Revista Brasileira de Ensino de Física, vol. 42, e20200160 (2020)
www.scielo.br/rbef
DOI: https://doi.org/10.1590/1806-9126-RBEF-2020-0160

Interdisciplinary study of the synthesis of the origin of the chemical elements and their role in the formation and structure of the Earth

K.A. Horvath*[1], P.S. Bretones[2], J.E. Horvath[3]

[1]Instituto Nacional de Pesquisas Espaciais, Divisão de Geofísica Espacial, São José dos Campos, SP, Brasil.
[2]Universidade Federal de São Carlos, São Carlos, Departamento de Metodologia de Ensino, SP, Brasil.
[3]Universidade de São Paulo, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, São Paulo SP, Brasil.

Received on April 27, 2020. Revised on July 07, 2020. Accepted on July 09, 2020.

We discuss in this work the issue of chemical element origin in the stars and the Big Bang, with the aim of linking the subject smoothly with the formation of the Solar System and the structure of the Earth in an updated and pedagogical fashion. A few cases in which these subjects are present but disjoint in different degrees are shown, and a suggestion for its introduction in a set of classes made, as well as issues in Teacher's Education and existing Curricula revisited. The goal is to break the boundaries of separated presentation and to emphasize the unity and coherence of sciences.
Keywords: Interdisciplinarity, Teacher formation, School curricula.

1. Introduction: Why Consider an Interdisciplinary Perspective for this Problem?

The separation of disciplines in science, now consolidated into well-known cases (Physics, Chemistry, Biology and so on) is a process that started with intensity in the 19th century[1]. All the classical antiquity and several centuries following considered the study of nature in a broader sense, and many thinkers contributed to the human knowledge from what would be today consider, ”different disciplines”, at that time quite related and unified. While it is clear that specialization favored a deeper understanding of a myriad of problems, it also created disjoint fields and precluded a wider vision of sciences. The effects on contemporary education are very visible, there is an utter fragmentation of the vision of the students, quenching a synthetic view of the world that does not encourage a flexible and efficient understanding, but rather a boxy appreciation of the problems.

Given the crescent complexity and difficulty of the world in which we live, many efforts have been put to redesign and update the school curricula, trying to regain that broader vision of scientific problems and understand its origin, connections and future possibilities. We believe that this is an important path forward and should be encouraged. The unity of all sciences, lost somewhere in the 19th-20th century can be regained and strengthened by taking concrete actions in this direction. An interface called *Astrochemistry* has been addressed for many years, involving a large number of phenomena related to space molecules and many other problems. When we come to the very origin of the Periodic Table, this denomination seems short: the synthesis of elements inside stars (termed ”stellar alchemy”) is adequate, but still insufficient. The cosmological aspects and, later on, geophysical issues call for a more general denomination. We suggest to use for this merge the name *Cosmogeochemistry*, a composed name designed to indicate the links between the cosmic origins of the chemical elements, the issue of the formation of the Earth and planets and the occurrence of chemical elements that stem from these complex and ample set of physical processes. By its very nature, this is a prime example of integration of disjoint subjects into a single, unifying thread. Its presentation and discussion would be an important benchmark against the excessive separation of knowledge in the schools, paving a general path towards the unity of sciences, as intended. As a very timely fact, a strong defense of an integrated curriculum in sciences has been recently published [2], which has a large overlap with our own views.

*Correspondence email address:: kaahorvath@gmail.com.

2. Interdisciplinarity and Contents in Science Teacher Education

When we refer to certain contents or areas of knowledge as studied by the various sciences, such subjects are traditionally (for historical reasons and/or the structure of each area) linked to specific disciplines.

For example, regarding Astrophysics, its contents span from cosmological themes with studies about the origin of the Universe and how the elements were created from the evolution of the stars, to the characteristics of the celestial bodies, their compositions, movements, etc. Regarding Geology, its contents are related to the evolution of our planet from its origin to its current state. And when we deal whith specific Chemistry contents, we find the structure of matter, the composition of substances, reactions and chemical bonds as the main subjects.

Such areas are structured according to the tradition or the way in which each one makes advances in research according to content blocks.

However, if we consider a sequence of contents starting from the very origin of the matter in the early Universe, followed by the origin of the elements inside the stars and their consequences for the origin of our Solar System, to the formation of the Earth to the current structure and composition of our planet, these subjects or content blocks are *not* addressed in initial teacher training. We can consider teachers with training in Astronomy, Geology or Chemistry. For each of these undergraduate courses, such content is not covered extensively, and their didactical, multiple aspects in classrooms at the most diverse school levels are seldom present.

Taking into account the fragmented reality of such contents in undergraduate courses, it can be imagined that the interaction between them can generate a quite distinct area(s) and, in this sense, we can call these products *interdisciplinary*. In Figure 1, for example, "Medicine" becomes interdisciplinary when granting a defined purpose to the empirical field represented by biology, chemistry and psychology" [3] and considered as purposive or pragmatic.

Thus, in the same way, we can consider *Cosmogeochemistry* as the union (more precisely, the merging) between Cosmology, Astrophysics, Geology and Chemistry.

Another important aspect is the presence or absence of certain contents in the school curriculum. As an example, we know that some contents are not covered at all in the curricula of several countries. Examples of this are Astrophysics or Cosmology contents, or if we look at Chemistry curricula or even Geosciences contents in Science curricula, we rarely find items about the origin of the elements existing on Earth. Therefore, much of what is worked on in schools and in the classroom depends on how curricula are presented in various countries and, particularly, in official public school curriculum programs. In addition, teaching materials available for teachers to work with, such as textbooks, and even teaching methodologies referring to the various contents need to be considered. All of this also goes through many aspects that occur in the reality of teaching, anywhere in the world.

As stated by Shulman [4],

> How might we think about the knowledge that grows in the minds of teachers, with special emphasis on content? I suggest we distinguish among three categories of content knowledge: (a) subject matter content knowledge, (b) pedagogical content knowledge, and (c) curricular knowledge. (Ref. [4], p. 9)

Taking Cosmogeochemistry as an example, it is reasonable to state that teachers are rarely trained comprehensively in content knowledge of their field, be it Chemistry, Astronomy or Geology, even less in more than one field for that matter.

However, the Cosmogeochemistry approach cannot be thought as an interdisciplinary area that requires the mandatory collaboration of teachers from various disciplines in classroom activities. Such efforts are important and very relevant, but in practice, create difficulties. For this reason, it is important to promote the approach of such contents with what is already found in teacher training programs.

The interdisciplinary approach creates a need to close gaps in content knowledge, and calls for initial and continuing training of teachers.Another step is addressing teaching methodologies and presence in the curricula to deal with the issues of pedagogical content knowledge and curricular knowledge, respectively.

With regard to the curriculum of undergraduate courses, as well as different levels of education in schools, in a very simple way, we may ask: can we promote discussions about how there are some substances on our planet? How did they originate? Why do some elements exist in large or small percentages?

The understanding of such contents leads to reflections by teachers and students about the origins and evolution of substances. This not only leads to thinking about our position and role in the Universe, but also to the aim of taking care of our planet from the point of view of sustainability and preserving the world in which we live in.

3. Cosmogeochemistry in Present School Curricula

As it stands, our main goal will be to provide a roadmap towards the discussion of Cosmogeochemistry in schools. A preliminary inspection shows that the contents about the origin of the elements are introduced in very few curricula in most of the countries. Moreover, this subject is not even mentioned, even less its important link and consequences for the origin of the Solar System and the development of Earth's structure and composition.

Disciplines such as Sciences or Chemistry do describe the Earth´s features, but even when the origin and occurrence of the elements or substances and the composition of the Earth's surface, atmosphere etc. are presented, there is no relation with the origin of the elements and its early chemical/geological evolution. The "cosmic" connection is simply not present in general.

3.1. USA curriculum

As definite examples, the USA Curriculum, the *Next Generation Science Standards*, has the HS-ESS1-3 Earth's Place in the Universe, Communicate scientific ideas about the way stars, over their life cycle, produce elements. Emphasis is on the way nucleosynthesis, and therefore the different elements created, varies as a function of the mass of a star and the stage of its lifetime, although details of the many different nucleosynthesis pathways for stars of differing masses are not assessed [5].

Other related items are

HS-ESS1-1, develop a model based on evidence to illustrate the life span of the Sun and the role of nuclear fusion in the Sun's core to release energy that eventually reaches Earth in the form of radiation, emphasizing energy transfer mechanisms from the Sun's core to the Earth and observations of masses and lifetimes of other stars.

HS-ESS1-2,construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe, with emphasis on the astronomical evidence of the red shift of light from galaxies as an indication that the Universe is currently expanding, the cosmic microwave background as the remnant radiation from the Big Bang, and the observed composition of ordinary matter of the universe, primarily found in stars and interstellar gases (from the spectra of electromagnetic radiation from stars), which matches that predicted by the Big Bang theory (3/4 hydrogen and 1/4 helium).

HS-ESS1-5, evaluate evidence of the past and current movements of continental and oceanic crust and the theory of plate tectonics to explain the ages of crustal rocks.

