Archaeology of other worlds: quest for alien life – Review

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Abstract

Curiosity is a hallmark of modern humans (*Homo sapiens sapiens*), which likely contributed to their survival, avoiding extinction that suffered at least eight other human sub-species like Neanderthals (*Homo sapiens neanderthalensis*) and Denisovans (*Homo sapiens denisova*). Such human curiosity goes beyond the planet Earth, into deep space. Due to limitations related to the speed of electromagnetic waves, telescopes are time machines. For instance, the most distant galaxy (MoM-z14) is ~13.5 milliard light-years away, which means that what we see is how it was at that time. Therefore, such cosmological archaeology allows to see how the Universe was in the past. Contacts with putative alien civilizations could be interesting, but also potentially dangerous, as history in our planet has shown when civilizations collide. The Drake equation estimates a high probability of alien communicative civilizations. Yet, the Fermi paradox points out the lack of evidence for such civilizations. The rationale is that the origin of life may be an event as rare as the Big Bang. That could mean that life only exists on planet Earth. Colonizing other worlds could represent backups against extinction events. But physical limitations prevent humans to reach far-away worlds, unless new technologies beyond current scientific knowledge could be developed. In any case, special attention should be taken to care for our planet Earth, which as far as we know is the only living planet in the Universe.

Key words: Big Bang, biosignatures, cosmos, exobiology, known Universe, molecular biology, light speed, universe expansion.

Resumen

La curiosidad es un rasgo distintivo del ser humano moderno (*Homo sapiens sapiens*), que probablemente contribuyó a su supervivencia, evitando la extinción que sufrieron al menos otras ocho subespecies humanas, como los neandertales (*Homo sapiens neanderthalensis*) y los denisovanos (*Homo sapiens denisova*). Esta curiosidad humana trasciende el planeta Tierra y se adentra en el espacio profundo. Debido a las limitaciones relacionadas con la velocidad de las ondas electromagnéticas, los telescopios son máquinas del tiempo. Por ejemplo, la galaxia más distante (MoM-z14) se encuentra a ~3,5 millardos de años luz, lo que significa que lo que vemos es cómo era en aquel entonces. Por lo tanto, esta arqueología cosmológica permite observar cómo era el Universo en el pasado. Los contactos con supuestas civilizaciones alienígenas podrían ser interesantes, pero también potencialmente peligrosos, como la historia de nuestro planeta ha demostrado cuando las civilizaciones chocan. La ecuación de Drake estima una alta probabilidad de la existencia de civilizaciones alienígenas con capacidad de comunicación. Sin embargo, la paradoja de Fermi señala la falta de pruebas de tales civilizaciones. La razón es que el origen de la vida podría ser un evento tan excepcional como el Big Bang. Esto implicaría que la vida solo existe en la Tierra. Colonizar otros mundos podría ser una estrategia de copia de seguridad ante posibles extinciones. Sin embargo, las limitaciones físicas impiden que los humanos lleguen a mundos lejanos, a menos que se desarrollen tecnologías que superen el conocimiento científico actual. En cualquier caso, debemos prestar especial atención al cuidado de nuestro planeta Tierra, que, hasta donde sabemos, es el único planeta con vida del universo.

Palabras clave: Big Bang, biofirmas, cosmos, exobiología, universo conocido, biología molecular, velocidad de la luz, expansión del universo.

Introduction

As shown in previous reviews, archaeology meets molecular biology (Dorado et al. 2007-2024). And such research may be also applied to alien worlds (exobiology), as revied in this article. The rationale is that light is not instantaneous; it has a finite speed of ~299,792,458 meters per second (almost 300,000 km/s) in a vacuum. Although such speed is very high for human capabilities, it is extremely low in cosmological scenarios. That has an interesting consequence. What we see when we look at the outer space is not how it is now, but how it was ~1.3 seconds ago for the Moon, ~8.3 minutes for the Sun, 4.4 years for Alpha Centauri star system, and ~2.5 million years for Andromeda galaxy. To put that into cosmological perspective, the Big Bang happened ~13.8 milliard years ago. The Milky Way is estimated to be ~13.6 milliard years old. Our solar system formed ~4.6 milliard years ago. The most distant galaxy discovered so far is MoM-z14 (figure 1). Its light takes ~13.5 milliard years to reach planet Earth. But amazingly, such galaxy is now ~33.8 milliard light-years away from planet Earth, due to the expansion of the universe. Such light originated ~280 million years after the Big Bang (Naidu et al. 2025). Therefore, that allows to see (and try to decipher and understand) past times, which is the essence of archaeology. That is cosmological archaeology. And it is fascinating.

