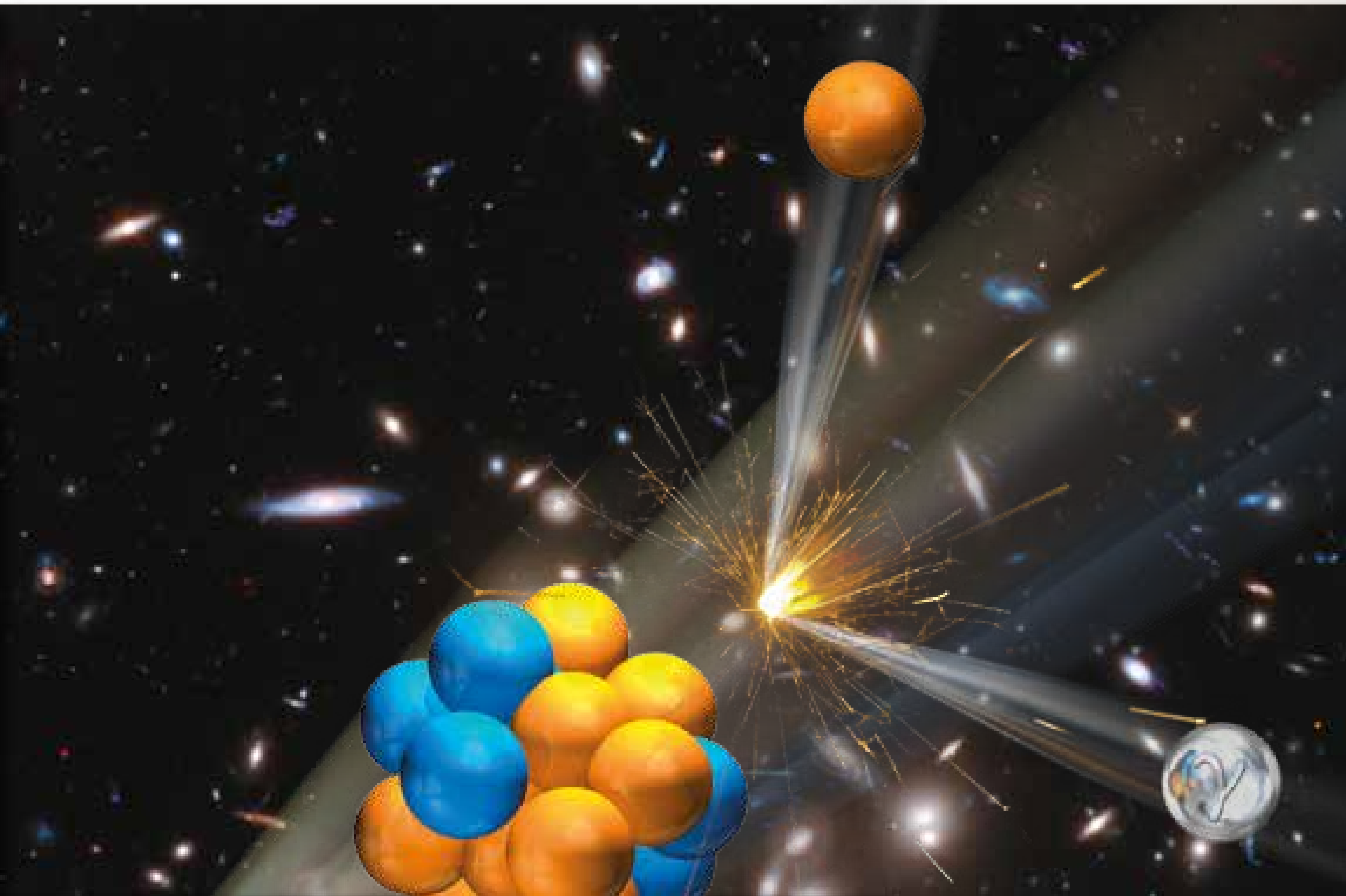


NUCLEAR ASTROPHYSICS: **COSMIC ORIGINS**

SCIENTISTS EXPLORE THE CREATION OF ALL THE ELEMENTS THAT WE FIND ON EARTH AND ACROSS THE UNIVERSE

European Science Foundation
SETTING SCIENCE AGENDAS FOR EUROPE

STARS, THE ORIGIN OF THE ELEMENTS AND US

TRACING THE PATH FROM STARDUST TO PEOPLE

All matter on Earth, including us, is composed of atoms, which in turn are made up of subatomic particles. These include negatively charged electrons, which surround the extremely dense atomic nucleus – itself composed of further particles: positively charged protons and neutral neutrons. The number of constituent protons in a nucleus defines the basic properties of each of the familiar elements, such as hydrogen, oxygen, carbon or iron. Atoms can then combine with others through their electronic 'glue', forming chemical bonds to generate millions of kinds of molecules – from simple water (two atoms of hydrogen and one of oxygen) through to the complex DNA genetic code characterising individual humans.

Elements, especially those consisting of heavier atoms with large numbers of protons, may have many 'isotopes', each with differing numbers of neutrons. This latter figure defines the particular isotopes of an element that can exist. The various combinations of protons and neutrons possible could, in fact, generate up to 10,000 different kinds of nuclei. Yet everyday stable matter is built from only about 300 nuclear species. These include 83 elements and their isotopes, which are found on Earth.

"WHERE DO THE ELEMENTS COME FROM, HOW WERE THEY MADE AND WHY IS THERE SO MUCH MORE OF ONE ELEMENT THAN ANOTHER? THE ANSWERS ARE BOTH EXOTIC AND MYSTERIOUS – AND LIE IN THE STARS."

WHY DOES THE SUN SHINE?

The Sun is an ordinary middle-aged star, one of 100 billion in our Galaxy alone. As such, it consists largely of hydrogen (a nucleus made of one proton) and helium (two protons, two neutrons). These, the lightest elements, are thought to have been made in primordial processes just after the Big Bang, nearly 14 billion years ago, and then condensed through gravity into massive incandescent balls of gas – the first stars. In stars, the tremendous pressure and heat drive the fusion of hydrogen nuclei into more helium, as well as carbon, oxygen, and other nuclei, with the release of huge amounts of energy. We see the manifestation of this process as the sunshine and warmth that sustains life, but also in the variety of elements around us – the oxygen we breathe, the carbon that is the basis of life and that we use as fuel.

WHAT IS NUCLEAR ASTROPHYSICS AND WHY DO WE NEED TO KNOW ABOUT IT?

Nuclear astrophysics is the study of the nuclear reactions that fuel the Sun and other stars across the Universe, and of how they create the variety of atomic nuclei. Almost all the elements found on Earth – except the very lightest ones – were exclusively made in stars. Understanding the underlying astrophysical processes gives us clues about:

- the origin of the elements and their abundances;
- the origin of the Earth and its composition;
- the evolution of life;
- the evolution of stars, galaxies and the Universe itself;
- the fundamental laws and building blocks of Nature.

