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Astrobiology in Europe from a scientific and policy making level

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1. Scientific summary

This thesis investigates the state of astrobiology in Europe, focusing on its scientific advancements and the policy landscape that influences its development. Astrobiology, the study of life's origins, evolution, and potential existence beyond Earth, has gained prominence since the European Space Agency (ESA) recognized the field in 1996. The research identifies key players, including ESA's Scientific and Human Robotic Exploration directorates, the European Astrobiology Network Association (EANA), and the European Astrobiology Institute (EAI). Despite significant progress, such as the ExoMars mission, the field faces challenges, including limited industrial participation and fragmented funding mechanisms.

Through interviews with stakeholders and a comprehensive literature review, the thesis addresses several research questions. It concludes that while astrobiology is increasingly featured in ESA's strategic plans, it has not yet achieved focal point status in Europe's space endeavors. The political landscape reveals a contrast with the United States, where private sector involvement in astrobiology is more pronounced. The thesis identifies critical bottlenecks, such as bureaucratic delays in funding and implementation, insufficient public visibility, and the lack of appropriate platforms for astrobiology experiments in space.

To enhance Europe's position in astrobiology, the thesis proposes several solutions: developing "applied astrobiology" to bridge fundamental research with commercial viability, appointing dedicated science communicators to raise public awareness, extending patent protection for astrobiology innovations, and improving coordination between EANA and EAI on the one hand, and industry and education on the other hand. The findings underscore the need for a unified strategy to secure Europe's leadership in the quest to understand life in the universe.

2. Popularizing summary

This master's thesis explores the exciting field of astrobiology in Europe, which looks into the origins of life and the possibility of finding life beyond Earth. Since the European Space Agency (ESA) began taking the field seriously in 1996, significant progress has been made, including missions like ExoMars, which aim to uncover the mysteries of life on other planets.

The research highlights the key organizations involved in astrobiology, such as ESA, the European Astrobiology Network Association (EANA) and the European Astrobiology Institute (EAI). However, it also reveals that there are challenges, including limited support from private companies and complicated funding processes that slow down research and exploration. Furthermore, the thesis answers important questions about the current state of astrobiology in Europe, comparing it to the more integrated approach seen in the United States, where private companies play a major role. It suggests ways to improve the situation, such as focusing on practical applications of astrobiology that could benefit life on Earth, increasing public awareness through better communication, and fostering collaboration between different organizations.

In summary, while Europe has made strides in astrobiology, there is still much work to be done to ensure it remains a leader in the exploration of life in the universe. The decisions made today will shape the future of this fascinating field and our understanding of whether we are alone in the cosmos.

3. Literature review

3.1 Introduction to astrobiology

3.1.1 What is life?

The origin, evolution, distribution and potential future of life throughout the universe are investigated by the field of astrobiology (Kaufman, 2022). However, defining the term of *life* is a very complex matter. The concept of life has been explained in numerous ways throughout history as multiple scientific and non-scientific fields come together to try and answer the question of what life is in a comprehensive way. Each definition emphasizes particular characteristics, associated with either physical or non-physical aspects that sustain life, which ought to be essential for something to be considered “alive”. No consensus has been reached for an unambiguous definition of life to this day. Our notion of life is deeply intertwined with a dynamic world, as well as with human self-perceptions. Consequently, the biological understanding of life is closely connected to philosophical, theological, cultural, societal, and political perspectives on life (Dunér, 2023; Preiner *et al.*, 2020).

Nonetheless, humans have investigated life and biology for centuries thanks to scientific research. Hence, we can attempt to characterize our life on Earth progressively. Currently, life’s characterization is based on the following list of descriptive properties: self-organization, growth, homeostasis, response to stimuli, storing of data and Darwinian evolution (including metabolism, reproduction and adaptation). Whether these characteristics are valid for life in the whole universe is not known (De Mol, 2023; Gayon *et al.*, 2010).

Although researching life on Earth leads to new insights, many uncertainties remain present, such as the origin of life. It has been established however, that life on Earth is dependent on carbon chemistry and liquid water. The main essential atoms related to living entities are carbon, hydrogen, nitrogen, oxygen, phosphorus and sulfur (CHNOPS). Carbon serves as the base scaffold and makes chemical bonds with other elements, resulting in various kinds of molecules. These molecules can diffuse, interact and reorganize in liquid water. Eventually, from these abiotic compounds, biological building blocks are assembled (Segura *et al.*, 2022). CHNOPS logically are quite common on Earth, but they are abundantly present on other planets, moons and comets as well. As these elements originate from the interior of stars, they are released in enormous amounts upon a star’s explosion. They can become part of molecular clouds, which in turn can evolve into protoplanets and other celestial structures. Hence, the wide distribution of CHNOPS beyond Earth makes a first reasoned argument for the possibility of life beyond Earth (Krijt *et al.*, 2022).

3.1.2 A brief history and context of astrobiology in Europe

In the past, astrobiology was primarily considered as the study of extraterrestrial life, often dismissing it as a speculative or fictional field. However, since the revolutionary discovery of exoplanets and extremophiles in the late 20th century, the view on astrobiology and its relevance has changed drastically. The scientific community was compelled to acknowledge and accept astrobiology, resulting in proper research being conducted (Mix *et al.*, 2006; Nascimento-Dias and Martinez-Frias, 2023). Now, astrobiology has evolved into a multidisciplinary field, which aims at solving ancient old fundamental questions, such as "How does life appear and evolve? Is there life elsewhere in the Universe and can it be detected? What is the future of life on Earth and beyond?" (Huynh, 2020).

The misconception that astrobiology is merely focused on the biology of extraterrestrial origin, is still quite common. This is a subsection, called exobiology, of the overarching astrobiology research. Astrobiology is a truly multidisciplinary field, which explores the fundamentals of life as a planetary phenomenon, encompassing its evolution and boundaries. Operations of course include the design of space missions to search for biosignatures or life elsewhere in the cosmos, but also research in certain terrestrial environments that are similar to domains found in space (i.e. planetary field analogues). Additionally, laboratory set-ups are implemented as well to mimic planetary and deep space conditions (i.e. laboratory analogues). Hence, research on life in the universe naturally requires an understanding of life on Earth and the nature of the environments that support it (Ledeberg, 1963; Mix *et al.*, 2006; De Mol, 2023; Martins *et al.*, 2017).

After the acceptance of astrobiology as a scientific field by the European Space Agency (ESA) in 1996, the first European initiative within this research field was establishing the ESA exobiology team. This team was tasked with assessing the state-of-the-art exobiology and related topics. They started investigating life in extreme conditions, other celestial bodies potentially harboring life, the use of planetary field analogues and made suggestions on future efforts to search for life in our Solar System (Brack *et al.*, 1999a; Brack *et al.*, 1999b; Horneck *et al.*, 2016). Five years later, the European Astrobiology Network Association (EANA) was established during ESA's first European workshop on astrobiology (EANA, 2024).

In 2016, the first European roadmap for astrobiology research was developed by the AstRoMap project, funded by the European Comission's 7th Framework Programme (FP7). The AstRoMap Consortium consisted of six partners from five European countries and was led by INTA Centro de Astrobiología in Spain. In addition to the five official partners, the project also benefited from the active participation of EANA (AstRoMap, 2025). Within this roadmap, astrobiology is considered the "*study of the origin, evolution, and distribution of life in the context of cosmic evolution; this includes habitability in the Solar System and beyond*." (Horneck *et al.*, 2016). The creators of the roadmap have determined five topics of interest, which represented European priorities within astrobiology research at that time, and set the foundations of astrobiology goals today. The research topics included the origins and evolution of (i) planetary systems, (ii) organic compounds, (iii) organic synthesis on Earth, (iv) life and habitability, and (v) biosignatures. Of course, progress in astrobiology research means that these research foci have evolved for current European astrobiology. Nonetheless, the European roadmap laid the groundwork for a European Astrobiology Institute (EAI), which was intended to provide the required coordination and funding to implement the aims delineated in this European roadmap (Horneck *et al.*, 2016). The roles and impact of EANA and EAI is further discussed in sections 6.1.2 and 6.1.3. Today, astrobiology is progressively more involved in science and becoming one of the foci of space missions; astrobiology centers, institutes and programs are established, and Europe is playing a leading role within this evolution (Milligan *et al.*, 2018).

The nature and interdisciplinary character of astrobiology make it a unique and rapidly evolving field, touching upon many different (scientific) domains. The questions astrobiologists try to resolve, change with insight gained on life on Earth and the continuous discovery of new exoplanets. Today, questions are posed on how to undisputably distinguish between life and non-life. Furthermore, astrobiology brings along societal implications. Operations need to be worked out with scientific rigor, but also with careful consideration of ethical, legal and practical issues. Social responsibility and the impact of science and technology need to be considered herein. This logically influences astrobiology policymaking. One such prominent issue is the trade-off between astrobiological exploration and planetary protection. Additionally, cross-disciplinary perspectives are essential components of the evolving astrobiology narrative. The public and space communities should be informed alike, in order to foster better-informed decision- and policymaking (Persson *et al.*, 2018; Milligan *et al.*, 2018; Race *et al.*, 2012).

The search for life in the universe needs a flexible and open-minded approach, where we constantly challenge existing ideas, rethink our methods, and adjust our criteria as new discoveries, technologies, and insights emerge. By reviewing the foci of the European roadmap and the EAI working groups, it is clear that the **origin of life on Earth** is a fundamental part within this search for life. As the early prebiotic conditions and history of Earth have been lost over time, searching for life on other celestial bodies can lead to insights on early Earth and the conditions when life first emerged. Research into the origin of life is a good example of how different disciplines need to integrate to comprehend the subject. It is one thing to solve the prebiotic pathways that could have led to life on Earth, which already requires knowledge from a combination of sciences (e.g. biology, chemistry, computational sciences, geology etc.), but we should also consider how life interacts with planetary processes and how these processes, in turn, affect the evolution of life. For this, even more disciplines need to come together for a comprehensive scientific explanation of the processes and outcomes, which is necessary to enable future predictions (Race *et al.*, 2012; De Mol, 2023).

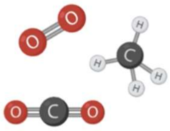
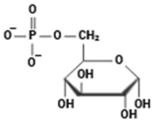
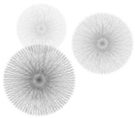
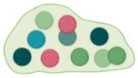
Another crucial branch within astrobiology is the research of **life in extreme conditions**, underscoring its interdisciplinary character once more. Extremophiles are microorganisms that thrive in extreme conditions found in certain environments on Earth, such as hot springs, glaciers, acid-mine drainages, soda lakes, high-radiation environments etc. These environments are all characterized by one or several extreme constraints for life. Remarkably, life has been discovered thriving in these extreme habitats, offering valuable insight into the limits of life. These incredibly harsh conditions are present in outer space as well, making it very interesting to study the biology and adaptation mechanisms of these extremophiles (Thombre *et al.*, 2020; Rampletto, 2013; Mottl *et al.*, 2007). Moreover, the investigation of extreme life on Earth is extended to the space environment by way of exposure experiments. The Biology and Mars experiment (BIOMEX) for instance, was an ESA/Roscosmos exposure experiment conducted in the EXPOSE-R2 facility on the International Space Station (ISS) in 2014. The aim of BIOMEX was to investigate the stability and degradation of biosignatures, as well as the viability of various extremophiles, in space and simulated Mars conditions, as a pretest in Low Earth Orbit (LEO). The findings contribute to understanding Mars's habitability, the limits of life, and the potential for lithopanspermia, while also serving as groundwork for future experiments on the Moon (de Vera, 2019). The ability of life to adapt to extreme conditions increases our belief and the likelihood of finding life within our Solar System and beyond.

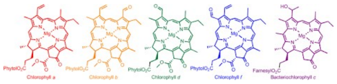
The habitats of extremophiles are a valuable source of information as well, specifically on habitability. Their (geo)chemistry and topological features mimic specific environmental conditions found on other planetary bodies beyond Earth. Hence, they are called planetary field analogues (PFAs). A notable example is the acidic river water in Rio Tinto, Spain, which has been studied for its biological processes, offering insights into the types of bacteria that could have existed on Mars. Other regions such as hot springs, deserts and permafrost areas in the Himalayas serve as analogues for Mars, Europa, and Titan. In addition to providing fundamental insight, these sites are also used to test equipment for space missions (Thombre *et al.*, 2020; Cavicchioli, 2002; Amils *et al.*, 2014).

Research into **biosignatures and habitability** are of paramount importance to the field of astrobiology, as they involve identifying signs of life and evaluating extraterrestrial environments in terms of their potential to support life respectively (De Mol, 2023). A more detailed review on biosignatures and planetary habitability is given in sections 3.2 and 3.3.

