL NUCLEI

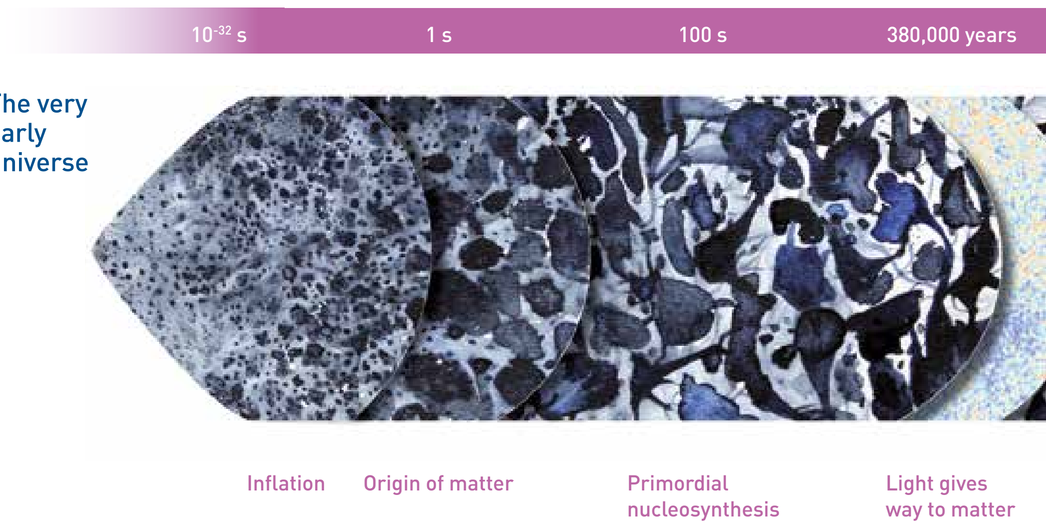
Nuclei form in stars. This idea, which British astrophysicist Fred Hoyle developed in the 1950s, gives a satisfactory explanation of the relative abundances of a huge number of nuclei—but not all.
Accepting that the universe has always been expanding, there must have emerged an early period in which it was extremely dense and extremely hot: observation of what is called "cosmic microwave background" (see p.27), the relic trace of the light emitted when the first neutral hydrogen atoms appeared, shows that there was a phase in time where temperature reached around three thousand degrees. Analysis of the relative abundances of light atomic nuclei (chiefly hydrogen, helium and lithium) proves that there was an earlier state in time where temperature was over ten billion degrees. This earlier state is when much of the destiny of the matter played out.

FOSSIL NUCLEI

Three nuclei refuse to fit the model of stellar nucleosynthesis—they are bona fide "primeval nuclei", fossil relics of the early moments of the universe.
The first one is deuterium (D), or "heavy hydrogen". Its nucleus has just one proton and one neutron. There is just one deuterium nucleus for every hundred thousand hydrogen atoms. Deuterium is the least stable atom in terms of stability, incapable of withstanding the stellar furnace in stars, it reacts as soon as the temperature rises to above a million degrees. So where could the deuterium still observable today come from?

The second primordial relic is named helium-4 (^4He). Stellar fusion widely produces helium-4 from four hydrogen nuclei. But not enough: the cumulative nucleogenesis of all the stars across the universe is still not enough to explain

The very early universe



its aggregate relative abundance, which is one helium atom for ten hydrogen. A number of stars were studied to measure the proportion of helium and three heavy elements (carbon, nitrogen and oxygen, nuclei chosen based on the rationale that they are pure products of stellar nucleosynthesis).

It was found that while the stars that had the most heavy elements were also the stars that had the most helium, the stars that counted the least heavy elements nevertheless still contained a fair amount of helium: none has less than seven helium atoms for a hundred hydrogen.

This observation has a natural interpretation: at their birth, the stars and the galaxies already contain 7% helium. Where does this fossil helium come from?

Finally, the third fossil relic nucleus is lithium-7 (^{7}Li). The abundance of lithium has been measured in a number of the stars in our galaxy. Despite being relatively very low, its abundance is practically identical in the oldest stars and increases in the youngest stars. This rise over time means that the stars must be making lithium, but the presence of a constant amount of lithium nuclei in the oldest stars also means that, like for helium, there must have been some contribution of lithium that predates the stars.

Where do the primordial deuterium, helium and lithium come from? The study of these primeval has come up with a reasonable scenario in which the universe experienced a temperature of greater than ten billion degrees.

