# Astrobiology: origin and evolution of life

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## Abstract

Astrobiology is not a discipline but an interdisciplinary grouping around the question of the origin and evolution of life on Earth and its possible presence elsewhere in the Universe. Astrobiology encompasses all fields interested in this question, from astronomy to biology, including geology and chemistry, but also the history and philosophy of science. The objectives are multiple and include in particular: to define Life, to determine its origin, to search for its oldest traces, to understand its mechanisms of evolution on Earth but also to search for life in the universe. Through this research, Astrobiology tries to determine if life could exist elsewhere in the universe and if so in what form, in order to try to answer an existential question: are we alone in the universe? For several decades, it has been clear that understanding the appearance of life on Earth is crucial in determining whether it is a coincidence or a reproducible phenomenon in specific conditions and environments. This understanding is necessary to make any conclusions about the possibility of life elsewhere in the universe. Despite active efforts, such conclusions have not yet been reached. These questions have emerged with the development of organic chemistry from the 19th century, space exploration in the 20th century (from 1969 with the Apollo missions) and the human quest to find life elsewhere (example of the Martian missions). Astrobiology then referred to the research and study of life outside our planet. Now and after major advances in the theme since the 1990s, this term brings together everything related to the question of the origin and evolution of Life on Earth or elsewhere in the Universe.

## Short definition of Astrobiology

Astrobiology concerns the search for the origins and evolution of life on Earth, and its possible presence elsewhere in the Universe. This vast field brings together interdisciplinary research on, for example, the traces of ancient life on Earth from the analysis of the oldest rocks; the physico-chemical conditions in which the primitive Earth found itself 4.5-4 billion years ago when life appeared; the diversity of organic matter available in these environments, which would have led to the development of prebiotic chemistry; the transition from the abiotic to the biotic with the emergence of chemical systems selected to make a living system; the evolution of the first entities on Earth up to our last universal common ancestor (LUCA), including the study of extremophile organisms such as Archaebacteria; the search for life elsewhere by space missions in the solar system, on exoplanets and in the Universe in general; and finally on the definition of life itself and its philosophical implications.

A deep interaction and interdisciplinary between the different disciplines of physics, chemistry, biology, geology, biochemistry, planetology, computer science, philosophy and epistemology is therefore necessary for the development and advancement of Astrobiology. Although each researcher specializes in a specific discipline, it is essential today to pay attention to other disciplines and advances made in other fields of research when it comes to understanding the question of the Origins of life and talk about Astrobiology.

## History of the question of the origins of life

Surprisingly, the question of the Origin of life is not a question that man has been asking since the dawn of time. Indeed, until the beginning of the 19th century, the theory of spontaneous generation, describing that life can appear spontaneously in any medium, was commonly accepted. This theory, adopted by many great scientists of the time, was even validated by experiments like that of Jean-Baptiste Van Helmont described in several works from 1648. The experiments showed that it was possible to see the “appearance” of a mouse in a jar filled with wheat flour, sealed by a (dirty) woman's shirt, placed at the back of a basement in the dark (variants speak of dirty blankets and other linens). These experiments and the theory of spontaneous generation remained in force until the beginning of the 19th century.
It was necessary to wait for the development of organic chemistry and the first syntheses of molecules to demonstrate that organic compounds follow the same laws as inorganic compounds and were therefore not necessarily linked to living organisms. One of the first memorable synthesis was carried out by Friedrich Wöhler in 1828 who successfully synthesized urea, a molecule identified in the liver of animals and considered only of biological origin by chemists such as Jöns Jacob Berzelius. At the same time, Charles Darwin (1809-1882), English naturalist and paleontologist, has conducted for several years, observations and work on species that would revolutionize our vision of the evolution of living things. In 1859, he published the first edition of his book "Origins of species". Although it is not about the origin of life in his work, the theory of evolution makes the notion that all living species derive and come from a common ancestor. The postulate falls: we are all linked to a common ancestor, whose form of life is much simpler than our current life.

The origin of life is therefore pushed back to the distant past, but the theory of spontaneous generation remains for these first living beings. A few years later (1861), it was Louis Pasteur, a fervent opponent of the theory of spontaneous generation and obsessed with microorganisms, who gave the final blow. He demonstrates with his “swan neck” experiment that when the air and the environment are properly sterilized, no microbe production is observed. From that moment, the theory of spontaneous generation is gradually abandoned.

At the end of the 19th century, science was then at an impasse, on the one hand Charles Darwin proposed that all species have a common origin, and on the other hand, Louis Pasteur demonstrated that spontaneous generation does not exist. Some great scientists of the time like Berzelius, or Lord Kelvins then proposed that life exists everywhere in the universe and that it came from elsewhere. It could have been brought to Earth by spores contained in meteorites or comets. This is the *panspermia* theory. Note that at present, no trace of life, bacteria or other spores have been found in these extraterrestrial objects, only organic molecules. Nevertheless this theory (still supported and modeled by some scientists nowadays) persists and was considered the only plausible explanation for almost a century. In 1924, new hypotheses about the origin of life were presented in a book by Alexander Oparin.

Following on from the work of 19th century chemists, who increasingly refuted the limit between the inorganic (the mineral) and the organic by synthesizing molecules such as sugars or amino acids in the laboratory, Alexander Oparin has proposed a continuity between the two. He has described in his book that matter could have evolved in our oceans, following the laws of physics and chemistry, transforming simple compounds into more complex molecules which, in the "primitive soup" will then form aggregates of matter and by complexification will lead to the production of cells. This concept is also proposed by a British geneticist, J.B.S Haldane, at the same time and independently. Although attractive, this hypothesis on the origin of life remains to be confirmed.

## Etymology: Exobiology and Astrobiology

From the beginning of the 1960s, the space contest was launched, and with it the first lunar and Martian exploration missions. The risk of biological contamination appears in language as much in the sense of transporting terrestrial microbes to other stars as of bringing extraterrestrial life back to Earth. Joshua Lederberg, microbiologist and geneticist (Nobel Prize for Medicine 1958) then closely followed the question of contamination and allowed the implementation of strict protocols for the decontamination of spacecraft. NASA has asked Joshua Lederberg to develop biochemical analysis protocols for lunar and Martian samples, taking into account our own contamination. It should be noted that in the 1960s, it was presumed unlikely by scientists that microbes would resist the conditions of space. We know today that this is not the case and for exemple the Tardigrades, a surprising species living on Earth, are able to resist extreme conditions including those of space. The case of Tardigrades is not isolated and other living species such as bacteria can also be resistant to an extreme environment.