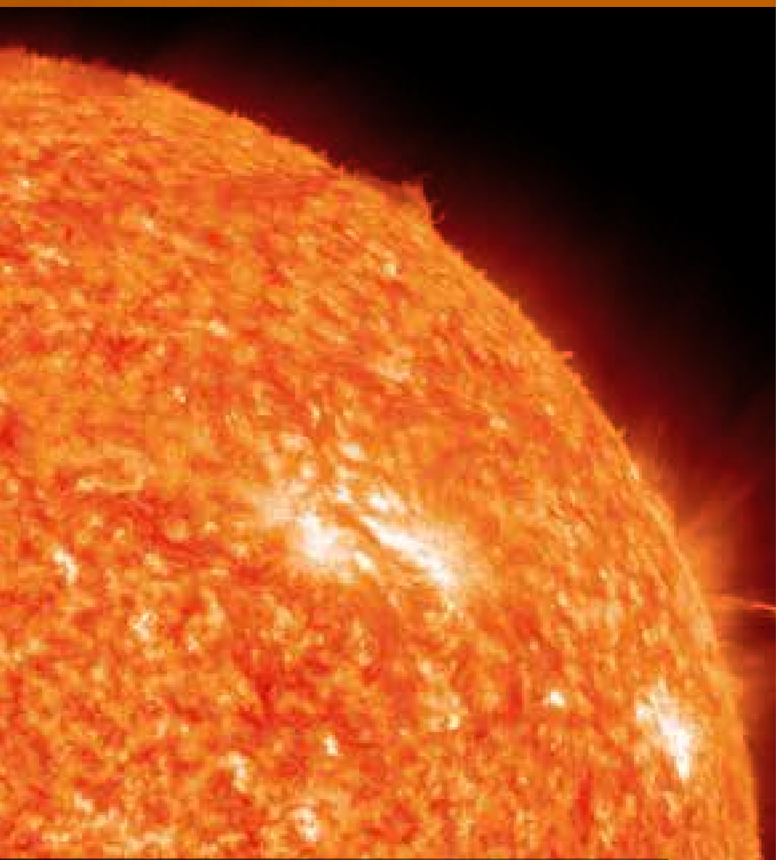
During their lives, stars generate many exotic, short-lived nuclei that do not exist on Earth, but are nevertheless significant in understanding the structure of all nuclear species and the fundamental forces governing them. In turn, this knowledge is essential to developing, for example, new types of safe energy and isotopes of industrial or medical use.

Nuclear astrophysicists pursue their research in several ways:

- by detecting and analysing emissions from stars, the dusty remnants from exploded stars and from compact 'dead' stars.
- by designing laboratory experiments that explore stellar nuclear reactions in the Big Bang, in stars and in supernova explosions.
- by analysing geological samples and those from extraterrestrial sources such as meteorites and the grains of 'stardust' they contain.
- by carrying out theoretical calculations on nuclear behaviour and its interplay with the stellar environment.

There have been many research successes in recent years but there are still many mysteries to solve. The European astrophysics community is playing a key part in taking this work forward. This booklet highlights the achievements, challenges and applications of this exciting multi-disciplinary scientific area.

Water, which is composed of hydrogen and oxygen, is the key to life on Earth. Hydrogen was made in the Big Bang, while oxygen was synthesised in stars via nuclear reactions



When the fusion fuel in their cores runs out, stars like our Sun eventually blow off their outer envelopes and their cores end up as quiescent 'white dwarfs'. However, stars that are much more massive collapse under their own gravity and then explode as a supernova, throwing out material far into space. During this violent event, ultrafast nuclear processes between transient exotic nuclei lead to the synthesis of many of the important elements that shape our life ('nucleosynthesis'). Such supernovae make the calcium in our bones, iron in our blood, silicon in the sand on our beaches, and rare and precious gold and platinum. Eventually, the material dispersed by this catastrophic death of a star condenses into new stars, perhaps with accompanying planets that could support life. We are, indeed, the children of stardust!

Nuclear astrophysicists investigate the processes underlying the creation of the elements and their influence on broader cosmic structures and their evolution, as the next pages will show.

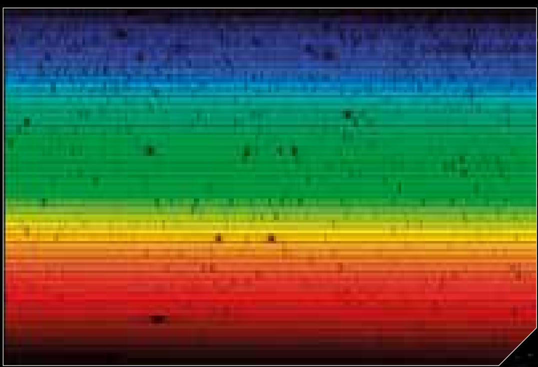
THE CREATION OF THE ELEMENTS AND THEIR ROLE IN THE UNIVERSE

OVER THE PAST CENTURY, WE HAVE BUILT UP A COMPREHENSIVE PICTURE OF WHAT STARS ARE, OF THEIR DIVERSE LIFE-CYCLES, AND HOW NUCLEOSYNTHESIS IN STARS HAS SHAPED THE EVOLUTION OF THE UNIVERSE AND LED TO THE FORMATION OF PLANETARY SYSTEMS LIKE OURS

During the 19th century, physicists had noted that the Sun's spectrum contained sets of dark 'absorption' lines that were also characteristically observed in the hot glow emitted from particular elements in the laboratory. Spectroscopic studies showed that matter across the Cosmos was, indeed, made from the same elemental building blocks. From this revelation, following the huge scientific steps made in the early 20th century – in uncovering basic physics (quantum physics and Einstein's Relativity theories), and astrophysics (the Big Bang and the expansion of the Universe) – researchers began the long journey to unravel where and how all the elements in the Universe were created.

WHAT WE NOW KNOW

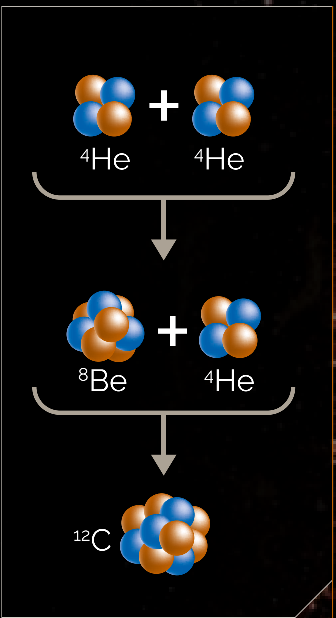
- The primordial elements, hydrogen and helium were made in the Big Bang.
- Our Sun and all stars are natural nuclear fusion reactors that manufacture the chemical elements.
- The processes in stars mediate the evolution of the galaxies and thus the Universe.
- Stars are key players for the emergence of life. The intermediate-mass stars produce carbon; massive stars and supernovae synthesise the oxygen we breathe, the calcium in our bones, and the iron in our blood.



