# 2019

# INTERNATIONAL YEAR OF THE PERIODIC TABLE

# Stellar Nucleosynthesis for Dummies

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## CHAPTER LIST

# Chapter 1: The periodic table yesterday and today

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The 2019 has been declared by UNESCO "International Year of the periodic Table", to celebrate the 150$^{th}$ anniversary of the publication of the Periodic Table by the russian chemist Dmitrij Mendeleev. In fact, March the 6$^{th}$ 1869, Mendeleev formally presented to the Russian Chemical Society his classification of chemical elements, with the title: "The Dependence between the Properties of the Atomic Weights of the Elements".

Mendeleev was not the first to propose such a kind of classification for chemical elements. At that epoch, in fact, other Tables were already published, in which the elements were ordered basing on the increasing atomic number or grouping elements with similar chemical properties. One of the main features of Mendeleev' Table is the fact that he left empty slots, basing on the periodic properties he had previously identified. For instance, he hypothesized the existence of three elements, naming them eka-silicon, eka-aluminum and eka-boron, being exactly one slot below the corresponding known elements (see **Figure 1**). Those elements were discovered in the following years (they are germanium, gallium and scandium, respectively).

| Reihen | Gruppo I. — $R^2O$ | Gruppo II. — $RO$ | Gruppo III. — $R^2O^3$ | Gruppo IV. $RH^4$ $RO^2$ | Gruppo V. $RH^3$ $R^2O^5$ | Gruppo VI. $RH^2$ $RO^3$ | Gruppo VII. $RH$ $R^2O^7$ | Gruppo VIII. — $RO^4$ |
|---|---|---|---|---|---|---|---|---|
| 1 | H=1 | | | | | | | |
| 2 | Li=7 | Be=9,4 | B=11 | C=12 | N=14 | O=16 | F=19 | |
| 3 | Na=23 | Mg=24 | Al=27,3 | Si=28 | P=31 | S=32 | Cl=35,5 | |
| 4 | K=39 | Ca=40 | —=44 | Ti=48 | V=51 | Cr=52 | Mn=55 | Fe=56, Co=59, Ni=59, Cu=63. |
| 5 | (Cu=63) | Zn=65 | —=68 | —=72 | As=75 | Se=78 | Br=80 | |
| 6 | Rb=85 | Sr=87 | ?Yt=88 | Zr=90 | Nb=94 | Mo=96 | —=100 | Ru=104, Rh=104, Pd=106, Ag=108 |
| 7 | (Ag=108) | Cd=112 | In=113 | Sn=118 | Sb=122 | Te=125 | J=127 | |
| 8 | Cs=133 | Ba=137 | ?Di=138 | ?Ce=140 | — | — | — | — — — — |
| 9 | (—) | — | — | — | — | — | — | |
| 10 | — | — | ?Er=178 | ?La=180 | Ta=182 | W=184 | — | Os=195, Ir=197, Pt=198, Au=199. |
| 11 | (Au=199) | Hg=200 | Tl=204 | Pb=207 | Bi=208 | — | — | |
| 12 | — | — | — | Th=231 | — | U=240 | — | — — — — |

**Figure 1: MENDELEEV ORIGINAL PERIODIC TABLE**

At that epoch more than 60 elements were known; today, the number has almost doubled (see **Figure 2**). The last 4 elements (nihonium, moscovium, tennessine e oganesson) were officially presented in 2016.

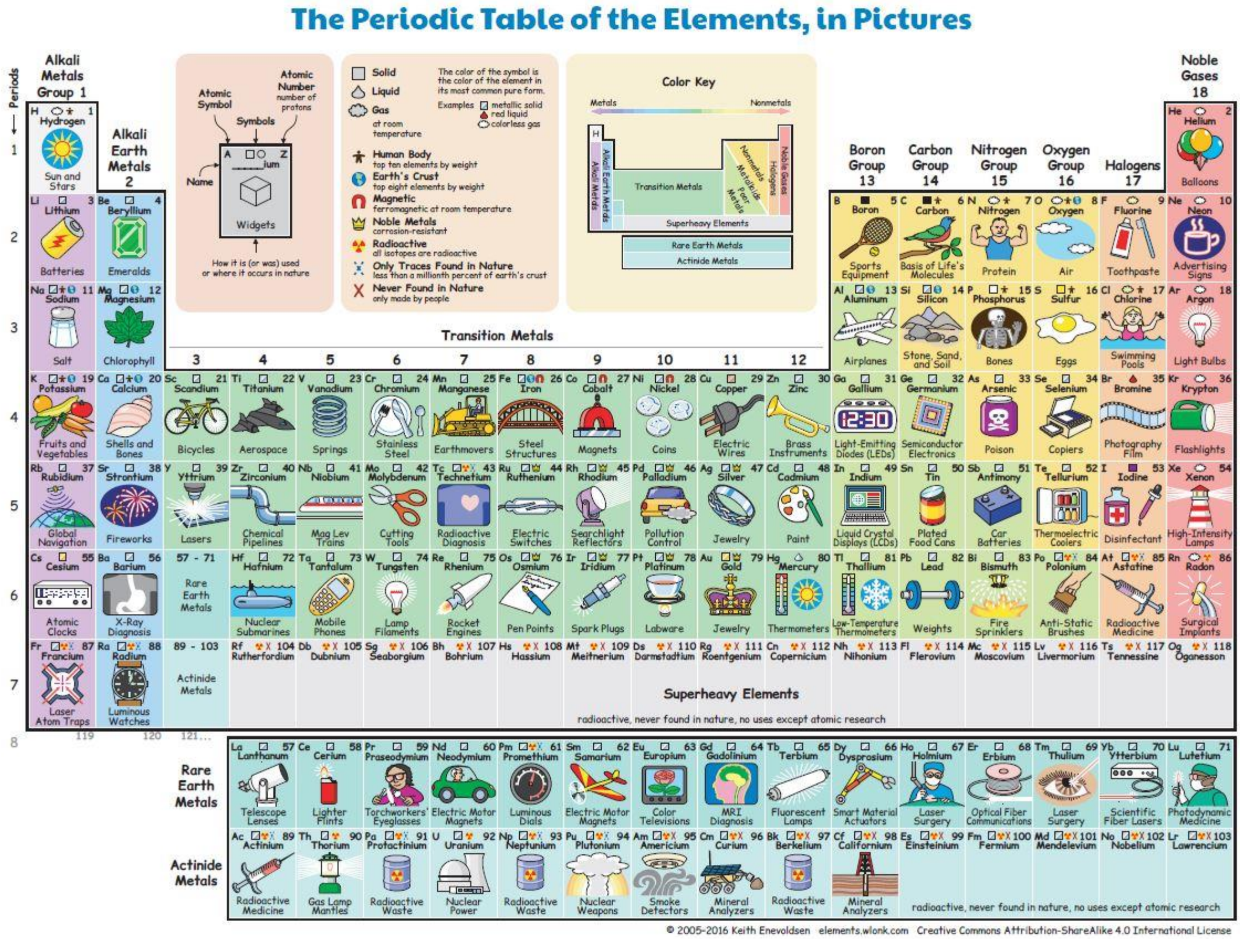


**Figure 2: THE PERIODIC TABLE TODAY**

The Periodic Table includes both stable elements (i.e. with an endless lifetime) and unstable elements (i.e. they transform to another chemical species). In nature, all elements can be found, apart from the Super-heavy ones, created artificially and with extremely short lifetimes.