HS-ESS1-6, apply scientific reasoning and evidence from ancient Earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history, with emphasis on using available evidence within the Solar System to reconstruct the early history of Earth, which formed along with the rest of the solar system 4.6 billion years ago. Examples of evidence include the absolute ages of ancient materials (obtained by radiometric dating of meteorites, moon rocks, and Earth's oldest minerals), the sizes and compositions of Solar System objects, and the impact crater record of planetary surfaces.

3.2. Australia curriculum

Regarding Australia [6], there is no mention of origin of elements (nucleosynthesis), in the national curriculum, although in the Earth and Environmental Science (years 11 and 12), we find

Unit 1: Introduction to Earth systems

Understanding the interior of Earth: as technology has not yet developed to enable direct study of Earth below a depth of about 10 km, science relies on secondary sources of data to develop models of the interior based on inference. This includes studying the propagation of seismic waves, using gravity maps developed via satellite technology, studying the composition of material ejected from volcanic eruptions and meteorites, analyzing the density of rocks, and studying Earth's magnetic field (ACSES009). The development of supercomputing has enabled the design of complex models of Earth's interior, demonstrating, for example, the way in which changes in the dynamics of the inner and outer core cause changes in Earth's magnetic field (ACSES010).

Observation of present day processes can be used to infer past events and processes by applying the Principle of Uniformitarianism (ACSES015), that is, stating and assuming that the same geological processes which shaped the Earth are still active steadily over billions of years.

A relative geological time scale can be constructed using stratigraphic principles including superposition, cross cutting relationships, inclusions and correlation (ACSES016).

Precise dates can be assigned to points on the relative geological time scale using data derived from the decay of radioisotopes in rocks and minerals; this establishes an absolute time scale and places the age of the Earth at 4.5 billion years (ACSES017).

It is known that Earth has internally differentiated into a layered structure: a (solid) metallic inner core, a (liquid) metallic outer core and a silicate mantle and crust; the study of seismic waves and meteorites provides evidence for this structure (ACSES018), at least as a general feature.

Rocks are composed of characteristic assemblages of mineral crystals or grains that are formed through igneous, sedimentary and metamorphic processes, as part of the rock cycle (ACSES019).

Soil formation requires interaction between atmospheric, geologic, hydrologic and biotic processes; soil is composed of rock and mineral particles, organic material, water, gases and living organisms (ACSES020).

Also, the learning outcomes of these subjects are described as:

Understand the key features of Earth systems, how they are interrelated, and their collective 4.5 billion year history understand scientific models and evidence for

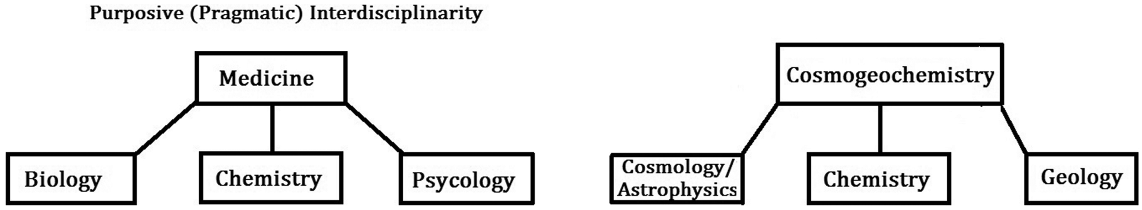


Figure 1: An analogy between Medicine as an Interdisciplinary subject and *Cosmogeochemistry* as presented in our work (adapted from Max-Neef [3]).

the structure and development of the solid Earth, the hydrosphere, the atmosphere and the biosphere understand how theories and models have developed based on evidence from multiple disciplines; and the uses and limitations of Earth and environmental science knowledge in a range of contexts use science inquiry skills to collect, analyze and communicate primary and secondary data on Earth and environmental phenomena; and use these as analogues to deduce and analyze events that occurred in the past evaluate, with reference to empirical evidence, claims about the structure, interactions and evolution of Earth systems communicate Earth and environmental understanding using qualitative and quantitative representations in appropriate modes and genres.

It is also worth noting that in some states additional material is included, for example, in the Victoria State Curriculum (Year 11), it is suggested to develop

Origin of atoms: describe the Big Bang as a currently held theory that explains the origins of the Universe. Describe the origins of both time and space with reference to the Big Bang Theory. Explain the changing Universe over time due to expansion and cooling. Apply scientific notation to quantify and compare the large ranges of magnitudes of time, distance, temperature and mass considered when investigating the Universe. Explain the change of matter in the stages of the development of the Universe including inflation, elementary particle formation, annihilation of anti-matter and matter, commencement of nuclear fusion, cessation of fusion and the formation of atoms.

3.3. Brazil curriculum

The Brazilian Curriculum does not have a large set of contents about the origin of the elements, the consequences in the origin of the Solar System and the development of Earth's structure and composition have been only scarcely mentioned in the Brazilian Curriculum. For example, the *Parâmetros Curriculares Nacionais* (National Curricular Standards), PCNs for Natural Sciences (5th to 8th grade) [7] state that phenomena like black holes, quasars, neutron stars, red giants, white dwarfs and others involving evolution of the stars and the Universe itself can be addressed in paradidactic-oriented lectures. A good starting point for these investigations by students is "how did all begin", which may originate a poster exposition or other activities at the end of this cycle.

It is also explicit that "the origin of planet Earth and its evolution will be investigated within the thematic bundle "Life and Ambient", using bibliographical sources".

The PCN for High School Level, in Chemistry [8] contains only a brief mention on the occurrence of the elements (in a critical tone) as

"Periodic properties (electronegativity, atomic radius, ionization potential etc.) are emphasized leaving aside significant contents, like the natural abundances, preparation methods, properties, applications and links between these subjects"

An attempt to improve this scarcity of contents was performed in 2017, the Brazilian Curriculum have changed and the *Base Nacional Comum Curricular* (Common Base National Curriculum), the BNCC eventually published [9] as a general guidance. Within Natural Sciences, from Elementary to Middle School this document has suggested, for instance, 9th Grade:

(EF09CI14) Composition, structure and location of the Solar System in the Universe: Description of the composition and structure of the Solar System (Sun, rocky planets, giant gas planets and minor bodies), as well as the localization of the Solar System in our galaxy (the Milky Way) and the position of the latter in the Universe (just one galaxy among billions).

(EF09CI15) Relate different visions of the sky and explanations about the origin of the Earth, the Sun and the Solar System linked to the needs of different cultural groups (agriculture, hunting, myths, spatial and temporal orientation, etc.).

(EF09CI16) Selected arguments about the viability of human survival outside the Earth, based on the necessary conditions for life, planetary features, distances and times involved in interplanetary and interstellar travel.

(EF09CI17) Stellar Evolution. Analyze the life cycle of the Sun (birth, life and death) based on the knowledge of stellar evolution for other stars and their possible effects of this cycle on our planet.

Finally, São Paulo State students at the last High School grade [10] are exposed to a discussion about the atmosphere, hydrosphere and biosphere as sources of materials and resources for the use of human beings.

Therefore, as we can see, there is no development or programs to explain or discuss the origin of the Solar System and the chemical elements and the later development of Earth's structure and composition, even less in an integrated fashion. The contents are insufficient and scattered over the years and disciplines. We suspect that this situation is similar to many other cases not addressed by us.

There are many other national cases that could be examined, but these examples show that in the cited Curricula, the origin of the atoms and the elements and also the Earth's composition, the solid Earth, the hydrosphere, the atmosphere and the biosphere, are individually addressed. However,the consequences of the origin of the Solar System on the development of Earth's structure and composition to reach the present state are not often considered. There seems to be a bridge to be constructed to harmonize and unify the whole subject. In fact the whole subject is a mosaic without apparent connection in the analyzed Curricula.

We shall discuss below a content step-by-step construction of such a connection, suitable for the introduction of the subject in the classroom. Our aim is to provide a tool to encourage the integrated view of the chemistry origin and evolution in a qualitative fashion, emphasizing the physical processes that led to the current situation from the early Universe until today.

4. A Preliminary Issue: Nuclear Fusion and Nucleosynthesis in a Nutshell

The basic elements of stellar and Big Bang nucleosynthesis have been discussed, under several points of views, in a few works. For instance, the work of Norman [11] focused on the stellar case and the recent paper by Gichuhi [12] concentrated on the "thresholds" specific of chemical concepts. A general framework starting from gravitation, energy and other fundamental concepts has been presented by Glickstein [13] as preliminary steps towards the comprehension of nucleosynthesis, and remains a useful tool to start this discussion.

We shall repeat here the fundamental facts and concepts of nuclear reactions for completeness. Many, if not all, school curricula indicate the nuclear energy source of the Sun and stars as a compelling subject, to be followed by energy transport across the solar interior and eventual radiation to the space, reaching the Earth and allowing life on our planet. For this purpose, and with the aim of providing a basis for the Big Bang and stellar nucleosynthesis, we present a briefing of the nuclear fusion in general as a starting point (see, for instance, Ref. [14]).