3.2 Biosignatures

As mentioned previously, there is no universally accepted definition of life. Consequently, the detection of life beyond Earth depends on identifying biosignatures (De Mol, 2023). These biosignatures are phenomena or features that potentially indicate past or present existence of life and can be divided into ten broad categories according to NASA, which are listed and explained below (Hays *et al*., 2015; De Mol, 2023; Schidlowski, 2001; Chan *et al*., 2019).

Stable isotope patterns 	These include unique isotopic patterns that require biological processes for their formation, such as the $^{13}C/^{12}C$ redistribution on Earth.
Atmospheric gases 	These point to gases which are produced by metabolic or aqueous processes and can be detected at planetary scales, i.e. carbon dioxide and methane.
Chemical features 	These encompass features or anomalies originating from substances that are formed or altered by life, i.e. many metabolites or proteins.
Minerals 	These represent (bio)mineral phases established by biological activity and characterized by a certain composition or morphology i.e. carbonate minerals.
Organic matter 	This implies organic compounds solely formed by biological processes, which do not have an abiotic source, i.e. lipids or polysaccharides.
Microscopic structures and textures 	These are microscopic structures, textures, fossils and films which have a biological origin, i.e. stromatolites.
Macroscopic physical structures and textures 	These include larger fossils or biofilms and indicate microbial ecosystems or larger organisms.

Surface reflectance features  	These include biological pigments which can potentially be detected remotely by their reflectance on a large scale i.e. chlorophyll.
Temporal variability 	This concept designates changes over time in atmospheric gases, surface features or reflectivity, which suggests the presence of life.
Technosignatures	These refer to artificial signals or large environmental modifications which would come from technologically advanced civilizations.

3.2.1 Context of biosignatures

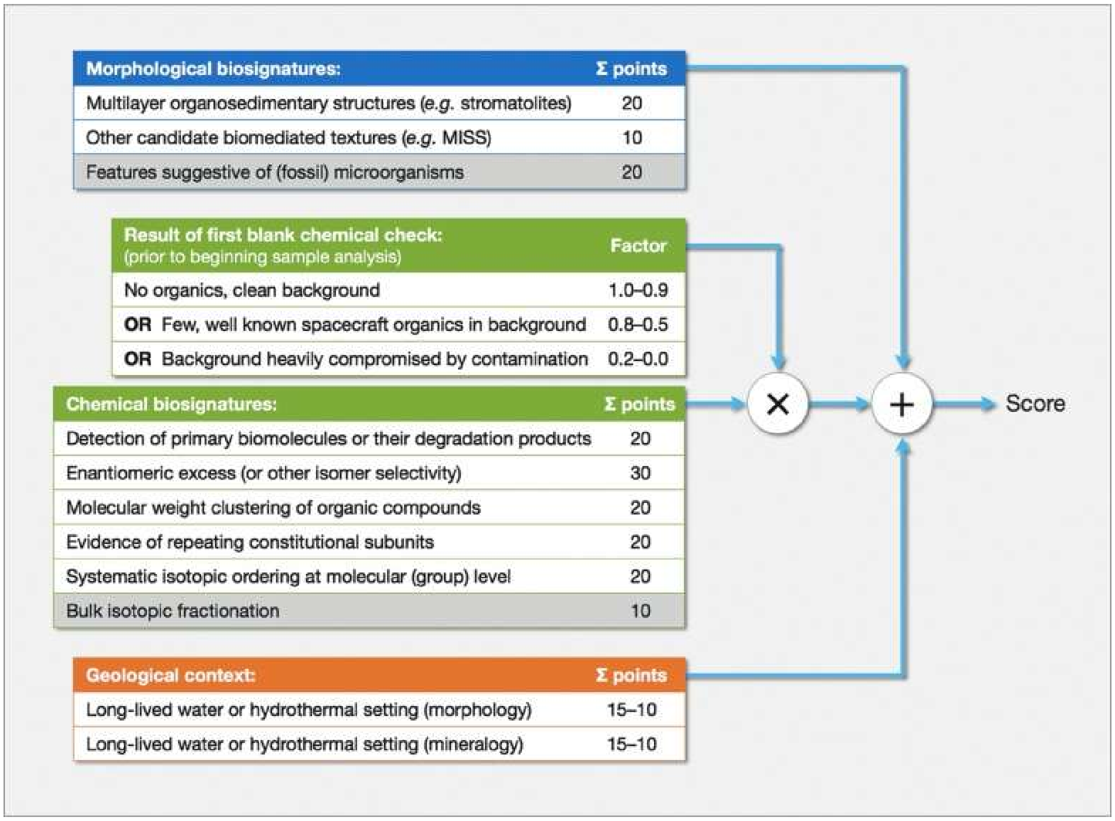
A biosignature, in its strictest sense, is defined as an observation that must have a biological origin to account for its presence, with all possible chemical or physical explanations ruled out (Harman and Domagal-Goldman, 2018). However, in practice, a biosignature represents a potential indicator of life. For instance, detecting certain changes in an environment might suggest the presence of life, but it is crucial to ensure these changes are not the result of purely chemical or physical processes. While chemical explanations are often possible, the likelihood of these explanations is frequently a topic of debate. Therefore, it is essential to evaluate all factors carefully to avoid interpreting a biosignature as a false positive. Such misinterpretations have led to global discussions among scientists and policymakers in the past, complicating astrobiology funding acquisition and discrediting the scientific field (i.e. Allan Hills 84001 meteorite) (Choi, 2016). On the other hand, false negatives, caused by the masking or destruction of biosignatures, present a significant challenge as well. Physical and chemical processes can weaken biosignatures to the point where they are barely detectable (Schwieterman *et al.*, 2018; National Academies of Sciences, Engineering, and Medicine, 2019a). A notable example hereof is the presence of perchlorates on Mars, which oxidize organic matter (Viso, 2023a). As the Viking missions preceded the detection of these perchlorates, the resulting data were ambiguous, resulting in an impact on funding for further astrobiology related missions to Mars (De Mol, 2023). Mars missions with an astrobiology incentive and their impact are discussed in more detail in section 3.4.1.

Consequently, a biosignature alone does not provide unequivocal evidence for the detection of life as the planetary and environmental context of the observation is of crucial importance for a correct interpretation. Hence, interdisciplinarity again is required for accurate and comprehensive detection and interpretation of biosignatures. Typically, data from fieldwork, laboratory experiments and space missions are combined by scientists from different fields. In such a way, they are able to account for biological processes, chemical organic molecule formation and geological planetary surface factors. Next to this, scientists need to communicate with engineers and technologists to design novel instruments to accurately detect biosignatures remotely or *in situ*. These designs do not only need to be performant in remote and uncharted environments, but they also need to be robust to accommodate logistic and technical constraints associated with space travel. Essentially, the interdisciplinary framework means that true biosignatures can be distinguished from abiotic signals effectively (Hays *et al*., 2015; Catling *et al*., 2018).

3.2.2 The ExoMars biosignature scoring grid

Biosignatures are extensively searched for, both on exoplanets and celestial bodies in our own Solar System, to evaluate their habitability. While various planets, asteroids and icy moons have been the focal point to look for signs of life, Mars has historically gained the most attention. The ExoMars mission, initially a collaboration between ESA and Roscosmos, focused on searching for signs of past or present life on Mars. The mission consisted of two parts: the launch of the Trace Gas Orbiter (TGO) to investigate trace gases in Mars' atmosphere, and the launch of the Rosalind Franklin Rover which is designed to examine water, surface and geochemical environments of Mars. While the TGO has already been collecting data since 2016, the launch of the rover was postponed due to technical and diplomatic challenges. It currently is scheduled to be launched as early as 2028 (Vago *et al*., 2023).

To maximize the likelihood of the Rosalind Franklin Rover finding signs of past life on Mars, researchers focus on gathering data from Mars' early Noachian period, when water connectivity was at its highest. Therefore, scientists now target large areas on Mars that could preserve evidence of prolonged, water-rich environments, which could have supported and nurtured microorganisms. Hence, the biosignatures that ExoMars addresses, are microorganism-based. These include microscopic structures and textures such as cellular fossils, macroscopic physical structures and textures such as laminated stromatolites indicating biofilms, and organic matter such as chemofossils (Vago *et al*., 2017). Assigning an observation as a biosignature is not evident and even when it is not ambiguous, a biosignature does not necessarily imply past or present life. This is why Vago *et al*. created a system to assign scores to three major groups of observations in preparation for the Rosalind Franklin Rover mission: morphological biosignatures, chemical biosignatures and their geological context. The scores are confidence values, which quantify how reliable the observations are with the goal of determining whether a location on Mars supported microbial life, either in the past or present. It is crucial to put all the observed elements into a geological context, to evaluate whether their presence makes sense. The ExoMars biosignature scoring grid, depicted in Figure 1, is a particularly useful tool for present and future missions with astrobiology goals, but is to be used as a guideline and not an absolute truth (Vago *et al.*, 2017).



Morphological biosignatures:	Σ points
Multilayer organosedimentary structures (*e.g.* stromatolites)	20
Other candidate biomediated textures (*e.g.* MISS)	10
Features suggestive of (fossil) microorganisms	20

Result of first blank chemical check: (prior to beginning sample analysis)	Factor
No organics, clean background	1.0–0.9
OR Few, well known spacecraft organics in background	0.8–0.5
OR Background heavily compromised by contamination	0.2–0.0

Chemical biosignatures:	Σ points
Detection of primary biomolecules or their degradation products	20
Enantiomeric excess (or other isomer selectivity)	30
Molecular weight clustering of organic compounds	20
Evidence of repeating constitutional subunits	20
Systematic isotopic ordering at molecular (group) level	20
Bulk isotopic fractionation	10

Geological context:	Σ points
Long-lived water or hydrothermal setting (morphology)	15–10
Long-lived water or hydrothermal setting (mineralogy)	15–10

Figure 1: The ExoMars Biosignature Scoring Grid for assigning a confidence value to a set of strong observations intended to determine if a Martian location hosted life. Biosignatures that the Rosalind Franklin rover cannot assess, are highlighted with a gray background. The numbers on the right represent the score assigned to each 'confirmed biosignature', indicating their relative significance (Vago *et al.*, 2017). Image credits: Vago *et al.*, 2017.

3.3 Planetary habitability

Cockell *et al*. define the term habitability as "the ability of an environment to support the activity of at least one known organism". Continuous planetary habitability, as opposed to instantaneous habitability, implies the ability of a planetary body to maintain habitable conditions over geological timescales, within its interior or on its surface. Also important to note is that habitable environments do not necessarily contain life. While on Earth the concepts of habitability and the presence of life are closely intertwined, this distinction becomes crucial when considering the habitability of other planetary bodies (Cockell *et al.*, 2016). Planetary habitability essentially revolves around the capacity to allow life to emerge and the ability to sustain it over time (Horneck *et al.*, 2016).

3.3.1 Criteria for the emergence of life

The emergence of life depends on certain essential criteria combined with adequate physical-chemical conditions to allow biological processes to occur. The first criterion is the presence of chemical building blocks, more specifically carbon (C), hydrogen (H), nitrogen (N), oxygen (O), phosphorus (P), and sulfur (S). As mentioned in section 3.1.1, these elements are fundamental for the synthesis of biomolecules like proteins, nucleic acids, and lipids, essential to support the complexity of life. Moreover, they are widely dispersed in our Solar System and beyond (Segura *et al*., 2022; Krijt *et al*., 2022).

Second, a universal solvent like liquid water is indispensable for life. It allows for the dissolving of compounds, which facilitates their diffusion and chemical interaction to create more complex (bio)chemical building blocks. Liquid water is primarily searched for in context of astrobiology and biosignatures because (i) hydrogen and oxygen are the first and third most abundant elements in the universe, (ii) life as we know on Earth is based on liquid water, and (iii) most molecules dissolve in it (Mottl *et al*., 2007). Nonetheless, other liquids can provide the same features. For instance, in the case of Titan, the Cassini spacecraft provided images of Titan's surface, on which liquid methane lakes were observed (ESA, 2007). Hence, the availability of liquid water or other solvents on a planetary surface, or in a subsurface environment like the believed subsurface ocean of Europa or Enceladus, are key requisites of habitability (Horneck *et al*., 2016). Important to note, however, is that our technology today is not advanced enough to detect signs of life on Titan-like exoplanets, which would be far away from their host star. We don't know what to expect in terms of spectral signatures from such exoplanets as well (Ramirez, 2018). Research is conducted and progress has been made regarding technology for the detection of spectral signatures in exoplanet atmospheres. One such technology is presented by Trujillo *et al*., comprising a high-throughput quantum chemistry method to rapidly acquire vibrational spectral data for a large amount of biologically relevant molecules. It could be a complementary tool to help unravel unknown spectral signatures. However, the efficiency is far from optimal and the technology needs to be refined to be accurate across different planetary environments (Trujillo *et al*., 2023). Thus, the search for extraterrestrial life on exoplanets must currently focus on identifying liquid water, pending future advancements in technology and biochemistry that could enable the investigation of planetary surfaces containing other solvents (Ramirez, 2018).