In the Periodic Table, elements are ordered with increasing atomic numbers (symbol Z), i.e. with increasing number of “protons” within the nucleus. The proton is a sub-atomic particles, with a mass equal to 1.7x10$^{-24}$ gr (about 2000 billionths of billionths of billionths of gram) and a positive charge equal to 1.6x10$^{-19}$ C (16 billionths of billionths of Coulomb, which is the charge transported in 1 second by an electric flux of 1 Ampere). Atoms are globally neutral, because around nuclei (positively charged) there are electrons, with negative charge. Inside nuclei there are also neutrons, which have a mass almost identical to protons, but without charge. Therefore, an atom consists of a nucleus (with protons and neutrons), surrounded by a "cloud" of electrons. The nucleus charge provides its atomic number (Z); its mass, instead, is commonly identified by the sum of nucleons (A=protons+neutrons: the masses of electrons are negligible with respect to nuclei).

Each chemical element has its typical "isotopic composition". “Isotopes” are atoms with the same atomic number, but with a different number of neutrons. In nature, there are mono-isotopic elements (as fluorine or gold), elements with many stable isotopes (tin has 10 isotopes: the largest number) and elements without stable isotopes (as technetium, which transforms to molybdenum).

The interested reader can explore the IUPAC Periodic Table of the Elements and Isotopes available at https://www.isotopesmatter.com/applets/IPTEI/IPTEI.html .

## Chapter 2: The element distribution in the Sun

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In the last 100 years, physicists and astrophysicists tried to answer the following question: where do the chemical elements come from? The physical conditions on the Earth do not allow the production of new elements, because very high temperatures are needed (at least one million degrees). As a consequence, all the elements known were already present in the proto-Earth at the epoch of its formation (which corresponds to the epoch of Sun formation, considering that our planet formed from the same material of our star).

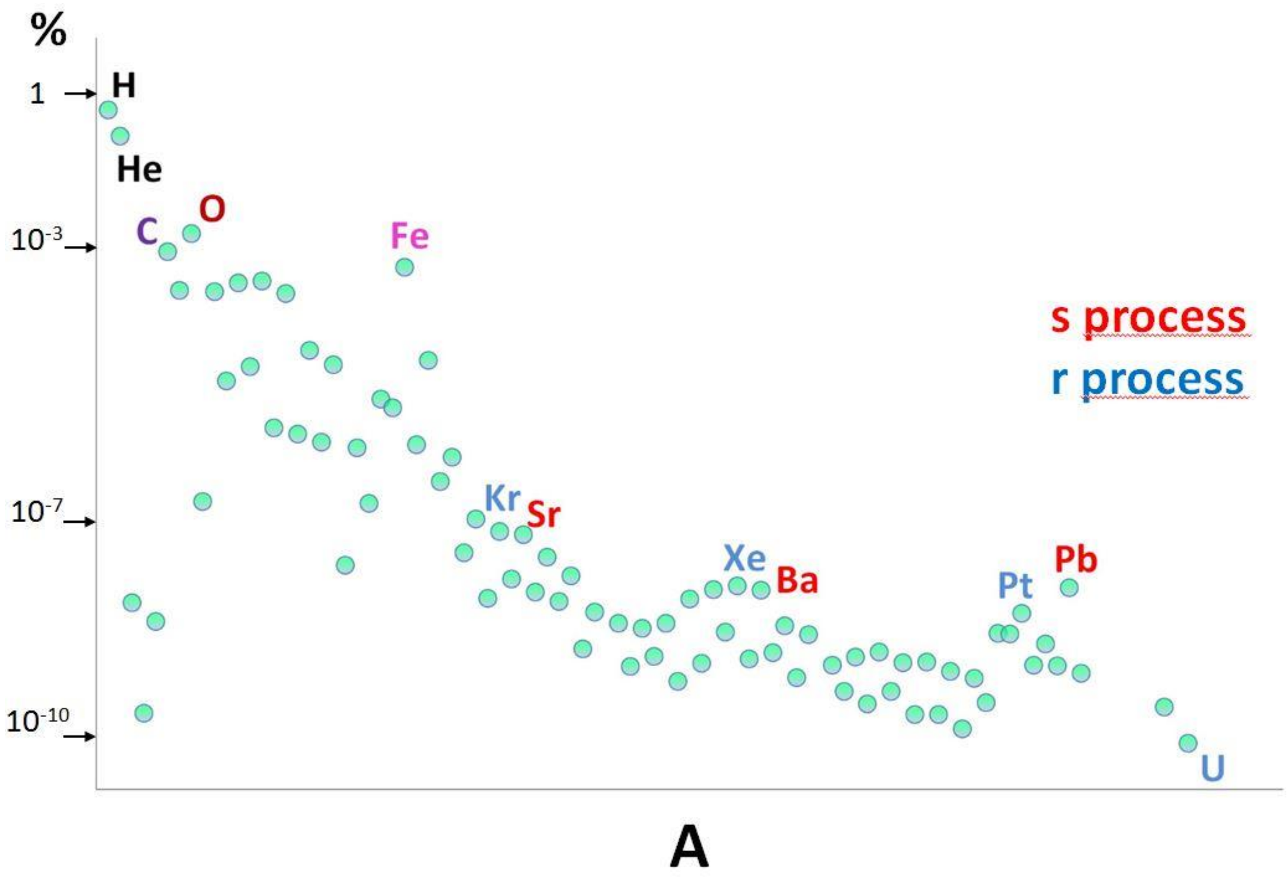


**Figure 3: THE SOLAR SURFACE CHEMICAL DISTRIBUTION**

Let's take our Sun as a reference to understand which are the most abundant elements in the Universe (in mass). In the Sun, the two lightest elements (hydrogen and helium) represent about 98% of its mass (H at 70%, He at 28%). **Figure 3** shows the distribution of the solar surface abundances (if not directly measurable, other sources have been considered). The scale of the vertical axis is logarithmic, necessary to properly visualize in a single plot abundances spanning about 10 orders of magnitude (from hydrogen to uranium, which is about 10 billion times less abundant).

Hydrogen and helium, as well as lithium, formed in the first hour of the Universe, while it was yet rapidly cooling after the Big Bang. Other elements formed in stars which evolved in the following billions of years. The only exceptions are beryllium and boron, which have been mostly created by spallation induced by cosmic rays.

# Chapter 3: The hydrogen burning

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Stars are able to synthesize all elements except hydrogen (whose production requires the extreme physical conditions of Big Bang). Before dealing with nuclear burnings, however, it is useful to introduce the concept of “plasma”. When atoms experience temperatures larger than 1 million degrees (a typical condition of stellar interiors), electrons, which orbit around nuclei in terrestrial conditions, can freely travel along the structure without being trapped by relative nuclei. The stellar gas, then, is formed by positive ions (nuclei) and negative ions (electrons). As a consequence, it is "ionized" and it becomes a “plasma”.