300-500 million years | Billions of years | 13.8 billion of years

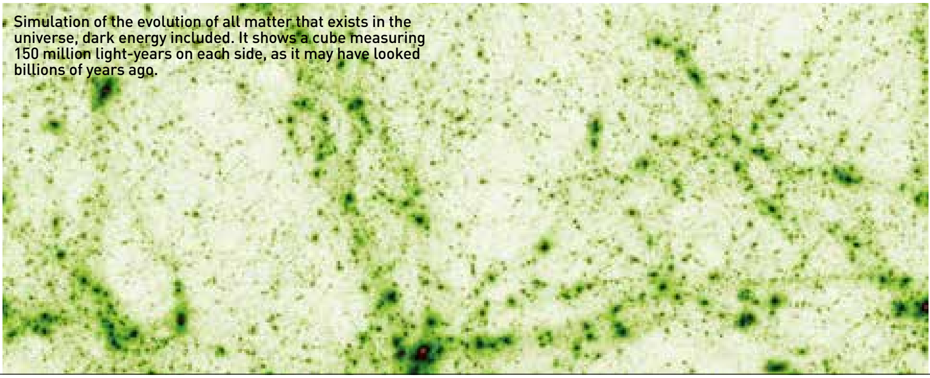
Dark ages | Star formation begins | Galaxy evolution | Present day

PRIMORDIAL NUCLEOSYNTHESIS

At ten billion degrees, the thermal motion of protons and neutrons is so violent that even strong nuclear forces cannot bind them as stable nuclei, so they decay into protons and neutrons.
The primordial cosmic soup is mix of these nucleons, interacting with electrons, photons and neutrinos. The neutrinos play a major role: as they get constantly absorbed and emitted by the nucleons, they convert the protons into neutrons and vice versa. These reactions maintain an equilibrium between number of protons and number of neutrons, in a temperature -dependent neutron-proton ratio.

With expansion cooling the universe, the temperature drops, to a point where the neutrinos can no longer interact with the nucleons, which breaks the equilibrium that had so far prevailed. The free neutron is an unstable particle that, with fifteen minutes lifetime, disintegrates into a proton, an electron and a neutrino. Its only way to survive is to assemble with a proton to form a deuterium nucleus. However, one, it takes heat to generate deuterium, and, two, once the deuterium is made, it has to be cooled to survive. Expansion orchestrates both these operations: the deuterium is produced when the temperature approaches a billion degrees, then saved from premature destruction by the expansion-driven cooling. During the window in which the deuterium nuclei form, they can also combine with other nucleons to successively produce helium-3, helium-4 and, in lesser proportions, lithium-7 nuclei.

The universe cooling to below the minimal temperature threshold for fusion puts a stop to this primordial nucleosynthesis, which had only three minutes in which to work! Once the universe gets too cold, its composition gets frozen out and stops moving, which is why deuterium can be found in interstellar space, primordial helium-4 can be observed in the older stars and galaxies, and lithium-7 can be observed at the surface of the oldest stars.



Simulation of the evolution of all matter that exists in the universe, dark energy included. It shows a cube measuring 150 million light-years on each side, as it may have looked billions of years ago.

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A GALAXY IS COMPOSED OF OVER 300 BILLION STARS, CLOUDS OF INTERSTELLAR GAS AND COSMIC DUST.

What is a galaxy?

Stellar density map of the Milky Way. The galactic plane is a projection of the galactic disc, which measures 100,000 light-years in diameter but just 1000 light-years in vertical height.

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The waves travelling around the primordial plasma created zones where pockets of matter started to accumulate. Gravity will then amplify these clumps and form a meshed network of cosmic filaments inside which the first galaxies are formed. In a few hundred million years, they will aggregate in their hundreds at the nodes where the filaments cross, forming clusters. Inside the cluster, the galaxies interact through their mutual gravities. The space between them is filled with a very hot tenuous gas that shines in the X-ray spectrum. Each galaxy counts hundreds of billions of stars, together with interstellar dust and gas, all held together by gravity.

GALAXY FORMATION ...

The earliest data on galaxy formation dates back to 1914, but clear evidence of other galaxies did not emerge until in 1920s, mainly through the pioneering work of American astronomer Edwin Hubble.

The galaxies come in three main morphological types: ellipticals, spirals, and irregulars (which also encompass lenticulars).