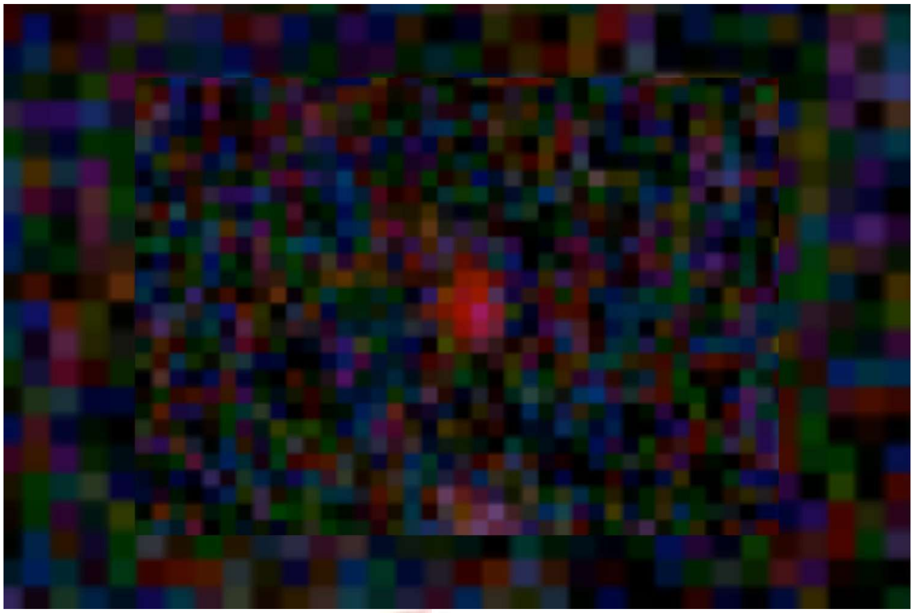

Figure 1. The most distant galaxy found so far is MoM-z14. It was discovered on 16 May 2025, using the James Webb Space Telescope (JWST). Previous telescopes did not have mirrors large enough to detect light coming from such large distances. © 2015 Naidu et al. (2025), Wikimedia Commons <http://commons.wikimedia.org> and Creative Commons <http://creativecommons.org>.

On the other hand, curiosity is a hallmark of current human sub-species (*Homo sapiens sapiens*). Such behavior probably was a key distinctive feature that saved us from extinction several times, during our biological evolution. That may contrast to other (at least eight) extinct human sub-species like Neanderthals (*Homo sapiens neanderthalensis*) and Denisovans (*Homo sapiens denisova*). In short, such curiosity made us wonder, for instance, what would be like the landscape beyond a mountain range or across seas and oceans. The consequence was a significant dispersion of modern humans across the planet Earth, colonizing virtually all habitats. Such behavior significantly increased our survival probabilities when environments were significantly modified; for instance, by drastic climate changes. All that is related to curiosity to know within planet Earth, but there is much more when looking much deeper in the planet and at the sky, as shown in the next section of this review.

On the contrary, it seems that other human sub-species rather remained in the same place, which reduced their survival odds in such changing environments. It must be taken into account that they belonged to the same *sapiens* species. That was recently discovered when new technological breakthroughs allowed to sequence their genomes (Dorado et al. 2008, 2015, 2016, 2021a). Thus, it was found that they inbred, generating fertile offsprings, which is the genetic definition of individuals of the same species. Therefore, they are not different species, but subspecies, although some modern humans seem to have difficulty recognizing such scientific-genetic fact, by definition. Besides, recent discoveries have shown that Neanderthals were not dumb, but as intellectually, emotionally and spiritually sophisticated or more than ourselves.

