Elements of Stars

by Maria Lugaro and Ewine van Dishoeck

What are stars made of? Less than 200 years ago this basic, simple question was deemed impossible to answer. As Auguste Comte put it in 1835: *"On the subject of stars...While we can conceive of the possibility of determining their shapes, their sizes, and their motions, we shall never be able by any means to study their chemical composition or their mineralogical structure."* Today, we have a broad, clear answer to the question: "What are stars made of?" We also understand its far-reaching implications in relation to the evolution of the cosmos. Satellites and many ground-based spectroscopic surveys routinely provide new discoveries on the chemical composition of astronomical objects. In parallel, the nuclear processes that produce the elements inside stars are investigated in increasingly sophisticated nuclear physics experimental facilities across the world. At the same time, supercomputers allow us to calculate detailed models of the evolution of stars and galaxies: how much of which element is produced where? Finally, the presence of tiny amounts of extra-solar material can be found within meteorites, whose analysis is reaching unparalleled precisions with uncertainties down to parts per million. How have we managed to travel from an impossible question to such broad knowledge filled with discoveries?

Figure 1. A slice (4.6 x 3.8 cm) from the Gujba chondrite meteorite, which fell in northeastern Nigeria on 3rd April 1984. The round drops are called chondrules and give the name to chondritic meteorites. This meteorite is a special, fascinating case because many of its chondrules are made of metallic iron, rather than silicate minerals. (Image by James St. John from Wikipedia, licensed under the Creative Commons Attribution 2.0 Generic license)

Elements of the Sun

Researchers began with the star closest to us, the Sun. In 1813, Joseph von Fraunhofer became the first scientist to systematically study the dark lines seen in the spectrum of the Sun, which were found to coincide with the emission lines of various elements such as H, Ca, Mg and Fe seen at high temperatures in the laboratory. One such line, at 587.6 nm, was originally unidentified and named *helium*, only to be assigned to the actual noble gas element when it was discovered on Earth in 1895.

A major breakthrough came in 1925, when Cecilia Payne-Gaposchkin discovered that the strength of stellar spectral lines depends not only on the stellar surface composition, but also on the degree of ionisation at a given temperature. Applying this discovery to the Sun, she found that C, Si, and other common 'metals' seen in the Sun's spectrum were present in about the same relative amounts as on Earth, however, He and H were vastly more abundant in the Sun than on the Earth. Here the word 'metal' is used in the astronomical sense, i.e., any element heavier than H or He.

Meteoritic rocks provide another way to determine the abundances of the Sun. Some primitive meteorites underwent little modification after they formed in the solar nebula and can thus carry accurate information on the elemental abundances of the gas from which the Sun and the planets formed. For example, carbonaceous *chondrites* (Figure 1) are ideal samples because they contain large amounts of organic compounds, which indicate that they experienced very little heating (some were never heated above 50 °C). An extremely close match is found between the elemental compositions derived from the Sun's spectra and those inferred from the analysis of meteorites. The advantages of meteorites is that their composition can be determined much more precisely than what is possible for the solar spectrum since they can be studied in the laboratory with very sensitive mass spectrometers. In particular, meteoritic analysis can obtain both isotopic and elemental abundances, while isotopic abundances are difficult or impossible to obtain from the solar spectra. However, some gases, such as H and the noble gases are not incorporated into rocks, and some major elements such as C, N, and O do not fully condense into rocks either. For these, we must rely on the Sun's spectral analysis. For the isotopic composition of

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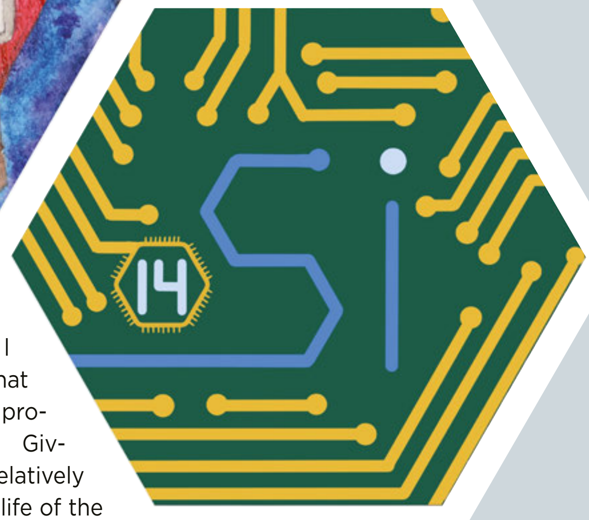

noble gases, on the other hand, the best data come from the analysis of the solar winds.