Joshua Lederberg, adept of the *panspermia* theory, then created the term Exobiology in 1960, during a scientific presentation to the COSPAR (Committee for Space Research). He laid the foundations of this new science, defined as the search for life elsewhere. The booming space exploration alliance from that time, from Alexander Ivanovich Oparin's book on the question of the origin of life and Miller-Urea's pioneering experience in the field of prebiotic chemistry, make Exobiology the new key discipline for searching for the origins of life through space exploration. With astronomer Carl Sagan and physicist Elliott Levinthal, Joshua Lederberg is interested in the potential for Martian contamination. They will all be part of the scientific teams of the Viking missions, which landed and studied Mars from 1976. Convinced of the presence of life on Mars, these missions were to confirm its presence. These on-board exobiology experiments contributed to the first developments of in-situ experiments on solar system objects.

At the same time, a community of researchers is created around the question of the origin of life, with scientists who, from the 1950s, began chemical studies for the synthesis of the first prebiotic molecules (see the Miller-Urey experiment, Figure 1). In 1973, an international society was founded bringing together different disciplines on these questions of the origin of life, ISSOL (International Society for the Study of the Origin of life: https://issol.org/).

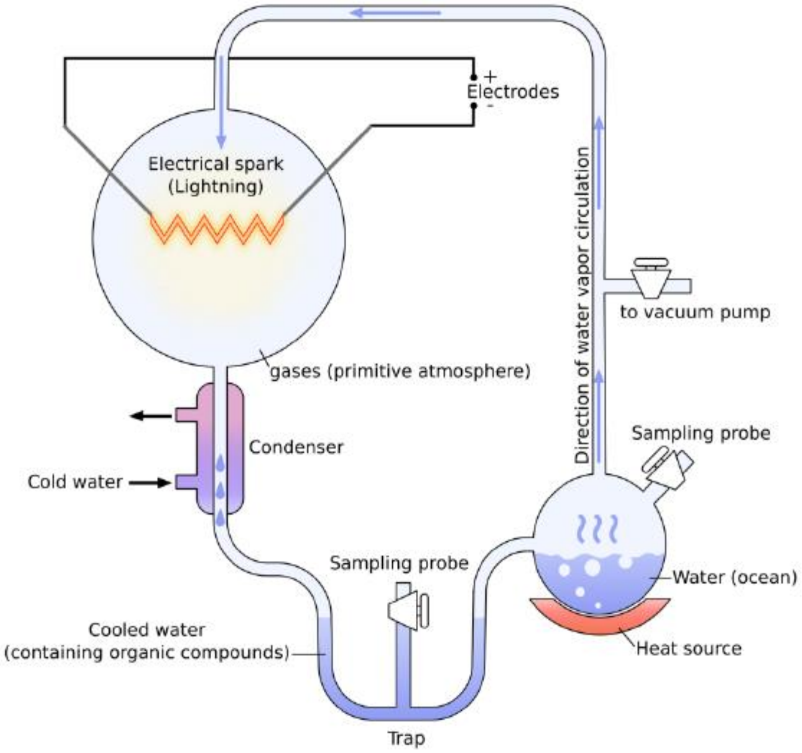

*Fig. 1 Illustration of the Miller-Urey experiment to simulate the early Earth environment and the formation of complex organic molecules in the oceans (Credit : La Barre, Stéphane. (2014). Marine biodiversity and chemodiversity - the treasure troves of the future. )*

In 1982 the International Astronomical Union (IAU) created the commission “Bioastronomy: Search for Extraterrestrial Life”, renamed simply Bioastronomy in 2006, then “Astrobiology” in 2015[1], ISSOL and the IAU-Astrobiology commission are still active and regularly organize international conferences bringing together researchers working on the question of the origins and evolution of life, as well as its presence elsewhere in the Universe. Many national

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[1] https://www.iau.org/science/scientific_bodies/commissions /F3/).

exobiology or astrobiology society have then raised in different countries (France, Germany, England).

The difference between the terms Exobiology, Bioastronomy and Astrobiology is now historic and should be used for the same definition: the search for the origin, evolution and distribution of life in the universe (including Earth).

## Define Life

Giving a definition of life, or at least of living beings, is one of the most complicated challenges of Astrobiology. Over the years and discoveries, we discover that the living is so complex, that it is very difficult to give the most complete definition. This question calls on scientific arguments but is also a philosophical questioning making any definition relatively non-objective and oriented according to the scientific field of the author.

Over time, different personalities and scientists have proposed definitions of life. One of the oldest dates back to Aristotle (~300 B.C.) and was quite basic: “By life we mean feeding, growing and wasting away by itself”. Since the origin of life was of no interest for centuries, its definition remained very factual.
The advent of science and the great discoveries in organic chemistry and biology from the 17th century brought new elements and the question of the definition of life arose. One of the definitions most used today is the fruit of the working group at NASA Exobiology program in 1995, of which Gerald Joyce was a member and to whom this definition is often attributed due to his own scientific work on self-replicating systems: "The life is a self-sustaining chemical system capable of undergoing Darwinian evolution".

During studies on the definition of living organisms, we realize that each definition is the point of view of the scientist in relation to his own knowledge and scientific field and that it would eventually be necessary to combine all these definitions to best approach a definition.

## Diversity of living things and search for the oldest traces of life on Earth

As terrestrial life is so far the only known example of life, Astrobiology concentrates a large part of its efforts on studying terrestrial life in all environments, particularly the most extreme, such as underwater hydrothermal springs, brine lakes or icy sites. This type of environment can be a good analogue for extraterrestrial locations. To better understand the limits of living organisms and the mechanisms at work in extreme environments, scientists are seeking to determine the phylogenetic and metabolic diversity of living organisms.

One of the branches of the tree of life (Figure 2) that is of particular interest is archaebacteria (or archaea), distinct from prokaryotic bacteria by their ribosomal RNA sequence and particularly adapted for extreme environments (in terms of pressure, temperature, salinity, nutrients, etc.). The specificity of archaebacteria was brought to light late, in 1977, when bacteria were discovered in hydrothermal vents, thanks to advanced analytical techniques (RNA sequencing). The archaea thus form a third group of living beings on Earth whose study provides essential information on understanding the limits of life on Earth and the search for our origins. Advances in metagenomics made possible, for example, to isolate in 2015 a new group of archaea, called the Asgard archaea, which are proposed as potential direct ancestors of eukaryotes. This type of organism is a prime target for studying possible life forms elsewhere, in environments such as Venus, Mars, or even the icy satellites around Jupiter and Saturn that have an ocean under their surface.