Curiosity to know beyond planet Earth

As described above, modern human curiosity is not restricted to the surface of Earth and water but also includes the exploration of much deeper inner and outer worlds, with a much larger range than before. That can be accomplished now using technologies that were not previously available. Examples include drilling the planet crust, as well as exploring the deepest ocean places. And –most significantly– observation and travel to Earth orbits, the Moon and beyond. The significance of such curiosity is not only the acquisition of new scientific information: the joy of knowledge (Beazley, 1977-1979). It has also the theoretical potential to protect us from future extinction events. There have been six major extinction events on planet Earth (Dorado et al. 2010, 2019). They include the Great Oxidation Event (GOE) and the Big Five (BF). The question is not if a new one will arise in the future, but when. Therefore, it would be convenient to colonize other worlds, besides our planet. They would represent backups when some critical catastrophe strikes.

Yet, a word of caution should be also considered in these scenarios. Watching the outer space is exciting, but sending messages out there could be dangerous. We may be eager to contact with alien civilizations, but when two civilizations make contact, one of them may dominates the other. At least, what is what has happened in human history. That should not be necessarily negative in theory, and in fact human civilization, prosperity, welfare and advancement have been accomplished that way in many instances. But it could be also disastrous for the weaker party, and that is what has usually happened in history. So, revealing our presence to a much advanced civilization in the Universe could mean the end of our culture and even existence. Yet, as explained below, most likely such potential danger is not real, for a shocking scientific reason.

Potential extinction scenarios in the future

There are different scenarios that could lead to extinction of humans, and even destruction of planet Earth, based on probabilities, including the certain one due to the Sun cooling and expanding to become a red giant, in about five milliard years (Dorado et al. 2010). They also include destruction of atmospheric oxygen in about one milliard years (Ozaki and Reinhard, 2021) and collisions with Andromeda galaxy in about five milliard years (Cowen, 2012; Sawala et al. 2025), although it seems now that other collisions with the Large Magellanic Cloud are more probable during the next 10 milliard years (Sawala et al. 2025).

The known Universe is reduced to the one that we can detect with the available visible-light and radio telescope technology. It must be taken into account the limitations of the speed of electromagnetic waves (300,000 km/s) and the fact that electromagnetic signals are blocked by matter in our galaxy (thus the two-cone shape of the known Universe pictures; figure 2). In such known Universe there are >200 milliard galaxies with >200 milliard stars each. The Drake equation tries to calculate the probability of communicative extraterrestrial civilizations in planets similar to ours. That should be very high in theory, if such equation is correct. But that is a great conditional “if”. In fact, the Fermi paradox points out the lack of evidence for such civilizations. As far as we know, life only exists in our planet Earth. In other words, there is a Great Filter preventing us to find alien life.