Nuclei are bound structures. They do not dismantle easily, as is obviously deduced from the general stability of matter (including ourselves), with a few exceptions. Two nuclei can give origin to a third one if attractive nuclear forces *bind* them together, which will happen provided the original nuclei can be very close. As a necessary result, energy corresponding to this binding must be *expelled* from the nucleus to the ambient. An analogy can be made using a well-known example: two massive point-like particles bound by gravitation. If m_1 and m_2 are the masses of the particles when they are free, the mass of the bound state will be

$$M = m_1 + m_2 - \frac{Gm_1m_2}{rc^2} < m_1 + m_2 \qquad (1)$$

that is, the binding energy is *negative* (the product of fusion has a lower mass, or higher binding energy, than the progenitors, (Figure 2), and this means that an equal amount of positive energy has to be expelled to the environment for the binding to happen. Changing the "gravitational" for "nuclear" forces (which do not have a simple mathematical expression), this is essentially what happens in a nuclear fusion. The question is now: provided each nuclei has a positive electrical charge, and therefore repel each other, in which conditions and how many fusions will happen as a self-sustained process?. These questions are motivated by the assertion that the Sun and stars maintain their structure for billions of years using the fusion as a "fuel", therefore a certain substantial number of fusions per second must happen to increase the internal pressure that resists the gravity.

The study of nuclear reactions was a big research topic in the 20th century, and even if details of very complicated reactions are still under scrutiny, the basics of the two-body fusion (hydrogen-hydrogen in the Sun, but also heavier cases along stellar evolution) are well understood. The particles that approach have to overcome the Coulomb electrostatic repulsion (both are charged) to fall inside the attractive part of the nuclear potential and fuse (Figure 2). Their kinetic energies are typically of the order of k_BT, with T the temperature of the environment. It can be checked, however, that the only nuclei that have a chance to approach to short distances must be very energetic, much beyond the typical energy k_BT. This means that a very small number of collisions of the total can lead to a fusion. Even worse, we shall see another big obstacle that is present for the fusion of hydrogen later on. For the moment, this is all what we need.

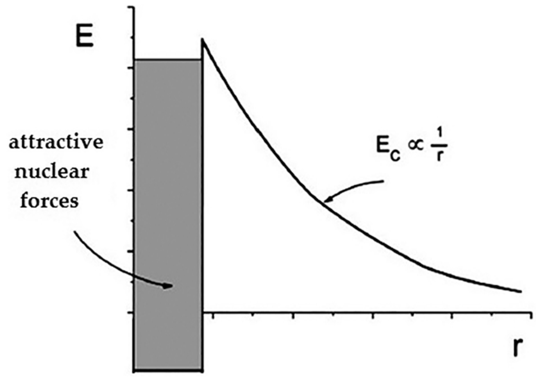


Figure 2: The effective potential between two approaching charged particles. Classically, the kinetic energy must be enough for the pair to overcome the Coulomb repulsion and reach the grey region, where attractive forces will produce the fusion. Since this has to happen from the top of the potential, the classical kinetic energies are not enough. Here is when nuclear fusion receives a "help" from Quantum Mechanics: unlike the classical case, the particles can indeed cross the Coulomb potential by means of the *tunnel effect*, a feature that makes possible to fall into the grey region and fuse with energies *lower* than the ones required in a classical analysis.

The calculation of such a rate is well beyond the scope of the present text, but as a general result the rate of energy generation per gram of fusing material can be expressed as

$$\epsilon_{12} = \epsilon_0 X_1 X_2 \rho^{\alpha} T^{\beta} \qquad (2)$$

whereϵ_0 is a numerical coefficient, X_1, X_2 are the fractional abundance of the nuclei which enter the reaction, ρ is the density and T the temperature of the environment. The exact exponents $\alpha$and β are very dependent on the type of fusion, for example, $\beta \approx 4$ for the whole cycle of hydrogen fusion in the Sun (the so-called *pp chain*) and $\beta \approx 16$ for another hydrogen fusion mode called the *CNO* (a catalytic cycle). Because of this difference, stars slightly more massive than the Sun (around $> 2\,M_\odot$) will be dominated by the latter, and their evolution will be accelerated. We will return to this point later.

For completeness we have indicated in Figure 3 the other process that can release energy at the nuclear level: the breakup of a large nucleus into two smaller ones, the nuclear fission, possible because of the interplay of nuclear

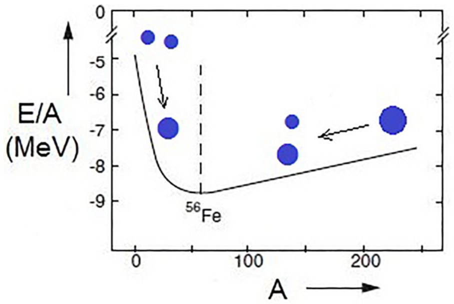


Figure 3: Nuclear fusion and fission at a glimpse. The vertical axis shows the binding energy (difference between the actual mass and the mass of isolated nucleons (in blue), multiplied by c^2, as a function of the mass number A in the horizontal axis. There are just two ways to gain energy, to be released by the process: the first is to fuse two nuclei to form a heavier one (left), called *nuclear fusion* and possible as long as the initial nuclei are light enough (iron $A = 56$ and surrounding species are the most bound and correspond to the minimum of E/A); the second is to break a very heavy nuclei into lighter ones, called fission and happening spontaneously for many species with $A > 200$. The first path is the one followed by stars, the second is the source of fission reactors and bombs.

and electromagnetic forces which produce a minimum in the E/A curve. Fission does not appear to play a major role in the evolution of stars, in fact it is quite difficult to produce very heavy nuclei, as we shall see below.

It is clear that the availability of heavier nuclei necessarily needs higher temperatures for their fusion to happen, and we shall relate this general feature to the fate of the stars below.

5. The Big Bang, the Stars and the Periodic Table

We are now in a position to start discussing the subject of interest. In spite of its great importance, it is rarely addressed in teaching in schools, or even in higher education. We start with the *origin of chemical elements* of the Periodic Table. In Chemistry classes the existence of all elements is taken for granted, without ever raising the question of their creation, as if it were automatically performed in Nature and we did not need to know how. But along the 20th century it became clear what happened initially, in the Big Bang nucleosynthesis. The important paper about the primordial synthesis of the elements by Alpher, Bethe and Gamow [15] had a new vision of the lightest nuclei which received a good deal of contribution from Brazilian researchers [16,17] among others. Later on, a progressive construction of a general picture showed how stars, the largest "ovens" in the present Universe that produce heavier elements from lighter ones, yield the bulk of the Periodic Table; and how explosive events complete it on the high A end. A brief of the sequence of nucleosynthesis follows.

5.1. Big Bang nucleosynthesis

The Big Bang formulation, and its consistency with observations regarding "primordial" elements, is considered an important pillar of modern science [18]. Moreover, its predictions for the nucleosynthesis yields are one of consequences that has contributed to consolidate the Big Bang as a viable model, not just a myth-like proposal.

The Big Bang is nothing but an early dense, hot state that the present Universe underwent billions of years ago. Actually, the very first instants (below a tiny fraction of a second) comprise a sequence of physical transformation of the matter content while the temperature and density dropped from gigantic values. Before a temperature of $\sim 10^{12} K$, it is accepted that not even the ordinary particles (electrons excluded) constituting our physical world (protons and neutrons) existed. They were rather "dissolved" into their fundamental constituents, *quarks* and *gluons*, which have been probed inside them in contemporary laboratory experiments. The Universe "freezes" from a quark-gluon soup to a gas of protons and neutrons in a phase transition at that borderline temperature. From this point on, the Universe evolves with a content of ordinary protons and neutrons (and electrons, of course), but their ambient temperature is still very high and quenches the formation of nuclei out of them. A general condition for nuclei to form is that the thermal energy of the protons and neutrons that are going to fuse is of the order of the binding energy of a nucleus, that is

$$k_B T_U \approx 1\, MeV, \tag{3}$$

(actually, the reactions start at lower temperatures, since there are very energetic particles for a given temperature that can break the forming nuclei). This equality can be expressed in IS units as

$$T_U \approx (0.1\, MeV)/k_B \sim 10^9\, K \quad . \tag{4}$$

This is the temperature at which the nucleosynthesis can start. When the Universe became cold enough for protons and primordial neutrons to form nuclei, this "assembly" (fusion) of nuclei took place while the expansion allowed it to (Figure 4). However, the density of protons and neutrons quickly became low enough to *interrupt* the building of heavier nuclei in the primordial nucleosynthesis, helped by an important fact: the absence of stable nuclei with $A = 5$ and $A = 8$ (a fact of the Periodic Table). Therefore, when the primordial nucleosynthesis buildup encountered this "bottleneck", the fusion sequence was truncated with a very small production of ^7Li(of the order of 10^{-5} of hydrogen) and just traces of ^9Be. Moreover, it is well established that at the moment the cosmic temperature dropped to the point that nuclei could be assembled, the number of protons was about 7 times the number of neutrons. Thus, out of 8 nucleons, 6 did not have a "partner", while the other two (one proton and one neutron) formed a bound state which later followed its evolution to form helium.