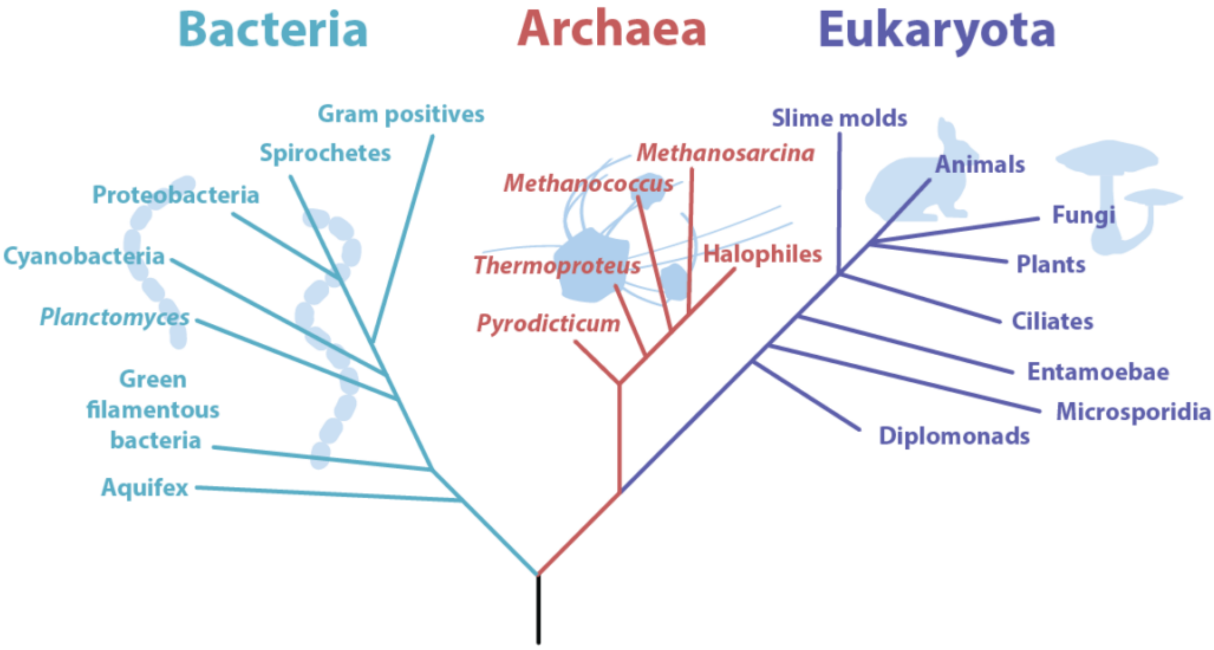

*Fig. 2 Simplified phylogenetic tree of living organisms, representing the three groups of living organisms: the eukaryotes of which we are a part, the bacteria which are uni- or multi-cellular prokaryotes and the archaea which are unicellular microorganisms separated from bacteria (Crdit: https://open.oregonstate.education/generalmicrobiology/chapter/archaea/)*

However, prokaryotes on Earth have had billions of years to evolve, adapt to their environment and put in place biochemical systems capable of withstanding, for example, extreme pressures or temperatures. It should also be noted that on Earth, it took about 1.5 billion years for microorganisms such as bacteria or archaea to colonize the oceans and produce enough oxygen, which then evaporated into the atmosphere and allowed the development of organisms using oxygen as an energy source. Unless there is the same evolution on another planet under the same conditions and with the same terrestrial contingencies (for example in terms of meteorology, plate tectonics, etc.), it is almost improbable to find these same entities outside Earth. But the study of extremophiles opens the field of possibilities of life in environments that are a priori inappropriate.

The search for the oldest traces of life on Earth is one of the axes of Astrobiology research, which could make it possible to fill our gaps on our ancestors to all. These studies encounter many difficulties due to the difficult preservation of fossils over geological time.

The first difficulty is that the earth is a "living" planet (tectonics, erosion), and so has evolved a lot since its formation 4.5 billion years ago. Any rock dating from the first geological era, the Hadean, is found anymore on Earth, only mineral named zircon. The search for fossils therefore focuses on the period after 4 billion years, at the time of the Archean era (4-2.5 billion), from which there are still sedimentary rocks on Earth, but they have nevertheless evolved. A fossil can take different forms, either it is possible to find debris or imprints of plants or animals (shells, traces), or if the structure of the fossil no longer exists, it is possible to identify physical signatures (structural) or chemical (in particular the isotopic ratios of carbon). In any case, it is now established, based on the genealogy of species, that the first living organisms must have been single-celled bacteria-like beings.

Thus, the second difficulty in the search for traces of ancient life, is that these organisms had to be microscopic. The oldest proven traces of life on Earth are dated to 3.48 billion years old, discovered in Australia. These are stromatolites (calcareous concretion formed by bacterial filaments), the shape of which indicates that there were bacteria, without these having been found. Although many proposals for traces of life are studied and published regularly by scientists, none to date has been fully confirmed by the community, and currently all traces older than 3.5 billion years are controversial, even if the limit of 3.8 billion years seems probable.

The third difficulty lies in the interpretation and comparison with abiotic systems, which could have formed traces similar to biological signatures or morphologies. Advances in analytical techniques since the 1990s, such as electron microscopy and isotopic analyses, often help to settle the controversy, in addition to experiments with abiotic systems. The search for fossil traces is therefore at the interface between biology, chemistry and geology, and requires extremely rigorous studies, with several methods of investigation to increase the probability of a biological and not only abiotic origin.

## Prebiotic Chemistry and the transition from non-living to living

Today, in all living species on Earth, among all the existing diversity, there are elementary bricks made of C, H, N, and O that we all possess. These bricks are proteins, the basis of replication, DNA (deoxyribonucleic acid) carrying genetic information, and amphiphiles, constituting cell walls for compartmentalization. These bricks are in fact sequences of "simple" molecules, such as amino acids for proteins, assemblies of sugars and nitrogenous bases with phosphorus for DNA, and lipids for membranes. Phosphorus is a crucial element in our living chemistry, despite not being one of the abundant atoms in the universe. Many studies therefore seek to determine why phosphorus was “chosen” as a key element in DNA and RNA (ribonucleic acid) and what is its origin (inorganic or organic). The elementary bricks that every living species on Earth have, are therefore five types of molecules (which are sometimes called bricks of life), amino acids, nitrogenous bases, sugars, phosphorus, lipids (or fatty acids). These elements are essential to terrestrial life and the study of their origin allows us to give more constraints to the origin of life itself. Abiotically, these molecules could have been formed in the Earth's atmosphere, but also in hydrothermal vents. In 1953, Stanley miller and his doctoral student Harold Urey have carried out the pioneer experiment demonstrating that earth’s atmosphere could have been the place for prebiotic chemistry. Since 1953, prebiotic chemistry experiments have multiplied and contribute a little more each day to understanding how it is possible to form the basic molecules of living organisms, namely proteins, DNA (or RNA- ribonucleic acid) and lipids in terrestrial conditions.