FIRST IDEAS

Fred Hoyle in the 1940s had advocated the idea that stars produce all the elements in the Universe. The hydrogen-fusion reactions that make the Sun and most of the stars shine had been worked out in detail by Hans Bethe and Carl Friedrich von Weizsäcker in the late 1930s. But many scientists remained sceptical, because it was thought that stellar interiors never become hot enough for fusion reactions; and even if they did, it was not clear how the fusion products could get out of the stellar core. This stimulated George Gamow and his student Ralph Alpher, in 1948, to evaluate in detail previous ideas on the synthesis of all elements in the hot, early Universe of the Big Bang. Later studies concluded that only a handful of the lightest nuclei (specifically, deuterium, helium-3 and helium-4, and some lithium-7) can be produced in the early-universe environment, and all other elements are synthesised in stellar or supernova interiors by a variety of nuclear processes. Most of these were defined and analysed in the seminal papers of Al Cameron, together with Margaret and Geoffrey Burbidge, Willy Fowler and Fred Hoyle (above left to right) in 1957 (the latter now referred to as the B^2FH paper).

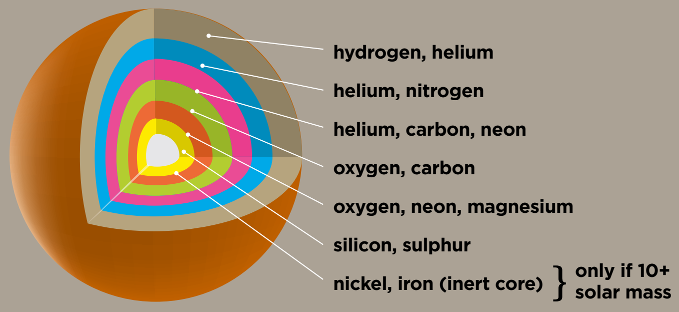
THE COMPLEX WEB OF CREATION



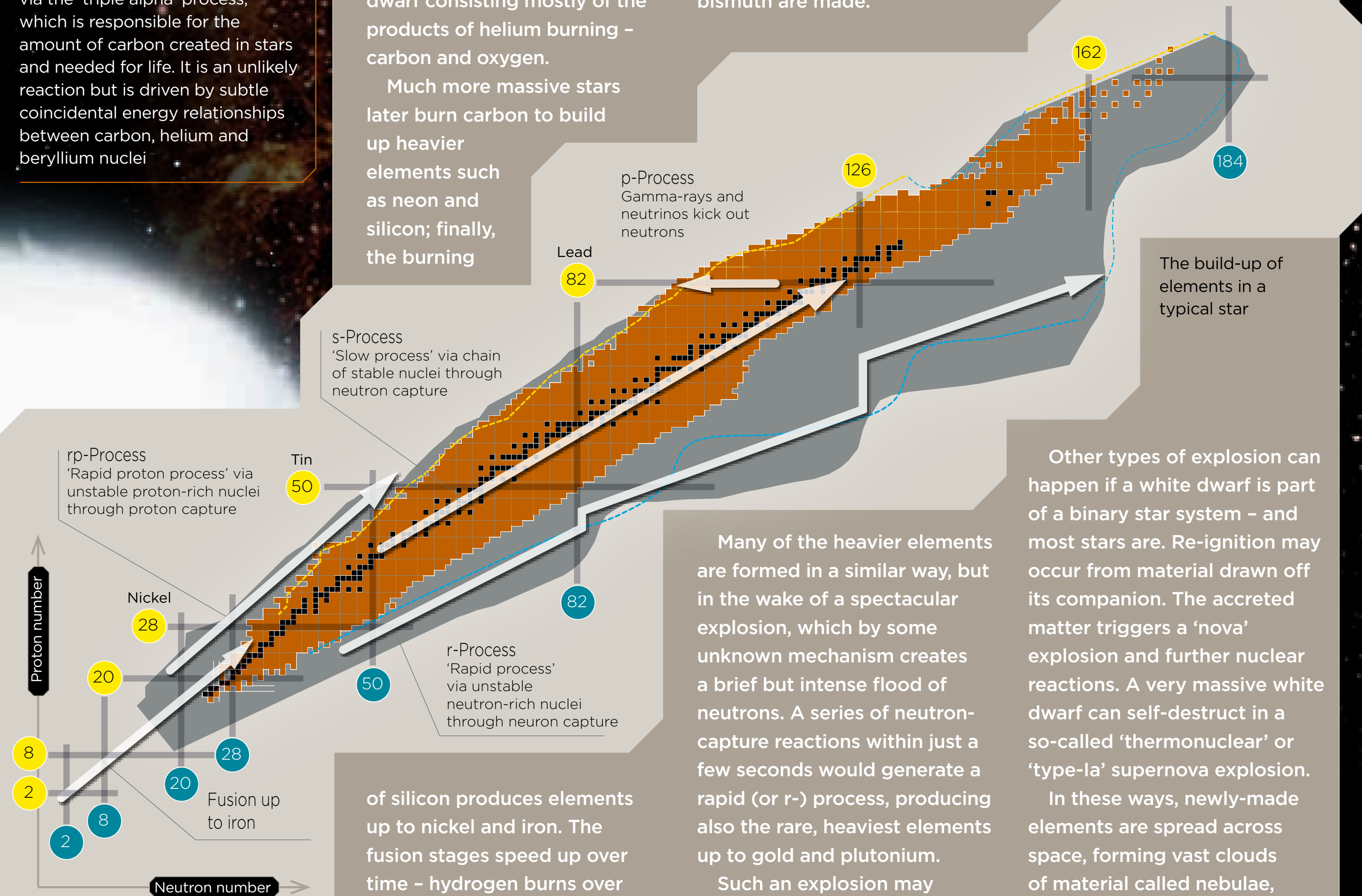
The 'burning' of helium to carbon via the 'triple alpha' process, which is responsible for the amount of carbon created in stars and needed for life. It is an unlikely reaction but is driven by subtle coincidental energy relationships between carbon, helium and beryllium nuclei

Today, we understand cosmic nucleosynthesis as the result of a complex series of reaction networks occurring at different stages in a star's life, and differing according to its overall mass. For most of their lives, stars 'burn' hydrogen to helium, but as the hydrogen is used up, helium starts burning to form carbon and oxygen. This is what will happen in the Sun. When all this fuel is used up, it will shrink under gravity to form a dense core, and the heat given off will cause the outer layers to swell creating a red giant. Eventually, the outer gas layers puff off, leaving behind a dense remnant – a white dwarf consisting mostly of the products of helium burning – carbon and oxygen.

Much more massive stars later burn carbon to build up heavier elements such as neon and silicon; finally, the burning of silicon produces elements up to nickel and iron. The fusion stages speed up over time – hydrogen burns over millions of years or more, while the last stages happen in a matter of days. At the red-giant stage, elements heavier than iron are built up by a process in which a nucleus captures a stray neutron to form a heavier isotope. If this isotope is unstable, the subsequent transformation of a neutron into a proton with the emission of an electron creates the next heaviest element. In this process, called the s-process for 'slow', small amounts of elements up to lead and bismuth are made.



A chart showing how the elements are built up in stars from the lightest nuclei through paths involving different nuclear processes



The build-up of elements in a typical star

Many of the heavier elements are formed in a similar way, but in the wake of a spectacular explosion, which by some unknown mechanism creates a brief but intense flood of neutrons. A series of neutron-capture reactions within just a few seconds would generate a rapid (or r-) process, producing also the rare, heaviest elements up to gold and plutonium.