 DOI: https://doi.org/10.1590/1806-9126-RBEF-2020-0160

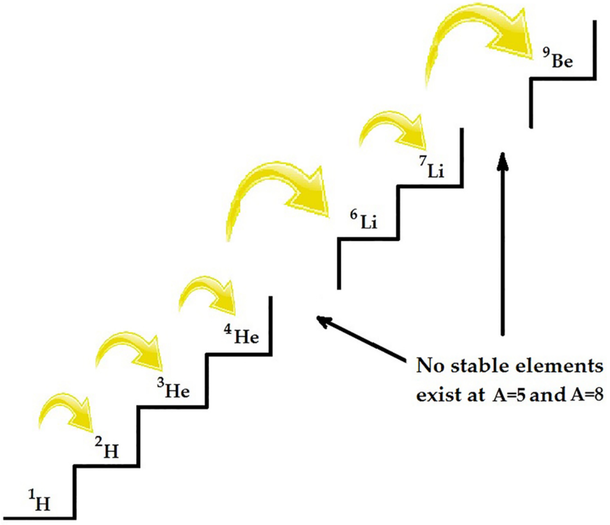


Figure 4: A basic scheme of the Big Bang nucleosynthesis. The fusions (yellow arrows) happen while the Universe expands and dilute the density of protons and neutrons. The "bottleneck" at $A = 5$, in which no stable nucleus exists, makes the production of lithium difficult. The little lithium produced cannot jump to beryllium for the same physical reason, this time the absence of a stable nucleus at $A = 8$, and just a residual fraction of ^9Be is ultimately produced. This will be the material out of which the first generation of stars will be formed billions of years after the Big Bang nucleosynthesis.

This estimations yields 75% hydrogen ("single" protons) and 25% helium (fused proton+neutron = deuterium nucleus, later combined into helium), pretty much what observations confirm. This sets the stage for the search of the places in which the rest of Periodic Table formed. A recent review by Liccardo et al. [19] can be consulted for the latest developments.

We end this part by noting that the very expansion of the Universe is much more concrete in this context than in any other: almost all of the primordial nucleosynthesis essentially is hydrogen and helium, and nothing much beyond lithium, precisely because expansion prevented it. If the expansion had happened much more slowly, or did not happen at all, the entire matter of the Universe would be fusioned into iron, and we would not be here to discuss science today.

5.2. Stellar nucleosynthesis

Stars are the natural sites for the Universe to keep on building the Periodic Table because i) they are formed out of the main leftovers of the Big Bang nucleosynthesis and ii) the temperatures and densities in their interiors are adequate to promote the fusion, without an energy source stars would not last much, certainly not $\sim$ billions of years as the Sun,but would quickly collapse and fade away. The whole subject in its modern form was started in a monumental paper by Burbridge, Burbridge, Fowler and Hoyle [20], a lecture strongly recommended even today.

A cursory inspection to Figure 3 will quickly indicate that the stellar nucleosynthesis would be able to advance until the elements around $A = 56$, the "peak of iron". This is essentially true, although there are processes pushing the mass limit to higher numbers. However, it is worthwhile to emphasize to the students that the very shape of the E/A curve, measured in laboratory, shows that exothermic fusion processes in stars cannot operate beyond this mass numbers. Let us now see how these main elements of fusion give rise to the whole existing variety, and afterwards how many elements much heavier than Fe that remain unexplained are actually produced.

The crucial ingredient for the nucleosynthesis inside a star is the stellar mass [21,22]. In fact a "star" is defined as the object that has a mass enough to ignite the fusion reactions of hydrogen in its interior. The theoretical calculations and many observations of faint objects indicate that this limit is around $0.08\,M_{\odot}$ for a solar composition. Only above this threshold the central temperature will be high enough to start the hydrogen fusion. As stated above, around $\sim 2\,M_{\odot}$ stars produce helium out of hydrogen, but in a more dramatic way (through the so-called CNO cycle mentioned above), again due to the strong dependence on the temperature of this reaction, which in turn depends on the stellar mass. A third important boundary for stars happens at $M \sim 8\,M_{\odot}$. Above this value the nuclear reactions can ignite carbon and heavier fuels if the mass is high enough. As a consequence, the evolution of $M > 8\,M_{\odot}$ will be very different than their lighter cousins, and their lives will end very differently.

The lower set of masses, $0.08\,M_{\odot} < M < 8\,M_{\odot}$ are called solar-type, are thought to ignite helium to form carbon past their maturity, but nothing beyond that. The reason is, again, that masses and structural conditions do not allow the high temperatures needed to ignite carbon, around $8 \times 10^9 K$. Their lives end in a pulsational instability that ejects the outer layers (carbon, nitrogen and oxygen due to secondary reactions) to the interstellar medium, with a compact *white dwarf*(the former stellar core) and *planetary nebula* as the outcome. This sequence illustrates an important aspect of the filling of the Periodic Table which in not often emphasized: in addition to the synthesis of the elements, it is very important that some physical process can put them into the interstellar medium, for example, all the composition of the white dwarf, thought to be carbon and oxygen, will remain "locked" in this stellar corpse and for all practical effects it will not participate in any other process after that. It is also worth to note that even very heavy elements can be synthesized by "dying" low/intermediate mass stars: the material is exposed for very long times to sources of neutrons, which end up building masses of isotopes with $A > 200$ through the so-called *s-neutron* process ("slow" because it proceeds over $10^4 yr$ or more in the end of the AGB stage, just before the ejection of the stellar envelope and the formation of a white dwarf, see below).

On the other hand, the fate of massive stars is quite different and has produced the most spectacular events registered in astronomical records: supernovae. The supernova is the result of the impossibility of the star to hold its structure when "Fe" is produced out of a "Si" core (the quotation marks are an indication that a lot of complexity surrounds this last fusion, silicon is not actually a single, unique species and iron is in fact a name for a set of elements around the 56 mass number). At its very end the star looks like an "onion" with concentric shells in which nuclear reactions are still taking place, the lighter at the outskirts and the "$2Si$" $\rightarrow$ "Fe" at the center. When the conditions are extreme, the star loses equilibrium, implodes and bounces ejecting all but its internal $1-2\,M_{\odot}$ "Fe" core, later transformed into a *neutron star* by the action of its own gravity [21,22]. Now all the envelope raw and synthesized material (several solar masses) will be ejected, although the heavier iron core will "lock" most of the heaviest material. Table 1 shows the outcome of the massive star nucleosynthesis ($20M_{\odot}$) case, showing in the last column the *duration* of each cycle to highlight the acceleration of the fusion reaction rate needed to hold the structure. These predictions have been overall confirmed by observations of young supernova remnants.

We now turn our attention to secondary products outside the main nuclear reactions. It is apparent that a buildup of heavier elements can happen provided protons or neutrons can be captured by the existing nuclei in the interior. The first, called the *p-process* has the disadvantage of working against the Coulomb barrier, and therefore is not exceedingly important. The capture of ambient neutrons, however, does not feel this Coulomb repulsion, and can proceed in two timescales: a long one, in which a relatively low density of neutrons can add mass to a nucleus $A \rightarrow A+1$ over >millennia; and a fast one in which a very high density of neutrons are added suddenly. The first is known as *s-process* (slow) and the second as *r-process* (rapid). In the first there is plenty of time for the formed nucleus to decay if it is unstable (the case of heavies in the AGB stars mentioned above), while in the second the neutrons are added so fast that no immediate decay is possible, and is considered a prime candidate to reach the highest mass numbers in the Periodic Table.

The distribution of nuclei observed in the solar neighborhood is shown in Figure 5. We see that there are orders of magnitude in the abundance of hydrogen, helium and the rest of the elements, even the very abundant carbon, oxygen and others. At the tail of the curve, with increasing A more than 12 orders of magnitude difference is present, indicating that the overall production of heavies in Nature is very small, but nevertheless intriguing. The nuclear structure is also important for this outcome, and it is a consensus that some elements can be produced exclusively by one or the other (s or r) processes and some other by the two of them. The colored lines mark the local maxima attributed to elements exclusively produced by the s and $r$processes. The very last ones (thorium, uranium etc) are the most problematic, because until recently no astrophysical site for the *r-process* to arrive at such mass numbers was identified. Apparently, type II supernovae are not enough to produce the heaviest isotopes, but a completely different class of events have been identified to contribute (see next section).

A figure with the outcome of the stellar life as a function of its initial mass, which determines how the end will be, is presented below (Figure 6). The planetary nebula contribution of light elements, the contribution of massive stars shown in Table 1, plus many elements also ejected in supernovae resulting from the s and r process and other secondary sources not discussed here (for example, massive stellar winds) complete the view of stellar nucleosynthesis.