Another hypothesis proposes that these molecules could have been brought by celestial objects (meteorites). The latter, coming from asteroids and comets, are of great interest to scientists because meteorites have proven to be of great organic richness (4-5 percent by mass). By falling to Earth, these pebbles from space could have brought to Earth some of the water and siderophilic elements found on its surface after differentiation 4.5 billion years ago. No life forms in these objects have yet been found, but they contain many molecules, thousands of molecules for carbonaceous meteorites, as diverse and varied as abiotic synthesis is capable of. A large number of amino acids are for example observed in meteorites, as well as sugars and many organic precursors for the formation of the other building blocks of life defined above.

These discoveries, which date from the 21st century, raise questions about the possibility of life elsewhere since the basic building blocks can be synthesized in space. But these objects also inform us of the genesis of the solar system, its origin and its complexity which in comparison with exo-planetary systems could be quite unique. The current understanding of the phenomena that potentially led to life would tend to say that the Earth had particularly favorable conditions for the appearance of Life, intimately linked to the formation of the solar system, to the Earth itself, and to all adjoining contingencies (even the presence of the moon proved essential).

The question, which is perhaps the most important in Astrobiology, is the understanding of the transition from the non-living to the living as it could have been done on the primitive Earth about 4 billion years ago. It is therefore a question of determining the passage between a chemistry of the non-living, that is to say the abiotic, represented by all organic and mineral matter present on the surface of the early Earth at the appropriate moment, towards a chemistry of the living, being the biotic, represented by the first living species. The major difference between the two, between the chemistry of the living and the non-living, is selectivity. Biological systems have selected organic molecules for their functioning and specific properties (like chirality), whereas abiotic chemistry contains everything that is possible to form in organic chemistry. This observation is verified by the analysis of meteorites, which contains thousands of very diverse molecules, distributed randomly and everywhere on

H/C vs O/C diagrams for example (Figure 3). With the same analytical method, analyzes of biotic chemistry show, on the contrary, concentrations of molecules in well-defined areas, with chemical families that have been selected, and a much smaller diversity (Figure 3).

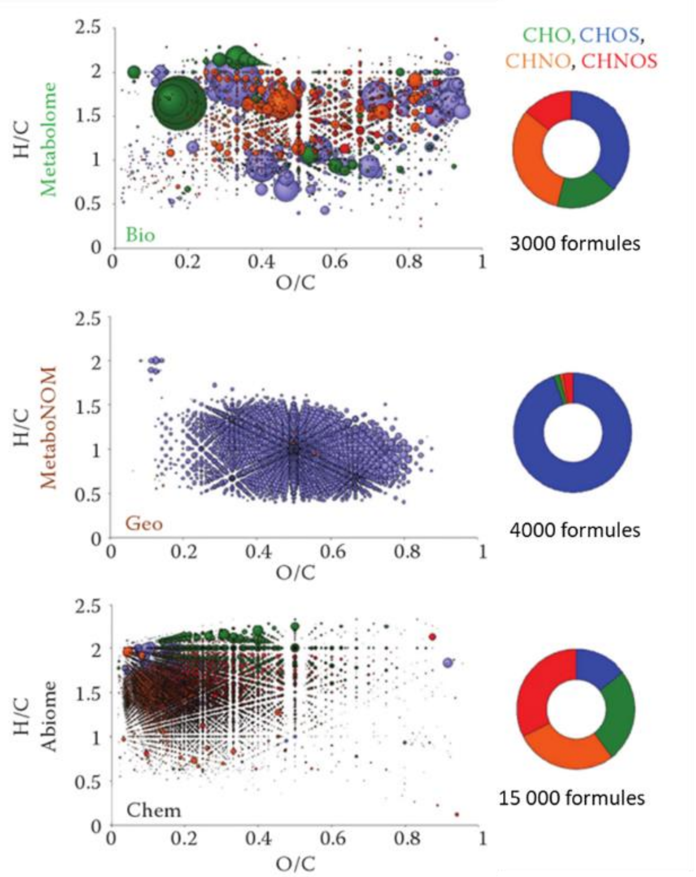

*Fig. 3. Detailed analysis by high resolution mass spectrometry of organic molecules present in three types of matter, represented in a Van Krevelen diagram of H/C vs O/C atomic ratios: at the top the molecular composition of a biological metabolome (biological sample), in the middle the composition of surface river water (geological sample) and at the bottow the composition of the abiotic organic matter of a meteorite. We note that the compositions of each material are very different, whether in terms of number of formulas or families of molecules (CHO vs CHOS vs CHNO vs CHNOS). Biological matter has selected a more limited diversity of molecules than abiotic matter. (Kolb, 2014)*

To achieve prebiotic chemistry, two major approaches are currently being studied: the top-down approach involves studying living systems and attempting to synthesize them, while the bottom-up approach focuses on abiotic chemistry and its potential evolution towards biological chemistry in a controlled environment.

Living things use three major chemical entities: proteins which constitute metabolism and enable replication and catalytic activity, DNA which carries genetic information and enables information to be encoded, lipid membranes which form a protective compartment and exchange of information thus allowing replication. As these entities are currently inseparable from our knowledge of living organisms, the top-down approach consists of determining which appeared first, why and how. Highly targeted chemical reaction systems catalyzed by minerals are being studied to determine whether in the laboratory it would be possible to form DNA, proteins and lipids similar to life in the same soup.

The bottom-up approach questions the entities necessary for life today and instead aims to understand how a chemical system could evolve by bringing together the elements under favorable conditions that existed on primitive Earth.. The first essential element for any form of life is the presence of a solvent, the most obvious and the most abundant in the universe, being water. The second essential element is organic matter, a diverse and more or less complex matter like that analyzed in meteorites. As a third element, we often mention the need for a source of energy capable of organizing matter into more complex molecules and above all allowing the non-reversibility of chemical reactions. This property should allow a self-organization of matter with perhaps the establishment of autocatalytic systems. This energy can come from photons from the Sun, from the temperature and pressure generated internally of a planetary body, or from oxidation-reduction processes with minerals (in hydrothermal vents for example). It is proposed that chemical systems, which are out of equilibrium and continuously supplied with matter and energy, can exhibit chemical selectivity, self-catalysis, and chemical replication properties. Once such a system is established, prebiotic chemistry may eventually lead to the formation of living systems.