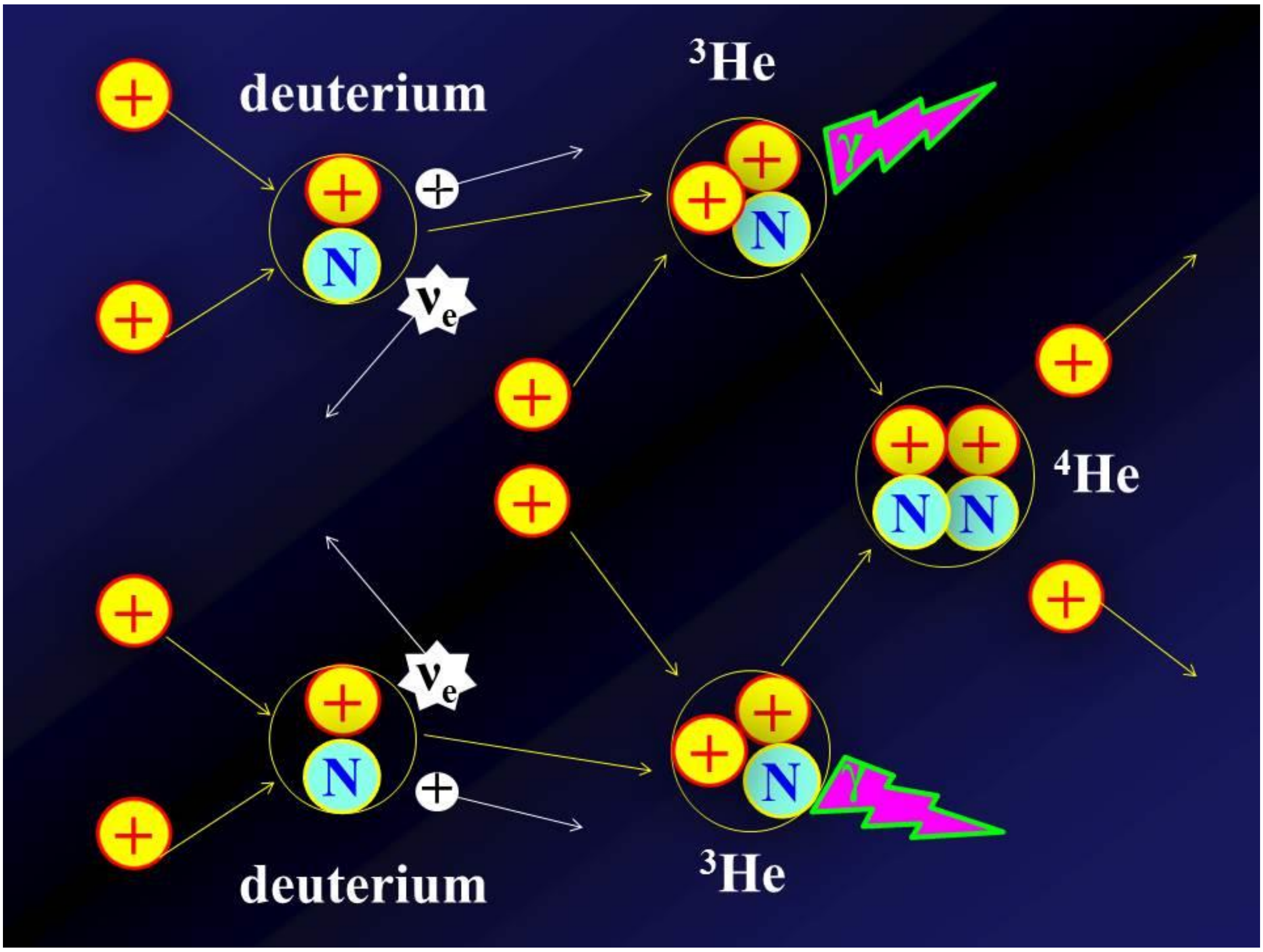


**Figure 4: SCHEME OF THE HYDROGEN BURNING**

Since the Sun is representative of the majority of stars shining in the sky, we can take it as a reference to introduce the concept of thermonuclear burning. Sir Arthur Eddington in 1920 firstly postulated that the energy produced in the solar core derives from the conversion of 4 hydrogen nuclei into 1 helium nucleus (at a pace of about 4 million tons per second). During this process other two nuclear particles form: positrons (similar to electrons, but with a positive charge) and neutrinos (those "fleeting" particles, weakly interacting with matter, are very numerous, billions of them transiting through a nail-sized surface each second).

The process regulating the conversion of H into He occurs in three separate phases (see **Figure 4**). During the first step, two hydrogen nuclei merge, producing a deuterium nucleus (formed by 1 proton and 1 neutron). Therefore, during this process one of the protons turns into a neutron: a "ß decay" occurred (a nuclear transformation governed by the weak force). Deuterium, in turn, captures a proton, forming an $^{3}$He nucleus (2 protons and 1 neutrons). Finally, two $^{3}$He nuclei interact, producing an $^{4}$He nucleus (consisting of 2 protons and 2 neutrons) and releasing two protons. The mass of an helium nucleus, however, is lower than the sum of 4 hydrogen nuclei. The mass difference is converted in energy, following the famous formula proposed by Einstein $E=mc^2$ (in a nutshell, it expresses the concept that mass and energy are nothing more than sides of the same coin).

The Sun produced such an energy in the last 4.6 billion years, with a power of 4 billion of billions of billions of Watt.

# Chapter 4: The helium burning

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The production of elements heavier than iron is definitely more complex, since there are no stable nuclei with atomic mass A=5 and A=8. Therefore, proton capture processes are not a viable solution to synthesize heavier species.

In 1951 Ernst Opik, and later in a more detailed way, Edwin Salpeter (Craaford prize in 1997), hypothesized that in Giant stars the energy counterbalancing gravity comes from the burning of 3 helium nuclei. In the Sun, this type of reactions cannot occur because the solar core is not hot enough and, as a consequence, the Coulomb repulsion prevails (i.e. two particles with the same charge push each other apart).

Helium burning occurs in two steps. During the first phase, two $\alpha$ particles (an acronym for helium nuclei) merge to form a $^{8}$Be nucleus, which in turn captures another $\alpha$ particle, producing $^{12}$C. The problem with this theory is the short $^{8}$Be lifetime, which decays back into two $\alpha$ particles in about $2x10^{-16}$ seconds (that is in about 20 millionths of millionths of second). The solution to this puzzle came in 1953 thanks to the English cosmologist Fred Hoyle (Craaford prize in 1997), who postulated the existence of a resonant energy level in the atomic structure of $^{12}$C. This state was later experimentally confirmed at Kellogg laboratories of the California Institute of Technology, from the group led by William Fowler (Nobel prize 1983). People refer to this level as the “level of life”, because the existence of carbon made possible the development of the life. The human biology, in fact, is based on the carbon cycle.

Once produced, however, $^{12}$C can capture another $\alpha$ particle, forming $^{16}$O. A new species appeared: oxygen! It would be trivial to magnify the importance of oxygen for us (just let us cite the fact that without oxygen we would not have water, being its stoichiometric formula H2O!!!). In the solar composition, oxygen is the most abundant element after hydrogen and helium (and carbon is on its heels; see **Figure 3**). Actually, it's the most abundant element in the Earth crust (see **Figure 5**): this demonstrates how much different planetary compositions are with respect to the stellar ones (and if we look to another planet, we would find further differences among planets).