The third criterion for allowing life to emerge, is an energy source. For Earth, the Sun is the prime energy source, enabling photosynthesis and a favorable temperature for liquid water. Besides the energy from a host star, energy can also be sourced from primordial heat, which refers to the heat retained within a planet during its first million years of development (Breuer, 2023). Earth's liquid core is thought to be a remnant of primordial heat supplemented with radiogenic heat originating from the decay of radiogenic elements. Additionally, tidal heating is a significant energy source as well. It arises from friction caused by the gravitational pull and elliptical orbit of a celestial body around another. Jupiter's moon Io is subjected to tidal forces generated by Jupiter and its nearby icy moons Europa and Ganymede. This gravitational push and pull result in an enormous amount of energy and heat which drives Io's great volcanic activity (Figure 2) (Dobrijevic, 2022).

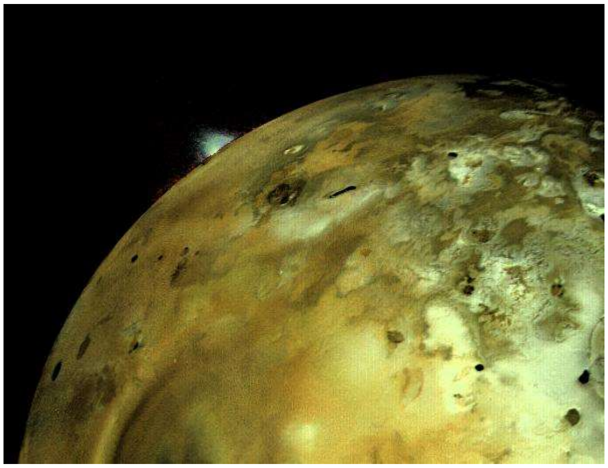


Figure 2: Jupiter's moon Io, the most volcanically active celestial body in the Solar System due to tidal friction with Jupiter, Europa and Ganymede. An immense volcanic explosion on Io is captured by Voyager 1 from 490000 km away. Image credits: NASA/JPL.

Tidal friction can result in ice melting into liquid water, which is believed to be the case for Europa. Crack lines in Europa's crust along with the distortion of Jupiter's magnetic field support the hypothesis of a liquid ocean on Europa beneath its icy crust, warmed by the tidal forces exerted by Jupiter (Hussmann and Spohn, 2004).

Lastly, life has constraints in temperature, pressure, pH, etc. Even though extremophiles on Earth prove that life can adapt to harsh environments, they have limits too, and most life depends on moderate conditions. Hence, factors such as atmospheric composition, protection from harmful radiation and geological stability play critical roles in sustaining life. However, our understanding of the geophysical conditions necessary to maintain life over geological timescales remains limited (Cockell *et al.*, 2024; Horneck *et al.*, 2016).

3.3.2 Criteria to sustain life

The first essential condition is continuous habitability. While instantaneous habitability is not unusual in the universe, habitable conditions on a planetary body, meaning the criteria for the emergence of life, must persist over geological timescales for life to evolve. Continuous habitability requires a second important factor, namely the dynamic stability of the planetary body. This refers to long-term equilibria that enable life-supporting conditions. It encompasses various aspects such as orbital and rotational stability, a stable magnetic field, geophysical activity i.e. plate tectonics and volcanic activity (Horneck *et al.*, 2016; Cockell *et al.*, 2024). Another factor to consider is the habitable zone, usually defined by the region surrounding one or multiple stars where conditions allow for liquid water bodies on the surface of a rocky planet. However, this definition has been reviewed since subsurface oceans, solvents other than water and other energy sources might harbor life as well (Ramirez, 2018).

To conclude, astrobiologists should look for life in our Solar System and the rest of the universe based on these current criteria for the emergence and sustainment of life. Laboratory simulations, field studies in planetary field analogues (PFAs) and space missions to celestial bodies like Mars, Venus, icy moons and asteroids contribute to the growing field of planetary habitability. Moreover, the pursuit of understanding habitability extends beyond our Solar System. Observations of exoplanets such as K2-18b, combined with theoretical models of their atmosphere, dynamics, and evolution, are essential to put Earth's uniqueness in perspective and to identify promising environments elsewhere. Progress in the field of planetary habitability will be driven by interdisciplinary collaboration and technological advancements (Horneck *et al.*, 2016).

3.4 Astrobiology missions with orbiters and/or landers

Over the past few decades, progress in space technology has enabled us to explore our solar system. Through flybys, orbiters, landers, rovers, and probes, detailed data about the geology and environments of celestial bodies like the Moon, Mars, Venus and icy moons and asteroids has been gathered. This research has revealed that some of these worlds may have once possessed the necessary conditions to support life and that a few could still harbor microbial life today (Lin, 2022). To understand the current state of the field of astrobiology and to see the direction towards which it is evolving, it is of paramount importance to look back on past missions. In this section, an overview of these missions is given and their results are discussed. This analysis provides an indication of astrobiology's prominence and evolution within ESA and European space policies, comparative to the U.S., as well as the technology and instrumentation developed for astrobiology purposes.

3.4.1 Mars

Mars has numerous Earth-like characteristics, making it one of the most fascinating planets and the prime focus of astrobiology research. Although Mars is currently a cold and arid world, it is believed that its past conditions were more hospitable, featuring environments that could support terrestrial life (Kanik and de Vera, 2021). During the first billion years of Mars' formation, it contained water bodies. Moreover, it is believed that the conditions then resembled Earth's early conditions when microbes emerged. Life may have originated near hydrothermal activity, where all necessary conditions might have been present, even beneath ice-covered standing bodies of water. This makes Mars a key focus in the quest to uncover signs of life within our Solar System (ESA, 2025g).

The first spacecraft to ever land on Mars was Viking 1 in 1976 (Figure 3). Back then, NASA's strategy was to send duplicate spacecraft to create redundancy in case of an unforeseen failure. Therefore, two identical Viking missions, comprised of an orbiter and lander to perform high-resolution imagery and study the Martian atmosphere as well as surface geological composition, were launched (NASA, 2024a). The landers were equipped with life-detecting instruments, such as cameras, meteorological instruments, a mass spectrometer, an X-ray fluorescence spectrometer and a seismometer. As the primary objective of the Viking missions was to search for life, an articulated arm was designed to dig into the Martian soil to gather samples. To assess present or past life and habitability on Mars, four experiments were executed on those samples. Photosynthesis activity was investigated, as well as metabolic gas production, the transformation of organic matter into CO_2, and the presence of organic molecules. Solely the third experiment showed positive results, potentially indicating microbial presence, but no organics were detected by the gas chromatography coupled mass spectrometer (GC-MS) (Forget, 2023). Unfortunately, the team overseeing the experiments was in a rush due to the competitive tension with the Soviets during the Cold War. This meant that the experiments were not calibrated with one another, resulting in quite ambiguous data and a lot of disputes within the scientific community. There was no unanimity regarding the conclusion of both Viking 1 and Viking 2 missions, except that the existence of life on Mars was not proven nor disproven (Forget, 2023). Hence, the lack of consensus within the scientific community did not convince policymakers to invest in astrobiology missions to Mars soon again.

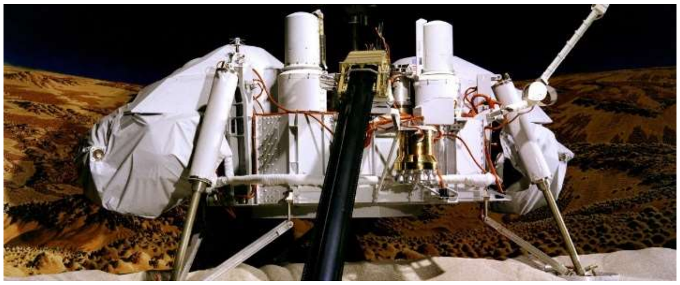


Figure 3: Viking lander, the first spacecraft to reach the surface of Mars where it searched for biosignatures. Image credits: NASA Astrobiology.

More than 30 years later, NASA's Phoenix mission to Mars (2007) was the astrobiology related successor of the Viking missions, consisting of a lander designed to study subsurface water ice and look for complex organic molecules in the Martian polar region. It contained five science instruments to fulfill its objectives, including small ovens and a laboratory to heat samples and examine volatiles, and a multi-spectral stereo camera to identify minerals (NASA, 2024b). As main results of this mission, the presence of subsurface ice was confirmed, and carbonate and perchlorates were detected (Viso, 2023a). As perchlorates oxidize organic matter during pyrolysis, this is seen as the reason as to why no organics were detected by the Viking landers. Viking GC-MS data was revisited in the context of findings from the Phoenix and later the Curiosity missions. The presence of chlorobenzene was reported, corroborating Curiosity's findings (Millan *et al.*, 2016). Thus, if the Viking missions had been more thoroughly prepared and not rushed, these perchlorates could have been detected earlier and additional astrobiology missions to Mars could have happened sooner.

Four years later, NASA's Curiosity rover was sent to Mars in 2011, as part of the Mars Science Laboratory mission. Curiosity's objective was to investigate whether Mars was habitable in the past by collecting forty-two rock samples with its drilling arm. Curiosity found chemical and mineral proof for the hypothesis that Mars used to have habitable environments. Indeed, its findings suggest that shallow rivers and lakes existed on Mars in its ancient history, and its analysis of Martian soil revealed essential elements for life, including C, N, O, P and S. As Mars lost its protective magneto- and atmosphere, it now experiences ionizing radiation levels of 76 mGy per year, as measured by Curiosity. Hence, surface microbes could have been gradually eliminated, but it is hypothesized that just one to two meters of Martian soil could protect microorganisms from this harmful radiation (NASA, 2024c; Lin, 2022). Recently, Curiosity has detected the largest organic molecules ever found on Mars: the long-chain hydrocarbons decane, undecane, and dodecane. These compounds, discovered in a rock sample called "Cumberland" within Gale Crater, may be fragments of fatty acids, which are essential building blocks of life on Earth. While their origin remains uncertain, the discovery suggests that organic chemistry on Mars may have reached a level of complexity necessary for the emergence of life. This finding also raises the possibility that biosignatures, or chemical evidence of past life, could be preserved on Mars despite exposure to radiation and oxidation over millions of years. The results bolster plans to return Martian samples to Earth for further analysis (Shekhtman, 2025).

As mentioned previously, ESA and Roscosmos also designed an astrobiology mission to Mars: ExoMars. In 2016, the ExoMars Trace Gas Orbiter and a demonstration lander were launched but the lander crashed on Mars' surface. In the second stage, the Rosalind Franklin rover will be sent in 2028. However, because of the Russian invasion of Ukraine, ESA discontinued its collaboration with Roscosmos on the Rosalind Franklin rover. In 2024, NASA and ESA decided to join forces with an agreement that the US will contribute to the mission in terms of launch service, throttleable braking engines and radioisotope heater units for the rover (ESA, 2024a). The overall aims of ExoMars are to investigate potential biology on Mars and to characterize the surface environment by looking for subsurface water and mapping the geochemical environment. Martian atmospheric trace gases, such as methane, their sources and spatial evolution, are studied by the TGO. Methane is particularly interesting because its presence can be a biosignature but of course can also be the result of geological processes. The TGO therefore does not only measure atmospheric gases, it also searches for geological explanations for these gases, like volcanoes (ESA, 2019a). Curiosity is equipped with the Tunable Laser Spectrometer (TLS), which measured atmospheric methane fluctuations (0.2-0.7 ppbv) with occasional spikes. However, the more accurate methane measurements of TGO were negligeable. Recently, the Royal Belgian Institute for Space Aeronomy suggested that the methane gas being measured by Curiosity actually originates from a part of the laser itself, contaminated with methane (Viscardy *et al.*, 2025). However, there is no unambiguous explanation yet for the discrepancy between the data of both missions, thus there is no clear view on how geologically or biologically active Mars is (ESA, 2019a). TGO did find a fast effect of atmospheric heating and inflation during storms on enhancing the escape of atmospheric water vapor. Finally, the TGO also contains a suite of instruments to uncover subsurface water-ice deposits up to a depth of 1 meter. Over the years, these have provided a map of considerable subsurface water ice deposits over many areas (Vago *et al.*, 2023). As a second part of the ExoMars mission, the Rosalind Franklin is set out to be the first rover to drill as deep as two meters beneath the surface of Mars, collecting samples shielded from surface radiation and extreme temperatures (ESA, 2024a). This provides a promising opportunity to study sedimentary deposits potentially containing isotope, chemical, mineral or organic matter biosignatures protected from the damaging effects of ionizing radiation at the surface (Vago *et al.*, 2023).