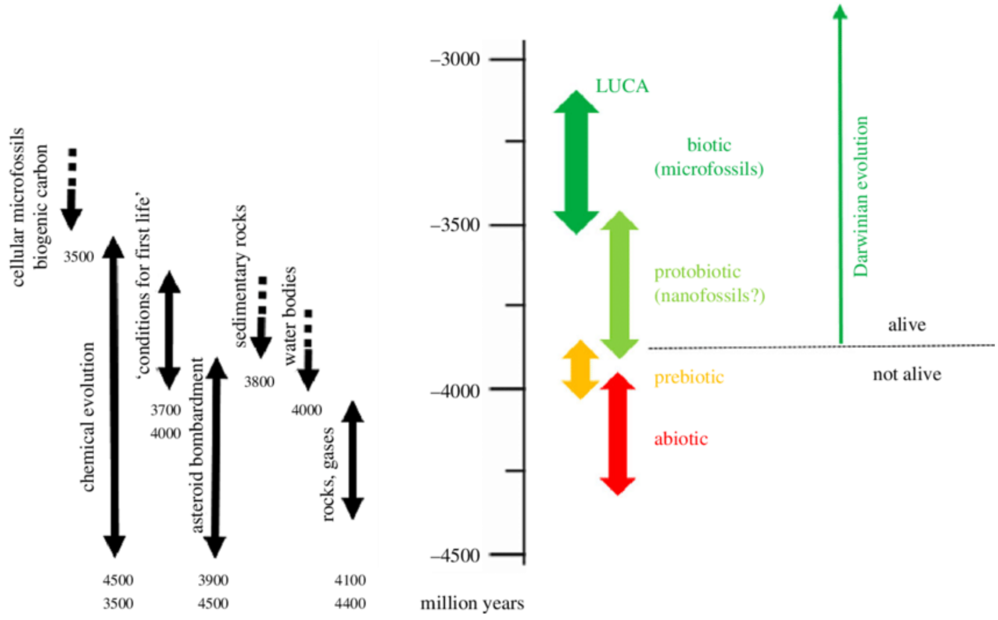

*Fig. 4 Origin of life as a planetary phenomenon. The geological timing data on the left. The abiotic to biotic progression is portrayed with speculative and somewhat arbitrary time demarcations, with some justifications as detailed in the text. The not-alive/alive demarcation, but which shloud be a continuum, is between prebiotic and protobiotic entities, defined by the emergence of replication and evolution. Credit : Lancet, Doron & Zidovetzki, Raphael & Markovitch, Omer. (2018).*

There would therefore not be a strict separation between an abiotic system and the biotic, but rather a continuity, passing through such prebiotic chemistry (Fig 4). how and where life has emergenced of life on Earth remains the most complex exobiological question and the possible chemical pathways are so numerous that it is not obvious that one day the answer will be found.

## Look for life elsewhere

To look for life elsewhere, you have to know what to look for, and one of the bases of Astrobiology, but also its weakness, is the search for life biologically similar to ours. The chemical distribution of atoms in the Universe has undeniably directed the use of carbon, nitrogen and oxygen for Life on Earth (Figure 5). It would be logical that these atoms are the same for other life forms in the universe, but with a structure of organic molecules possibly different from life on Earth.

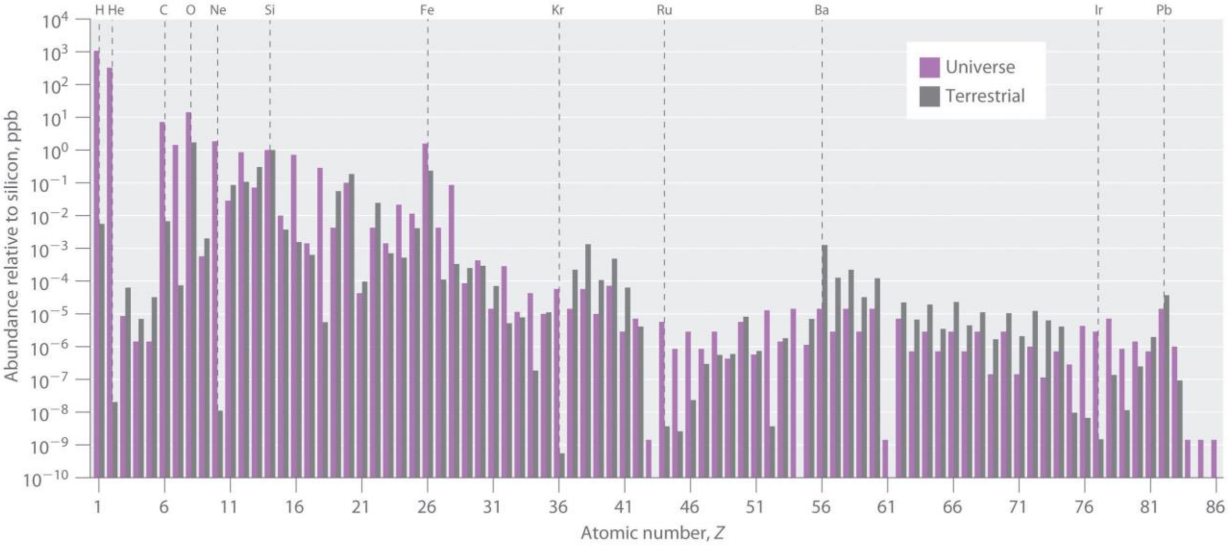

*Fig. 5 Abundance of chemical elements in the Earth and Universe (logarithmic scale). The most abundant elements after hydrogen and helium are oxygen, carbon, and nitrogen, apart from the inert gas, neon and closely followed by iron and nickel.*