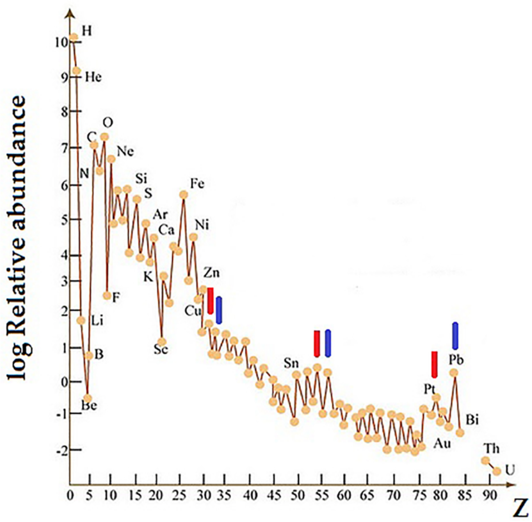


Figure 5: The abundance of elements in the solar neighborhood. Red lines indicate peaks corresponding to s-process production, slightly shifted from the r-process ones (blue).

Table 1: Nucleosynthesis of a $20\,M_{\odot}$ star with the same initial composition of our Sun.

"Fuel"	Main Products	Secondary Products	Ignition Temperature ($10^9\,K$)	Duration of stellar cycle (yr)
H	He	^{14}N	0.02	2×10^7
He	C, O	$^{18}O, ^{22}Ne$	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar, K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr, Ni, Mn, Co	3.5	<1 week

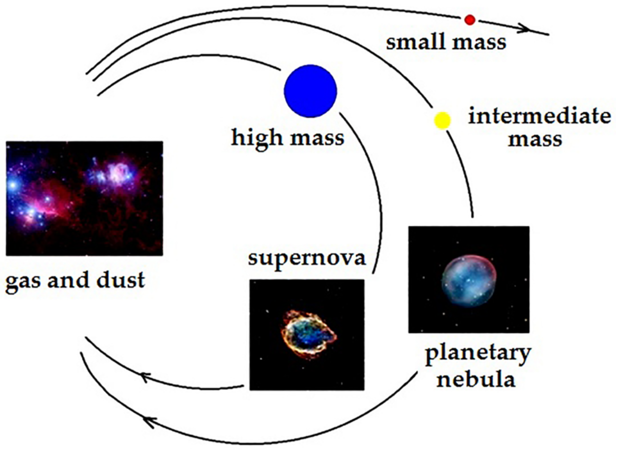


Figure 6: The stellar lives and the return of synthesized elements to the interstellar medium as a function of the mass. Note that the "small mass" stars are those that will end their lives in the future, and have not contributed to enrich the ISM as yet.

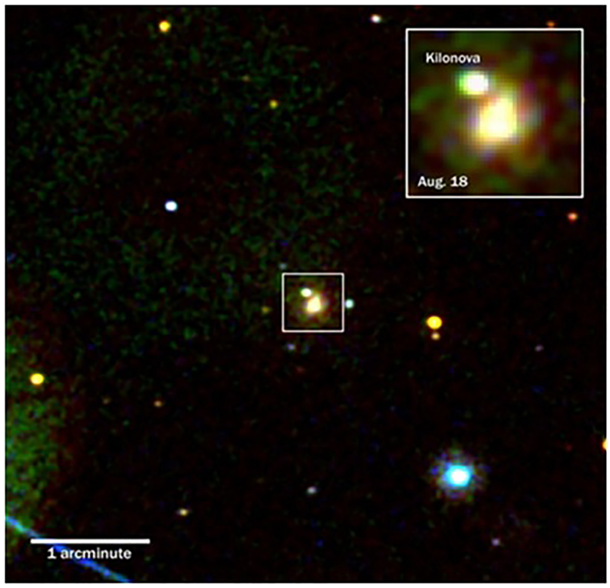


Figure 7: An image of the ultraviolet transient of GW170817 detected by the mission *Swift*. The "kilonova" faded away very quickly, this is why it is very important to have a rough location as soon as possible to hunt for the optical/UV/IR counterpart, as it was the case due to the rapid announcement of the gravitational LIGO/Virgo Observatories.

5.3. Cosmic catastrophes (neutron star mergers) and heavy elements

As stated in the previous section, there was a great deal of discussion over decades among the researcher about the origin of the heaviest elements (actinides). This is because to go beyond the $A = 200$ in mass requires extreme conditions. Not even the most extreme known catastrophes were confirmed as the source of these "third peak" nuclei, even less the uranium and heavier ones. The r-process remained a prime candidate for their production, but neither the theory nor the observations were capable of confirming this origin.

In 1989 a novel idea [23] about the origin of these elements appeared: instead of building very heavy nuclei from quite light ones, the idea was to suddenly *decompress* the matter inside a neutron star, forming "droplets" (ordinary nuclei). Neutron stars harbor matter above the so-called *nuclear matter density*, well in excess of $10^{14} g\, cm^{-3}$. Therefore, a neutron star is for practical purposes as a big, macroscopic nuclei with $A \sim 10^{57}$ particles (that number corresponds to about the mass of the Sun). This enormous density can be roughly visualized by asserting that a basketball ball full of neutron star matter would weight about 5 times the weight of all 7 billion living human beings. The central idea is that binary neutron star systems will inspiral and merge from time to time, and the ejected matter, naturally decompressed by the expansion, would form "droplets" (nuclei),reprocessed very quickly by rapid ambient neutron capture to $A > 200$. A rate of one collision in the galaxy per 300 000 yr or so was expected to occur.

More than 27 yrs after this suggestion, and with scattered evidence that the merging of neutron stars was actually related to gamma-ray transients observed from the 70's, the simultaneous detection of a transient called GW170817 confirmed many of the initial expectations and allowed for the first time a glimpse of the production of nuclei in such an event. The relativistic stars spinning around each other at a fraction of the speed of light collided and produced a perturbation in the very fabric of spacetime, a *gravitational wave* reaching the Earth and allowing a search with essentially any instrument available. More than 70 detections in gamma-rays, infrared and other electromagnetic frequencies have been reported (Figure 7). In particular, it was seen that the evolution of the transient brightness in time needed some agent to retain somewhat the outcoming radiation. Later work showed that this phenomenon of a delayed brightening, termed *kilonova* could be attributed to the existence of *lanthanide* elements $140 < A < 180$) formed in the ejection. In fact, a direct detection was claimed [24] and the consensus about the correctness of the picture strengthened.

In addition to these spectacular results, the production of very heavy elements (mostly actinides) was indirectly deduced from the behavior of the transient evolution. The radioactive decay of actinides is the best known explanation for the observations. The production of around $20\, M_\oplus$ of gold and more than $100 M_\oplus$ of platinum (the symbol "$\oplus$" represents the mass of the planet Earth) are needed to explain the details of the event. These numbers are enough to explain the heaviest component of the Periodic Table. We may say that gravity, producing the shrinking of the orbit of the two neutron stars, comes to the "rescue" the production of heavies, which were buried inside a stellar graveyard. The merger/kilonova events allow the ejection of $\sim 10^{-3} M_\odot$ contributing to lanthanides and actinides of the Periodic Table. It is possible, and seriously considered, that this type of events are the *only* source of gold, platinum and heavier nuclei, and certainly all nuclei beyond uranium [25, 26]. Thus, Nature manages to complete the Periodic Table known to us in a novel and spectacular fashion.

6. The Formation of the Sun and the Solar System

The problem of the origin of the Solar System has occupied a central position in scientific thought for many centuries and there are several ideas attributed to great thinkers in History. One of the historical milestones of this problem was the so-called nebular hypothesis formulated by the German philosopher Immanuel Kant (1724-1804) in 1755, according to which the Sun and the planets had formed from a primordial nebula. The idea was developed by the Frenchman Pierre-Simon de Laplace (1749-1827), sustaining that the Sun and the planets had formed *in the same process,* a hypothesis that received considerable support when it was possible to measure the relative abundances of the chemical elements that form both the Sun and the planets. These measures were very similar, although there are notable differences attributed to the formation process itself.

One of the challenges is quite clear from the very beginning: the ISM has a "light" composition which is completely different that the Earth's one. The process of formation made the planet what it is, leaving relatively heavy elements in the crust and atmosphere, and even heavier ones which are thought to compose the mantle and core (see below). To compare both, Figure 8 shows the striking difference between the ISM and the Earth chemically viewed.

The complete history of the origin of our Solar System involves a series of physical processes understood in a very satisfactory, but not comprehensive way. While new studies are being developed on the observational aspects of star formation and their theoretical description, it is already possible to answer some of the most important questions. The first is that today we know much more about the formation of stars and planets precisely because we can *observe the process directly*, as exemplified in Figure 9. Within a relatively short distance from the Sun there are several regions of star formation where stars can be observed and be catalogued at various stages of their formation. Thus, it is possible to imagine how our Solar System was formed.

Another complementary way to understand the formation of stars and planets is to carefully observe the signals left by the processes that we want to understand in our own Solar System. We will see that some ideas explain in a simple way what is observed, while others can be discarded because they leave something to be desired, or because they predict facts that do not correspond to the observations. In general, there is an ambition of astronomers to fully explain the formation of stars, and that of the Sun and its planets as a particular case. This requires a lot of work, a lot of imagination and a little luck, in fact, a formula that can be applied to any field of Science.