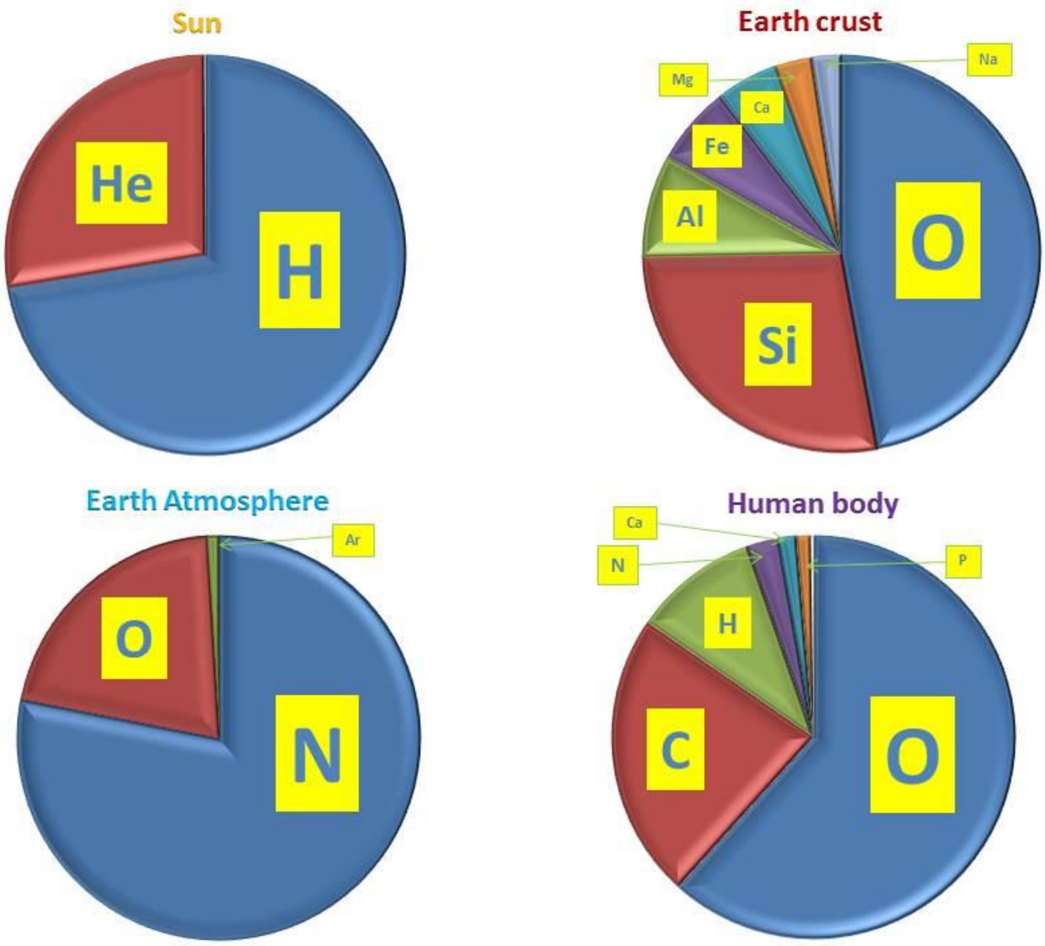


**Figure 5: COMPARISON BETWEEN CHEMICAL COMPOSITIONS**

As it is shown in **Figure 5**, the crust composition strongly differs from the atmosphere. The latter, in fact, is dominated by nitrogen. This element forms through the so-called “CNO cycle”: an alternative burning channel with respect to that occurring in Sun interiors. This process, studied in detail by Hans Bethe (Nobel prize 1967), is efficiently activated in stars slightly more massive than the Sun.

We also highlight that the chemical composition of a human body is still different, being dominated by oxygen, carbon and hydrogen (all in all we do not need that many elements to survive, even if "the devil is into details"!). It's funny to realize that our bodies last for less a century, while the atoms constituting them (some billions of billions of billions) are AT LEAST 5 billion years aged!!!

# Chapter 5: From carbon to iron

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Obviously, the cosmic nucleosynthesis does not stop at the elements previously described. In fact, in massive enough stars (at least 10 times the solar mass), the central temperature is so large to trigger a large sequence of $\alpha$ captures. As a consequence, heavier and heavier elements are synthesized: neon ($^{20}Ne$), magnesium ($^{24}Mg$), silicon ($^{28}Si$), sulfur ($^{32}S$), argon ($^{36}Ar$), calcium ($^{40}Ca$), titanium ($^{44}Ti$), chromium ($^{48}Cr$), iron ($^{52}Fe$) and, finally, nickel ($^{56}Ni$). The latter is unstable and decays to its stable isobar $^{56}Fe$ in about 70 days (passing through $^{56}Co$).

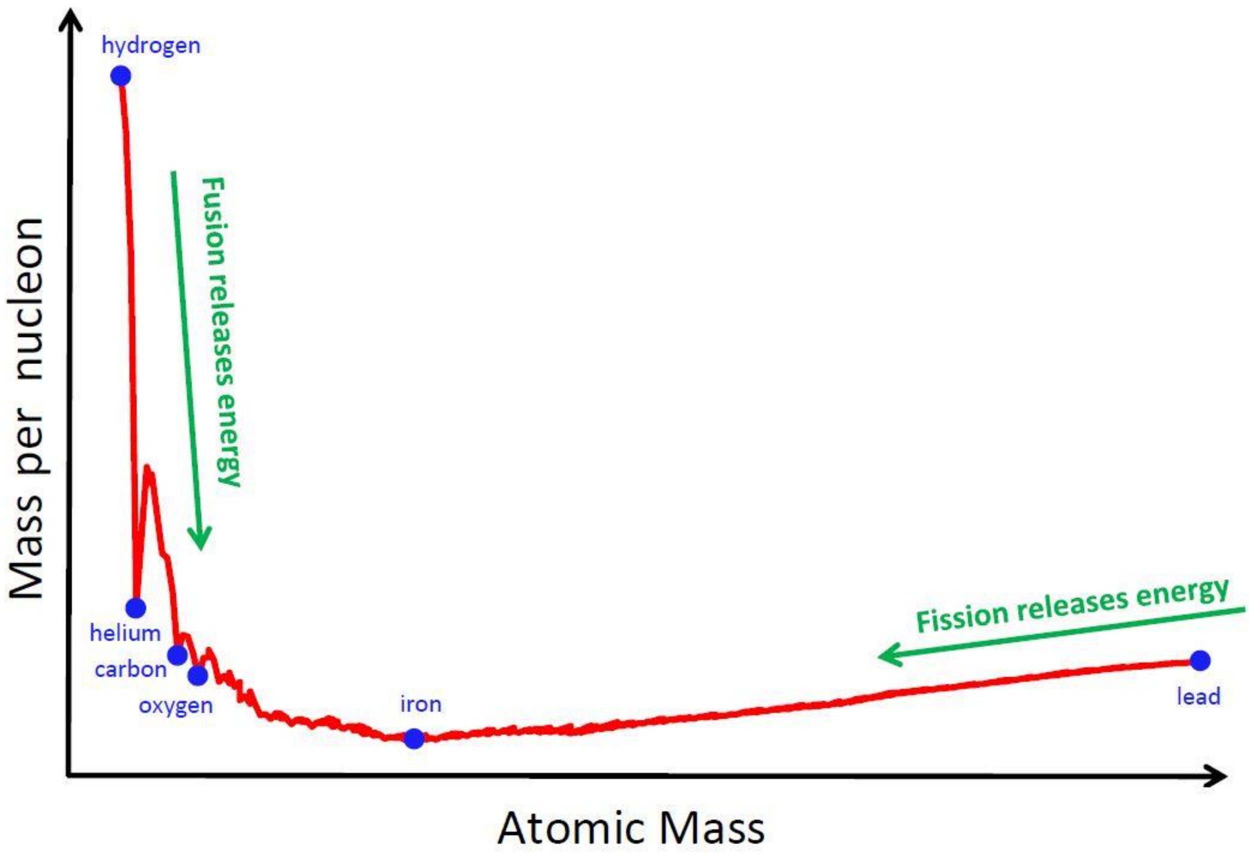


**Figure 6: THE STABILITY OF CHEMICAL ELEMENTS**

As it is shown in **Figure 6**, iron has one of the lowest mass per nucleon (in other words, it is one of the most stable nuclei, because it has a very large binding energy per nucleon). Basically, it means that the production of isotopes heavier than $^{56}Fe$ through charged particles (as those previously described) needs energy, instead of releasing it (i.e. the process becomes "endoenergetic"). Moreover, the Coulomb repulsion increases with the charge of reactants (i.e. the number of protons of the two interacting nuclei). Therefore, elements heavier than iron cannot be produced via charged particle reactions.