In 2020 China launched its first interplanetary mission, called Tianwen-1, to Mars. The mission consisted of an orbiter, lander and the Zhurong rover. Among the many scientific goals, Tianwen-1 investigates Mars' atmosphere, topography, (sub)surface morphology and water-ice content. The Zhurong rover is equipped with scientific instruments such as a mineralogy spectrometer, with which the composition of the (sub)surface material can be analyzed for mineral biosignatures (NSSDCA, 2022; Stein, 2021).

In the same year as Tianwen-1, NASA's Ingenuity Mars Helicopter and Perseverance rover as part of NASA's and ESA's Mars Sample Return mission was launched as well. Ingenuity was designed to be a technology demonstration of the first controlled flight on Mars. Its great success resulted in 72 completed flights, additional insight into its aerodynamic limits and a preview of Martian areas which could be interesting for Perseverance to epxlore (Davis, 2024). The Perseverance rover was built to conduct scientific research and is currently looking for signs of ancient life in the Martian soil and atmosphere. It gathers Martian samples in tubes, which are planned to be sent back to Earth in 2028 (Figure 4) (Viso, 2023b). At the end of its journey, thirty-eight of Perseverance's tubes will be filled with Martian samples and five will be used as control “witness tubes” to assess the cleanliness of sampling. Thus far, twenty-six samples have been collected by Perseverance, of which one is atmospheric, two are regolith and twenty-three are rock core (Davis, 2025).

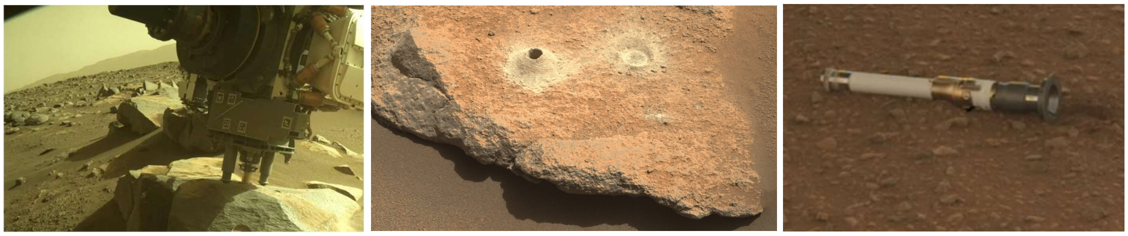


Figure 4: Photograph of the Mars Perseverance drill, taken by the Front Right Hazard Avoidance Camera of the rover (left). A drill hole in Martian rock made by Perseverance (middle). Deposit of the first sample of Perseverance on Mars (right). Image credits: NASA/JPL-Caltech.

To ensure that interesting and relevant samples are collected, Perseverance carries three instruments. One is the Planetary Instrument for X-ray Lithochemistry (PIXL), which is an X-ray fluorescence spectrometer to identify and map the elemental make-up of surface samples. Changes in textures that are the result of past microbial life such as microfossils can thereby be identified. These instruments lack the resolution and sensitivity needed for *in situ* life detection though. So, returning samples to Earth is crucial to identify biosignatures like microfossils (Lin, 2022). Recently, Perseverance has uncovered intriguing signs in a rock that could hint at ancient microbial life on Mars. This rock sample, featuring dark-rimmed "leopard spots", was found to contain high levels of iron and phosphorus, which resemble formations created by microorganisms on Earth. While these features could also result from non-biological processes, their discovery marks a significant step in evaluating potential biosignatures on Mars. Researchers emphasize the need for further analysis, including returning the sample to Earth, to confirm whether these chemical patterns are indeed linked to past life (Witze, 2025).

The Mars Sample Return mission is quite complex as it demands coordination of different robots. It is considered to address one of the top priorities for solar system exploration and will hopefully settle the debate of the origin of methane on Mars. The aim is to bring Mars regolith, rock, and gas samples to Earth to perform detailed laboratory analysis and look for biosignatures such as organic matter, microscopic structures and textures and chemical features. Next to the astrobiology aim of finding evidence of past life, the formation and alteration history of these samples would provide transformative insights into Mars' geological processes and environments. Additionally, the samples will help advance our understanding of planetary-scale formation and evolution within the inner solar system and contribute to the preparation of future human exploration of this planet (NASA, 2024d; NASA, 2025a). NASA's Sample Retrieval Lander (SRL) is planned to touch down near the Perseverance rover landing site. The SRL will bring along the Mars Ascent Vehicle (MAV), a small rocket–being the first to launch off from another planet–on which the collected samples of Perseverance would be loaded. The lander will be able to transfer the sample tubes into the MAV thanks to its Sample Transfer Arm (STA), a contribution from ESA. Once SRL carrying the samples is launched from the surface, ESA's Earth Return Orbiter (ERO), will capture SRL in Mars orbit and safely return it to

Earth. ERO is set to make history as the first spacecraft to retrieve an object from orbit around another planet and successfully complete a round trip to Mars and back (NASA, 2024e; NASA, 2025a).

A crucial aspect of the Mars Sample Return mission is the decision on sample containment, curation, distribution and analysis protocols. The integrity of the returned Martian samples needs to be preserved while maximizing their scientific potential. In this regard, as well as for legal and ethical reasons, it is incredibly important that forward and back contamination is avoided, which is not evident.

3.4.2 Venus

Venus is the second planet from the Sun and has an extreme environment in terms of temperature, pressure and acidity. It contains a thick atmosphere composed of 96% CO_2, which induces a significant greenhouse effect, leading to surface temperatures above 500 °C and an atmospheric pressure of 92 bar. However, at some point in time, it had more beneficial conditions for life than Earth, including moderate temperatures and a terrestrial ocean (Forget and Helbert, 2023; De Mol, 2023). Recently, Constantinou *et al*. disputed the idea that Venus used to be liquid-water habitable. They found that Venus' interior is extremely dry and that the planet's volcanic gases contain no more than 6% water by mole fraction, which is significantly less than water-rich magmas on Earth under similar conditions. This dryness supports the idea that Venus emerged from its magma ocean phase already desiccated, and has since maintained a dry surface (Constantinou *et al*., 2025). Now, Venus is no longer in the habitable zone and has lost all the surface water it might have had. Anything organic will have been degraded by now as the planet's surface is hostile to organic compounds and biosignature fossils. Hence, it is highly unlikely to find biosignatures of past life on Venus. However, the low and middle cloud layers in Venus' atmosphere do provide a habitable region for past or present life, meaning Earth-like temperatures and pressures. These clouds are permanently present and stable, containing highly concentrated sulfuric acid. Anything in these clouds remains in orbit for an exceptionally long time, meaning that potential acidophilic micro-organisms that could withstand a pH lower than 1, can reside there (Forget and Helbert, 2023; De Mol, 2023).

Even though now most missions with astrobiology aims are focused on Mars because this planet is the most like Earth, Venus has peaked astrobiology interest because of a number of peculiarities. First, particles of different sizes have been detected in the habitable cloud layers. These particles are non-spherical, which could point towards minerals created through biotic or abiotic processes but also salts or cosmic dust. Second, Venus' cloud layers contain sulfur-containing absorbents such as SO_2, CS_2, COS which absorb certain UV wavelengths. However, the complete UV absorption spectra of Venus cannot be assigned to these molecules alone, nor to other known chemical substances. Some biosignatures though, including ferroproteins, photosynthetic pigments, biochemicals associated with green sulfur bacteria and lipids, could potentially account for the remaining discrepancies. Hence, there could be unknown chemistry present in the atmosphere, or perhaps microbiological activity. Another point of interest is the co-occurrence of O_2 and NH_3 in Venus' atmosphere, which is solely the case on Earth when life is present. Lastly, in 2020, ground-based radio telescopes ALMA and JCMT potentially detected the presence of phosphine (PH_3) in Venus' atmosphere. On Earth, phosphine is a byproduct of microbial metabolism. Its detection in Venus' atmosphere hints at the possibility of an ongoing biological or geological source. However, several researchers are skeptical of this finding. All these curiosities and observations show that closer investigation of Venus' clouds is required and thereby space missions to potentially unravel and confirm the (bio)chemical processes taking place (Seager *et al.*, 2022; De Mol, 2023; Greaves *et al.*, 2021; Akins *et al.*, 2021).

Most of the general information about Venus is gathered through spacecraft exploration. Between 1962-1989, the Soviet Venera and Venera-Halley (VeGa) missions, along with the American Pioneer Venus missions, marked the initial phase of spacecraft exploration of Venus. These were designed to view, analyze and characterize the surface and atmosphere of Venus, providing a fundamental understanding of the planet's conditions, but not the physical processes responsible for maintaining these physical and chemical conditions (Titov *et al*, 2023). After a gap of about fifteen years, the first astrobiology related mission resumed the investigation of Venus. This mission was ESA's Venus Express orbiter, launched in 2005, and ESA's first mission to our neighboring planet (Figure 5) (Forget and Helbert, 2023). It focused on Venus' atmosphere dynamics and the investigation of geology and surface physics. This mission contributed to our understanding of Venus' clouds, including the presence of previously mentioned unknown UV absorbers. It was after Venus Express' findings that the hypothesis came forth of cloud-based microbial life being the UV absorbers. Next to this, the mission also provided pioneering results on the composition and chemistry of the atmosphere and discovered strong temperature and density variability in the atmosphere among other results (Titov *et al.*, 2023).

Figure 5: Artist's impression of the Venus Express spacecraft orbiting Venus. Image credits: ESA.

In 2010, the Japanese space agency JAXA launched the Venus Climate Orbiter, known as "Akatsuki" with similar research objectives as Venus Express, along with the search for indications of active volcanism. However, the Akatsuki probe failed to insert into Venus' orbit at first. Only in 2015, it entered Venus' orbit successfully. It complements and builds upon the Venus Express mission, which retired in 2014, by having five cameras that capture images of Venus at different wavelengths and with higher resolution. The observation of Venus' clouds in multiple wavelengths provides different information. In the Infra-red for instance, topography and motion of the clouds can be investigated (Figure 6). While publication of findings and results is currently awaited, Akatsuki's Longwave Infrared Camera (LIR) provided the first-ever revelation of the global structure of thermal tides across the equator of Venus' upper cloud layer. The UV images on the other hand reveal the spatial distribution of SO_2 and the unidentified absorber near cloud-top altitudes, while also offering insights into cloud-top morphology and haze characteristics (Forget and Helbert, 2023; Lakdawalla, 2018; Kouyama *et al.*, 2019; Yamazaki *et al.*, 2018).

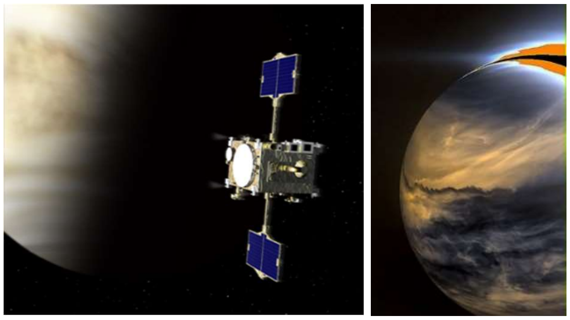


Figure 6: JAXA's Akatsuki spacecraft inserting into Venus' orbit (left). Image credits: ISAS/JAXA. Venus' night side, captured by Akatsuki's Infrared camera (IR_2). Dark areas point to high-altitude cold clouds, whereas bright features indicate mid-altitude hot clouds. At the top right, Venus is overexposed by sunlight (right). Image credits: Damia Bouic.