Despite active research since the first Apollo missions, the exploration of many planets and some samples return (lunar from 1969, comets in 2006 and asteroids in 2010, 2023) no trace of life has yet been found in our solar system. The astrobiology community has therefore rethought and joined its knowledge to determine in which specific environments it would be possible to find signs of microscopic life. The research in prebiotic chemistry defined above brings, for example, constraints, based on terrestrial life. A new term has been defined to conceptualize this aspect of favorable environment; it is the notion of habitability. It was first proposed that a planetary body is habitable as long as it contains liquid water. In each planetary system, it will then be possible to define a habitable zone where liquid water may be present on the surface of bodies, depending on the size of the star, the distance of the planetary body from the star and the stability of its orbit to remain in the habitable zone (Fig. 6). In recent years, the definition of the habitable zone has been reviewed and greatly expanded with the discovery of the large oceans of liquid water beneath the icy surface of the Jupiter and Saturn's moons (Enceladus, Europa, Ganymede, Titan, Callisto) (Figure 6 ). The notion of habitability today refers to a habitable body, which, in addition to liquid water, would contain organic matter (C, H, N, O, etc.), energy (solar or thermal-geological activities) and a certain stability over time to allow life development. The search for life elsewhere therefore begins by first seeking out these habitable environments. The notion of habitability is a term debated within the Astrobiological community, because its definition is linked to the conditions that allowed the emergence and evolution of the only life (terrestrial) that we know and nothing tells us that we targets the right habitable objects by considering only those conditions. The extension of the habitable zone to subsurface environments (as shown in Figure 6), is one example of our research into the possibility of life in these environments in the solar system. In addition, studies in phylogeny and terrestrial biology have also imposed constraints on research when dealing with non-macroscopic life forms, such as microscopic bacteria, chemical traces, or fossils of possible current or past existence.

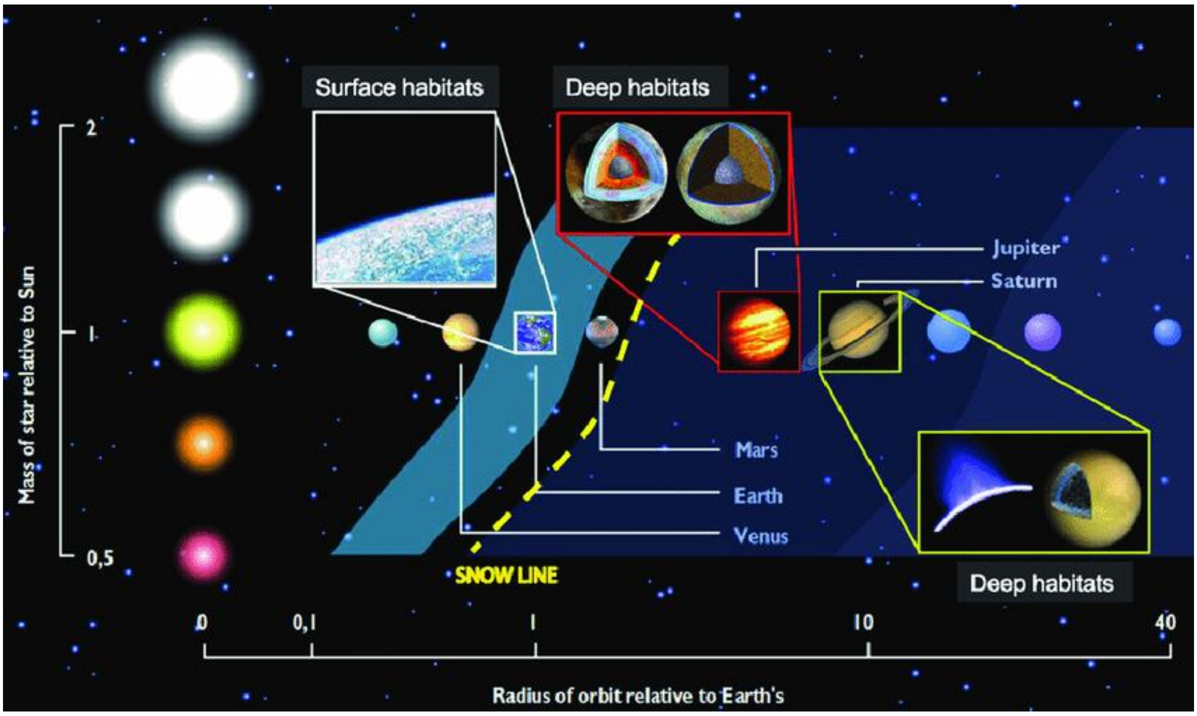

*Fig. 6 Schematic representation of habitable zones in the solar system. The habitable zone is defined where there is liquid water: this zone depends on the mass of the star and the distance of the body from the star for the water to be stable on the surface or under it. With this definition and in our solar system, the Earth would be just in the middle of the habitable zone while Mars is at the limit. The icy satellites of Jupiter and Saturn would also be habitable bodies due to the presence of liquid water under their layer of ice (Credits: Neal Powell, Imperial College, London).*

## A short tour of the planetary bodies of our Solar System and their astrobiology interest

Mercury, the closest planet to the sun, is too hot and with too little atmosphere to have created the necessary conditions for the development of life. Venus, our "sister planet", on the contrary, has a relatively complex organic chemistry, with sulfur and phosphorus molecules in an extremely dense atmosphere composed of more than 96% of $CO_2$. However, it is not in the habitable zone of the solar system because it lacks an essential component: water. Having benefited from exogenous inputs like the Earth after its formation, it is proposed that Venus may have had liquid water on its surface and a water-rich atmosphere 4.5 billion years ago and for some short time. But at present the surface of Venus is only active volcanism with temperatures around 460°C. If life developed on Venus at the most favorable moment, it is proposed that it survived in the form of microorganisms in the clouds of its atmosphere, much more lenient in terms of temperature (~75°C). Several space missions have studied Venus since the 1960s and despite proposals for the existence of extremophile microorganisms in the clouds of Venus, no evidence has been formally observed so far.

Mars, the fourth planet in the solar system has often been proposed as the best site in the solar system to have had, or still have, the possibility of life. Mars sparked the craze for the search for traces of life very early in the history of solar system exploration because British and Italian astronomers (William Rutter Dawes and Giovanni Schiaparelli) had reported seeing gigantic irrigation canals observing the surface of Mars in 1860-1870. These canals, interpreted as connecting inhabited areas, would have allowed the transport of foodstuffs between them. Despite the development of telescopes and the proliferation of observations, notably by Percival Lowell (1855-1916), it was not until the 1940s that these observations were confirmed due to new, less blurred observation data that better defined the contours of the craters and valleys of Mars. Overflights by American Mariner probes in the 1960s and 1970s definitively demonstrate the non-existence of channels on the surface of Mars. Nevertheless, the astrobiological interest for the planet Mars persists, because Mars presents relevant characteristics, which legitimize the possibility of a Martian life. The existence of microbial life was actually considered in the 1970s during the preparation of the Viking mission. The two landers were then equipped with instruments capable of carrying out three experiments intended to highlight Martian life, for example by detecting biological photosynthetic activity, or by providing nutrients to Martian bacteria. All three experiments gave negative responses, all interpretable by abiotic processes, such as surface oxidation leading to matter decomposition and $O_2$ outgassing. The Viking mission, however, confirmed the presence of liquid water in the past of Mars, by observing riverbeds, dry rivers or even dendritic valleys, confirming that the planet was, at least in the past, habitable. Later, hydrated rocks that can only form in an aqueous medium, such as clays or sulphates, were observed by orbiting probes and vehicles on the surface (such as Mars Express orbital probe).