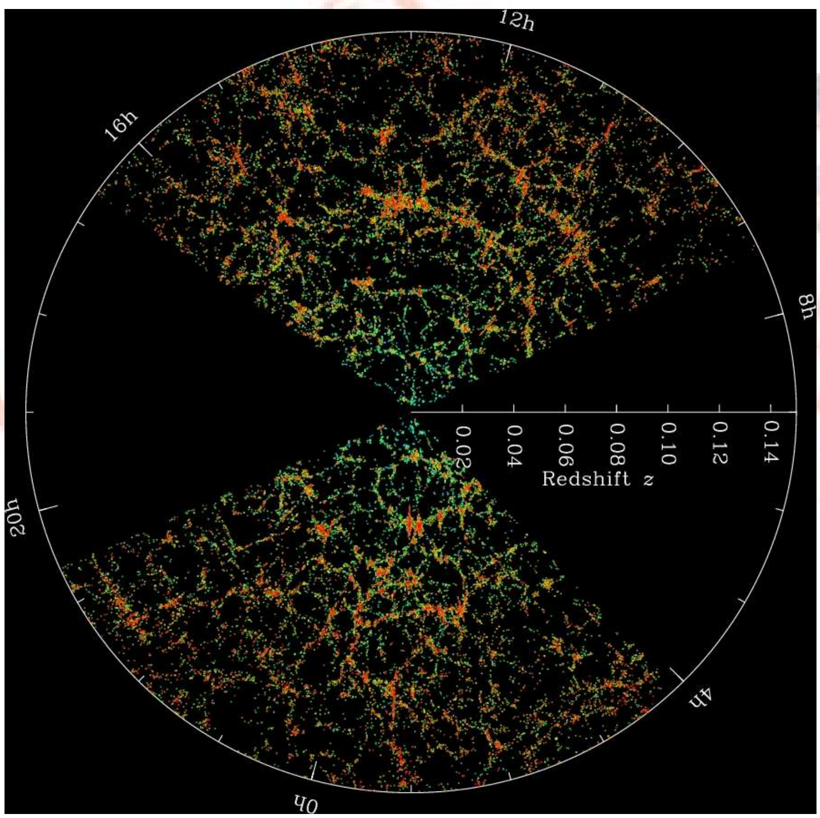

Figure 2. Known Universe. Earth is at the center, and each point represents a galaxy. The two empty cones were not mapped, because objects like stars, planets and dust in our galaxy obscure the view of the distant universe in such areas. © 2010-2013 M. Blanton and Sloan Digital Sky Survey (SDSS)-III <https://www.sdss3.org/science/gallery_sdss_pie2.php>.

That includes the self civilization destruction by means of pollution, climate change and global warming, as well as global nuclear war. Indeed, the famous scientist Carl Sagan proposed that we do not receive signals of alien intelligence because, probability, they annihilated themselves in such kind of fight. But as described below, the explanation for such Great Filter can be much basic and simple.

Molecular biology to explore outer worlds

So far, the search for alien life has been carried out mostly trying to identify biosignatures (detectable signs being unique to life), being are considered hallmarks of life on planet Earth. That includes biological molecules or products of biological activity, as are found in our planet. Concerning the potential forms and shapes of biological entities, Darwinian evolution is considered a path-dependent process. Therefore, as stated in the French book "Le Hasard et la Nécessité: Essai sur la Philosophie Naturelle de la Biologie Moderne" (in English, Chance and Necessity: Essay on the Natural Philosophy of Modern Biology; Monod, 1970), life forms and evolution depend on such two factors. Therefore, it would be expected that evolution may give rise to biological entities with different forms-shapes and functions (Grefenstette et al. 2024). Nevertheless, both evolutionary convergence and constraints should limit the process. Therefore, even though "surprising" biological entities may exist, if such constraints are universal, life anywhere is expected to be quite familiar to what is known in planet Earth (Sole et al. 2024). Of course, that is assuming that such hypothesis is correct.

Besides, it must be taken into account some concepts like the origin of life (abiogenesis), life (self-sustaining chemical system, capable of Darwinian evolution), habitability (survival of life) and biosignatures (as described above), which may be different in different scenarios (figure 3; Keller et al. 2025). Different biosignatures (and abiosignatures; formed by nonliving processes) have been proposed (figure 4; Chan et al. 2019), including the "The Ladder of Life Detection" tool (Table 1; Neveu et al. 2018), and organic-catalytic agnostic activities (Georgiou et al. 2023). They have been recently reviewed, including technosignatures (Jia et al. 2023).