An alternative solution may come from nuclear fission. While in a fusion process two nuclei merge in a single larger nucleus, during the fission the contrary occurs, i.e. an heavy nucleus breaks down in smaller components, releasing energy (this process is the heart of nuclear reactors). The problem is that the fission process requires the presence of very heavy elements (the so-called Actinides), which are exactly the elements we would like to produce. Therefore, fission cannot solve our problem.

The theory described above is confirmed by the distribution of chemical elements on the solar surface (previously shown in **Figure 3**). As it can be easily noted, iron presents a peak (it is the 5$^{th}$ most abundant element in the Universe, after hydrogen, helium, oxygen and carbon).

# Chapter 6: Supernovae

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One may wonder how a massive star, which succeeded in producing iron (as well as lighter elements), could expel its internal nucleosynthesis products in the interstellar medium.

Once thermonuclear burnings end, there are no more nuclear reactions preventing the core contraction process (which occurs due to the very large gravity). When electrons in the core start being captured by protons (thus producing neutrons), the center of the star (enriched in nickel and iron) loses the electron contribution to pressure. At that point, an irreversible process begins, with the core collapsing and the overlying material falling on it with increasing momentum. When the nucleus of the star cannot be compressed any more, the overlying material literally "bounces" on it.


**Figure 7: A SCHEMATIC REPRESENTATION OF A TYPE II SUPERNOVA**

This is the origin of the "type II Supernova" (SN II) phenomenon. During this huge cosmic explosion (the light emitted by the SN II is comparable to that of the hosting galaxy), most of the material of the internal layers is lost to the interstellar medium (this process is ideally represented in **Figure 7**).

One of the most important elements produced by SN II is oxygen (we already mention it before). Moreover, there is a consistent production of magnesium, silicon, calcium and, obviously, iron (through the expulsion of $^{56}$Ni). If we check the percentages of the chemical elements in the human body, we may conclude that SN II products are enough for the development of life (at least for our limited knowledge of it). However, there are still a couple of problems.

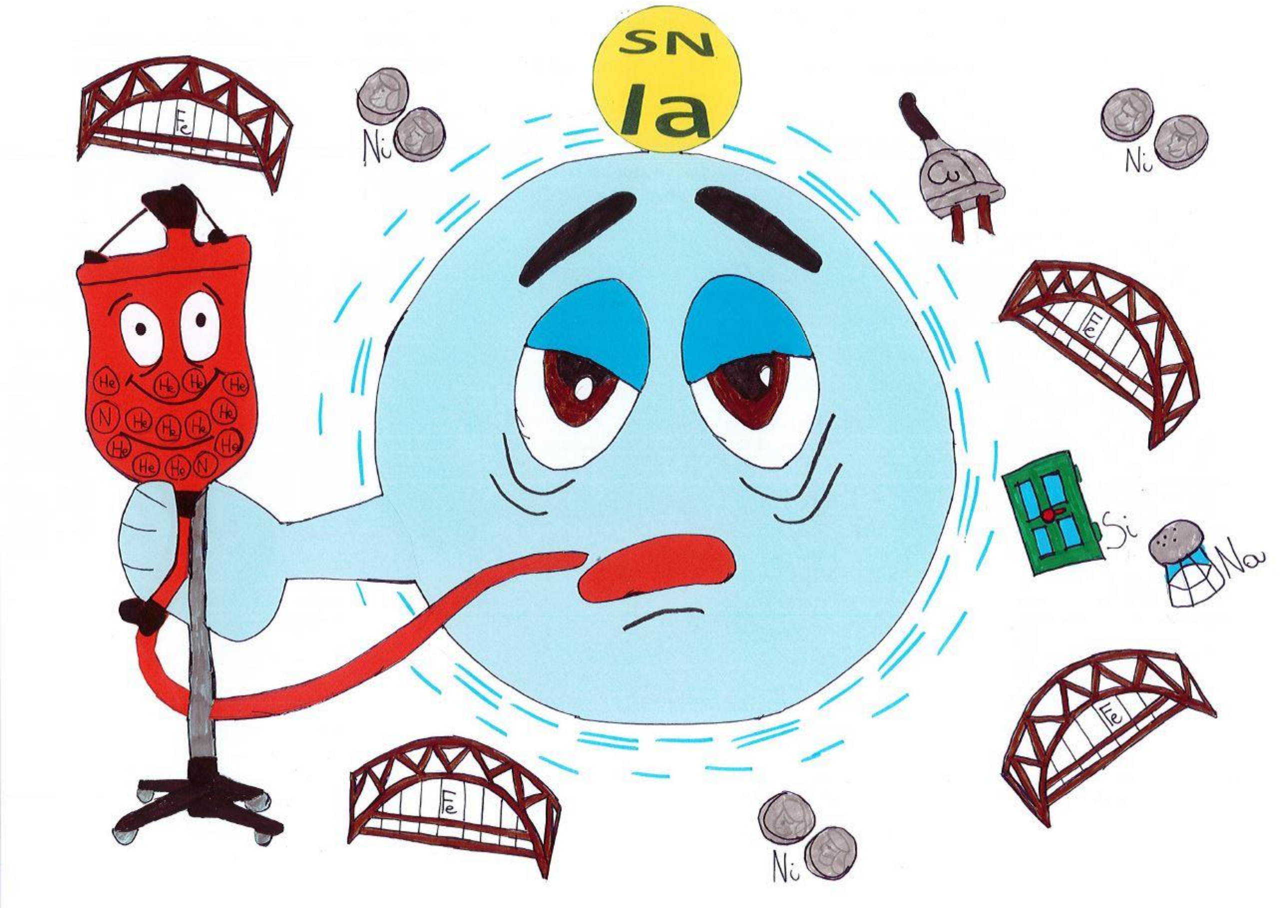


**Figure 8: A SCHEMATIC REPRESENTATION OF A TYPE Ia SUPERNOVA**

First, the iron in our Galaxy requires another production channel, being the contribution from SN II not enough to reproduce the observed trend. Such a contribution comes from "type Ia Supernovae" (SN Ia, ideally represented in **Figure 8**). Unlike SNe II, which explode when their cores collapse under the gravity force, SNe Ia require the presence of two stars belonging to a binary system (note that the majority of stars in the night sky are not single stars, but are binaries rotating around the center of mass of their system). In those systems, both stars already evolved to the White Dwarf stage and one accretes matter on the other. When the accreting star attains the physical conditions to trigger carbon (or helium) burning, a thermonuclear runaway occurs (higher temperature implies higher energy and so on) and the star explodes. Those systems are the main iron producers in the Universe. Moreover, they synthesize other elements of the iron peak, as nickel and copper (see **Figure 8**), as well as lighter elements, as silicon and calcium.

The second problem to be discussed closely affect us, since it is related to technology. As a matter of fact, if cosmic nucleosynthesis would stop at iron, we would miss a lot of chemical elements (most of them essential to modern technological systems). How could we break the deadlock? The only way is to request the intervention of a nuclear particle previously mentioned: the NEUTRON.