With the observation of traces such as flows, deltas, or even signs of tsunamis near the coast, it was discovered that Mars had indeed had rivers, oceans and lakes on its surface. According to geophysical models, Mars could have had liquid water for at least 1 billion years on its surface. This water, still present in the minerals that currently cover the surface of Mars, has been identified by probes in orbit and rovers on the surface. At the present time, water ice is present at the pole in the ice caps and it is strongly suspected that water is present in greater quantities in the Martian crust (probably in the form of ice mixed with the minerals). The pressure on the Mars surface is currently excessively low to maintain liquid water (6 mbar). In the past however, and due to the presence of a now extinct magnetic field, Mars may have had a much denser atmosphere. The major handicap of Mars is to be a small planet, which did not have enough internal energy to maintain geological activity generating the magnetic field, essential for maintaining its atmosphere against the solar winds. Mars is considered a dead planet for a long time but on which life could have developed at the same time as on Earth and perhaps persist underground. Finding life on Mars would provide many answers about the appearance of life on Earth. Furthermore, if life were to exist on Mars, even in the form of microorganisms, and given that the planet is no longer geologically active, it should be possible to discover it in the form of fossil traces on the surface or even to hope that it has survived underground.

The atmosphere of Mars is thin and rich in $CO_2$, allowing the penetration of solar and cosmic rays over billions of years, resulting in a highly oxidizing and completely dry surface. The Phoenix mission's lander (2008) identified oxidants such as perchlorate and peroxides. Currently it has been shown that they are largely responsible for the degradation of organic matter on the surface and are contaminants for analyses carried out by rovers. We had to wait for the “Mars science laboratory” (MSL) mission with the “Curiosity” rover, which landed on Martian soil in 2012, to finally be able to determine whether Mars was composed of carbonaceous matter. This NASA/JPL mission carries on board an instrument capable of detecting and identifying organic molecules (sample analysis at Mars-SAM). It is a mass spectrometer with either an upstream gas chromatograph with a pyrolyzer to vaporize molecules and separate them, or a pulsed laser to desorb molecules from the sample surface. It was in 2015 that the first organic molecules were discovered (chlorinated aromatic rings and alkanes). Since then, other organic molecules have been analyzed in the Martian soil according to the mineralogical composition. In 2022, no molecule of the “building blocks of life” type has been identified to date, but studies are continuing in other places on the planet and new missions are planned. In particular, hopes rest on the exploration of the Mars subsoil, protected from surface oxidation and irradiation. Previous rovers have indeed already revealed that under the first centimeters of the surface, it was possible to have ice, but it is not known what happens beyond these first centimeters. The main future astrobiological mission to Mars is the ESA Exomars mission, which should dig up to 2 m deep to recover samples not altered by the surface and which could therefore contain much more preserved material. The Exomars mission also includes the instrument described above (GC-MS) and will analyze organic molecules. The mission was postponed to the end of the 2020s following world conflicts. Mars has not said its last word and remains a target of choice for research of traces of life and knowledge in planetology.

Other habitable bodies of astrobiological interest have been discovered in recent decades beyond the asteroid barrier, these are the satellites of giant gas planets. their related giant planets are of limited interest for astrobiology because they have no surfaces and therefore no rocks. On the other hand, they are of considerable importance for understanding the formation and origin of the solar system. It is their satellites that are of interest, in particular Ganymede, Callisto and Europa around Jupiter, Enceladus and Titan around Saturn. Revealed thanks to the Cassini-Huygens probe (1997-2017) which visited these worlds for 15 years, these icy satellites have surprised by their diversity and the abundance of liquid water they contain. Europa for example, would contain an ocean 10 times larger than on Earth, while the satellite is three time as small as Earth. This liquid water is maintained by the tidal effects generated by the gravitational attraction of the moons with Jupiter. On the side of Saturn, it is Enceladus, which is of particular interest to astrobiology with the discovery in 2014 of water geysers on its surface, which extend up to 100 km above its surface. Such observation has, revealed without any doubt the presence of an ocean under the ice sheet. Studies in astrobiology are then interested in the possible emergence of life in these environments, which have been defined as habitable (Figure 6). Saturn's largest satellite, Titan, is also of great interest due to the large amount of organic matter formed in its atmosphere. In 1980 and 1981, the Voyager-1 and Voyager-2 probes passed over Titan and revealed a world with an extremely dense atmosphere composed mainly of nitrogen and methane. The atmosphere is so dense that it obscures the surface of the satellite. The chemistry in Titan's atmosphere has proven to be extremely complex, notably resulting in the formation of organic aerosols that sediment on the surface. The Cassini-Huygens mission, of which Huygens was a lander that crossed Titan's atmosphere to land on its surface, confirmed this complex organic chemistry in the atmosphere. Stunning images of the surface covered with organic grains, dunes and hydrocarbon lakes were obtained. Astrophysical models have proposed that Titan may harbor an ocean of liquid water beneath its surface. Titan then presents all the ingredients previously defined for the emergence of a rich prebiotic chemistry and a possible form of life. Geochemical evolutionary models suggest that from the first million years after the formation of Titan, this subsurface ocean was in contact with the atmosphere, in which the first complex molecules would have felt. By analogy with the Earth, the presence of hydrothermal sources - which constitute a source of energy for organic molecules and a potential environment for prebiotic systems - is envisaged in this ocean of Titan. The possibility of life in the ocean of Titan cannot therefore be excluded and could have persisted for several billion years. The very ambitious new NASA mission (Dragonfly), which targets Titan should be essential from this point of view. Selected in June 2019 as part of NASA's New Frontiers programs, the mission should leave in 2027 and arrive on Titan in 2034. The novelty of this mission lies into the exploitation of the dense atmosphere of Titan (1.5 times that of the Earth) and its low gravity to fly an aeropter, named aerobot, with a mass of 450 kg on its surface. The scientific objectives are multiple, such as affirming the presence of an ocean in the subsurface of Titan, analyzing surface materials to identify molecules of astrobiological interest, characterizing Titan's meteorology, or even measuring seismic activity to determine Titan's internal activity. For this, the aerobot will have four groups of instruments on board, including a mass spectrometer coupled with gas chromatography (DraMS-GC), which is a French contribution with CNES and a legacy of the Martian missions.