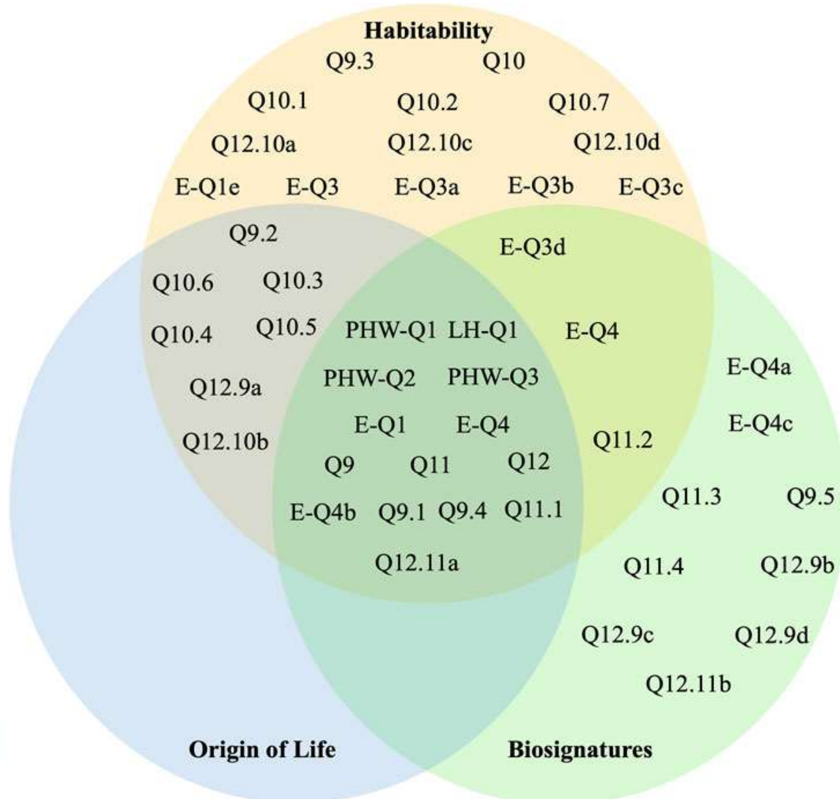

Figure 3. Exploration of origin of life in exoplanetary science. The Venn diagram shows relationships between origin of life (blue), habitability (orange) and biosignatures (green). © The authors, in Frontiers Media (Keller et al. 2025).

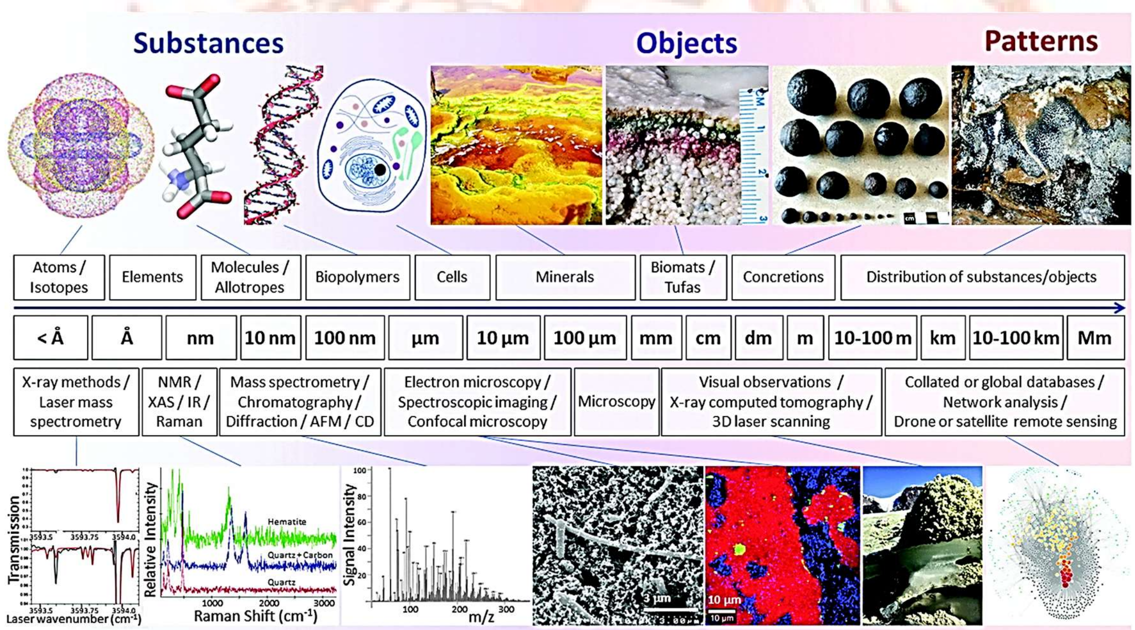

Figure 4. Proposed biosignatures. Such life detection methods range from atoms and molecules (left) to planetary ones (right). © The authors, in Mary Ann Liebert (Chan et al. 2019)

Table 1. "The Ladder of Life Detection" tool. This is a proposed procedure to design exobiology experiments, to help ascertain the putative presence of microbial life in space missions. © The authors, in Mary Ann Liebert (Neveu et al. 2018).