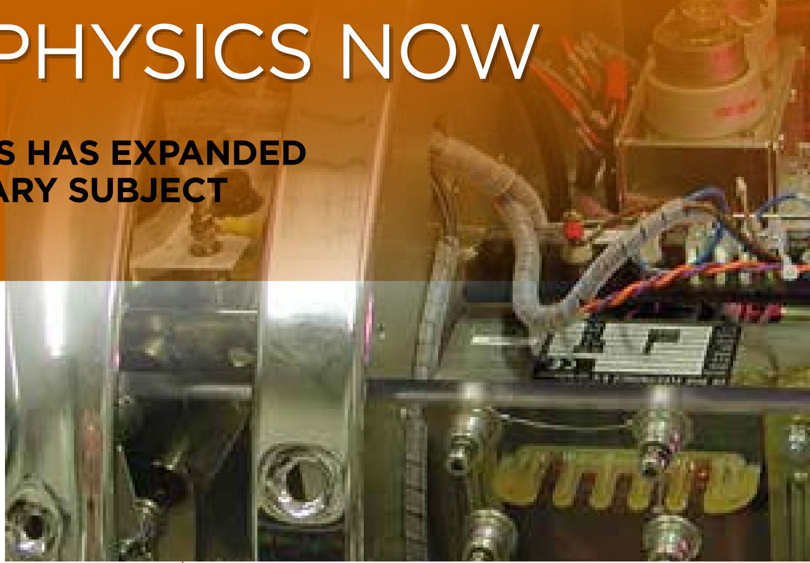
Such an explosion may happen when the nuclear fuel in a massive star runs out, and the central core collapses under gravity, which creates a gigantic shockwave that rushes outwards. The neutron-rich heavy elements may form in its wake in just a few seconds, together with lots of oxygen and other elements up to iron. We see this collapse as a supernova – an object shining millions of times brighter than the Sun. Left behind is an ultra-dense object – a neutron star or a black hole.

Other types of explosion can happen if a white dwarf is part of a binary star system – and most stars are. Re-ignition may occur from material drawn off its companion. The accreted matter triggers a 'nova' explosion and further nuclear reactions. A very massive white dwarf can self-destruct in a so-called 'thermonuclear' or 'type-Ia' supernova explosion.

In these ways, newly-made elements are spread across space, forming vast clouds of material called nebulae, which eventually condense into the next generation of stars and planets. With each subsequent generation, more and more of the elements heavier than hydrogen are created in the Universe.

NUCLEAR ASTROPHYSICS NOW

THE FIELD OF NUCLEAR ASTROPHYSICS HAS EXPANDED TO BECOME A TRULY MULTI-DISCIPLINARY SUBJECT



Theorists have developed and keep refining the models of nucleosynthesis reactions, and of stellar interiors and supernova explosions, while observational astronomers scrutinise the abundances of elements and their isotopes across the galaxies, in stars and in the dispersed material between the stars and galaxies – all across cosmological evolution. Here on Earth, experimental nuclear physicists study the behaviour of the relevant nuclei in the laboratory.

Part of the LUNA accelerator in the Gran Sasso underground laboratory; it is used to study the nucleosynthesis of the lightest elements

CURRENT TOOLS OF NUCLEAR ASTROPHYSICS RESEARCH

ACCELERATOR EXPERIMENTS

A key way to study nuclei and reactions of astrophysical significance is to re-create them in the laboratory. Nuclear physicists fire beams of subatomic particles or ions (atoms stripped of most of their electrons) at targets to create new nuclei through nuclear reactions. The nuclei are separated out into beams to study how they react. Mapping the secondary particles and gamma-rays provides clues to the structure and stability of such rare and unstable nuclei. Small, specialised accelerator laboratories around Europe, or dedicated units at large central facilities, employ such beams of both stable and radioactive ions, as well as protons, neutrons and lasers. Experiments probing the very slow, infrequent reactions that make the lightest elements are studied in underground laboratories to avoid interference from cosmic rays.

STARDUST IN THE LABORATORY

Meteorites contain tiny grains of stardust left over from previous generations of stars. The isotopic composition of these 'pre-solar' grains are analysed by cosmochemists using specialised mass spectrometers to provide important information about the nuclear history of their parent stars. We have even found Fe-60 nuclei from a nearby supernova in a crust sample from the Pacific ocean floor.

COSMIC REACTIONS IN THE LABORATORY

Heavy-ion collisions and high-power lasers can be used to simulate the hot, high-pressure conditions that exist inside stars at all stages of their lives, and to study the nucleosynthesis that occurs.

ASTRONOMICAL TELESCOPES

The spectra of stars reveal the proportions of elements present. Large, ground-based observatories feature sophisticated spectrographs that can detect elements and their isotopes in galaxies, stars and nebulae from radio through visible wavelengths. To observe at the shorter wavelengths of ultraviolet/X-rays to gamma-rays, instruments must be sent into space above the absorbing atmosphere. Such satellite observatories are able to map the distribution of isotopes in space, and home in on active sites such as supernovae, novae, neutron- star systems, and regions of intense recent star-birth, where nucleosynthesis reactions leave their observable traces.

Neutron-induced nucleosynthesis is studied at the neutron time-of-flight facility at CERN in Geneva

Isotope composition in meteorites can be analysed at the nanoscale using a type of mass spectrometer called a nanoSIMS

Two of the four units of ESO's Very Large Telescope in Chile

NEUTRINO DETECTORS

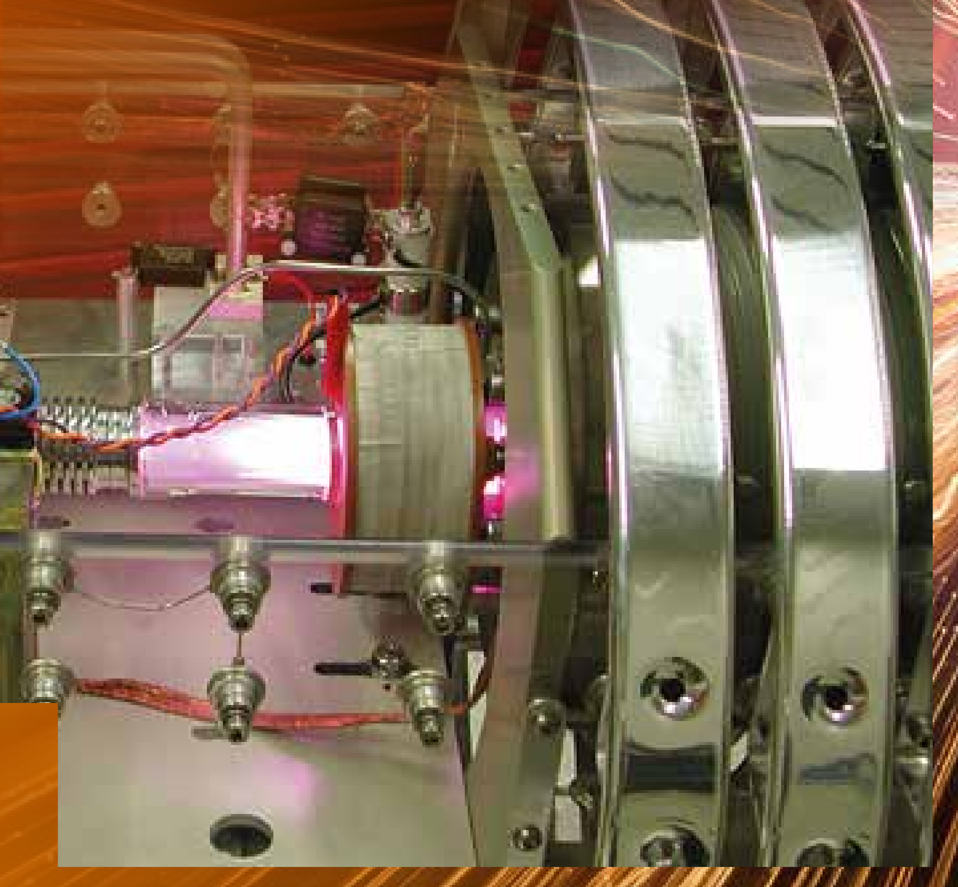
Neutrinos are ghostly subatomic particles with hardly any mass, and are produced in profusion in nuclear astrophysical processes. Because they hardly interact with materials, they are difficult to detect, but also escape from deeply embedded nuclear reaction sites, such as the interior of our Sun. Neutrino detectors are located deep underground (neutrinos can pass through the Earth while other particles cannot).