## Beyond the Solar System

With the current state of knowledge and advances in the field of Astrobiology, it is very difficult to hypothesise an inhabited planet and the proven presence of life in our galaxy or beyond. There seem to be more and more potential sites for the development of life, but what about the actual development of life? Beyond our solar system, depending on the number of stars in the universe, it is likely that billions of other planetary systems exist, with habitable zones, organic matter and the energy necessary for life. It was in 1995 that Didier Queloz and Michel Mayor observed an exoplanet for the first time. Since then, and with the advancement of observation techniques, today (2023) more than 5500 exoplanets have been located, observed and listed in our galaxy. The discovery of these extrasolar planets has led to major discoveries, such as questioning the formation of our own solar system. The first detections of exoplanets revealed above all the presence of gaseous giant planets, of the Jupiter type, orbiting very close to their star in systems with 1, 2 or 3 planetary bodies. This paradigm compared to our solar system counting 8 planets, caused a thorough reconsideration of the hypothesis of our solar system's formation. New models of solar system formation have been studied. The most remarkable was proposed in 2011 by Kevin Walsh, Alessandro Morbidelli, and Sean Raymond and provided answers to a number of enigmas about the composition and position of the different bodies in our solar system. The model states that Jupiter would have upset the embryonic planets by migrating towards the sun and then would have returned to its current position, thanks in part to the presence of Saturn (Figure 7). The approach of Jupiter up to ~1.5 AU gradually truncated the protoplanetary disk and the material available downstream of Jupiter was reduced. This model makes it possible, for example, to explain the small size of the planet Mars and its disastrous fate, whereas in a model of static formation, Mars should have been larger than the Earth.

Another major discovery concerns the observation of a majority of red dwarf class stars in our galaxy. They are small stars, very active and with lifetimes of the order of a hundred billion years. In comparison, our sun will only live for about ten billion years and therefore if life developed (or did) on a planet around a red dwarf, it would have time to develop and become more complex, at least as much as on Earth. However, because of the low mass of red dwarfs (< 0.4 solar mass), exoplanets need to be relatively close to the star to be in the habitable zone. This results in a rotation speed on itself similar to their rotation around their star and they will therefore always present the same face at day or night. This parameter is extremely important because it will affect the climates and seasons of the exoplanet and therefore directly affect the potential forms of life.

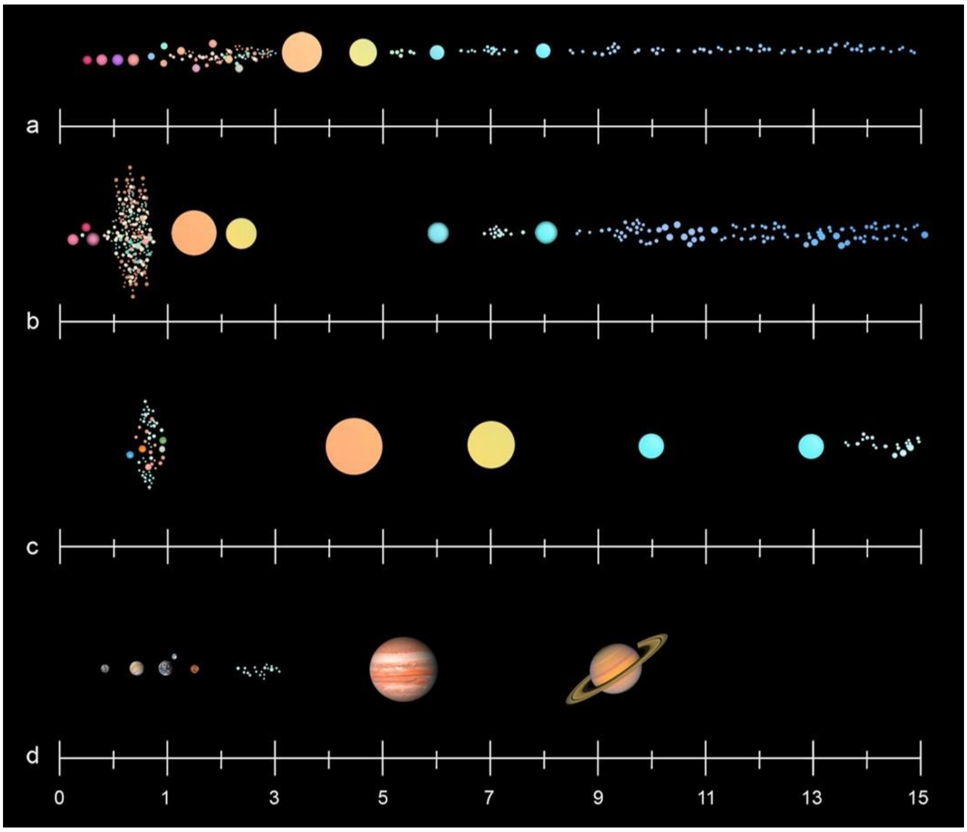

*Fig. 7 Schematic representation of the "grand tack" hypothesis to explain the formation of our solar system and its planets; a) beginning of the model with the formation of the giant planets in progress, then b) first migration of Jupiter towards the sun with Saturn, c) second migration of Jupiter towards the outer solar system carrying Saturn and pushing asteroids and comets beyond 13 AU, d) position of the planets currently with the asteroid belt between 2 and 3 AU. @ Black Alley*

It is also proposed that the presence of atmosphere on exoplanets located in habitable zones is a major habitability condition. Recently, exoplanets with water-rich atmospheres have been observed. However, we do not currently know all the scenarios favoring or altering the maintenance of an atmosphere on these exoplanets orbiting around stars of different types than our Sun.

The diverse exoplanets observed to date, with extremely varied rotation speeds, obliquities, and densities, make the notion of habitability even more difficult to define. The impact on the emergence or maintenance of life in these environments is still unknown and constitutes a significant area of research in Astrobiology.

## Conclusions

The studies in astrobiology, described here, reflect the difficulty and complexity of answering questions about the origin and evolution of life and the presence of life elsewhere. Interdisciplinarity is crucial in astrobiology and is key to major advances in the field.

In summary, astrobiology tries to determine if life could exist elsewhere in the universo, by studying our own origin and if so in what form, in order to try to answer an existential question: are we alone in the universe?

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