In 1956, Harold Urey and Hans Suess published the first table of the "cosmic" abundances. Effectively, these were the abundances of the Sun, however, it was then assumed, and as we will see not proven wrong until the late 1950s, that all stars, and the whole Universe as a matter of fact, have the same chemical composition as the Sun. This was the basis of the accepted theory of the time for the origin of the elements, that all of them, from H to Th, were produced together during the Big Bang and their abundances in the Universe were not modified by any further process thereafter. Now we know that the Big Bang only produced H and ^{4}He, with trace amounts of ^{2}H, ^{3}He and ^{7}Li.

Abundances in other stars

As the quality of spectroscopy observations improved in the 1950s, it started to become possible to identify giant stars that actually show a very different chemical composition from the Sun. These "anomalous" stars showed higher abundances of heavy elements such as Sr and Ba. In 1952, Paul Merrill made a revolutionary discovery; he observed the absorption lines corresponding to the atomic structure of Tc in the spectra of several giant stars. Merrill was at first cautious about this result because the element he identified does not even exist on Earth: being fully radioactive, Tc is only artificially produced. Merrill showed that stars also produce Tc. Given the relatively short half life of the Tc isotopes (a few million years at most, much shorter than the lifetime of the observed stars), the Tc lines were the first indisputable demonstration that this radioactive element is made *in situ* in the stars where it is observed.

This finding brought a radical change in the way we understand the origin of the chemical elements: the idea that nuclear reactions inside stars are responsible for the production of most of the chemical elements in the Universe began to take shape and garner authority. Today we know that a huge variety of chemical compositions exist among stars and other places in the Universe, with different processes contributing to this diversity.

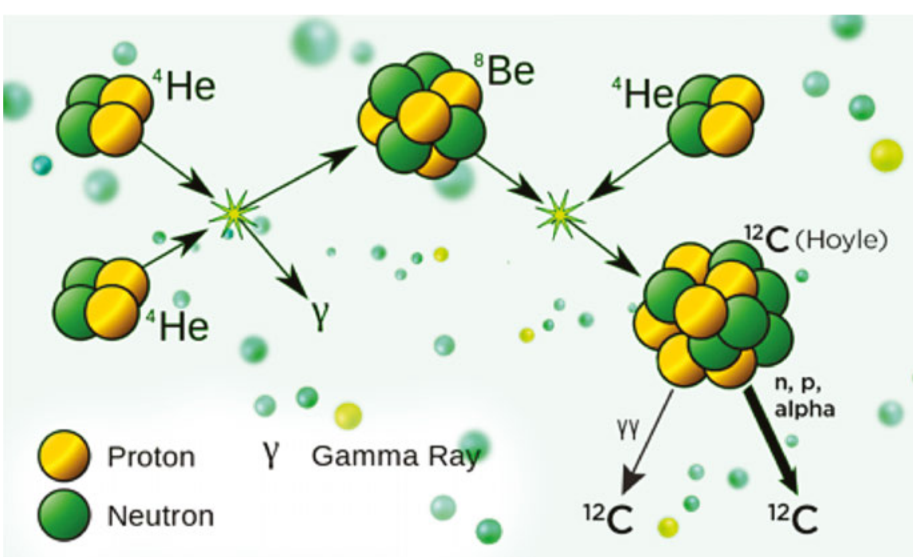

Figure 2. The processes involved in the triple-α reaction that makes carbon in the Universe. Two ^{4}He nuclei (α particles) create ^{8}Be, capture of another α particle produces ^{12}C in an excited state at the energy predicted by Fred Hoyle. The excited state decays onto the ground state of ^{12}C by ejecting particles. (Image from National Superconducting Cyclotron Laboratory NSCL, Michigan State University).

Nuclear processes in stars

Stellar interiors and explosions are like giant nuclear reactors: the ideal environments for nuclear interactions to happen. Matter can reach extremely high temperatures (for example, 10 million K in the core of the Sun and up to billion K in supernovae) and at the same time a high density is maintained due the force of gravity (for example, roughly 100 gr cm^{-3} in the core of the Sun and up to 10^{10} gr cm^{-3} in supernovae). Such conditions force nuclei to remain in a confined volume and to react via a huge variety of nuclear interaction channels. This complexity and diversity created all the variety of atomic nuclei from C to Th in the Universe.

The nuclear processes that produce the chemical elements were first systematically organised by Burbidge et al. (1957). Nuclear interactions driven by the strong and weak nuclear force result in fusion, fission, and the decay of unstable nuclei. Complex networks of such reactions can occur depending on the temperature, the availability of the interacting nuclei, and the probability of the interaction itself.