COSMIC-RAY DETECTORS

Cosmic rays consist of subatomic particles and nuclei, accelerated to energies much higher than ever attained in terrestrial particle accelerators. They can reach us from distant supernovae, so are also material messengers of nuclear processes in the Universe.

COMPUTERS AND THEORY

Theoretical studies of the conditions in stars and how they evolve, the nuclear reaction rates, and how matter and energy is produced and transported to the surface are used to compare with both astrophysical observations and laboratory measurements. Supercomputers need to be employed to carry out three-dimensional simulations of stellar interiors and their sometimes fast evolution – conditions not possible to reproduce in the laboratory. Theories of nuclear structure and stability, based on quantum descriptions of the fundamental strong and weak nuclear forces holding nuclei together, are essential to link stellar models to nuclei born there.



SOME ACHIEVEMENTS AND THEIR IMPLICATIONS

OUR UNDERSTANDING OF THE UNIVERSE HAS EXPANDED GREATLY THROUGH THE STUDY OF NUCLEAR ASTROPHYSICS

BIG-BANG NUCLEOSYNTHESIS

Measurements of the abundances of hydrogen and helium in the Universe confirm the principles of the Big Bang theory.

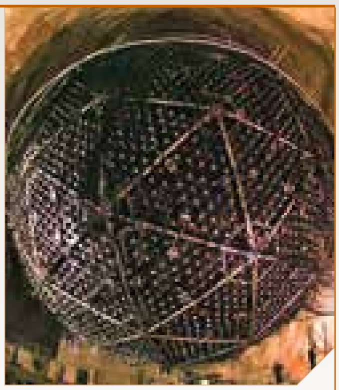
THE EVOLUTION OF THE UNIVERSE

Spectroscopic studies of the composition of stars of all generations, ages and sizes, across all wavelengths of light, have provided a remarkable description of the evolution of Universe and its constituents. Rare but significant unstable nuclei, such as aluminium-26 and iron-60, have been identified by gamma-ray observatories. These isotopes act as probes of the details of stellar and galactic processes.

The INTEGRAL gamma-ray space observatory

HOW THE SUN WORKS

Measurements of neutrinos emitted in solar nuclear reactions seemed to indicate – rather alarmingly – that our model of how the Sun works was wrong. Far fewer than expected seemed to reach the Earth. This stimulated a new development in particle-physics theory and our understanding of the fundamental laws of Nature, which showed that neutrinos could change their form. With this idea, improved neutrino measurements confirmed the basics of the solar model, and now new precision tests of nuclear neutrino fluxes are being done, also utilising seismic data to constrain the Sun's interior.



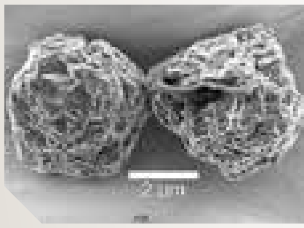
The SNO in Canada, which confirmed the behaviour of solar neutrinos

MAKING THE LIGHTEST ELEMENTS

Hydrogen-burning reactions leading to elements helium to boron have been measured in the LUNA accelerator project at the Underground Gran Sasso National Laboratory in Italy. Fundamental calculations can be compared with these, and teach us about nuclear reactions at the lowest energies, as are characteristic for stars.

STARS REVEAL THEIR SECRETS IN THE LABORATORY

Neutron-capture rates associated with the s-process in giant stars are being measured by firing neutron beams at specific targets. Using databases of those reactions, results from the analyses of pre-solar grains can be interpreted. Such dust grains can be found in meteorites and analysed in the laboratory. They have also revealed extreme isotopic ratios of elements such as carbon, oxygen and silicon that provide clues to the nucleosynthesis processes that made them in giant stars and supernovae.



SUPERNOVA EXPLOSIONS PROBED

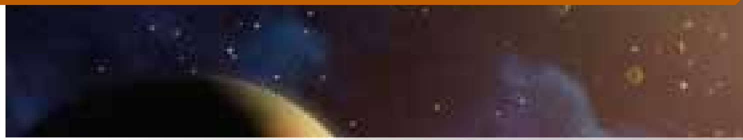
Supernova 1987A – the first such explosion to be close enough to us to study in detail – provided a test of theories of nucleosynthesis. Neutrino observatories detected 24 neutrinos, which was consistent with theoretical models of core collapse. Elements going from oxygen to calcium were detected early in ejecta through supernova spectroscopy, and after a few months, the heavier elements from deeper inside, nickel, cobalt and iron, were identified. The X-rays and gamma-rays from their radioactive decays are proof of their synthesis in the supernova. Recently, the INTEGRAL gamma-ray observatory measured the radioactive decay of a more long-lived isotope titanium-44, also synthesised in the supernova interior.

THE MINIMUM AGE OF THE UNIVERSE

The Very Large Telescope of the European Southern Observatory has measured the tiny amounts of uranium and thorium present in very ancient stars. Using this radioactivity 'clock', the age of this star could be determined as 13.2 billion years. It most likely was born from the remnants of a supernova from the first generation of supergiant stars that formed after the Big Bang, 13.8 billion years ago.

THE MYSTERIES TO UNCOVER

UNDERSTANDING NUCLEAR REACTIONS AND NUCLEI IN A WIDE RANGE OF COSMIC ENVIRONMENTS HAS FAR-REACHING IMPLICATIONS FOR OUR QUEST TO ANSWER THE BIG QUESTIONS: THE NATURE OF MATTER, THE EVOLUTION OF THE UNIVERSE AND OUR OWN ORIGINS

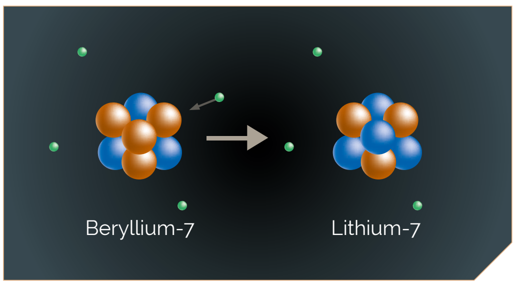


Although we now have built up a basic description of nuclear astrophysical processes, there are many issues that are unresolved. Many nuclear reactions happen with very low probability. The exotic nuclei thought to be significant in nucleosynthesis mostly cannot be made in nuclear experiments. The reaction networks are extremely complicated and happen in extreme, complex environments that are still poorly understood, and are difficult or impossible to reproduce on Earth.