	RUNG (Roughly, subjectively ordered by (top to bottom): 1. decreasing strength of evidence for life 2. increasing ease of measurement)	FEATURE (Listed in no specific order within a given rung)	MEASUREMENT	TARGET	LIKELIHOOD (... that the feature would be a biosignature, given the criteria to the right)	INSTRUMENTAL CRITERIA			CONTEXTUAL CRITERIA				
						Quantifiable (Detectability)	Contamination-free (Likelihood of false positive)	Repeatable	Detectable (Detectability)	Survivable (Likelihood of false negative)	Reliable (Ambiguity of feature)	Compatible (Specificity to Earth life)	Last-resort (Ambiguity of interpretation)
LIFE	Darwinian evolution	Changes in inheritable traits in response to selective pressures	Not practical under mission constraints	• In situ • Sample return	No	-	-		-	N/A (extant)	-	-	-
LIFE	Growth & Reproduction	Concurrent life stages or identifiable reproductive form, motility	Cell(-like?) structures in multiple stages	• In situ • Sample return	Low	Hard	Low		Med (don't identify stages, timing off, sample size low)	High?	Ambiguous. What is a cell? What morphological differences exist?	Earth	Med / High
LIFE	Metabolism	Major element or isotope fractionations indicative of metabolism	Deviation from abiotic fractionation controlled by thermodynamic equilibrium and/or kinetics	• Remote sensing • In situ • Sample return	Low / Med	Easy	High		Medium	High	Hinges on understanding of context	Earth?	Low
LIFE	Metabolism	Response to substrate addition	Waste output (compound, heat)	• In situ • Sample return	Low / Med	Easy	Low		High	N/A (extant)	Hinges on understanding of context	Earth	Medium
LIFE	Metabolism	Co-located reductant and oxidant	Deviation from abiotic distribution controlled by thermodynamic equilibrium and/or kinetics	• Remote sensing • In situ • Sample return	Med / High	Med (linked to specificity of instrument)	Low / Med	Number of replicates depends on: • Characteristics of the instrument, • Heterogeneity of the sample, • Likelihood of systematic errors, • Required values of the relevant statistical parameters, • Value and cost of information.	Med / High	High	Mixed reactions, large inventory of chemistries	Generic	Low / Med
LIFE	Molecules & Structures Conferring Function	Polymers that support information storage and transfer for terran life (DNA, RNA)	Abundance	• In situ • Sample return	Low	Hard (instrument specificity must be high); RNA hard to measure on Earth	DNA: high; RNA: low (reactive)		Low (technology limited, only terran); RNA highly reactive	Low (hydrolysis in water)	Reliable	Earth	Negligible
LIFE	Molecules & Structures Conferring Function	Structural preferences in organic molecules (non-random and enhancing function)	Polymer with repeating charge	• In situ • Sample return	Low / Med	Need a lot of material and overprinting must be discernable	Low		Med / High	Low (hydrolysis in water, diagenesis)	How much preference needed to detect?	Generic	Low
LIFE	Molecules & Structures Conferring Function		Enantiomeric excess > 20% in multiple amino acid types	• In situ • Sample return	High	How much excess necessary?	Low		Low	Medium	Mixed sample both processes present	Generic	Low
LIFE	Molecules & Structures Conferring Function	Pigments as evidence of non-random chemistries (e.g. specific pathways)	Spectral feature and/ or color, otherwise see "structural preferences"	• Remote sensing • In situ • Sample return	Low / Med	Easy (fluorescence)	Low		Low (limitation of what we are looking for)	Low (diagenesis)	How to define pigment as we don't know it?	Earth (can one abstract?)	Very low
SUSPICIOUS BIOMATERIALS	Potential biomolecule components	Organics not found abiotically (e.g. hopanes, ATP, histidine)	Presence	• In situ • Sample return	Medium	Easy if enough material	Low		High	High	Low	Earth?	High
SUSPICIOUS BIOMATERIALS	Potential biomolecule components	Complex organics (e.g. nucleic acid oligomers, peptides, PAH)	Presence	• Remote sensing (PAH) • In situ • Sample return	High	Easy if enough material	Low		High	Medium	Abiotic production known	Generic	Med / High
SUSPICIOUS BIOMATERIALS	Potential biomolecule components	Monomeric units of biopolymers (nucleobases, amino acids, lipids for compartmentalization)	Presence	• Remote sensing • In situ • Sample return	Med / High	Limit of detection, need a lot of material	High		High	Med (diagenesis)	Abiotic pathways known	Generic	Medium
SUSPICIOUS BIOMATERIALS	Potential metabolic byproducts	Distribution of metals e.g. V in oil or Fe, Ni, Mo/W, Co, S, Se, P	Presence	• In situ • Sample return	Medium	Easy except background issue	Low		High	High	Background known	Generic	Medium
SUSPICIOUS BIOMATERIALS	Potential metabolic byproducts	Patterns of complexity (organics)	Deviation from equilibrium (P(Poisson distribution of pathway complexity) < 0.01?) or abiotic kinetic distribution	• In situ • Sample return	High	Background issue, material limited	Low		High	Medium?	Limited documentation of abiotic vs. biotic differences	Generic	Medium
SUSPICIOUS BIOMATERIALS	Biofabrics	Textures	Biologically mediated morphologies, preferably with co-located composition	• In situ • Sample return	Medium	Medium	Low		Medium	High?	Highly ambiguous	Earth	High
	Habitability	Liquid water, building blocks, energy source, gradients		Redox, temperature, pH, energy, disequilibria									