# Chapter 7: Neutron capture processes

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The neutron is a nuclear particle with a mass similar to the proton, without electric charge. Since neutrons do not feel the Coulomb repulsion, they are the best candidates to solve our problem. However, in stellar interiors neutrons are locked into nuclei. The nuclear force, in fact, does not allow them to spontaneously abandon the nucleus. Thus, since free neutrons rapidly decay into protons (in about 8 minutes), we need a neutron source able to maintain a neutron flux lasting across the time. Finally, in order to efficiently activate neutron capture processes, the number of available neutrons must be very high.

Stellar observed abundances can be reproduced by postulating the existence of two neutron capture processes only: the slow neutron capture process (s process) and the rapid neutron capture process (r process). Their typical neutron fluxes are 10 millions of neutrons per cubic centimeter and more than 1 billion of billions of billions of neutrons per cubic centimeter, respectively.

Nuclear theory of s and r processes is very well known since 1957, when Margareth and Geoffry Burbidge, together with William Fowler and Fred Hoyle, published an article on the Reviews of Modern Physics with the title "Synthesis of the Elements in Stars". Such an article represents, full-fledged, the Nuclear Astrophysics Bible.

In **Figure 9** we report a detail of the so-called “ß stability valley“, which maps the positions of stable isotopes along the periodic table. In the (A,Z) space, stable isotopes are placed along a roughly straight path, starting from hydrogen (which has A=Z=1) to lead (A=208 and Z=83, i.e. a nucleus with 208 nucleons, of which 83 are protons). In **Figure 9** we plot stable isotopes only, whit empty spaces representing the unstable ones (thus non-drawn isotopes also exist!).

For a fixed atomic number (Z), decay lifetimes decrease to infinitesimal values when departing from the stable isotopes region in both directions (to the left, i.e. for lower atomic masses, as well as to the right, for larger atomic masses). It is therefore straightforward to imagine the ß stability valley as a narrow canyon, with stable isotopes distributed along the valley floor and the unstable ones along the cliffs, at various heights basing on their lifetimes (the fastest the decay, the closer the position to the canyon summit).

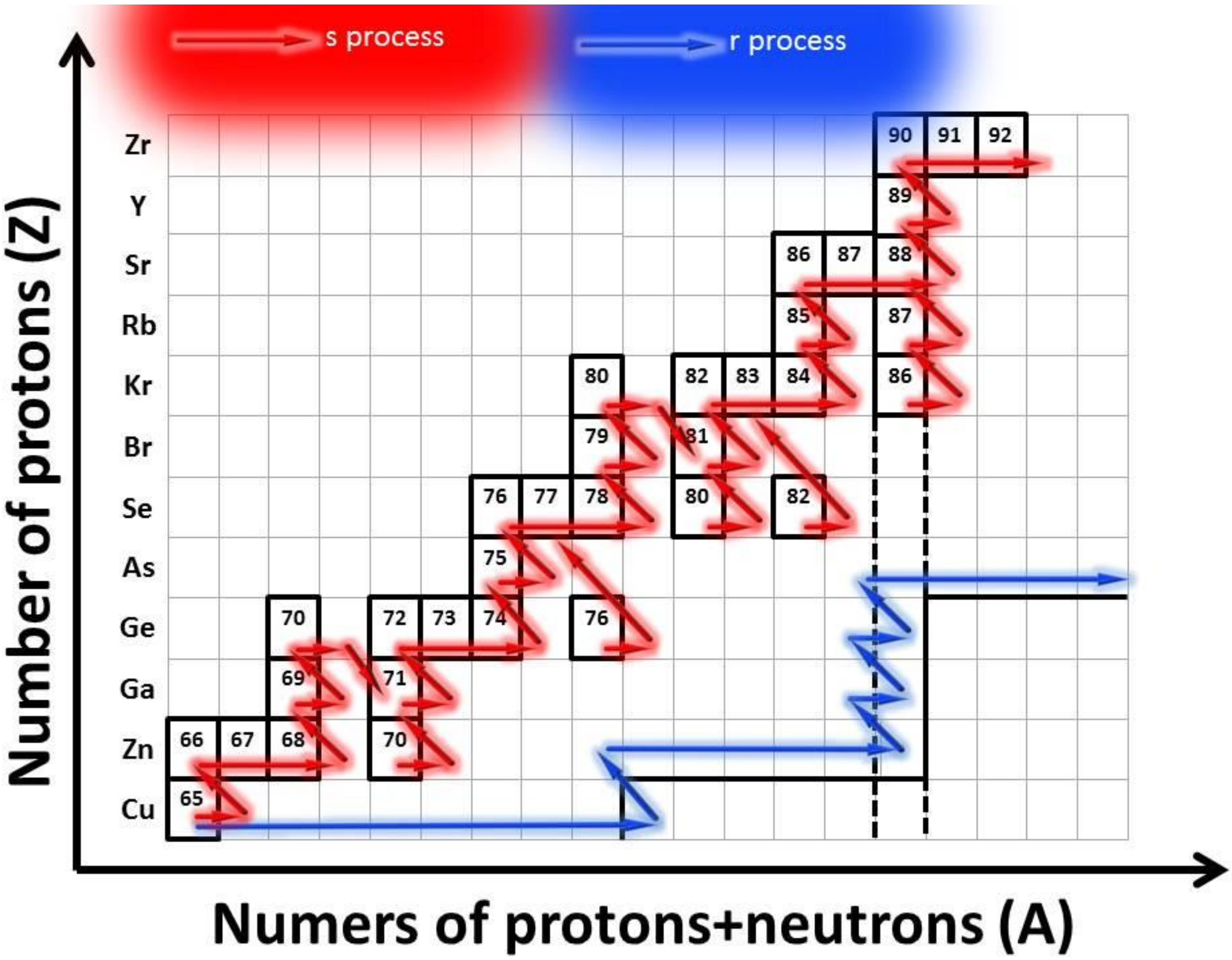


**Figure 9: THE SLOW AND RAPID NEUTRON CAPTURE PROCESSES**

The s process, represented by horizontal red arrows (each one is a neutron capture), ALWAYS occurs close to the ß stability valley. Each time an unstable nucleus is created by a neutron capture on a stable one, it has the time to decay to its stable isobar (a stable nucleus with the same atomic mass, but a different atomic number) before capturing another neutron. Those decays can be $ß^+$ (protons transform into neutrons: downward arrows) or $ß^-$ (neutrons transform into protons: upward arrows).

Along the s-process path, there exist nuclei whose nuclear structure is so particularly stable (they are named “magic” nuclei) that the corresponding elements accumulate with respect to the neighbors (red filled boxes). As a consequence, we have “peaks” in the distribution of heavy elements synthesized via the s process (at N=50, N=82 and N=126). This is illustrated in **Figure 3**, which shows how the s process is characterized by 3 prominent peaks: the first at strontium-yttrium-zirconium (Sr-Y-Zr), the second at barium-lanthanum-cerium-neodymium (Ba-La-Ce-Nd) and the third at lead (Pb). The s process is responsible for the production of half the elements heavier than iron.