OPEN ISSUES AND CHALLENGES

LACK OF LITHIUM IN THE EARLY UNIVERSE

The amount of lithium-7 observed in the oldest stars in the outer reaches of our Galaxy is far less than predicted by calculations of Big-Bang nucleosynthesis. Answers may be found through better interpretation of spectroscopic observations, or by invoking the existence of exotic particles that could be constituents of so-called dark matter, which is thought to make up about 25 per cent of the Universe. Establishing the precise mix and density of matter, whether dark or nuclear, in the primordial Universe is a prerequisite for understanding its evolution.



THE EARLY STAGES IN STARS

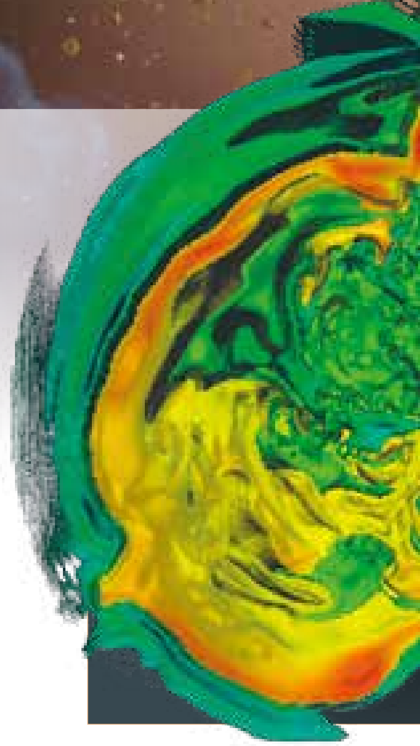
Although synthesis of the light elements is quite well understood, there are critical reactions, such as the fusion of carbon and helium to oxygen, that are hard to predict from theory and need better laboratory measurements. Recently, the amounts of carbon and oxygen in the Sun were shown to be one-third less than previously thought. Furthermore, these abundances do not tally with results from helio-seismology measurements.

ADVANCED STAGES OF NUCLEAR BURNING

There is a huge dearth of information about the reaction paths leading to the heavier elements. They require much better theoretical models of nuclear structure and stability, to be supported by new experimental measurements using both stable and radioactive nuclear beams to investigate the complex variety of pertinent reactions and their outcomes.

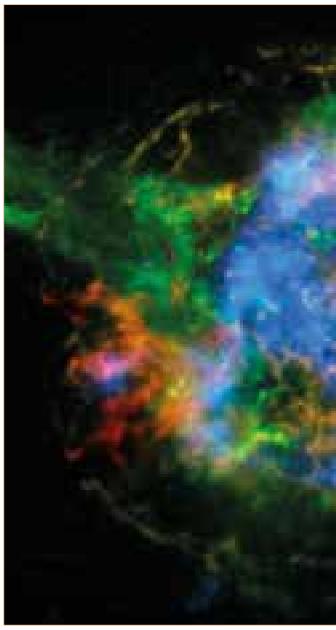
WHAT DETERMINES THE FATE OF A STAR?

We still do not understand the details of the processes that determine whether a star becomes a red giant and then a white dwarf, or explodes as a supernova leaving behind a neutron star or a black hole. Investigation of the underlying nuclear and transport processes is vital here.



HOW AND WHERE ARE THE HEAVIEST ELEMENTS MADE?

We know that large numbers of neutrons need to be present in a highly energetic environment to make the heaviest elements like gold and uranium. Supernovae interiors, and material falling onto neutron stars or black holes, seem likely candidates. The enormous number of rapid neutron-capture and possibly neutrino-induced reactions in these extreme environments needs theory combined with experimental studies constraining structures of the exotic nuclei involved. Complex interplay between the burning shells of intermediate-mass stars also play an important role in heavy-element synthesis.

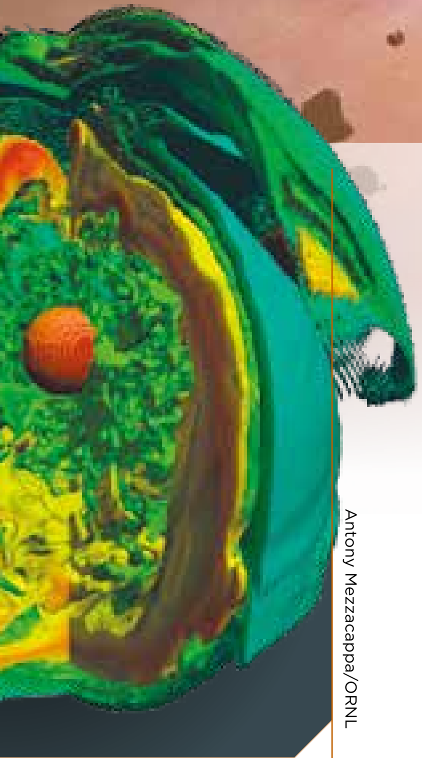


A PHYSICAL MODEL FOR SUPERNOVAE

We still have a poor understanding of how supernovae occur and what happens when the 'flames' of explosive nuclear burning zip through the entire object within a second or less. Precise understanding of the flame shapes, wrinkles, and speeds in such exotic matter are key to a realistic model. The neutrino 'wind,' as it comes off the resulting cooling neutron star and interacts so weakly with surrounding matter, may be a key driver in the genesis of heavy elements.

HOW DO THE ELEMENTS BECOME DISPERSED ACROSS SPACE?

We do not know exactly how stellar winds and supernova ejecta spread over entire galaxies, forming gas clouds that give birth to the next generation of stars. Galactic archaeology – the structure and behaviour of galaxies across time and the composition of the constituent stars – and the astronomy of ejecta in X-rays and gamma-rays will help to clarify this picture.



Antony Mezzacappa/ORNL

Computer simulation of a supernova core collapse and shockwave

THE NATURE OF NEUTRON STARS?

Neutron stars are extreme objects thought to be composed of various kinds of exotic nuclear or quark matter, which need to be explored further through computer simulations, in high-energy experiments, and observations of neutron-star phenomena.

THE ROLE OF BINARY SYSTEMS

About half of all stars form in pairs or multiples, and stellar evolution is changed when stars are close together. Our models for the enrichment of the Universe with heavy elements currently ignore interactions between stars in binary systems. The outer material of a giant star could be quickly siphoned off by the gravitational pull of its companion. If one companion is a neutron star, its gravitational pull will suck hydrogen and helium from its partner onto its surface causing a runaway thermonuclear explosion. It is proposed that the high density of protons would trigger nuclear reactions involving the rapid capture of protons (the rp-process) to create unusual short-lived proton-rich nuclei. Such species need to be studied in accelerator-based experiments.