Modern observations have provided further insight and information:

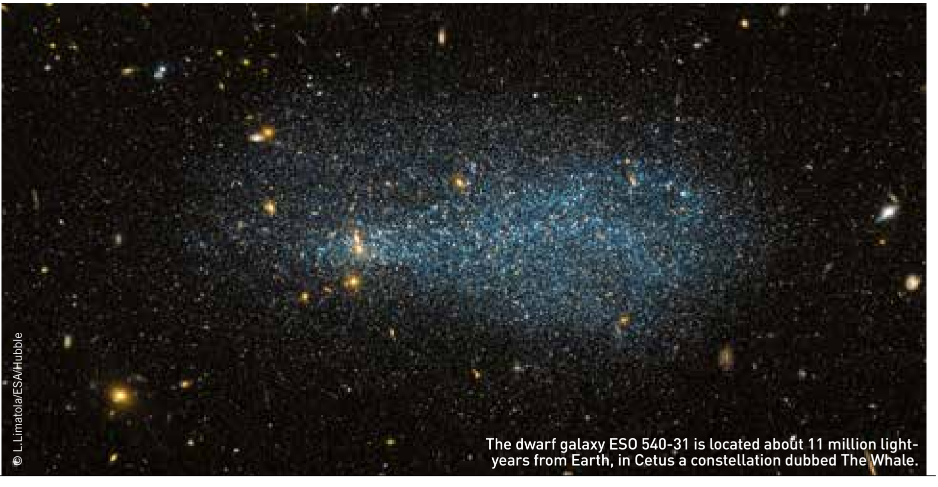
- elliptical galaxies have relatively little interstellar gas and dust and are dominated by old stars;
- spiral galaxies are typically packed with interstellar gas and dust and contain a mix of young stars and older stars;
- irregular galaxies are relatively packed with interstellar gas and dust and relatively high count of young stars.

... AND EVOLUTION

Working up from this information, researchers have built a theory of galaxy evolution that suggests elliptical galaxies are actually the result of collisions between spiral and/or irregular galaxies. These collisions strip them of the bulk of their gas and dust and throw their stars into random orbits.

The Milky Way

Our solar system belongs to the Milky Way. The Milky Way has a whole number of satellite galaxies, but two of them really stand out: the Large Magellanic Cloud and the Small Magellanic Cloud, which are visible to the naked eye from in our southern hemisphere.



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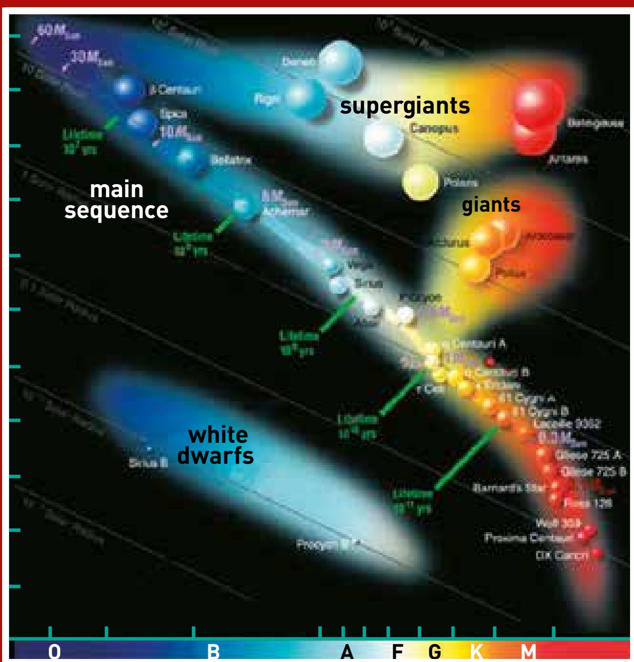
The dwarf galaxy ESO 540-31 is located about 11 million light-years from Earth, in Cetus a constellation dubbed The Whale.

The closest galaxy is Andromeda, at a distance of 2.3 million light-years. Our galaxy is still deep in evolution. Clues to recent nucleosynthesis are provided by observation of radioactivity in its disk and the detection of aluminium-26 decay in different directions. Aluminium-26 is a relative short-lived radioactive nuclide that survives for around 1 million years (compare to the galactic disk, which is aged at around 10 billion years). These studies bring sharp evidence of the mechanisms that culminate in the formation of aluminium-26. The goal is to understand how this isotope managed to get produced by stars and survive being ejected into the interstellar medium before decayed, i.e. in less than a million years. Its essential sources appear to be supernovas and massive 'Wolf-Rayet' stars.