The remaining half is synthesized through the rapid neutron capture process (r process). In this case, isotopes very far from the ß stability valley can be produced via a series of multiple neutron captures starting from a single stable isotope (horizontal arrows in **Figure 9**). In fact, due to the extremely large neutron flux, unstable nuclei just synthesized cannot decay and in turn are forced to capture a neutron. Such a sequence proceeds until isotopes with very short lifetimes (milliseconds) are created. In fact, due to the extremely high neutron flux, freshly synthesized nuclei cannot decay and are forced to experience multiple neutron captures. This series of neutron captures leads to the synthesis of isotopes with very short lifetimes (milliseconds). At such conditions, the ß decay may be faster than the neutron capture and the nucleus can decay, increasing its charge (upward blue arrows). In correspondence of neutron magic nuclei (see above) elements accumulate (colored blue boxes). Once the neutron flux comes to an end, those isotopes can decay to their relative stable isobars along the stability valley. In Figure 3, as a consequence, the three peaks of the r process appear: the first in correspondence of selenium-bromine-krypton (Se-Br-Kr), the second at tellurium-iodine-xenon (Te-I-Xe) and the third at iridium-platinum-gold (Ir-Pt-Au). Moreover, it's worth stressing that also long-lived terrestrial radioactive elements (as thorium and uranium) have been created by the r process.

The two neutron processes we just described are extremely different. It's amazing that all heavy chemical elements have been created in so different and unique conditions (for the sake of clarity, there are other intermediate processes, whose relevance, however, is marginal with respect to the main components s and r). There is still one aspect to be understood: WHERE do these process occur? This question kept busy nuclear astrophysicists in the last 40 years...and cause them to lay awake at night!!!

The stellar environments of in terest to us are two: low mass stars during their Asymptotic Giant Branch phase (for the s process) and neutron star binary systems (for the r process).

# Chapter 8: AGB Stars

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The Asymptotic Giant Branch (AGB) evolutionary phase is reached by stellar objects that do not have enough mass to trigger the series of thermonuclear burnings leading to iron production.

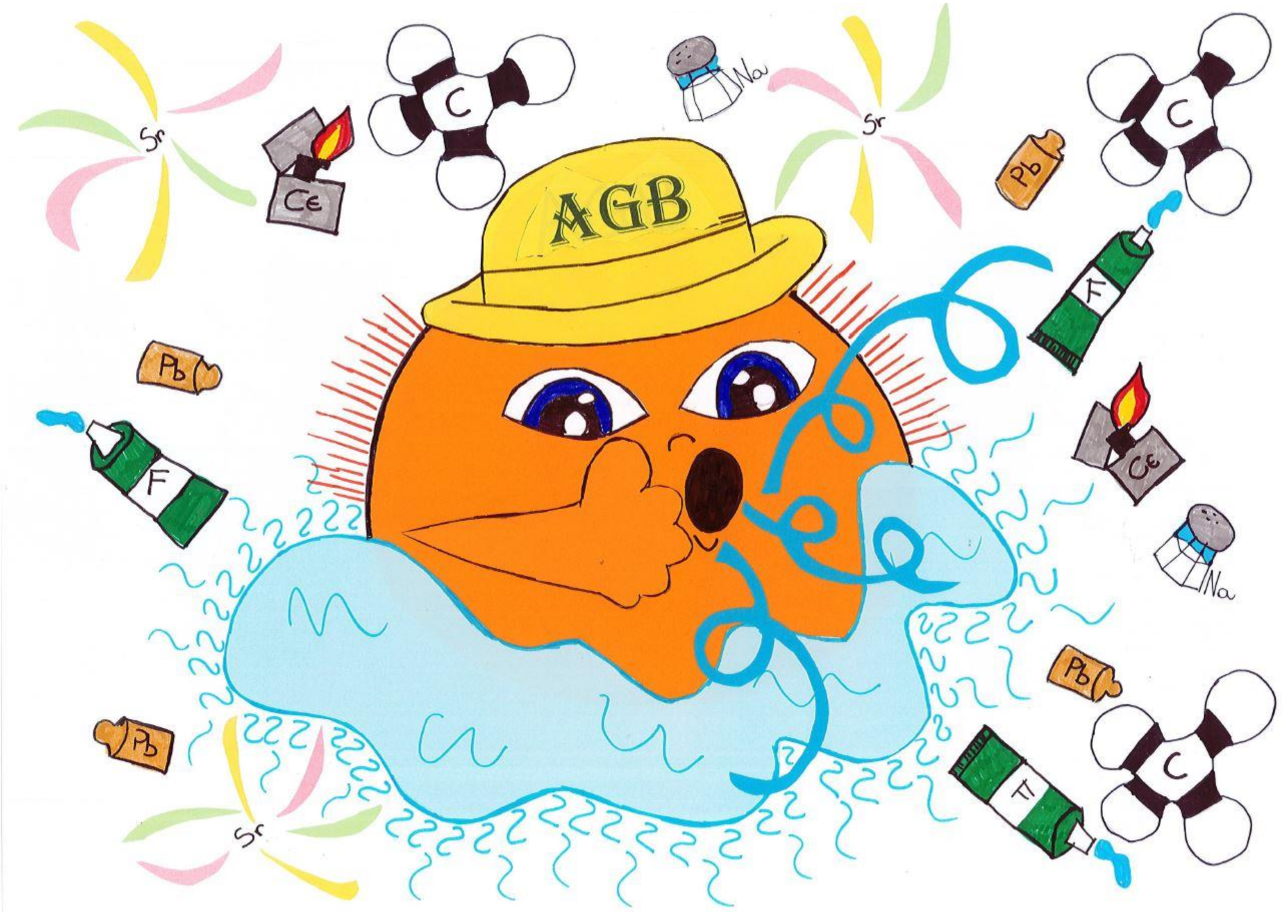


**Figure 10: A SCHEMATIC REPRESENTATION OF AN AGB STAR**

AGB stars look like enormous onions, since their structure is layered. The core, made of carbon and oxygen (the "ashes" of previous helium burning), is surrounded by a stellar shell in which helium burns and, more externally, by another thin shell in which hydrogen burns. The structure, then, is wrapped by a cool and expanded convective "envelope", whose dimensions are enormous (the stellar core it's like a nut in a 100 meters hot air balloon!!!). Those stars are extremely luminous (10000 times the Sun) and rather cool (the surface temperature is around 3000 K, to be compared with the 5500 K of the solar surface). A so low external temperature allows the formation of complex molecules, which in turn merge in larger structures, forming dust grains (some millionths of meter sized). AGB stars are the most efficient dust producers in the Universe. Those grains interact with the light from the central star and gain momentum, dragging with them the stellar gas. This process is at the origin of the mass-loss phenomenon in AGB stars, which are among the most important “chemical polluter” of interstellar medium. Many of the elements formed in their interiors, thus, is re-distributed in the space (this process is ideally represented in **Figure 10**).

One of the most important product of AGB stars is carbon: the majority of the carbon in the Universe is thought to come from these stellar objects. Besides carbon, those stars produce many other light elements, as nitrogen (the main component of Earth atmosphere), fluorine (an essential ingredient of toothpaste) or sodium (can you imagine to live without salt?). Not to mention heavy elements: without those stars we would not have lead, an element used by humans since more than 3000 years, or less known elements as strontium (without which kids could not appreciate a night fireworks show).

# Chapter 9: Neutron star binary systems

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A neutron star is the remnant of a massive star (at least 10 times more than our Sun), once thermonuclear burnings leading to iron production extinguished. The mass of a neutron star is about 2-3 times larger than the mass of the Sun. If it would be even larger, the structure would collapse forming a black hole (note that large part of the initial mass has been lost during previous evolutionary phases).