Chandra/NuSTAR/NASA

The Cassiopeia A supernova remnant showing X-ray emissions from heated iron (red), silicon and magnesium (green) and titanium-44 (blue)

WHAT ABOUT THE SPECIAL CASE OF SUPERNOVA TYPE-IA EXPLOSIONS?

Detecting the light emissions of the 'standard candles' of supernovae type Ia in the early Universe has been the main evidence for the idea that its expansion rate is accelerating due to 'dark energy' pushing it apart. However, in a young universe when the proportions of heavier elements – in particular, carbon and oxygen – were lower, the supernovae mechanism could have been slightly different, making these objects less reliable cosmic measuring sticks. Thermonuclear re-ignition also happens in colliding binaries composed of two white dwarfs. How can we extrapolate the different candidate supernova models to the early low-metal-content Universe if we do not understand each of them?

A BETTER UNDERSTANDING OF FUNDAMENTAL THEORY

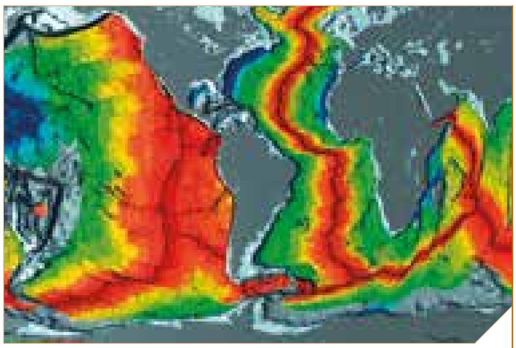
Atomic nuclei are tiny complex 'many-body' systems whose properties are mediated by electromagnetism, and the strong and weak nuclear forces. The daunting challenge for theorists is to describe nuclei in terms of these interactions, and in extreme astrophysical environments. Nevertheless, they do act as important quantum laboratories for exploring the fundamental laws of Nature.

WHAT TRIGGERED THE BIRTH OF OUR AND OTHER SOLAR SYSTEMS?

The current thought is that a nearby supernova triggered the condensation of our Sun and the planets from a giant molecular cloud, and provided some of the heavy elements we are familiar with. This is supported by the fact that the decay product of iron-60, nickel-60, has been found on Earth. Iron-60, which has a half-life of 2.6 million years, could have been created only under supernova conditions. We do not know whether similar events are essential to make other planets in the Galaxy with the right proportions of elements for life.

WHAT IS THE ROLE OF RADIOACTIVE ELEMENTS IN THE EARTH'S EVOLUTION?

Radioactivity generated in the Earth's interior keeps it liquid and is responsible for its geological activity. We do not know to what degree the radioactive elements such as uranium influenced the structure and water content in the early Earth's history.



Radioactivity drives tectonic plate activity

AN EXCITING FUTURE

ALTHOUGH THERE HAVE BEEN TREMENDOUS ADVANCES IN NUCLEAR ASTROPHYSICS, THERE IS MUCH MORE TO BE DONE

The GAIA spacecraft

Progress in nuclear astrophysics is truly multi-disciplinary and multi-national: advances in astronomical instrumentation are generating ever-improving imaging and spectroscopy over both wider and deeper fields of view; high-precision analytical equipment increasingly allows us to measure minuscule amounts of rare isotopes in terrestrial rocks and meteorites; and sophisticated accelerator systems and detectors potentially provide the tools to probe unusual, transient nuclei and reactions. All this research is brought together and complemented by theoretical work, often requiring high-performance computing.

Further progress can be achieved through a greater synthesis of research efforts across the disciplines, based on focused collaboration between different expert groups. The education of young scientists needs to be enriched with specialised interdisciplinary courses and workshops. Along this line, two initiatives have been set up by the European Science Foundation: EuroGenesis (www.esf.org/index.php?id=5456), which addresses the origin of the elements and the nuclear history of the Universe; and CompStar (http://compstar-esf.org), focusing on compact stars and supernovae.

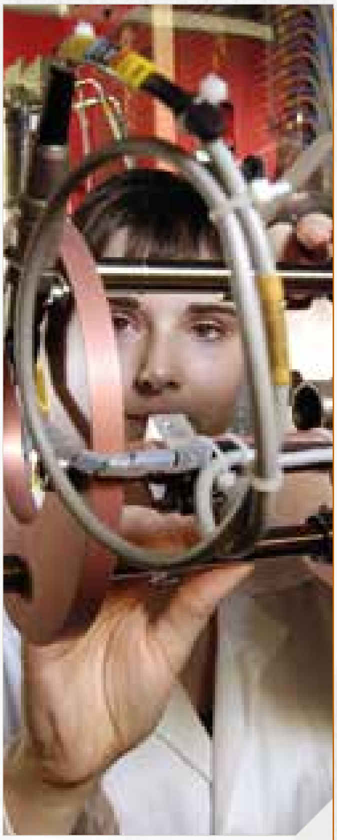
CURRENT AND FUTURE PROJECTS

Below are some international projects that will benefit nuclear astrophysics:

ASTRONOMICAL OBSERVATORIES

Improved (multi-object) spectrometers at all wavelengths will provide extensive information on the origin of the elements:

Gaia – the ESA Gaia spacecraft, launched in December 2013 is surveying a billion stars in our Galaxy, and will provide spectroscopic information on stellar structure and evolution.



Working at the GANIL nuclear research facility in France

The FAIR facility for nuclear research in Germany

LAMOST – the recently commissioned Large Sky Area Multi-Object Fibre Spectroscopic Telescope in China is carrying out a five-year spectroscopic survey of 10 million stars in the Milky Way.

ALMA – the international Atacama Large Millimetre Array, under construction in Chile, will analyse the composition of gas clouds where stars are born.

e-ELT – the 39-metre European Extremely Large Telescope, also to be built in Chile, will be ready in the early 2020s, will study in spectroscopic detail the birth and evolution of stars and planets.

INTEGRAL carries the only current telescope which can measure the variety of gamma-rays from cosmic radioactive nuclei; this ESA mission was launched in 2002 and may continue into the next decade.

JWST – the 6.5-metre James Webb Space Telescope, to be launched in 2018, will complement terrestrial telescopes from space, to reach the earliest stellar generations.

NuSTAR – the NASA Nuclear Spectroscopic Telescope Array 2012 mission maps in X-rays newly synthesised titanium-44 in the debris of nearby young supernovae.

ASTRO-H and ATHENA are Japanese and European X-ray spectroscopy projects respectively, planned for launch between 2015 and 2028, which will measure the hot interstellar gas related to regions where nucleosynthesis happens.

LABORATORY ANALYSIS

New generations of instruments capable of probing material with nanometre-resolution are being developed to measure pre-solar grains more efficiently. Lasers are used to measure the precise composition of selected isotopes in samples.

ACCELERATOR-BASED RESEARCH

A new generation of facilities will enable experiments probing nucleosynthesis, and the extreme conditions in which they occur, to be carried out:

Radioactive ion beams – several European nuclear research laboratories, including GSI (FAIR) in Germany, CERN (HIE-ISOLDE) in Switzerland, EURISOL (several European sites hope to host this next-generation experiment), and Legnaro (SPES) in Italy, open a new era with next-generation facilities: These create nuclei never made before, and allow their properties to be determined – essential for understanding nuclear reactions in cosmic explosions.