No further missions have been sent to Venus to this day, but several are scheduled. Planned to be launched in 2026 is the private low-cost Venus Life Finder mission, designed by Rocket Lab and the Massachusetts Institute of Technology (MIT) (The Planetary Society, 2025a). This mission consists of three parts, of which the first is an atmosphere probe containing an autofluorescing nephelometer. With this science instrument, the probe will scan the distribution and size of molecules in Venus' habitable cloud region, as well as potentially record autofluorescence of organic material in these clouds. Detecting organic compounds in Venus' atmosphere would be a significant biosignature but would not be definite proof of life. Nevertheless, it would reinforce the idea that Venus, often dismissed as uninhabitable, exhibits fascinating activity in its clouds and possibly harbors life. The second part of the mission is a balloon which will investigate biosignature atmosphere gases, non-volatiles transportation such as metals and particles. The last part is a sample return mission of cloud particles and gas for enhanced analysis on Earth (The Planetary Society, 2025a). Other missions to Venus are planned for the future. In 2028, the Indian Space Research Organisation (ISRO) will launch the orbiter Shukrayaan-1 to study the atmospheric chemistry and geological structure of Venus (The Times of India, 2024). NASA has planned the Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging (DAVINCI) mission for 2031. Its aim is to perform a full study of the origin, evolution and current state of Venus' atmosphere and surface. Its astrobiology-related aim is to study the chemical and isotopic composition of Venus' clouds as a biosignature (NASA, 2025b). In the same year, Roscosmos will implement the Venus lander Venera-D mission, designed to investigate Venus' atmosphere, surface and the possible interaction between the two. Its overall aim is to try and answer the question of why Venus is so different from Earth (Zelenyi *et al.*, 2022). Lastly, ESA's EnVision, in partnership with NASA, is planned to also launch in 2031 with the same overall aim as Venera-D, but without a lander. It will investigate Venus' interior, from its inner core up to the atmosphere, and the interaction between the different planet layers. This mission will potentially provide overall insight into the history, activity and climate of Venus, and regarding astrobiology, into the habitability of its surface (ESA, 2025i).

3.4.3 Icy moons

Next to the planets in our solar system, certain moons are also a prioritized target of interest for astrobiology. Specifically, Jupiter's moons Europa, Ganymede and Callisto; and Saturn's moons Enceladus and Titan, provide an environment which could harbor life (Figure 7). As previously mentioned, the three essentials for life and habitability are liquid water (or another solvent), access to nutrients and an energy source. Jupiter and Saturn's moons are very distant from the Sun, meaning that they do not receive sufficient solar radiation to sustain life. However, these icy moons are subjected to tidal heating, an energy source believed to maintain a subsurface ocean in a liquid state beneath their icy crust. Hence, they are called subsurface ocean worlds. Europa and Enceladus are considered prime targets in the search for present or past life. If Europa has a relatively thin ice crust, dissociation of surface ice due to Jupiter's radiation could result in oxygen reaching the subsurface ocean and potentially modifying its chemistry. Hydrothermal vents, quite like those found on Earth's seafloor, may also be present under its subsurface ocean, leading to the release of minerals and nutrients from the rocky/silicate interior. This implies however that the subsurface ocean of icy moons should not be too deep, otherwise high water pressure could lead to an ice layer between the water and the rocky interior. As a result, contact between nutrients and the liquid ocean would be blocked and life would not be possible. On Europa, the three requirements for the emergence of life are met, as well as a thick ice crust, shielding potential life in the ocean from Jupiter's harmful radiation (Sephton *et al.*, 2018; De Mol, 2023; Lin, 2022). In terms of habitability, a differentiation should be made between surface liquid water worlds, like Earth, and interior liquid water worlds, like icy moons. The former may support conditions suitable for oxygenic photosynthesis, which enables the accumulation of atmospheric oxygen and the potential emergence of complex life and intelligence over geological timescales. On the other hand, icy moons where liquid water may exist only beneath the surface, are unlikely to lead to such complex life (Cockell *et al.*, 2016).

Figure 7: Icy moons in our Solar System, potentially harboring life. From left to right, shown to scale: Europa, Ganymede, Callisto, Enceladus and Titan. Image credits: Jarvis Labs, NASA/JPL/Space Science Institute and Adrian Bayer.

NASA, ESA and the Italian Space Agency (ASI) collaborated on the first space mission to the Saturnian system, named Cassini-Huygens. It was launched in 1997 and consisted of the American Cassini orbiter and the European Huygens lander. Cassini orbited the Saturnian system to study its rings as well as its moons. In total, the mission lasted for twenty years. One of the major discoveries of Cassini was the detection of icy plumes, containing water, carbon dioxide, methane, propane, acetylene, hydrogen and silica from fissures on Enceladus. Cassini flew through such a plume in 2015 and its mass spectrometer detected these molecules, pointing to the presence of a subsurface liquid ocean, most likely with hydrothermal activity on the rocky bottom. If microbial life exists on Enceladus, it could exploit hydrogen as an energy source for the process of methanogenesis, in which hydrogen reacts with dissolved carbon dioxide to produce methane. Additionally, the plumes could transport potential microorganisms or organics through the ice crust, after which they would fall on the surface under the influence of gravity. The identification of methane and analyzation of easily accessible surface deposits by future missions could provide supporting evidence. The Huygens lander on the other hand, touched down on Titan in 2005, providing evidence of liquid methane and ethane seas on the surface of this icy moon and complex hydrocarbons in its atmosphere (Barnett, 2024; De Mol, 2023; Lin, 2022). The data obtained from the Cassini-Huygens mission, which ended in 2017, have significantly intensified scientific interest in the icy moons of Jupiter and Saturn, prompting further investigation into their potential habitability. However, there is no unanimous consensus on the hypothesis of subsurface oceans on these icy moons. Recently, Meyer *et al*. proposed another theory behind the detected plumes on Enceladus, not involving a subsurface ocean. Shear heating along the moon's fissures may generate partial melting within the ice shell, with interstitial convection enabling fluid to escape as geysers. Their results suggest that the internal melting rate could feasibly account for the observed plume activity (Meyer *et al*., 2025). Future missions to the Jovian and Saturnian systems might resolve this uncertainty.

In 2023, ESA's Jupiter Icy Moon Explorer (Juice) was launched. The estimated arrival year at Jupiter is 2031, after four flybys. A main objective of this mission, is to investigate the habitability of Jupiter's icy moons Ganymede, Callisto and Europa. Juice is equipped with ten scientific instruments, including remote sensing as well as a payload for *in situ* research. Notable examples include MAJIS (Moons and Jupiter Imaging Spectrometer), designed to analyze the composition of ice and minerals on the surface of these icy moons, as well as to observe cloud structures and atmospheric components on Jupiter. RIME (Radar for Icy Moon Exploration) on the other hand is an ice-penetrating radar instrument intended to investigate the subsurface structure of the icy moons, capable of probing to depths of approximately nine kilometers (ESA, 2022).

Six months after the launch of Juice, NASA's Europa Clipper mission was launched as well. This mission is dedicated to investigating Europa in great detail by 2030, conducting 49 flybys of this icy moon. The overall objective is to determine the habitability of Europa, employing nine sophisticated and high-resolution remote-sensing instruments such as the Mass Spectrometer for Planetary Exploration/Europa (MASPEX). More specifically, the mission aims at investigating the moon's composition, determining the ice crust thickness and characterizing its geology and surface-ocean exchange processes (Figure 8). The data obtained from Europa Clipper will be instrumental in informing the design and objectives of a prospective lander mission aimed at conducting *in situ* life detection experiments on Europa's surface (Barnett, 2025; Lin, 2022).

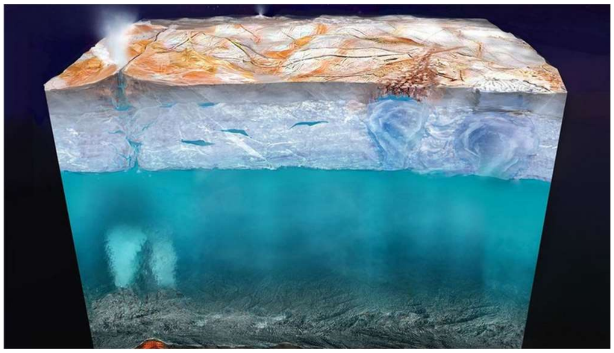


Figure 8: Hypothesized model of Europa's cross section. Image credits: NASA/JPL-Caltech.

In 2028, NASA's Dragonfly mission will launch and fly for seven years to Titan. The aim of this mission is to investigate different locations on this moon during >3 years to characterize its habitability. Dragonfly is a nuclear-powered rotorcraft lander that will sample materials and analyze surface composition with a mass spectrometer and neutron and gamma ray spectrometer across various geological settings. The extent of prebiotic chemical processes can thereby be examined, and chemical indicators that could suggest the presence of water-based or hydrocarbon-based life can be searched for. In merely ten minutes, Dragonfly will be able to travel several kilometres and by the end of its mission, it will have covered hundreds of kilometres on Titan (Johns Hopkins University Applied Physics Laboratory, 2025; Jones, 2025).

3.4.4 Asteroids and comets

Asteroids and comets in our Solar System have also been of great interest to astrobiology research. These bodies are significant because they may contain traces of early life or offer clues about the processes from the early formation and evolution of the Solar System, and the prebiotic chemistry of celestial objects. Rich in organic compounds, they help scientists understand when and under what conditions complex organics first formed. Additionally, the transport and deposition of organics from asteroids and comets may have supplied essential molecules that contributed to the emergence of life on Earth and perhaps other worlds. This forms the basis for the theory of panspermia, meaning the spreading of life from one celestial body to another (De Mol, 2023; Glavin *et al.*, 2025).

In 1999, NASA's Stardust mission launched to Comet Wild 2 and returned samples from its tail to Earth in 2006. It is the first sample return mission gathering cometary material and its primary objective was to investigate the evolution of solid matter and dust particles in the protoplanetary disk (Leroux, 2023). The most crucial finding after isotope data analysis from the samples was the detection of extraterrestrial cometary glycine (Elsila *et al.*, 2010). While other amino acids are complex and more likely to be contaminated by terrestrial sources, glycine is the simplest amino acid, commonly found in proteins and can form in abiotic conditions. Detecting glycine in these cometary particles provided direct evidence that the basic building blocks of life can form in space. As comets have not changed since a few billion years ago, they could have transferred ingredients of life to prebiotic Earth (ESA, 2016).

Other sample return missions include JAXA's Hayabusa missions, which explored near-Earth asteroids. The first Hayabusa spacecraft was launched in 2003 towards asteroid Itokawa. It successfully collected dust samples from the asteroid's surface and returned them to Earth in 2010. The second Hayabusa spacecraft, launched in 2014, gathered samples from asteroid Ryugu, which were brought to Earth in 2020 (Levasseur-Regourd, 2023). Analysis of the Itokawa and Ryugu samples revealed chemical biosignatures: evidence of non-proteinogenic extraterrestrial amino acids and a variety of amino acids originating from multiple formation mechanisms, respectively (Parker *et al.*, 2022; Parker *et al.*, 2023). Hayabusa2 is currently on an extended mission to a smaller asteroid named 1998 KY26, where it will arrive in 2031 (Dooling, 2025). Around the same time as Hayabusa, ESA's Cornerstone mission Rosetta launched in 2004. It consisted of the Philae lander, which deployed on Comet 67P/Churyumov-Gerasimenko in 2014 (Figure 9). Rosetta was the first mission to rendezvous with a comet and track its development over time, as well as the first to deploy scientific instruments onto a comet's surface. This mission contributed greatly to the hypothesis that comets played a role in the origins of life on Earth. It detected glycine in comet 67P's gas, along with ammonium salts, both key to prebiotic chemistry. However, its deuterium-to-hydrogen (D/H) ratio was much higher than in Earth's oceans, suggesting that comets like 67P were not the main source of Earth's water, though isotopic data indicated they may have contributed 20% of Earth's early atmospheric volatiles. Rosetta also found molecular oxygen (O_2) in high concentrations, challenging existing comet formation models. Additionally, phosphorus, essential for DNA and ATP, was detected in both gas and dust. The Philae lander identified polyoxymethylene (POM), reinforcing the idea that comets delivered complex organic molecules to early Earth (Cottin, 2023).

Figure 9: Rosetta spacecraft and Philae lander approaching Comet 67P. Image credits: ESA.

NASA's first spacecraft to reach an asteroid and return a sample or rock and dust to Earth was OSIRIS-REx. The mission launched in 2016 and arrived at asteroid Bennu in 2018. It reached its goal in 2023 when the sample capsule containing 60 grams of Bennu's surface matter was successfully brought to Earth. Now, the spacecraft, renamed OSIRIS-APEX, has been sent on a new mission to asteroid Apophis (NASA, 2024f). The Bennu sample was expected to shed light on whether asteroids that struck Earth billions of years ago brought water and other ingredients for life to our planet. After careful analyzation, the rock and dust revealed the presence of essential molecules to life in addition to salty remains of water. A diverse array of organic compounds was detected, including fourteen of the twenty biological amino acids, formaldehyde, carboxylic acids and all five nucleobases present in DNA and RNA. Although building blocks of life have been found previously in extraterrestrial rocks, exposure to Earth's environment can easily compromise such samples. Hence, sample return missions are crucial to preserve pristine specimens like Bennu's and enable precise detections (Glavin *et al.*, 2025). The latest discoveries provide compelling evidence for the theory of panspermia, suggesting that asteroids may have delivered the building blocks of life to Earth, which were interacting with water almost from the very beginning (Dunn, 2025).