These considerations lead us to try to identify not only the formation of stars, but also planetary systems today in the Universe. The search for planets around stars is, in fact, one of the most active fields in Astronomy and there is already an important set of known extra-solar planets. But there is still little data on the formation of planetary systems, due to the difficulties in observing the stars themselves forming like those in Figure 9, since

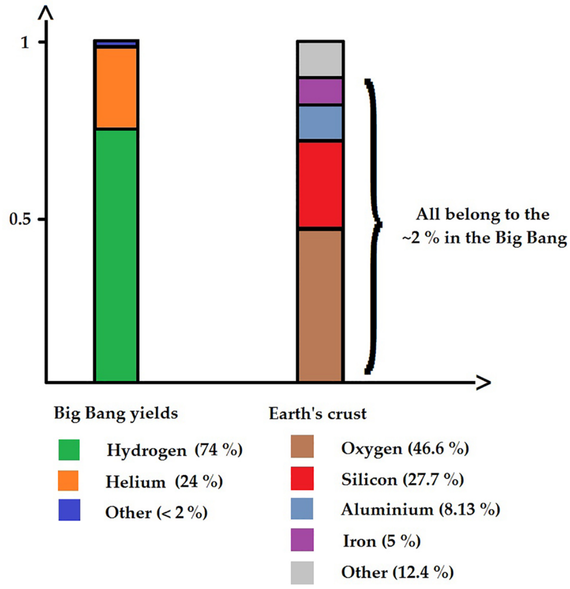
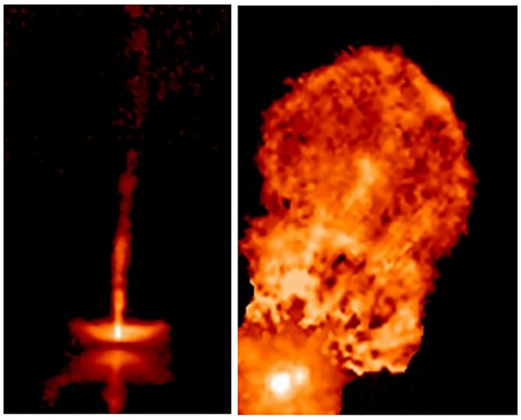


Figure 8: The Big Bang+stellar nucleosynthesis abundance of elements (note that almost all the stellar contribution comprises the top $\leq 2\%$ blue bar on the left), and the abundance found at the surface of the Earth (right bar). The physical and chemical processes due to the formation of the Solar System must account for this large difference.

9a



9b

Figure 9: Two stars in formation captured by the Hubble telescope (HH 30, left and XZ Tauri, right). The matter accretion disk and perpendicular jet are clearly visible on the left panel (9a). These environments favor the formation of planetary systems from the disk matter, as must have happened in the Solar System. We may be observing the birth of new planets in them.

they are being born in the middle of the gas and the dust of the "mother cloud". However, there is a consensus, reached after more than a century of interdisciplinary studies involving physicists, astronomers, geologists and other scientists to say that the formation of the Solar System must have happened something like this:

About 5 billion years ago, a large cloud of gas (enriched by elements heavier than helium accumulated by the successive ejections of stellar material) began to contract due to gravitation. It is likely that the collapse process started with the passage of waves that disturbed the cloud, exchanging energy with the gaseous components, facilitating its physical transformation. A recent idea is that the collision of the Milky Way with dwarf galaxies acted as a trigger of star formation, a type of event speculated for the origin of the Sun and Solar System [27]. As gravitation imposed itself on the resistance offered by the internal pressure of the cloud, smaller regions were isolated within it, and continued to collapse to form "cocoons" where these processes continued (called Bok globules). The addition of neighboring matter over the denser regions gave rise to the first phases of what would become a star (stage known as TTauri, Figure 9b), with jets emerging from it. After a few million years, the contraction raised the temperature to the millions of degrees, allowing the young Sun to establish the energy generation that keeps it shining today. Even though it was at least 30% less bright, it already had all the characteristics observed today and was already accompanied by the equally young planets.

An important fact to be taken into account is that the orbits of all the planets in the Solar System are practically contained in one plane (with the exception of the orbit of the Pluto-Charon binary system). The initial nebula must have been roughly spherical, and when collapsing, formed a disk around it as the speed of rotation increased, flattening it. In fact, the nebula could not have collapsed without causing the rotation to be "transferred" outwards, in other words, centrifugal forces would have prevented the contraction if this transfer had not happened (more strictly, astronomers speak of the transfer of angular momentum in the proto-planetary nebula, that is, the particles were collapsing when the angular momentum was decreasing. Note that since there were collisions and other important processes, the angular momentum was *not* constant for each particle in the formation of the Solar System.

Since there wasn't a powerful energy source in its center yet, as the Sun was still in formation, in a few million years the disk's material had cooled and formed grains (of the same composition as some rocks, that is, silicon, magnesium, aluminum etc.) and "ices", or bits of light elements solidified by low temperatures (containing mainly hydrogen and helium). These particles aggregated to form small objects in the beginning, but they grew slowly until reaching sizes of a few kilometers, forming small bodies called planetesimals. The planetesimals frequently collided, which prevented them from grouping too quickly due to the action of gravitation. After a certain time, estimated to be up to 100 million years, embryos of the current planets (called protoplanets at this stage) were formed and were accreting material until the end of their formation process. At this stage, the heat released by the gravitational aggregation process, literally "melted" matter if the protoplanet was more than 500 km in size. This is what happened to the Earth and the other inner planets and modified its structure, since the heavier elements (iron, for example) sank, while the lighter ones (silicon, aluminum) occupied the planetary surfaces. Geologists call this process *differentiation*, which will be discussed in more detail as we study the Earth shortly thereafter. The described stages of planet formation are shown in Figure 10.

The Sun's influence was important at some point to separate the disk's material. Originally there were many more "ices" than grains of dust (say, in the proportion of 90% and 10%), but when the sun "lit", the temperature increase did not allow the "ices" to survive in the inner part. Thus, while the planetesimals close to the surviving Sun were formed from rocky material, in the outermost orbits they were constituted of "ices" (Figure 11). That is why we observe that the giant outer planets are made of light elements, while the four innermost ones (Mercury, Venus, Earth and Mars) are rocky. The segregation of elements mentioned above is due to the evaporation of light, volatile compounds in the inner Solar System, while the transport of angular momentum outwards preserved them in the outer Solar System, were the temperatures were much cooler. Therefore, the Earth and near rocky neighbors end up with a composition reflecting the "$\leq$ 2%" (carbon, oxygen, aluminum, iron etc.) at the top of the left bar in Figure 8, the one contributed essentially by stellar evolution.

Another very important fact for the Solar System was the presence of the "protojupiter". It is possible that it formed in a similar way to the Sun, that is, di-

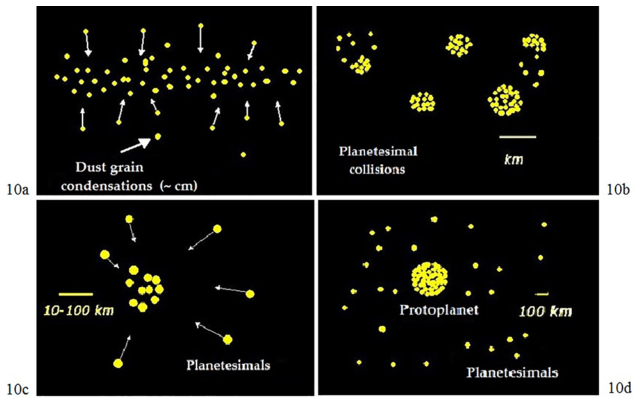


Figure 10: Primordial stages of planet formation. Panel 10a) represents the earliest stage, where dust grains collapse together to form planetesimals (panel 10b)). Collisions competed with gravitational collapse (panel 10c)) until the latter prevailed. Protoplanets spread and merged with planetesimals (panel 10d)) forming our current Solar System.

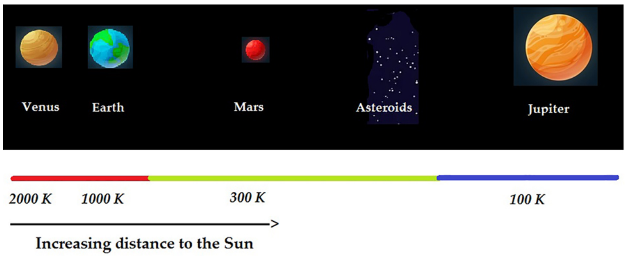


Figure 11: Initial average temperatures in the interplanetary medium as a function of solar distance (not to scale). Only substances that are solid at high temperatures can form rocky planets, like Venus and Earth, while the "ices" concentrated in cooler regions such as Jupiter's orbit and beyond. Note these temperatures are *not* the planets' ones, which are determined by the energy balance between solar energy, inner energy and what is radiated back to space.

rectly as a condensation of the nebula, and not by the aggregation of planetesimals. Regardless of this, a protojupiter functioned as a center that attracted and spread a large number of planetesimals. In fact, it is believed that he was the "culprit" forspreading a good part of the "ice" planetesimals towards the inner planets, where they melted/evaporated.