> Distance that light travels in a vacuum in a year, i.e. about 10,000 billion km.

STELLAR EVOLUTION IN OUR GALAXY

This diagram plots the luminosity of a star against its surface temperature (luminosity values are given on scale baselined against solar luminosity = 1). The stars clearly cluster into several regions:

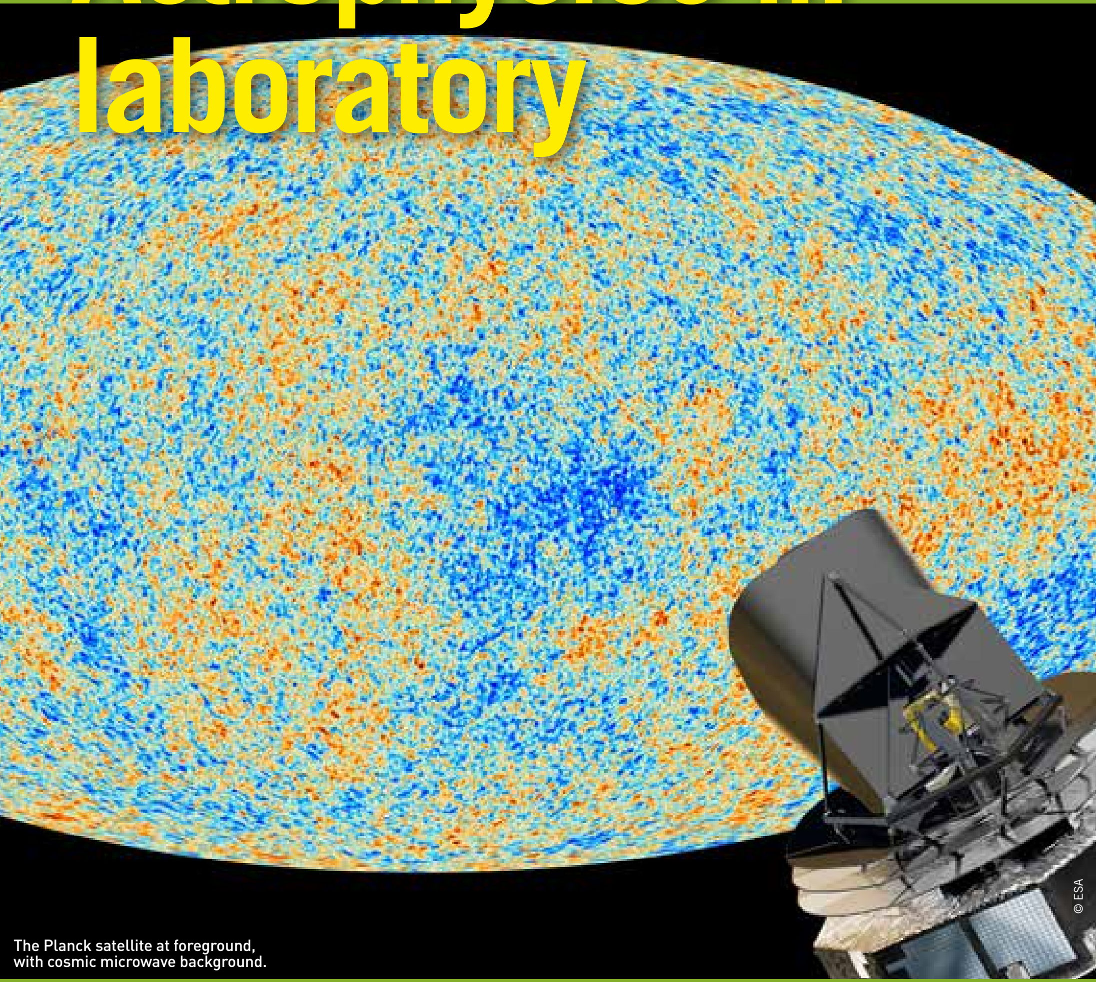


- The central band, termed main sequence, which plots the stars in their longest phase of their lifetime, where their core is fusing hydrogen to helium.
- At top-right are the stars in more advanced phases of the nuclear combustion chain: nuclear fusion of helium to carbon and oxygen, and the nuclear fusion of carbon to heavier elements, neon, magnesium and silicon. These are the red giants and red supergiants.
- At bottom-left are the white dwarfs, the final phase of low-mass stars like our Sun.