FAIR – the Facility for Antiproton and Ion Research will host a range of projects enabling new research on the properties of dense nuclear matter and atomic structure in extreme electromagnetic fields, advancing our understanding of neutron stars and of plasma conditions inside stars and planets.

LUNA-MV – the LUNA Collaboration is developing a more powerful accelerator in the Gran Sasso underground laboratory to measure accurately the very slow reactions associated with hydrogen burning.

Neutron sources – more intense neutron beams are being developed, such as the European Spallation Source, FRANZ and nTOF-EAR2 at CERN, which will be capable of measuring neutron-capture reactions.

ELI – one component of the planned European laser facility, the Extreme Light Infrastructure, will be built in Romania and dedicated to nuclear physics experiments.

COMPUTING AND THEORY

Advances in computers are the key to developments of the complex theories of nuclear structure, supernova explosions, and cosmic evolution of the abundance of the elements: superfast calculations enable theories and their parameters to be widely explored, and to guide experiments and compare their results with theoretical predictions. Also support for databases of thousands of nuclei and their reactions, and advanced graphics-processing to visualise complex data or theories, are key drivers of the field.

SPIN-OFFS AND RELEVANCE FOR SOCIETY

The technology and skills developed for nuclear astrophysics research are helping to find solutions to many of the challenges our society faces today.

HEALTH

Detectors developed for nuclear physics have been adapted for medical imaging and diagnosis: MRI (magnetic resonance imaging), PET (positron emission tomography) and CT (computer-aided tomography). Beams of atomic nuclei are also used to destroy cancerous tumours, and radiotherapy based on injections of radioactive substances is a part of cancer treatment.

Ionising and nuclear radiation is also used to sterilise medical equipment, household items and food, by utilising their lethal effects on microbes.

COMPUTING AND INFORMATION PROCESSING

The computational tools developed by researchers modelling stellar interiors and supernovae explosions have inspired a variety of computing methods used in, for example, medical imaging and engineering, or simply to provide faster internet support and faster processors.

ENERGY

Energy supply is one of the biggest challenges for the next decades, and many countries will continue to rely on nuclear power. The techniques of nuclear astrophysics are used to improve the efficiency and safety of nuclear reactors, and technology is now available to 'clean' the radioactive waste so far generated. In the future, reactors employing fusion reactions like those in the Sun will generate safe nuclear energy.

ENVIRONMENT AND ANALYSIS

The evolving global climate and our effect on it is of great importance. Technologies from astrophysics and nuclear physics have improved tools for remote-sensing.

Radioactivity from both natural events, such as volcanoes, and manmade sources are monitored. Measurements of trace isotopes can track subsurface water flows.

Detecting minute amounts of characteristic isotopes was pioneered in nuclear astrophysics laboratories, and now allows us to identify art forgeries, determine the age of artefacts and materials, analyse geological samples, and monitor environmental pollution.

Security has been improved by detectors and analytical techniques from nuclear astrophysics that can track sensitive materials at national borders, and scan cargo and baggage for explosives, radioactive or fissile materials.

Short-lived radioisotopes can probe manufacturing processes and analyse product performance, for example, wear and tear in engine components..

A SKILLED WORKFORCE

Understanding the puzzles of the Universe attracts talented students to study physics in an international and multi-disciplinary environment. This training produces highly-skilled individuals with the analytical and technical abilities needed by industry and government to solve the problems faced by society today.

This brochure was supported by the European Science Foundation, as a spin-off from its EuroGENESIS programme and a service to the entire nuclear astrophysics community.
www.esf.org/eurogenesis

European Science Foundation
1 quai Lezay Marnésia
BP 90015
F-67080 Strasbourg Cedex
France

FURTHER INFORMATION

Website: http://origin-of-the-elements.eu/European Nuclear Astrophysics (EU)

COMMUNITY INFORMATION

Throughout Europe, about 100 research groups with 225 senior scientists from 19 countries are actively involved in this science theme as of today. More are likely to be integrated in coming years, as astronomical facilities such as the Sloan Digital Sky Survey or the Gaia space mission, and nuclear research facilities such as RIKEN, FAIR, and FRIB, add major data for nuclei of the Universe. Research groups are supported in their home countries – Austria, Belgium, Croatia, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Portugal, Romania, Spain, Sweden, Switzerland, and the UK – and by their home institutions, often through specific research grants. International research networks and organisations are dedicated to this field (for example, HGF's NAVI in Germany and JINA in the US, and UKAKUREN in Japan and Russia). International conferences typically attract several hundred scientists (for example, *Nuclei in the Cosmos*, with a history of 13 bi-annual conferences so far).

EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE

Editor:
Nina Hall, ninah@ealing.demon.co.uk
Design:
h2o Creative Communications
September 2014

AUSTRIA
TU Vienna
VERA Vienna

BELGIUM
Brussels Observatory
ISOL@MYRRHA, Mol
KU Leuven
Liege University
ULB Brussels

CROATIA
RBI Zagreb
U Zagreb

CZECH REPUBLIC
Astronomical Inst. Prague

DENMARK
DCC Copenhagen
U Aarhus

FINLAND
U Helsinki
U Jyväskylä
U Oulu

FRANCE
CEA Saclay
CSNSM Orsay
Ganil
IAP Paris
IPHC Strasbourg
IPN Orsay
IRAP Toulouse
Observatoire de Paris
Paris Nat Hist Museum
U Nice
UPJV

GERMANY
AIP Potsdam
ESO Garching
GSI Darmstadt
HZDR Rossendorf
LMU München
MPA Garching
MPE Garching
MPICH Mainz
MPP Munich
MPIK Heidelberg
TU Berlin
TU Darmstadt
TU Dresden
TU München
U Bochum
U Bonn
U Erlangen-Bamberg
U Frankfurt
U Giessen
U Heidelberg
U Köln
U Tübingen
U Würzburg

GREECE
INP Demokritos
U Thessaloniki

HUNGARY
ELTE University Budapest
MTA Atomki Debrecen
U West Hungary

ISRAEL
Hebrew U Jerusalem
Tel Aviv U
Weizmann I Rehovot

ITALY
Arcetri O
IAS Rome
INFN Frascati
LNGS Gran Sasso
OA Roma
OA Teramo
U Bologna
U Catania
U Naples
U Perugia
U Pisa
U Torino
U Trieste

NETHERLANDS
Radboud U Nijmegen
SRON Utrecht
U Amsterdam

PORTUGAL
U Coimbra
U Lisbon

ROMANIA
Horia Hulubei Bucharest

SPAIN
IA Andalucia
IA Canarias
ICE Bellaterra
IEM Madrid
IFIC Valencia
U Alicante
U Barcelona
U Huelva
U Seville
U Valencia
UAM Madrid
UCM Madrid
UGr Granada
UPC Barcelona
USC Santiago de Compostela

SWEDEN
Lund O
Onsala Space O
Stockholm U
Uppsala U

SWITZERLAND
CERN Geneva
EPFL Lausanne
ETH Zürich
U Basel
U Bern
U Geneva

UK
Liverpool John Moores U
Queen's U Belfast
U Cambridge
U Central Lancashire
U Edinburgh
U Hertfordshire
U Keele
U Manchester
U Portsmouth
U Surrey
U York
UC London