However, the *water* content of these planetesimals could condense and formed Earth's oceans, which otherwisewould be a much drier planet. The protojupiter was also responsible for the scattering of small ice planetesimals up to distances of perhaps $\sim$ 100 000 AU, where we they can still be found.

These bodies are still in very distant orbits, but from time to time disturbances from neighboring stars "push" some into the interior Solar System, and they can be observed from Earth as comets. Near the "protojupiter", planetesimals reached enormous speeds, and so their collisions were very violent,preventing them from forming a protoplanet. This is the origin of the asteroid belt that is located between Mars and Jupiter, in other words, asteroids are *not* part of adestroyed planet, but the "pieces" that did not form one. Finally, large planetesimals spread to orbits beyond Pluto, forming the so-called *Kuiper belt*, discovered in the last decade through high-resolution images. We will see later that there is still plenty of room for surprises in the study of theSolar System, some of them recently revealed.

Recent discoveries back up the idea that planetesimals formed by gravitational collapse of dust and pebbles in the solar nebula. On Jan. 1st 2019, the *New Horizons* spacecraft flew by a 36 km wide object in the Kuiper Belt named *Arrokoth*, obtaining information about its geometry, composition and structure. Its shape, formed by two lobes, indicates the merging of two separate objects in a scenario where impacts had a *low speed* (simulations indicate that it must have been lower than 15 km/h). The object has craters that indicate the surface's age to be about 4 billion years, and its mostly homogenous outer layer presents methanol ices and carbon organic

Figure 12: The New Horizons image of the body Arrokoth in the Kuiper Belt, showing the two pieces joined by a low-velocity collision. This is likely a remnant of the stage c) in Figure 10. (Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute/Roman Tkachenko).

materials. All evidence points towards gravitational collapse of local matter being the main mechanism that formed planetesimals like Arrokoth. A view of this object can be found in Figure 12.

7. Earth's current structure: Core, Mantle and Crust

After the initial stages and under the influence of its own gravitational field, the young Earth underwent a process called differentiation: in the existing fluid, the heavier elements (Fe, Ni) ended up sinking to the center, while the lighter ones (Si, Mg, O, Al) formed a layer that cooled and produced the currently observed structure. Detailed studies concluded that this process was completed in a few *Myr* [28]. We can compare the current Earth to a cherry covered in chocolate (!): The external chocolate is analogous to Earth's crust, a solid layer of varying thickness (always thinner than $\sim$ 70 km) which is much smaller than its radius. Below the crust we find the mantle (the cherry pulp), composed essentially of Si, O and Mg, and towards the center we find the nucleus (core) that contains heavier elements like Fe and Ni. This layer structure is complex and dynamic, since the Earth shows many signs of activity, such as volcanism and earthquakes. To better describe Earth it is necessary to look a little

 DOI: https://doi.org/10.1590/1806-9126-RBEF-2020-0160

more closely at the composition and structure of the crust, mantle and core.

The crust: It is the outermost solid layer, and the only one accessible by direct studies. It's mainly made up of basalts and granites, corresponding to the regions of the oceanic and continental crust respectively. The overall composition is roughly 2/3 of basalt (igneous rocks, or solidified lava), 1/3 metamorphic rocks (i.e. rocks that have been subjected to changes in pressure and temperature, thus changing their structure) and 1/3 sedimentary rocks (produced by weathering and subsequent processes). Over 90% of all rocks in the crust contain *silicates*. When subjected to tensions, the crust deforms, and can fracture beyond a certain critical threshold, thus giving origin of the "shallow" earthquakes that originate there (see below).

The mantle: the mantle begins immediately below the crust, and can be divided into upper and lower mantle. The upper mantle is more rigid and forms, together with the crust, the lithosphere. The main composition throughout the mantle is of iron and magnesium silicates, in particular the compounds olivine and pyroxene formed under high pressure. The main differentiation in the mantle comes from changes in the stability of certain silicates. There is a transition zone (from 410-660 km), and the lower mantle extends from there down to about 2900 km. The region between 2700 and 2900 km has anomalous seismic wave propagation and is known by geophysicists as the D'' layer.

The core: It consists of two different regions separated by a transition from liquid to solid phase. The liquid core (2900 to 5150 km) is composed of nickel-iron. Convective movements of the electrically charged material take place there. The solid core, of little over 1200 km radius, where iron and nickel have solidified has a crystalline structure (the cherry core) and movements are not possible there. The core temperature is high, certainly higher than 7000 K, and it remains so due to residual heat from Earth's formation, the decay of radioactive elements that were in the primordial nebula (thorium, nickel, titanium, etc.), and the latent heat released by the material that solidifies from the inside out, gradually increasing the solid core's size.

There are some controversies regarding the structure and composition of the Earth, for example, the nature of the most central region and the energy balance and core temperatures. Of course, some changes from new research are always possible. In addition to well-known tools such as the study of seismic waves that bring structure information when they cross the Earth, other methods are developed to complement and assist in the study of our planet. The structure and composition that have been described above are shown to scale in Figure 13.

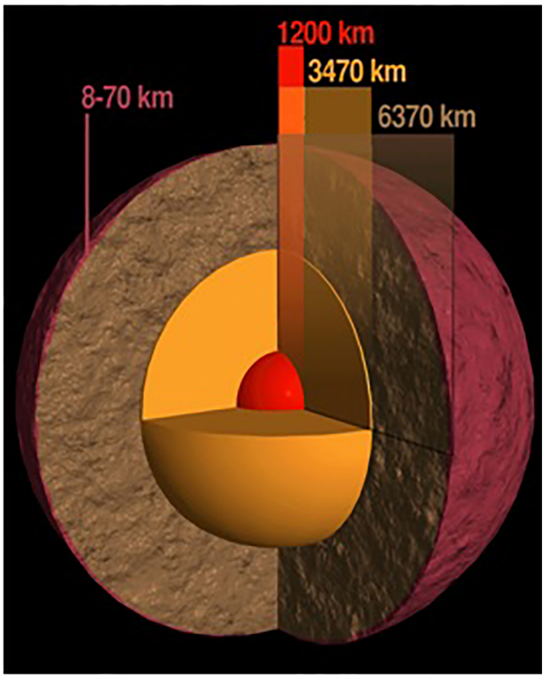


Figure 13: Earth's inner structure, showing crust, mantle and core (inner and outer) as described in the text.

Origin of the Moon

A very important issue for planet Earth is the Moon's formation. We see that the Moon has an influence on Earth in the form of tides and was fundamental, for example, to establish the first calendars. But it is not so clear how the Moon formed and ended up in its current orbit. There have been all kinds of ideas about it along History. Over time, most of these ideas were abandoned, but some continued to be seriously considered and, with the advancement of instrumentation and continuous discussion, they could be tested. The five theories most considered over time are:

1) The Moon was formed far from Earth and was captured later.

2) The Earth and the Moon condensed from the same initial protoplanetary cloud.

3) The Moon separated from the Earth, but it was formed inside it, possibly in the "hole" that today is occupied by the Pacific Ocean.

4) The planetesimals that bombarded Earth in the early stages of the Solar System collided and formed the Moon from the remains of the collision.

5) A large planetesimal, possibly the mass of Mars, collided with Earth and pulled out a large mass of matter that formed a disk around it and formed the Moon from it.

There is now evidence that allows us to eliminate the first 3 hypotheses, some of which are: the different composition of the Earth and the Moon and the relatively low density of the Moon, which indicates the *absence* of an iron metallic core. These data do not favor a common origin. The capture is very unlikely also for a less massive planet like ours. At present, the latter theory is the one with the greatest acceptance: apparently the Moon had a particularly violent origin and is, yes, a "daughter" of the Earth, but this origin made her present a composition similar to the Earth's crust, while the iron of nucleus is

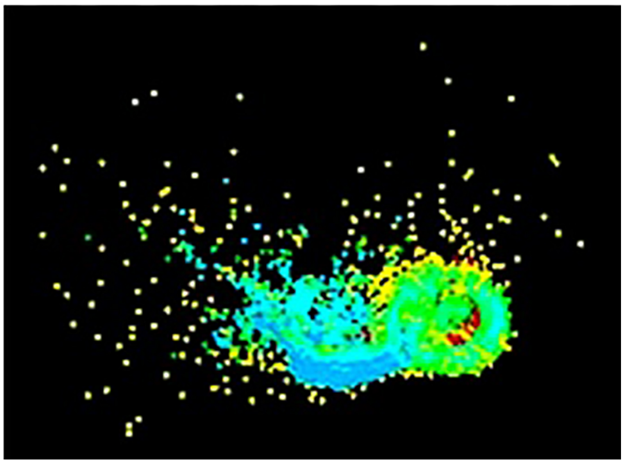


Figure 14: A computer simulation showing the impact of a large planetesimal on a young Earth (right) to form the Moon from the ejected matter [29].

absent because it was not much affected by the "shallow" collision of a large planetesimal (Figure 14).

8. A Proposal of a Didactic Sequence

We have completed our exposition and discussion of the contents and the question of how to use them naturally arises. In spite that each teacher is likely to have their own view of how to present this material, heavily influenced by time constraints, educative context, and many other factors, we believe that a set of five classes should be enough to motivate, present, and discuss the subject, leaving the important message to the students of how to think the chemistry of the present Earth integrated with its cosmic origin, the very source of the elements as stated above. The practical suggestion for a sequence follows.