The point that a star maps to in the Herzsprung–Russell diagram will move over the course of its lifetime.

OBSERVATION AND THEORY ARE NOW BACKED UP BY COMPUTATIONAL NUMERICAL SIMULATION AND EVEN EXPERIMENTS.

Astrophysics in laboratory



The Planck satellite at foreground, with cosmic microwave background.

TELESCOPES AND SATELLITES

Astrophysics has made most of its discoveries using telescopes in ground-based observatories or satellites in space.

All radiation combined forms the electromagnetic spectrum, which runs from radio waves up to X-ray or gamma rays, with each region of the spectrum providing specific information. For example:

- infrared radiation tells us where and how stars and planets form;
- visible light gives us clues on the gaseous properties of stellar photospheres;
- X-ray and gamma radiation reveal what are sometimes tremendously violent phenomena marking the end of a star's life: supernovas, pulsars, neutron stars, black holes.

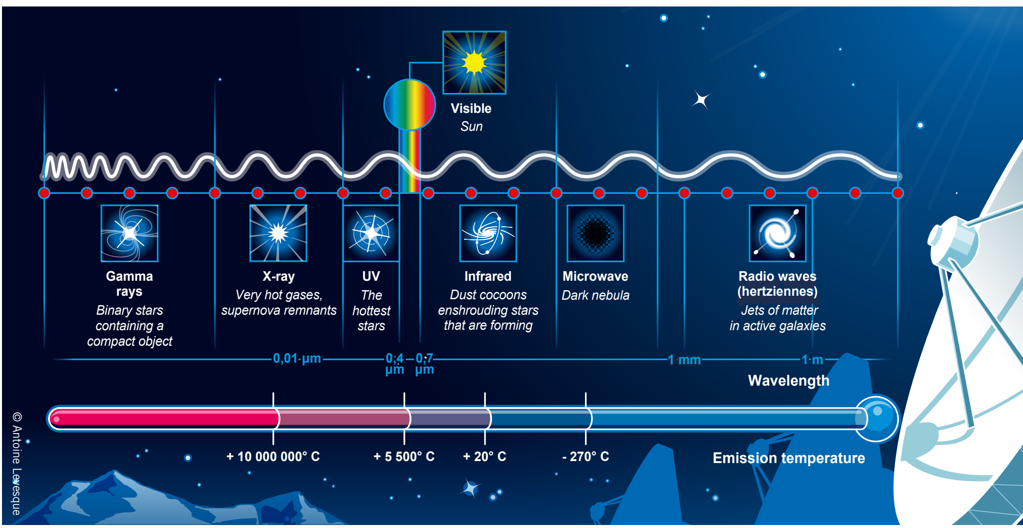
What differentiates each band of radiation is its wavelength, which is a measure of the energy the radiation is carrying. As the wavelengths get shorter, the radiation is carrying more energy and was emitted by hotter gas. Conversely, the large wavelengths are characteristic of radiation carrying less energy and emitted by colder objects.

The data thus collected is interpreted to ascertain the star's luminosity, surface temperature, radial velocity or chemical composition.

IN THE LAB

Recreating, here on Earth, these tremendously violent phenomena, which shake the planets and the interstellar medium, was long though inconceivable, as it would take absolutely phenomenal amounts of energy to heat and compress the matter into a plasma resembling those observed in astrophysics.

The huge strides forward made in laser science and capacity has now made this laboratory astrophysics a reality. The specimens studied with the high-energy lasers, like the Laser Integration Line (and soon the Megajoule Laser) at the CEA's Cesta research facility, measure up to a few cubic centimeters. Experiments like this serve to acquire pure physics data and analyze dynamic astrophysical phenomena playing host to instabilities, radiation and magnetic field.




© H.Raguet/Science&Avenir/CEA
LIL experimental chamber.


© P.Stroppa/CEA
Ion beam line produced by the CIME cyclotron at the Ganil.

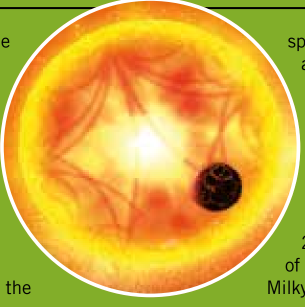
Physicists can then use plasma scaling laws to deduce what could happen inside a plasma system of astrophysical size.
Thanks to the heavy ion accelerators at the Ganil facility, physicists are also able to explore the infinitely small, like the structure of nuclei, their thermal and mechanical properties, and so on. They create exotic nuclei, which do not exist on Earth but are found in the core of stars, and recreate tiny 'stars' in their lab facilities.