**Figure 11: A SCHEMATIC REPRESENTATION OF A NEUTRON STAR MERGER**

In a neutron star the density is awfully high (a cubic centimeter weights about 200 million tons: on the Earth this would amount to a marble cube 400 meters sized!!!). The extreme physical conditions of this system (in particular the gravity, 100 billion times the Earth gravity) ensure that its interior is full of neutrons (this composition does not characterize other stars or previous evolutionary phases). It's therefore natural guessing that a rich nucleosynthesis develops in these stars. However, the large density does not allow the production of new chemical elements (the structure is basically "frozen"). The situation is completely different if there are two neutron stars, i.e. when we are dealing with a neutron star binary system. In this situation, the two stars rapidly rotate closer and closer until they come into contact and merge (Neutron Stars Merger, NSM, ideally represented in **Figure 11**). At that point, a huge cosmic explosion develops (to put it simply, actually thing are a little bit more complex). As a by-product of the merging, gravitational waves are generated (they have been postulated by Albert Einstein about 100 years ago).

August the 17$^{th}$ 2017, the VIRGO and LIGO interferometers observed gravitational waves generated by a NSM, one thousand of billions of billions of kilometers far from us (the light produced by that merging travelled for 130 million years to arrive here... this means that the event occurred when the dinosaurs were still alive on the Earth, in the Cretaceous period).

In the days after the detection of gravitational waves from GW180817 (this is the name assigned to the source), basically all telescopes on the world pointed toward it. The reason is simple: observe an increase of the light curve after 4-5 days from the stellar merging (see e.g. the web pages of the Italian INAF GRAWITA collaboration; https://www.grawita.inaf.it/). Such an increase of the luminosity (indeed observed) is the smoking gun that, during the NSM, an enormous amount of heavy elements were formed through the r process. The presence of those metals (in particular the lanthanides), in fact, ensures that the structure is warmed up by their decay (during this process a lot of light is produced, which interacts with the stellar gas, heating it).

Actually, the r process nucleosynthesis is more complex, because the high neutron flux leads to the production of Actinides. Those isotopes have very small lifetimes, because they fissionate spontaneously (or as a result of a neutron capture), that is they break in two lighter nuclei, producing new neutrons. The "pieces" of a recently fissionated actinide, however, may in turn capture neutrons. A cyclical process then sets up, named “fission recycling”. Such a process determines the fact that r process nucleosynthesis (in particular the heaviest isotopes) is almost independent on the physical conditions of the merger.

NSMs produce a plethora of chemical elements (see **Figure 11**). Some of these elements are known (and are very precious, as gold or silver), while others are completely unknown and have almost unpronounceable names. Without them, however, modern technology would not have developed: for instance, we could mention europium (essential to create colors in modern televisions) or erbium (without which we would not have fast optic fibers). And what about modern cellphones...???

## Chapter 10: Elements, stars and a modern cellphone

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Cellphones are probably the most symbolic case of the chemistry complexity (and its stellar origin) in our society: to construct one of them, in fact, more than 50 different chemical elements are needed (as shown in **Figure 12**).

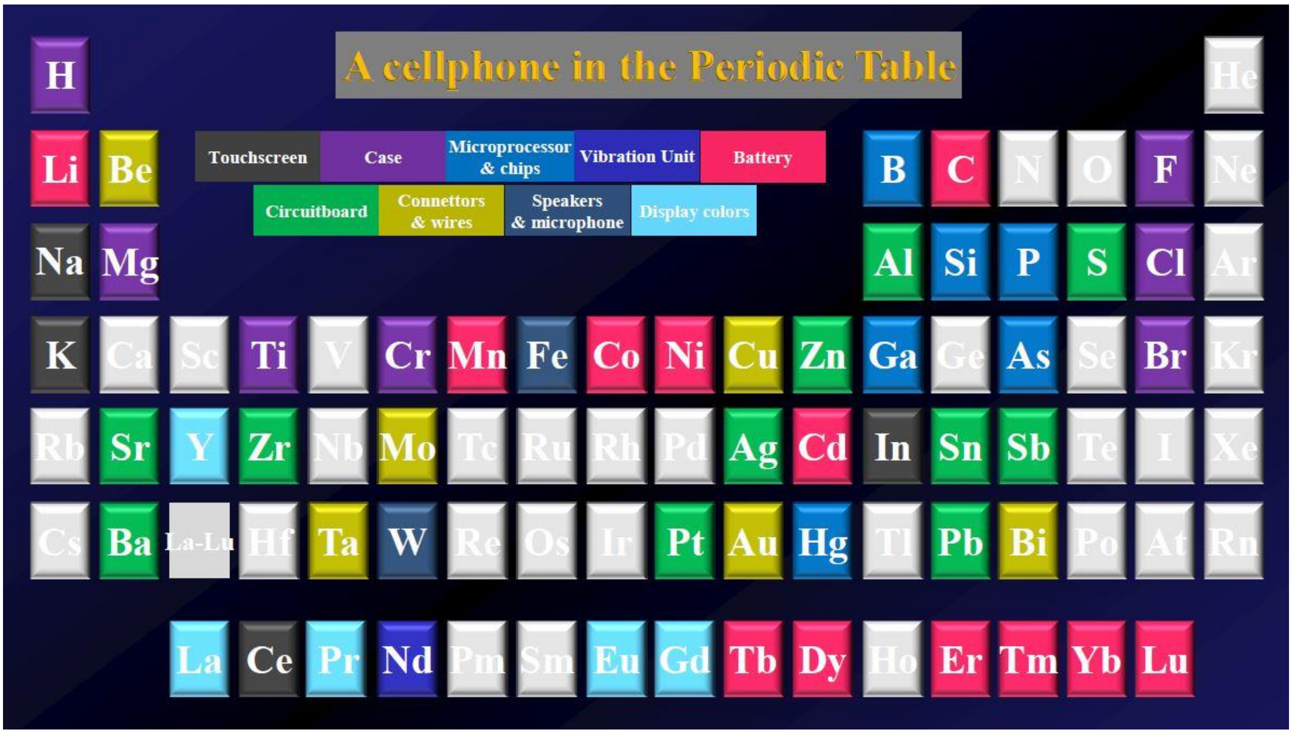


**Figure 12: ELEMENTI CHIMICI PRESENTI IN UN CELLULARE**

It's amazing to realize that a single cellphone requires the presence of chemical elements synthesized in each of the stellar classes previously described.

As a matter of fact, NSMs produced elements essential for the touchscreen (indium and tin, which help to conduct electricity), for the implementation of display colors (europium and gadolinium), for the proper functioning of batteries (dysprosium, erbium, ytterbium and thulium), for the circuit-board (silver and platinum) and, finally, for the construction of connector and wires (gold and tantalum).

AGB stars are equally important, considering their contribute to the circuit-board (strontium, barium and lead), as well as to some display colors (lanthanum and praseodymium), without forgetting the neodymium of the vibration unit.

Finally, there are the elements coming from Supernovae, without which we could not construct the case (magnesium, titanium and chromium), wires (copper) as well as all components containing iron.

Therefore, we can safely conclude that we are not just biological SONS OF THE STARS, but without them we could neither do trivial things in our daily life, as using a computer, switching on a TV or doing a simple phone call!

**If you have questions and/or curiosities don't hesitate to contact me at: sergio.cristallo@inaf.it**

A particular word of thanks to professor Sebastiano (for the critic revision of the contents done from above ...or from below...his 10 years) and to my estimated colleague Luciano. I would like to also thank Egizia, for her marvelous drawings, and my two babies Sabrina and Sarastella, for the moral support!