8.1. Class 1

Start this class outside of the classroom. As an example, with the students walking in a garden, beach or anywhere in contact with nature and asking them: - As you see the sky, the land and water, and think about the sky, how could you explain the origin on the substances? How were they formed to be here now? It may be appropriate to confront several emerging views of these questions, writing down the different explanations. After this, an exposition about these points follows:

Present the Big Bang model as a currently held view that explains the initial instants of the Universe. Explain carefully the need of a changing Universe over time due to expansion and cooling, the basic dynamical features of the Big Bang. The changes of matter in the first stages of the Universe need not start with complicated things, such as Inflation, elementary particle formation, annihilation of anti-matter and matter, and the like. But it is important to stress the formation of protons and neutrons and the onset of nuclear fusion, how does it stop and which atoms are formed. It may be appropriate to stress that these 75% hydrogen, 25% helium with traces of deuterium, lithium etc. are observed in distant (old) galaxies, while the Big Bang model *predicts* them.

Make some questions for the contents of the next class: What about the origin of the *other*, very abundant elements on Earth, well beyond lithium/beryllium?

8.2. Class 2

Start by the questions made in the end of the last class. After this, explanation about the contents:

The stars as nature's ovens where elements are formed by the very same fusion, which in turn support the stellar life over billions of years.The need of a range of temperatures driven by the mass of the star.The origin of the different elements produced inside stars varies as a function of the mass of a star and the stage of its lifetime, with emphasis on the ejection/explosion processes. The origin of very heavy elements in cosmic catastrophes (supernovae/ neutron stars collision)

Make some questions for the contents of the next class: What about the origin of the Solar System? Why is the composition of planets so different?

8.3. Class 3

Start by the questions made in the end of the last class. After this, explanation about the contents:

The origin and evolution of the Solar System, starting with a <u>cloud</u> of gas and dust in which preexisting elements were present. Under its own gravitational attraction, the cloud collapsed into a rotating disk of matter (solar nebula). Ideas and results about the induction of the collapse of the cloud (a nearby supernova, turbulent eddies and their role). The onset of nuclear fusion (hydrogen ->helium) in the compacted nebular core, giving birth to a star. Discuss the fate outer part of the rotating disk—the matter not incorporated into the new Sun-as the raw material for the planets and other orbiting bodies of the Solar System. The birth of the Sun, which makes up more than 99.9 percent of the mass of the entire Solar System, is taken to be the time at which the planets started to form (which in turn carry almost all the angular momentum, as required by the collapsing cloud view). Present independent and objective evidence for a $\sim$ 4.5 billion years old age (geological, meteorites).

Make some questions for the contents of the next class: What about the effects of the evolution of the Solar System for the Earth's structure and composition?

8.4. Class 4

Start by the questions made in the end of the last class. After this, explanation about the contents:

The effects of the evolution of the Solar System for the Earth's structure and composition. Accretion of the early Earth; Effects of planetesimal impacts; Planetary differentiation. Volatile elements, rocky planets and gas giants.Late heavy bombardment.Diffusion of heavy elements.The formation of the Moon.Independent evidence for the planetesimal buildup.

Make some questions for the contents of the next class: What is the Earth's structure and composition? How does it relate to the elements?

8.5. Class 5

Start by the questions made in the end of the last class. After this, explanation about the contents:

Earth's structure and composition. The solid Earth, the geosphere, the hydrosphere, the atmosphere and the biosphere.The magnetic field and biological life.Earth's dynamics.

9. Conclusions

We have motivated in this work the need of an interdisciplinary approach of one of the big questions in contemporary science: that of the origin of the elements in the Periodic Table, their cosmological/astrophysical production sites and their role in the formation of the Solar System and the planets, with emphasis on the Earth's case. It is remarkable that for the first time astronomers have identified directly events (neutron star mergers) which complement the formation of lanthanide and actinide groups, even though the exact fractions will be subject to examination. We believe there are good reasons to expect that such an integrated, Cosmogeochemistry view to produce a significant impact on the way several isolated disciplines are seen. A separate and specific problem would be to prepare teachers exposed to this interdisciplinary view, even if how exactly to achieve this goal is out of the scope of the present work. All in all, the attempts to present these contents as a whole, interwoven pack will be visible for the students quite clearly, helping them to act in their contemporary world.

Acknowledgements

J.E.H has been supported by the CNPq Agency (Brazil) and FAPESP Agency (São Paulo State) through the grant *Projeto Temático* 2013/262584. We acknowledge informative exchange of ideas on the USA and Australian Curricula with Robert Hollow and Saeed Salimpour. An anonymous referee pointed out the references [2], [16] and [17] and we thank them for that.

References

[1] R.Stichweh, in: *International Encyclopedia of the Social & Behavioral Sciences*, edited by N.J. Smelser and P.B. Baltes (Pergamon, New York, 2001).

[2] R.D. Blanford and K.S. Thorne, American Journal of Physics **88**, 518 (2020).

[3] M.A. Max-Neef, Ecological Economics **53**, 5 (2005).

[4] L.S. Shulman, Educational Researcher **15**, 4 (1985).

[5] `https://www.nextgenscience.org/dci-arrangement/hs-ess1-earths-place-universe`, accessed in April 2020.

[6] `https://www.australiancurriculum.edu.au/senior-secondary-curriculum/science/earth-and-environmental-science/?unit=Unit+1`, accessed in March 2020.

[7] BRASIL, Parâmetros Curriculares Nacionais: Ciências Naturais – 3° e 4° ciclos (Ministério da Educação, Brasília, 1998) p. 94-95. Available in: `http://portal.mec.gov.br/seb/arquivos/pdf/ciencias.pdf`, accessed in July 2020.

[8] BRASIL, Parâmetros Curriculares Nacionais: Ensino Médio (Ministério da Educação, Brasília, 1999), p. 239. Available in: `http://portal.mec.gov.br/seb/arquivos/pdf/ciencian.pdf` , accessed in July 2020.

[9] BRASIL. Base Nacional Comum Curricular (versão final) (Ministério da Educação, Brasília, 2017), p. 351. Available in: `http://basenacionalcomum.mec.gov.br/images/BNCC_EI_EF_110518_versaofinal_site.pdf` , accessed in July 2020.

[10] SÃO PAULO. Proposta Curricular do Estado de São Paulo: Química (SEE, São Paulo, 2008), p. 54-55. Available in: `http://www.rizomas.net/images/stories/artigos/Prop_QUI_COMP_red_md_20_03.pdf` , accessed in July 2020.

[11] E.B. Norman, Jour. Chem. Educ. **71**, 813 (1994).

[12] G.K. Gichuhi, World Jour. Chem. Educ. **7**, 209 (2019).

[13] N. Glickstein, J. Chem. Educ. **76**, 353 (1999).

[14] R.W. Conn, *Nuclear fusion,* available in: `https://www.britannica.com/science/nuclear-fusion/Fusion-reactions-in-stars`, accessed in March 2020.

[15] R.A. Alpher, H. Bethe and G. Gamow, Phys. Rev. **73**, 803 (1948).

[16] P.S. Toledo and G. Wataghin, Phys. Rev. **73**, 79 (1948).

[17] C. Lattes and G. Wataghin, Phys. Rev. **69**, 237 (1946).

[18] G. Mathews, M. Kusakabe and T. Kajino, International Journal of Modern Physics E. **26**, 1741001 (2017).

[19] V. Liccardo, M. Malheiro, M.S. Hussein, B.V. Carlson and T. Federico, European Physical Journal A **54**, 221 (2018).

[20] E.M. Burbridge, G.R. Burbridge, W.A. Fowler and F. Hoyle, Rev. Mod. Phys. **29**, 547 (1957).

[21] D. Arnett, *Supernovae and Nucleosynthesis* (Princeton University Press, New Jersey,1996).

[22] J.E. Horvath, *Fundamentos de Evolução Estelar, Supernovas e Objetos Compactos* (Livraria da Física, São Paulo, 2011).

[23] D. Eichler, M. Livio, T. Piran and D.N.Schramm, Nature **340**, 126 (1989).

[24] E. Pian, P. D'Avanzo, S. Benetti, M. Branchesi, E. Brocato, S. Campana, E. Cappellaro, S. Covino, V. D'Elia, J. P.U. Fynbo et al., Nature **551**, 67 (2017).

[25] J.A. Johnson, Science **63**, 474 (2019).

[26] `http://blog.sdss.org/2017/01/09/origin-of-the-elements-in-the-solar-system/`, accessed in March 2020.

[27] C. Gallart, E.J. Bernard, C.B. Brook, T. Ruiz-Lara, S. Cassisi, V. Hill and M. Monelli, Nature Astronomy **3**, 932 (2019).

[28] N. Moskovitz and E. Gaidos, Meteoritics& Planetary Science **46**, 903 (2018).
[29] R.M. Canup and E. Asphaug, Nature **412**, 708 (2001).