NUMERICAL SIMULATION

After observation and instrumentation, the third avenue driving astrophysics research is simulation. The main thrusts of simulation work have been cosmology, stellar physics, the study of protoplanetary disks and the interstellar medium.
The development of supercomputers has now made it possible to remodel the evolution of all matter in the universe. The next big challenge posed for computers is to manage to resolve the gravity, fluid mechanics and gas law physics equations governing these movements, starting out from known initial data.
To validate their theories, researchers cut the universe into cubes that drill down in box size according to mass density of matter.
The biggest simulation to date was led by the Horizon project, which reproduced the evolution of 70 billion particles of dark matter in a cube measuring 6 billion light-years on each side (half of the observable universe!) meshed into 140 billion cells.

ASTEROSEISMOLOGY

The surface of a star plays host to the turbulent movements that vibrate the convective region and resonate sound waves from the surface to the core. As space is dominantly pervaded by a vacuum, scientists cannot 'hear' the waves directly, so they record the swelling and shrinking movements by analyzing the surface movements. Each of these million pulses has to be studied one by one. This makes it possible to determine the speed of sound and, therefore density and temperature inside the star, shell by shell. Stellar seismology took off as a science with the SOHO satellite that set out to study the Sun, but also the Kepler satellite observing other stars. The adventure is set to continue with the launch of the ESA's Plato mission, scheduled for 2025, which will study the vibrations of hundreds of thousands of stars in the Milky Way.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X-RAY AND GAMMA-RAY ASTRONOMY

INTEGRAL

The hot radioactive traces of star explosions emit X rays and gamma rays. These rays are what astrophysicists want to observe, as it is this most energetic form of electromagnetic spectrum that provides the sharpest clues on new atoms being synthesized in the universe. Integral (INTErnational Gamma-Ray Astrophysics Laboratory), launched in October 2002, studies the radioactivity in the Milky Way and its neighboring galaxies. The data captured serves to refine models of the stars and better understand the dynamic processes that orchestrate how stars explode. The mission set for this space telescope is to detect the gamma radiation emitted by long-lived radioactive elements like aluminium-26, medium-lived elements like titanium-44, and short-lived elements like cobalt-56. It also serves to identify where active nucleosynthesis is happening in the galaxy.

H.E.S.S.

The H.E.S.S. system of telescopes installed in Namibia observes the ripples caused by particles or high-energy gamma rays entering Earth's atmosphere. It works out where these rays come from to help gain deeper insight into sources like the Crab Nebula, a remnant of a supernova that exploded in 1054. Over a hundred sources have been inventoried so far, some that are supernova remnants or pulsars, others that remain of unknown origin.

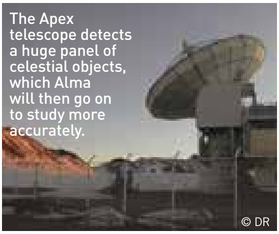
INFRARED ASTRONOMY

HERSCHEL

The Herschel satellite launched in April 2009 has provided images of the universe in far-infrared and submillimetric wavebands. These images serve over three dozen observation programs focused on the origin of the mass of stars, the formation of massive stars, the evolution of the galactic interstellar medium, and the history of the evolution of galaxies.

ALMA

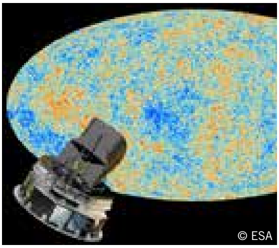
Here on Earth, in Chile, the 66 telescopes arrayed together in the Alma observatory analyze the radiation emitted by the very cold clouds of gas and dust that are home to star birth.


The Apex telescope detects a huge panel of celestial objects, which Alma will then go on to study more accurately.

© DR

PLANCK

Between 2009 and 2012, the Planck space telescope mapped the all-sky celestial sphere in 9 wavelength bands of the infrared spectrum coming from different sources: stars, interstellar dust, galaxies, galactic clusters, and more. By filtering the radiation emitted from each source out of the full image, in 2013 it provided the photo of the oldest radiation in the universe, the cosmic microwave background, emitted 13.8 billion years ago! Analysis of this cosmic microwave background has served to validate the standard cosmogenic model of a universe expanding at an accelerated pace, probably formed by a phase of exponential expansion called inflation.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