4. Research Questions

Astrobiology has seen significant advancements in the past decades, driven by exciting research and discoveries on Earth, Mars, Venus, icy moons, asteroids and exoplanets, but also by technological progress and attempts for more coordinated research. However, despite its growing attention, the field of astrobiology does not seem to be as valued and popular as other fields in space science and exploration. By analyzing the state-of-the-art in astrobiology, this master dissertation explores the development and significance of astrobiology in Europe and discusses several research questions pertaining to Europe's role and strategic direction. These are:

- RQ1: Is astrobiology a focal point in Europe's space endeavours?
  Understanding the extent to which astrobiology is prioritized within ESA and European space policies is crucial to assess future mission planning and investment.

- RQ2: Who are the key players in European astrobiology, and how can industry be incentivized?
  Exploring the role of research institutions such as ESA and the private provides insights into policy coordination and governance. Examining the involvement of industry with these research institutions sheds light on funding models and future partnerships.

- RQ3: What is the political landscape of astrobiology in Europe and how does it differ from the U.S.?
  Comparing the European sector with its American counterpart, currently considered as the most advanced, reveals strengths, weaknesses as well as potential collaboration opportunities.

- RQ4: What bottlenecks exist in astrobiology research?
  Identifying technological, financial, and regulatory challenges helps determine key factors hindering progress.

- RQ5: Which crucial technologies or facilities are missing in Europe for the next big leap in astrobiology?
  Identifying gaps in infrastructure and instrumentation highlights current bottlenecks and improves the understanding of political and financial choices. Moreover, it underlines areas needing investment for crucial breakthroughs.

5. Research Methodology

To address the research questions set out above, experts in relevant fields were contacted to discuss the state of astrobiology. Through background checks, interviews were prepared and tailored to their expertise. Insights and visions were compared to critically discuss the research questions and to obtain a comprehensive view on astrobiology in Europe. Below, a short description of the interviewees and their expertise is given, as well as a diagram to indicate the discussed topics and interdisciplinarity of the interview panel (Figure 10). In accordance with the legal ground of 'public interest' provided by the GDPR legislation, the names and job descriptions of the stakeholders are disclosed to underpin research results. An integrated ethical review is performed and accepted by the Social and Societal Ethics Committee (SMEC) through the Privacy and Ethics (PRET) platform.

Dr. Petra Rettberg (DLR, Germany)

The Deutsches Zentrum für Luft-und Raumfahrt (DLR) is Germany's national research institution for aerospace, energy, transportation and security, conducting both scientific research and technological development. It is organized into multiple research fields, each comprising specialized institutes focused on topics such as aeronautics, space, energy, and digitalization. DLR operates under the supervision of the German government and collaborates with industry partners, universities, and international organizations (Deutsches Zentrum für Luft-und Raumfahrt, 2025). Dr. rer. nat. Petra Rettberg, retired in 2024, was head of the Astrobiology working group at the DLR Institute of Aerospace Medicine for more than 20 years. Her research was primarily focused on astrobiology, planetary protection, radiation biology and the survival mechanisms of microorganisms under extreme conditions, both on Earth and in space. She was the principal investigator (PI) and co-investigator (Co-I) on various space experiments and is actively involved in various international projects and organizations, including the European Astrobiology Institute (EAI) and the Committee on Space Research (COSPAR), where she continues to play a pivotal role in planetary protection efforts. Additionally, she contributed greatly to the AstRoMap project, shaping the 2016 European Astrobiology Roadmap.

The interview with Dr. Rettberg focused on the history and evolution of astrobiology research, industrial players and institutions in Europe, AstRoMap and its consequences, Mars Sample Return, planetary protection and missing technologies essential in keeping Europe at the forefront of astrobiology research. The meeting took place virtually on 27 January 2025.

Dr. Hilde Stenuit (SAS, Belgium)

Dr. Hilde Stenuit is an astrophysicist and Principal Scientist at Space Applications Services (SAS), where she leads initiatives to facilitate commercial access to space for research and technological advancements. She already worked 25 years at SAS and played a pivotal role in developing the International Commercial Experiment Cubes (ICE Cubes) service, Europe's first commercial platform providing rapid and direct access to the International Space Station (ISS) for diverse experiments. Her career at SAS has encompassed various roles, including operations specialist for ISS modules and the Automated Transfer Vehicle (ATV), as well as supporting research on national Soyuz missions and the ISS. She also contributed significantly to ESA’s ISS Mission Science Office, focusing on scientific coordination and research planning for ISS experiments. Additionally, Dr. Stenuit is actively involved in educational outreach, exemplified by her role as Director of Metaspace at Metavisionaries and her TEDx talk, "How New Drugs Could Come From Space", where she discussed the potential of microgravity environments in pharmaceutical development.

The interview with Dr. Stenuit focused on the involvement of the private industry in astrobiology, post-ISS plans of SAS, the role of policy to incentivize space-related activities, technology gaps and the promise of artificial intelligence and machine learning for space commercialization as well as astrobiology research. The meeting took place virtually on 28 January 2025.

Dr. Nicol Caplin (ESA, The Netherlands)

Dr. Nicol Caplin obtained her PhD in plant biology and radioecology. She started as a research fellow in astro/exobiology at ESA in 2018, where she took on the role as project scientist for exobiology research programs on the ISS, managing requirements for on-orbit implementation of experiments. She was also the coordinator of ESA’s Astrobiology Topical Team and provided scientific support through the ESA Plant Biology working group. As of 2021, Dr. Caplin worked as a Deep Space Exploration Scientist within ESA’s Human and Robotic Exploration (HRE) department. Her background in plant biology together with her logistics and coordinator expertise in space missions demonstrates her interdisciplinary skills. Dr. Caplin actively engages in science communication, sharing insights into astrobiology and space exploration through interviews and podcasts. Notably, she featured in an episode of ESA’s Meet The Experts: “Extreme Life”, where she talked about extreme life forms. Recently, she participated in the RMC STORY documentary: “Sommes-nous seuls dans l’univers” where she took the opportunity to explain the astrobiology research at ESA and highlighted the interdisciplinary character of the research field. Additionally, she took part in educational outreach by joining events designed to educate students about careers in the space industry.

The interview with Dr. Caplin focused on the organization of ESA, the importance of astrobiology research with ESA's programmes, Voyage 2050 and the role of the European Space Education Resource Office (ESERO). The meeting took place virtually on 7 February 2025.

Frank De Winne (ESA, Germany)

Frank De Winne was a senior test pilot and squadron commander in the Belgian Air Force, whereafter he joined the European Astronaut Corps based to become an astronaut affiliated with ESA. During his astronaut career, he served as a flight engineer aboard the ISS and later became the first European to command the ISS during Expedition 21. Following his space missions, De Winne transitioned into leadership positions within ESA. In 2012, he was appointed head of ESA's European Astronaut Centre (EAC) in Cologne. Five years later, he became responsible for ISS operations at ESA, and in 2020, he assumed the role of ESA's ISS Programme Manager.

The interview with Frank De Winne focused on the organization of ESA, European industry participation and the political landscape of space science. The meeting took place virtually on 17 March 2025.

Dr. Jean Pierre de Vera (DLR, Germany)

Dr. rer. nat. habil. Jean-Pierre Paul de Vera is an astrobiologist at DLR, specializing in the study of life's potential in extraterrestrial environments. He contributed to space experiments like BIOPAN 6 on the FOTON M3 satellite and the LIFE experiment on the EXPOSE-E platform of the ISS. In 2009, he joined DLR's Institute of Planetary Research, leading studies on the physics of water on other planets and its significance for life. That same year, he assumed leadership of the Mars Simulation Laboratory. During the 2009/10 GANOVEX 10 Antarctic expedition, Dr. de Vera collected samples for the ESA's BIOMEX experiment, which he has led as chief scientist since 2010. Currently, Dr. de Vera is preparing the new ESA space experiment BIOSIGN, aiming to simulate the environmental conditions of Mars and the icy moons of Jupiter and Saturn in near-Earth orbit. In addition to being a member of the EAI's Management Committee, he is also president of the European Astrobiology Network Association as of 2022.

The interview with Dr. de Vera focused on biosignature detection, technological and political challenges within astrobiology and the interplay between European astrobiology initiatives. The meeting took place virtually on 31 March 2025.

Tom Verbeke & Sophie Pireaux (BELSPO, Belgium)

The Belgian Science Policy Office (BELSPO) is a federal public service responsible for shaping and implementing Belgium's science policy at the federal level. It supports government decision-making by providing validated data through its own research programmes in areas such as climate change, sustainable development, health, and mobility. BELSPO manages ten federal scientific institutes and oversees BELNET, the national research network providing high-speed internet to academic and public institutions. A major part of its work involves managing Belgium's federal space policy, including its substantial contribution to ESA, which accounts for over 40% of BELSPO's budget. Rather than conducting its own space research, BELSPO partners with international organizations like ESA and CNES to carry out Belgium's space activities (ESA, 2025h). Tom Verbeke, alumnus of the Master of Space Studies program, is a Program Manager at BELSPO, where he has been serving since October 2016. In this capacity, he represents Belgium at ESA, focusing on human spaceflight, microgravity research, space exploration and education. Sophie Pireaux has been working at BELSPO for eleven years and currently concentrates her efforts on the programme for the development of scientific experiments (PRODEX) budgeting at the Space research & Applications department. Their role is pivotal in coordinating Belgium's contributions to ESA, ensuring alignment with national priorities and fostering international collaboration.

The interview with Tom Verbeke focused on the role of BELSPO within ESA activities, the role of ESERO and funding schemes of research and industry. The meeting took place virtually on 5 May 2025. The interview with Sophie Pireaux focused on BELSPO and ESA budgeting statistics, as well as industry participation in the space sector. The meeting took place virtually on 22 May 2025.

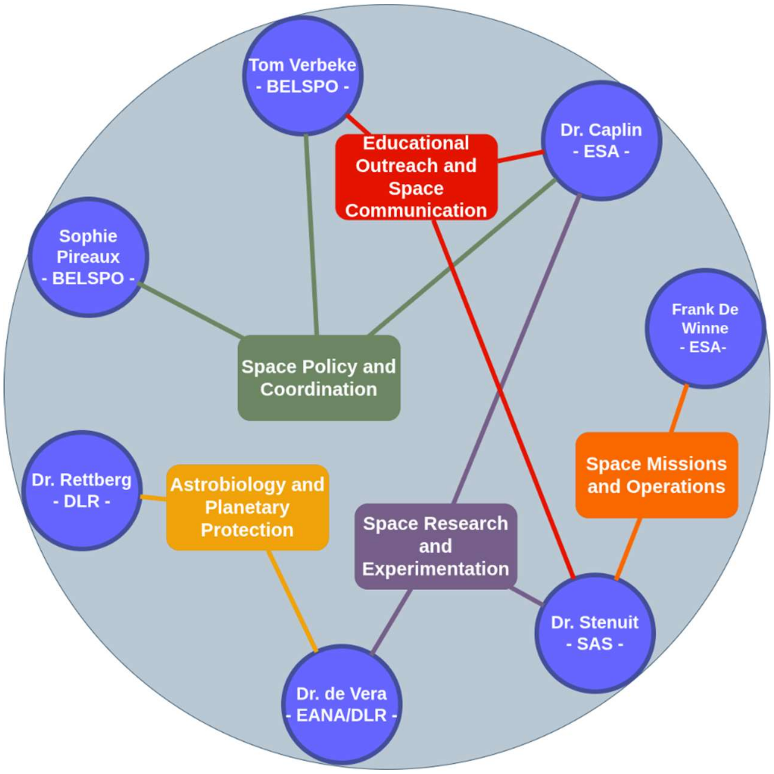


Figure 10: Diagram indicating the topics discussed during the interviews and the interdisciplinarity of the interview panel. Created with draw.io.

Oxford Nanopore Technologies (United Kingdom)

Oxford Nanopore Technologies is a UK-based company specializing in innovative DNA and RNA sequencing solutions. Their nanopore sequencing technology enables real-time, portable, and scalable genetic analysis, making it useful in various fields, including healthcare, agriculture, and environmental monitoring (Oxford Nanopore Technologies, 2025). Their Oxford Nanopore Technology MinION sequencer has been tested in microgravity to carry out real-time genomics and transcriptomics. It was launched to the ISS in 2018, where DNA and RNA were successfully sequenced for the first time in low-Earth orbit (Oxford Nanopore Technologies, 2018). Such proof-of-concept technology demonstration is promising in the field of astrobiology as it enables the study of genetics in space without needing to return samples to Earth, i.e. for deep-space missions and planetary exploration.