Hydrogen burning activates at temperatures from 10 million K and is responsible for the cosmic production of N by conversion of C and O into it. It also creates a large variety of minor isotopes, for example, ^{13}C and ^{17}O are produced via proton captures on ^{12}C and ^{16}O, respectively, followed by the fast (order of minutes) decay of the radioactive isotopes ^{13}N and ^{17}F. *Helium burning* occurs from 100 million K and is mostly identified with the "triple-α" (^4He + ^4He + ^4He) reaction producing ^{12}C, with a following α capture on ^{12}C producing ^{16}O (Figure 2).

Because the nucleus of ^8Be consists of 2α particles, it is extremely unstable, and would break before capturing another α particle. To solve this problem, Fred Hoyle predicted that a quantum energy level must exist in the ^{12}C nucleus near the energy where the ^8Be + α reaction would be more likely (a so-called "resonance"). This observation was experimentally confirmed later on and considered as a potential application of the anthropic principle (i.e., that observations of the Universe must be compatible with the conscious and sapient life that observes it) since without this resonance no carbon would exist, and hence no life such as that on the Earth.

In stars with mass below roughly ten times the mass of the Sun, nuclear burning processes do not proceed past He burning. When the nuclear fuel is exhausted, the stellar central region becomes a degenerate, inert

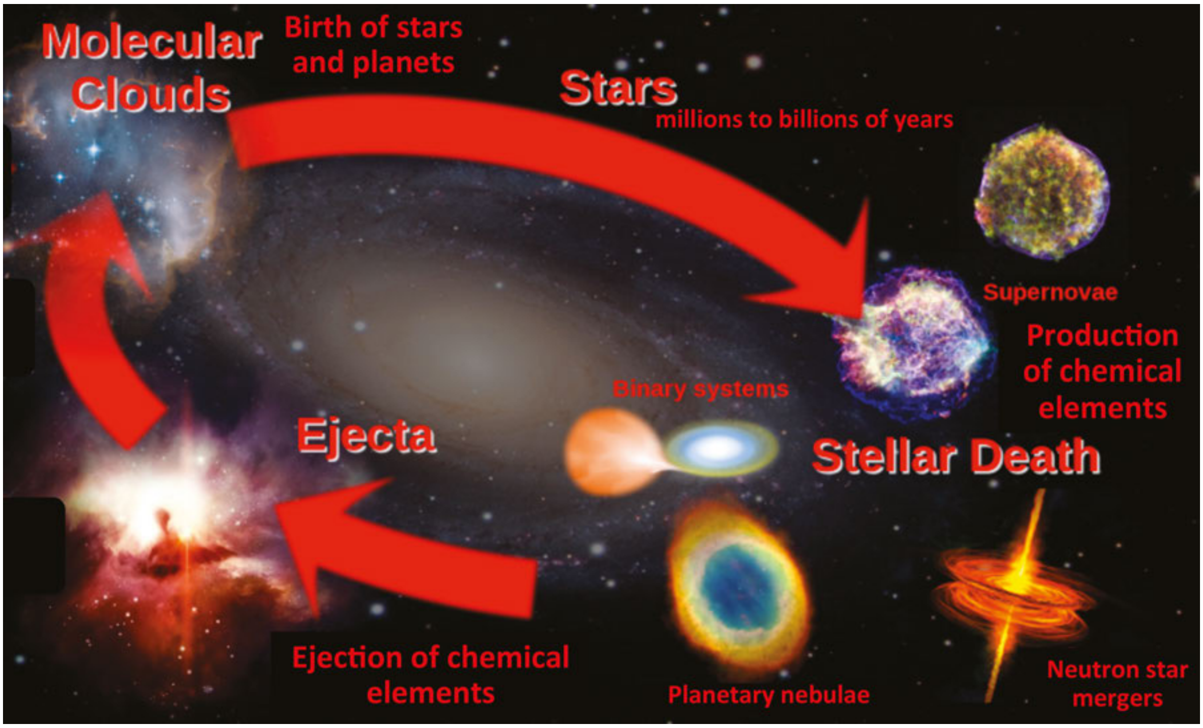

Figure 3. The cosmic cycle of chemical matter in a galaxy. Stars and their planetary systems are born inside cold and dense regions (molecular clouds on the upper left in the figure). Stars can live millions to billions of years: the smaller their mass the longer they live. Chemical elements are produced during the lives of stars and when the stars die, the elements are then ejected back into the galactic gas via winds or explosions. When the gas cools down again, a new generation of stars is born from matter with different chemical composition (figure courtesy of Richard Longland, images from NASA).