Of course, in relation to that, the discovery of megastructures could allow to identify alien life, and in such a case, the existence of intelligent life. Yet, so far none has been identified. Among the biosignatures, translation products have been recently proposed (McKaig et al. 2024). But alien life could be different to what we know in our planet (Cleaves et al. 2023; Grefenstette et al. 2024). So much that even machine learning (ML) algorithms based on artificial intelligence (AI) have been developed to identify agnostic molecular biosignatures. They are based on pyrolysis-gas chromatography (GC), coupled to mass spectrometry (MS) (GC-MS) (figure 5; Cleaves et al. 2023).

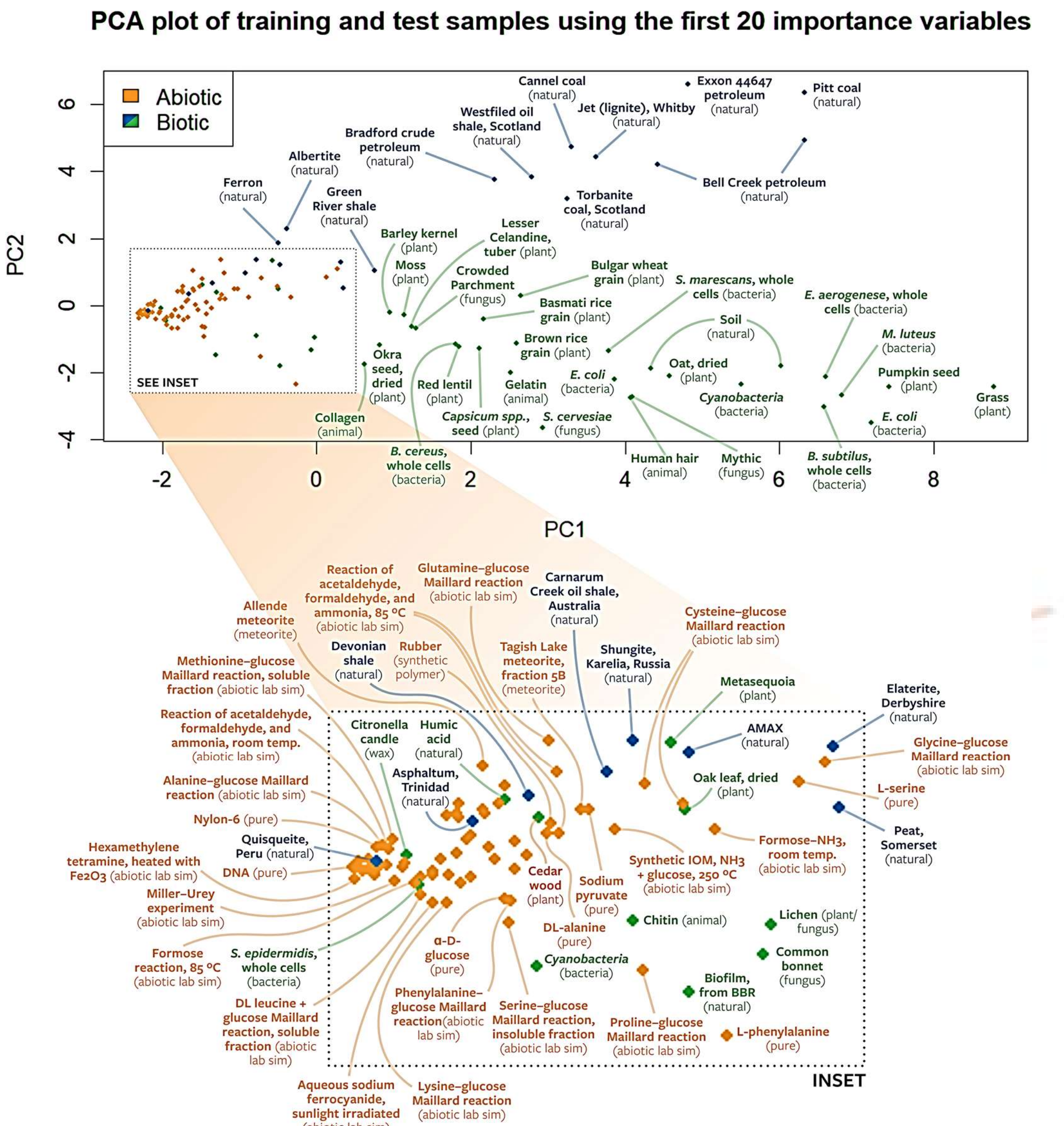

Figure 5. Proposed agnostic biosignatures based on artificial intelligence and machine learning. Abiotic, living and taphonomic suites of organic molecules are arranged in clusters. Abiotic (orange) and biologically-derived samples (green/blue) are shown. Taphonomically-modified biological samples (blue) are separated from contemporary biological samples (green). © The authors, in National Academy of Sciences (Cleaves et al. 2023).

Additionally, an interesting approach has proposed the use of molecular biology to obtain information that could reveal alien life. Thus, the power of nucleic-acid technologies could be used to identify life, even when not based on nucleic-acids. The rationale is that aptamers (single-stranded DNA or RNA molecules that fold into specific 3D shapes) can bind both inorganic and organic molecules. Then, such molecules could be analyzed, to tell apart signatures derived from non-living versus living systems. Besides, the corresponding aptamers could be amplified/sequenced (Johnson et al. 2018). But, also as explained below, such biosignatures may not exist.

Concluding remarks and future prospects

Searching for alien life is exciting. But the Fermi Paradox raises a word of caution. In fact, it is not surprising that we have not been able to identify alien life. All filters previously indicated should be considered. One of them is the limitation of the speed of electromagnetic waves. Such restriction not only applies to signals or communication messages, but also to travel. No starship can reach such speed, and even it that could be accomplished, we could not explore most of the