The customer service department of the company was contacted on 9 January 2025 to discuss their involvement in space technology development and (inter)national collaboration with institutions and companies. Unfortunately, they were inclined to meet but referred to scientific publications such as *"The Limits, Capabilities, and Potential for Life Detection with MinION Sequencing in a Paleochannel Mars Analog"* by Maggiori *et al* in 2020, or researchers employing their technology for astrobiology.

6. Results and Discussion

Over the past three decades, astrobiology has undergone significant advancements, characterized by groundbreaking insights into Earth's early development, the potential for life on other planets within our solar system, and the diverse nature of exoplanets. Concurrently, the broader space sector has experienced rapid growth. Since 1990, more than twenty-five scientific missions to other planets have been initiated by various countries, and the number of artificial satellites orbiting Earth has increased dramatically, from fewer than 500 to over 10,000 (Wordsworth *et al.*, 2025). This chapter presents a discussion and perspective based on insights from conversations with experienced stakeholders, focusing on specific aspects of astrobiology's evolution within the space sector. This analysis is further enriched and supported by publicly available data. The information gathered around the structure of ESA mainly comes from Frank De Winne and Dr. Caplin, while the information about ESA's budgeting and outreach comes from Tom Verbeke and Sophie Pireaux. The discussion on the European Astrobiology Network Association and the European Astrobiology Institute is mostly based on information from Dr. Rettberg and Dr. de Vera. Information on scientific and technological aspects of astrobiology is gathered from Dr. Stenuit, Dr. Caplin and Dr. de Vera. Finally, discussion on the political landscape and industry participation in astrobiology is mostly based on conversation with Frank De Winne, Dr. Stenuit, Dr. Rettberg and Sophie Pireaux.

6.1 Pan-institutional astrobiology organizations in Europe

To understand the European astrobiology landscape and space mission focal points, it is important to identify key players and their interaction. While many researchers are active in the field of astrobiology, individually or through small collaborations, it remains quite complex to establish bold goals and missions that inspire the public. A great amount of funding is required, which implies the need for international collaborations and pan-institutional organizations. Through these, the field needs to work towards long-term goals, gain political attention, and align engineers and scientists to develop and implement cutting edge technologies compatible with the complexity of space. Here, European pan-institutional organizations are discussed to understand their vision, strategic role, and interaction with one another.

6.1.1 The European Space Agency

The European Space Agency (ESA) was founded in 1975 to consolidate advanced space science and engineering across borders. It was originally established by merging the European Space Research Organisation (ESRO) and the European Launcher Development Organisation (ELDO) to coordinate efforts in European space research and accessibility. From the start, ESA's responsibility has been to enable and implement large space-related projects beyond individual nations. It has thus taken up the role of a technical organization and refrains from implementing policy. In 1975, ESA was founded by 10 member states, however, today it counts 23 member states, of which some are under a cooperation agreement, like Canada (Figure 11) (ESA, 2025a; ESA, 2025b).

Figure 11: ESA's member states (dark blue) and cooperating states (dark gray). Image credits: ESA.

To understand ESA's strategic role and vision, one needs to look at Article 2 of the ESA Convention (ESA, 2005), stating:

"The purpose of the Agency shall be to provide for and to promote, for exclusively peaceful purposes, cooperation ***among European States*** *in space research and technology and their space applications, with a view to their being used for* ***scientific purposes and for operational space applications systems****:*

a. by elaborating and implementing a ***long-term European space policy****, by recommending space objectives to the Member States, and by concerting the policies of the Member States with respect to other national and international organizations and institutions;*

b. by elaborating and implementing ***activities and programs*** *in the space field;*

c. by coordinating the European space programme and ***national programs****, and by integrating the latter progressively and as completely as possible into the European space programme, in particular as regards the development of applications satellites;*

d. by elaborating and implementing the ***industrial policy*** *appropriate to its programme and by recommending a coherent industrial policy to the Member States."*

From this excerpt, it is clear that not every partner (i.e. Canada) can become a full member as ESA's Convention states that they should be European States. While a member state contributes financially, has voting rights and allows its companies and institutions to fully participate in ESA programs and contracts, a cooperating state has a limited partnership with ESA, allowing access to specific projects but without full membership benefits or decision-making power. However, Canada has negotiated a special arrangement and does have a place in the council as well as contributes to ESA projects under a cooperation agreement. If desired, a cooperating state can follow the five-year Plan for European Cooperating States (PECS), during which ESA supports the country to develop its knowledge and space industry in order to become an associated member state, which is an intermediate step before full membership (ESA, 2025b; ESA, 2025c).

Article 2 of ESA's Convention also states that ESA focuses on scientific and operational activities, excluding commercial and military applications. While ESA maintains a non-military stance, it collaborates on space-based technologies for safety and security applications, addressing risks and informing stakeholders (ESA, 2025d). ESA taking up a military role would require all member states to be on board, which is difficult to achieve. Some ESA members have neutrality policies (e.g. Switzerland, Austria), while other member states have their own national military space programme and policy (e.g. France, Germany). Nevertheless, ESA has invested in more strategic programs over the past decades. As of 2003, it has partnered with the European Union to develop and implement a high-precision localization system for civil and military purposes (Galileo), and which is independent of other systems like the American GPS or Russian GLONASS (ESA, 2023). Similarly, in 2014, ESA participated in the EU Space Programme Copernicus of the European Commission, which aims to leverage earth observation for enhanced climate change mitigation and civil security (Copernicus, 2025).

Although commercial applications are not mentioned in Article 2 of the ESA Convention, commercialization of space activities has increased drastically since 1995. The term 'New Space' is now used to describe the emerging private-sector space industry, characterized by commercialization, innovation and competition (Lecky, 2016). New Space has led to the development of smaller, specialized satellites and decreased launch costs, reducing barriers to entry and accelerating innovation. Driven by new commercial supply-oriented policies, this shift has encouraged more players to take commercial risks to capitalize on the expanding public and private markets. According to the European Space Policy Institute (ESPI) Space Venture report of 2019, private investment in the U.S. reached €5 billion in 2019, compared to just €188 million for European start-ups. The U.S. commercial space boom—heavily backed by the government—has inspired similar policies in Japan and China and pushed some European companies to set up operations in the U.S. ESA stated that Europe too must take advantage of the commercial space sector for the benefit of our own society and economy. Hence, one of ESA's priorities for 2025 is "*Boosting commercialization for a green and digital Europe*" (Aschbacher, 2021), thereby once more deviating from the original aims set out in Article 2 of the ESA Convention. The challenge for ESA in this context lies in securing the consensus of all member states.

For 2025, ESA’s budget amounts to 7,68 billion euro, which is distributed across various space related activities belonging to two main categories. The first category are the mandatory activities (also called the basic activities), to which each member state contributes based on its Gross National Product. This is used to pay administration costs and to research essential technologies that might become useful in the future. In 2025, basic activities account for 334,4 million euro, or 4,4% of the budget. The second category are optional activities. Member states can freely choose to subscribe to these activities, including Earth observation, navigation, space transportation, human and robotic exploration, and others, accounting for 90,7% of the budget (ESA, 2025e).

As mentioned in article 2 of the ESA Convention, ESA implements a long-term European space policy. To guide the themes of space missions within the scientific program, ESA establishes ~20-year long-term visions that consolidate Europe’s scientific goals. The first of these long-term plans was the ‘Horizon 2000’ (1984-2005), which produced four high impact missions (ESA-ESRIN, 1995):

- SOHO (Solar and Heliospheric Observatory): Launched in 1995, the mission aimed to study the Sun’s internal structure.
- XMM-Newton: Launched in 1999 (and still operational), this X-ray observatory studies high-energy events, such as black holes and neutron stars.
- Cluster: Launched in 2000, four identical spacecrafts studied Earth's magnetosphere and its interaction with the solar wind.
- Rosetta: Launched in 2004, this spacecraft was the first to orbit and land on a comet, thereby providing insights into its composition.

The results of the Rosetta mission contributed greatly to the theory of panspermia, as mentioned in section 3.4.4. The mission's findings uncovered a broader range of molecules than had been detected before and showed that Comet 67P harboured both primitive and altered organic compounds (Grady *et al.*, 2018).

From 1995 until 2015, ESA’s second long-term vision, called ‘Horizon 2000 Plus’, came into effect. Building on the ‘Horizon 2000’ program, various missions were extended. The cornerstone missions of this programme were designed with the aim to increase knowledge, develop novel instrumentation and advanced technology to support future mission requirements (ESA, 1995). The identified cornerstone missions are (ESA, 2025f):

- Gaia: Launched in 2013 as a successor to the Hipparcos mission, this observatory created a 3D map of the Milky Way and observed over a billion stars to provide insights into the structure of our Galaxy.
- LISA (Laser Interferometer Space Antenna) Pathfinder: Launched in 2015, this mission served to demonstrate the technology for the future LISA gravitational wave observatory in space.
- BepiColombo: Launched in 2018, the mission will study Mercury and thereby uncover information about the history of our Solar System.

The Gaia mission, primarily designed for stellar cartography, has significantly advanced astrobiology by enhancing our understanding of exoplanets, which are key to assessing the potential for life beyond Earth. Gaia's precise measurements of stellar positions and movements have enabled the detection of exoplanets through astrometry, identifying subtle stellar wobbles caused by orbiting planets. This method complements other detection techniques and has contributed to the discovery of over 5,000 exoplanets to date. Gaia's data have also been instrumental in characterizing exoplanetary systems, providing insights into their formation and evolution, and informing the selection of targets for missions focusing on detailed exoplanet observation like ESA's Cheops, Plato and Ariel. With future data releases anticipated, Gaia is expected to further expand our knowledge of exoplanets, thereby supporting the search for habitable worlds and advancing the field of astrobiology (ESA, 2024b).

While Horizon 2000 Plus was ongoing, the ‘Cosmic Vision’ plan kicked off in 2005 and continues to run until 2025. It mainly focuses on ESA’s large-class (or L-class) mission JUICE. L-class missions are European flagship missions, launching approximately once per decade. Besides JUICE, two medium-class (or M-class) missions called PLATO and ARIEL, where breakthrough science with a cost-cap is the objective, were initiated. Two such M-class missions are launched every decade to foster international cooperation. Smaller missions allow member states to take the lead and enable fast development and innovative implementation (ESA, 2021).

- JUICE (Jupiter Icy Moons Explorer): Launched in 2023, the mission will explore the icy moons of Jupiter and assess their habitability.
- PLATO (Planetary Transits and Oscillations of stars): Scheduled to be launched in 2026, this mission will hunt and study terrestrial exoplanets in the habitable zones of stars resembling the Sun.
- ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey): Scheduled to be launched in 2029, this mission will analyze the atmosphere of exoplanets in the Milky Way.

Cosmic Vision focuses on four fundamental questions regarding our Solar System and thereby contributes to understanding life and the conditions that allow its emergence (ESA, 2025f):

*“**(i)** What are the conditions for planet formation and the emergence of life?*

***(ii)** How does the Solar System work?*

***(iii)** What are the fundamental physical laws of the universe?*

***(iv)** How did the universe originate and what is it made of?”*

JUICE will explore Jupiter’s largest moons—Europa, Ganymede, and Callisto—to assess their potential habitability. These icy worlds are believed to harbor subsurface oceans, making them prime candidates for hosting life beyond Earth. By analyzing their atmospheres, magnetic environments, and surface compositions, JUICE aims to determine whether the necessary conditions for life exist. This directly aligns with Cosmic Vision’s goal of understanding planetary formation and the potential for life in our Solar System. PLATO on the other hand, focuses on detecting and characterizing Earth-sized exoplanets in habitable zones around Sun-like stars. By studying planetary transits and stellar oscillations, PLATO will provide data on the structure and evolution of exoplanets, offering insights into their potential to support life. This mission furthers the Cosmic Vision objective of identifying the conditions necessary for life to emerge beyond Earth. Finally, ARIEL takes the search for habitable worlds even further by analyzing the atmospheres of exoplanets. By conducting large-scale observations of planetary atmospheres, ARIEL will reveal the chemical compositions, thermal structures, and cloud formations of distant worlds. This data will help scientists understand the processes behind planet formation and evolution, directly contributing to ESA’s efforts to uncover the fundamental mechanisms shaping habitable environments (ESA, 2025f).