C-O core, and H and He continue to burn in shells around the core. In more massive stars, instead, the temperature in the core increases further and a larger variety of reactions can occur. These processes involve *C, Ne, and O burning*, and include many channels of interactions, with free protons and neutrons driving a large number of possible paths. The cosmic abundances of the "intermediate-mass" elements, roughly from Ne to Cr, are mainly the results of these nuclear burning processes. Once the temperature reaches a billion K, the probabilities of fusion reactions become comparable to those of photo-disintegration and the result is a *nuclear statistical equilibrium*. This process favours the production of nuclei with the highest binding energy per nucleon, resulting in a final composition predominantly characterised by high abundances of nuclei around the Fe peak.

Beyond Fe, charged-particle reactions are not efficient anymore due to the large Coulomb barrier around heavy nuclei with the number of protons greater than 26. *Neutron captures*, in the form of *slow* (*s*) and *rapid* (*r*) processes, are instead the main channels for the production of the atomic nuclei up to Pb, U, and Th. The *s* process requires a relatively low number of neutrons (~10^7 cm^{-3}) and is at work in low-mass giant stars, producing the Tc observed in these stars. The *r* process requires a much higher number of neutrons (> 10^{20} cm^{-3}) and occurs in explosive neutron-rich environments. The stellar site of the *r* process has been one of the most uncertain and highly debated topics in astrophysics. Neutron star mergers are now considered as the first observationally proven site of the production of *r*-process elements like gold, based on spectra of the *r*-process supernova ('kilonova') associated with the 2017 gravitational wave source GW170817 (Kilpatrick *et al.* 2017).

From stars to the interstellar medium and back

Atomic nuclei created inside stars are expelled into the surrounding medium and recycled into newly forming stars and planets (Figure 3). In stars born with masses similar to the Sun and up to roughly ten times larger, matter is mixed from the deep layers of the star to the stellar surface, and ejected by the stellar winds that peel off the external layers of the star. These processes are most efficient during the final red giant phases of the lives of these stars. When most of the original stellar mass is lost, the matter expelled by the stellar winds can be illuminated by UV photons coming from the central star, producing what we observe as a colourful planetary nebula. These stars contribute to the chemical enrichment of the Universe most of the C, N, F, and half of the elements heavier than Fe, the *s*-process element such as Ba and Pb. Eventually the core of the star, rich in C and O produced by previous He burning, is left as a white dwarf.

More massive stars end their lives due to the final collapse of their Fe-rich core. Once nuclear fusion processes have turned all the material in the core into Fe, neither fusion nor fission processes can release energy anymore to prevent the core collapse. As the core collapses, matter starts falling onto it, which results in a bounce shock and a final core-collapse supernova explosion. The exact mechanism of the explosion is not well known although it has been recognised that neutrinos play a crucial role. The supernova ejects into the interstellar medium the fraction of synthesised nuclei that do not fall back into the newly born central compact object: a neutron star or a black hole. The ejected material is rich in O and other common elements such as Mg, Si, and Al.

Binary interaction involving accretion onto a white dwarf can lead to explosive burning and a thermo-nuclear supernova that tears the whole white dwarf apart. These supernovae are responsible for producing most of the Fe in the Universe. Binary interaction between neutron stars and black holes can lead to their merging and, as mentioned above, the production of *r*-process elements like Au.

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Together, these different processes in different types of stars determine the chemical evolution of galaxies (Figure 3). The next generation of stars forms out of matter of a different composition, depending on the time and place of their birth, and on the full history of their host galaxy. One of the aims of current large (millions of stars) stellar surveys with high-resolution spectroscopy is to derive such chemical diversity and exploit it to understand the formation and history of galaxies within a cosmological framework.

Far-reaching implications

The chemical fingerprints left by the nuclear reactions that take place in stars provide us the opportunity not only to answer the questions of what are stars made of and where the chemical elements come from, but also to study the evolution of the cosmos in a huge range of scales. Observations of the chemical composition of the oldest stars provide us with a glimpse into the early Universe and analysis of the chemical signatures of stellar populations can tells us how galaxies formed.

Closer to home, investigating and interpreting the composition of meteoritic materials and the signature of the nuclear processes left there by different types of stardust provide us with insights on how our own Solar System formed. For example, we now know that the Earth is roughly $1/10^4$ times richer in nuclei produced by the *s* process in giant stars than Solar System bodies that formed further away from the Sun (Poole *et al.* 2017). How this tiny but robust difference came about in the solar proto-planetary disc is a matter of debate. It represents one of many current questions whose answers allow us to use the chemical elements in stars to understand the evolution of the cosmos, from the Big Bang to life on habitable planets.

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