Universe. Such problem increases with time, due to the Universe accelerated expansion. Unless, of course, that there is some scientific knowledge that we have not gained yet, allowing to travel at higher speeds, as happens in science-fiction movies. As an example, the idea that physics had reached its peak knowledge was prevalent around the end of the 18th and the beginning of the 19th century, shortly before the discovery of electromagnetism in 1820. At that time, it was thought that classical mechanics provided a complete and final framework for physics, making any further discoveries highly unlikely. As it is known, electromagnetism opened an amazing new field of developments and further discoveries, in which much of our current technology is based. So, we must spend much more resources and time in scientific research and less fighting between ourselves, contaminating, changing environments including climate, and eventually destroying planet Earth.

But there is more. In fact, the explanation to the Fermi paradox could be much more basic than all that. Probably, the generation of the first cell (abiogenesis) is so unlikely as the Big Bang event that generated our Universe. Once the first cell arises, the rest is a matter of time, including the evolution from prokaryotic to eukaryotic cells. In other words, the generation of the first cell from lifeless matter would be almost impossible (albeit not impossible; as the Big Bag is). Since in 13.8 milliards, each of them happened once. And we are lucky that they happened. Because they may require much longer times to happen. But again, only scientific research can determine the truth of all these possibilities. In any case, that highlights the relevance of taking care of Earth, being the only known living planet in the Universe.

To summarize, the incredibly small (quantum mechanics world), the incredibly large (accelerating expanding Universe) and abiogenesis are the three most exciting and provocative mysteries of nature. Although we have gathered significant knowledge about them in recent years, we still do not know the answer to basic questions to fully decipher them. We do not know if we ever will have such knowledge, but that is the scientific challenge, and what makes it even more provocative and interesting.

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