While Cosmic Vision is drawing to a close, ESA’s future framework is lined out in the ‘Voyage 2050’ vision, established in 2021, which creates a direction for future space missions between 2035-2050. Here, three priorities are outlined for future large-class scientific exploration missions, of which two are astrobiology-themed (ESA, 2021):

- The first main priority will be to assess the habitability of the ocean-bearing moons in our Solar System, with advanced instrumentation, potentially an in-situ unit to search the subsurface oceans for biosignatures.
- The second main focus will be on the investigation of the Milky Way’s history, together with research on the habitability of temperate exoplanets in our galaxy.
- The third main priority will be to unravel the origins of the universe and black holes with new technologies and physical probes.

From these long-term plans, an evolution in ESA’s priorities is noticeable, with astrobiology-related themes gaining increased attention. While Horizon 2000 and Horizon 2000 plus do not explicitly address astrobiology research topics, Cosmic Vision and Voyage 2050 clearly denote a focus on fundamental astrobiology questions such as the critical conditions for the emergence of life, habitability and the quest to find life elsewhere in the universe.

6.1.2 The European Astrobiology Network Association

Since the late nineties, exo/astrobiology has seen a significant increase in attention across the scientific community, both space and non-space related. Interesting topics have been e.g. the chemical origins of life on Earth, extremophiles, and technology development to detect life. This triggered ESA to incorporate exo/astrobiology as a field of research, building on missions such as Rosetta, Cassini-Huygens and Mars Express. In 2001, ESA and a group of European scientists called the European Exobiology Network, co-organized a workshop to enhance Europe's resources for a leading role in exobiology. The workshop was held at the European Space Research Institute (ESRIN) in Frascati, Italy, with the following objectives (ESA, 2019b):

- *"identify the European potential in Exo/Astrobiology*
- *foster European cooperation through joint projects in Exo/Astrobiology*
- *strengthen the European Network in Exo/Astrobiology*
- *encourage young scientists to participate in exo/astrobiological research in Europe*
- *promote a constructive research interface between exobiological expertise in Europe and the rest of the World for the benefit of the discipline and the planet*
- *develop a perspective for longer term Exobiology research, especially in relation to human missions to Mars"*

These aims and discussions during the first European Workshop on Astrobiology have led to the conceptualization of the European Astrobiology Network Association (EANA). Hence, EANA was established in 2001, for individuals interested in astrobiology, including early-career researchers. The main focus of EANA is to **connect existing astrobiology networks** and to **provide a platform** for scientists to collaborate, exchange expertise, and share resources. Other activities include **outreach** of astrobiology research, books, initiatives and job opportunities. EANA is governed by a council representing 18 European countries and Japan (AbGradE, 2025a; EANA, 2024).

Since its inception, EANA has held annual meetings in various member states. During the 13th EANA meeting in July, 2013 in Szczecin, Poland, the Astrobiology Graduates in Europe (AbGradE) committee was established. AbGradE is now an independent organization, managed by PhD students and postdoctoral researchers, for early-career scientists and students in astrobiology and related fields to build academic connections and exchange ideas. They organize workshops, symposia, lectures and host their own meeting right before the annual EANA conference. Over the years, AbGradE has built strong relationships with universities and other entities while maintaining its partnership with EANA, aligning with their scientific focus (AbGradE, 2025b). This platform is clearly meant to be exclusively for students and early-career scientists, without experts, to develop and discuss their own ideas, fostering healthy competition. AbGradE members are typically also EANA members as they are the future generation for astrobiology research.

6.1.3 The European Astrobiology Institute

Astrobiology is a highly interdisciplinary field, addressing fundamental questions that necessitate a well-coordinated and collaborative approach among researchers from diverse scientific backgrounds. To advance astrobiology research effectively and avoid fragmentation within the European astrobiology community — caused by redundant or overlapping initiatives — the 2016 AstRoMap Report strongly advocated for the establishment of a pan-European platform dedicated to research, training, outreach, and dissemination in astrobiology. Hence, the European Astrobiology Institute (EAI) was created to fulfill this role. Such an institute was considered essential to maintaining Europe's leadership in this field compared to other global regions (European Science Foundation, 2025).

This virtual institute, established in 2019 and hosted by the European Science Foundation, is a collaborative network of European research institutions, universities, and other stakeholders dedicated to advancing the field of astrobiology. Its mission is to strengthen Europe's role in astrobiology and foster interdisciplinary cooperation across various scientific domains, by closely working with organizations such as ESA and EANA (EAI, 2025a; European Science Foundation, 2025).

The EAI has six scientific working groups that focus on specific research topics (EAI, 2025b):

- *Formation and Evolution of Planetary Systems and Detection of Habitable Worlds:* Investigating the processes behind planetary system formation, the factors defining habitability, and methods for detecting habitable environments.
- *Planetary Environments and Habitability*: Exploring the co-evolution of physical, chemical, geological, and biological processes on Earth to draw parallels for other planets.
- *Evolution and Traces of Early Life and Life Under Extreme Conditions*: Studying the origins of life, its development in extreme environments, and the implications for extraterrestrial life possibilities.
- *The Pathway to Complexity: From Simple Molecules to First Life:* Examining the origins and stability of complex organic molecules necessary for life, and the processes leading to the formation of biopolymers and the first cells.
- *Biosignatures and the Detection of Life Beyond Earth*: Developing strategies and technologies to detect signs of life on other celestial bodies.
- *Historical, Philosophical, Societal, and Ethical Issues in Astrobiology*: Addressing the broader implications of astrobiology, including cultural perspectives and ethical considerations.

The six Core Organisations supporting the EAI are CNRS & CNES (France), DLR (Germany), FNRS (Belgium), INAF (Italy) and Centro de Astrobiología (Spain). Furthermore, the EAI managed to obtain 21 participating entities across Europe, which are all research institutions (EAI, 2025c). In contrast to EANA and AbGradE, EAI does not provide membership for individuals but only for institutions. The rationale to focus on institutions is most likely because institutions have more stable funding and support, which is essential for large and ambitious astrobiology missions.

The EAI has established a list of concrete goals and core tasks. First, they aim to **serve as an advisory body**, offering expertise to European research organizations and decision-makers on astrobiology-related matters. Second, EAI **coordinates outreach activities** to engage the general public, industry, and other stakeholders. Moreover, they **stimulate collaboration with industry** to foster technological developments relevant to astrobiology research, benefiting Europe. Finally, EAI aims to **secure necessary financial resources** for its activities through a coordinated engagement with European funding bodies (EAI, 2025b).

6.1.4 The interaction between pan-institutional organizations

From the meetings held with the various stakeholders contacted in the framework of this master's dissertation, it was apparent that ESA is a well-established organization but that the effectiveness of EANA or EAI is not always clear. Moreover, the latter two organizations are mainly known in academic environments and not so much by industry.

Through personal communication with the current president of EANA, Dr. Jean-Pierre de Vera, it is clear that EANA has made progress since its inception. He is committed to maintaining EANA's welcoming atmosphere and is seeing a gradual increase in community size. One of the intentions behind the establishment of EANA during the ESA workshop in 2001, was that EANA's return would be to foster the creation of new ESA astrobiology topical teams and the development of, or contribution to, astrobiology-focused missions. Indeed, EANA members, many of which are representatives from national astrobiology societies in Europe, are actively involved in Mars, icy moons and exoplanet missions, such as the development of ExoMars and contribute to JUICE. Additionally, EANA actively supports the AbGradE committee and cooperates with EAI as it was crucial in founding both initiatives. Within the EANA community, members discussed how they can enhance impact and make significant progress on the level of projects financed by the European Union (EU). It was suggested that the establishment of an astrobiology institute with different working groups would be more effective in bringing together researchers and having them collaborate on advanced projects with the support of the EU. Hence, EU politicians were convinced to create the European Astrobiology Institute.

From discussions held with Dr. Rettberg, who is a member of EANA and who actively participated in 2 working groups of the EAI, it is evident there exists controversy about the roles of EANA and EAI. Questions about the delineation of both institutions were also shared by Dr. Caplin, indicating that the field of astrobiology is not unanimous among researchers in Europe. While significant efforts have been made to provide astrobiology a valued place within European space science and exploration with initiatives such as EANA and EAI, continual communication between these institutions and their respective roles in the political, scientific and societal landscape is needed to enhance their impact. In contrast to EANA's leadership, persuaded that EANA has achieved significant results and is on the right track, not all members agree on the actual amount of progress. To some, EANA comes across as a bottom-up initiative built by interested scientists, which turned out to be a loose group of people working on astrobiology without a clear strategy. Despite research being published by EANA members and highlighted during the yearly workshop/conference, communication and interaction between members occurs sporadic and feels disjointed. Dr. Rettberg contributed to the 2016 European roadmap and supported the establishment of the EAI. The common idea behind the EAI was to make it *the* partner for ESA to reach out to for astrobiology-related endeavors in Europe. It should be a strategically advising group of scientists in this area. This goal, however, does not appear to be achieved thus far. Instead, the institute strongly resembles EANA and is mainly a continuation of what was being done already: the organization of workshops, field trips, seminars and small conferences. Additionally, only a few members of working groups actually attend meetings, communicate with each other and are engaged. Since the COVID pandemic, attendance to the working groups also declined and attempts to communicate and write overview papers fell back.

From these conversations with Dr. Caplin and Dr. Rettberg, it became clear that a lack of engagement within EAI was holding back its impact. Members are very optimistic when initially joining the EAI, but this enthusiasm and engagement falters over time, potentially because of a lack of facilities leading to slow or no implementation of astrobiology experiments. To remedy this lack of engagement, **EAI leadership needs to reinvent themselves** or pass the torch to new management, providing the opportunity to not only reinvigorate the working groups but also to strategically coordinate with EANA and ESA. Dr. Rettberg still supports the idea of a European institute for astrobiology research, but the EAI is not what was envisaged during conception and failed to fulfill its role as a strongly coordinated advisory body. Based on public data as well as personal communication, the main reason for this discrepancy appears to be funding. This bottleneck and its impact on European astrobiology research is further discussed in section 6.2.

EANA's executive board on the other hand believes that EANA and EAI are cooperative but independent entities, each focusing on different but complementary goals. In fact, there are three pillars of astrobiology in Europe, each important and necessary: EANA, EAI and AbGradE. Information about the role and management of AbGradE is provided in section 6.1.2. EANA is focused on joining individual people who are active in astrobiology within their country to get in touch with other astrobiology scientists and experts, while EAI is connecting institutions to enable larger research projects. A lot of members of the executive board of EANA are in the management committee of EAI to facilitate collaboration and to contribute to EAI's activities such as research and seminars. Hence, EAI and EANA are more intertwined than one might think, which should lead to enhanced communication and coordination. However, such a high level of interaction can lead to both institutions growing too much towards each other, leading to similar roles in the astrobiology field. Both EANA and EAI organize their own annual conference on similar topics, creating a (false) perception that both entities compete with one another and little coordination takes place. When addressing this issue to Dr. de Vera, this confusion was recognized and efforts were made to create one united voice for European astrobiology towards the general public and policy makers.

Besides the unconcerted actions of EANA and EAI, a lack of interaction with several research groups in Europe is also noticeable. For instance, the German Thomas Carell group conducts research on prebiotic chemistry, but they are not connected to the EANA or EAI. This lack of communication and cohesion will inevitably lead to unintentional duplication of research and potential oversights. From discussions with Dr. Caplin, it seems that similarly, scientists at ESA working on astrobiology projects don't always communicate enough with one another and with their delegations. Undoubtedly, this plays a crucial role in fostering coordination and raising awareness about the importance of astrobiology to member states. After all, it is ESA's member states who hold the decision-making power. If they actively support astrobiology research, management at ESA will follow. Hence, there is a strong case that **delegates should be shown the benefits of supporting astrobiology research, in order to create momentum**.

From discussions with Frank De Winne, it became clear that the essence of ESA is to execute and integrate scientific, strategic and technical programmes that individual member states cannot realize on their own. Therefore, ESA, in the first place, is its member states with their policy and visions. The agency possesses extensive expertise and proposes high-level direction, but it is the member states who make the decision on program activities. It seems, however, that the known bottleneck of Europe's fragmentation also creates some friction here. ESA was created to build a European space industry to which member states contribute and tune in to their national space activities. However, the realization of this idea hasn't happened yet as ESA's member states want to keep their own priorities. In comparison, the integrated nature of the U.S. allows them to create more momentum.

ESA is structured in eleven directorates, from which some are mandatory programmes such as Science (SCI) and others are optional programmes such as Human and Robotic Exploration (HRE), for which Dr. Caplin worked. While mandatory programs are financially supported with a defined sum each year, the amount of funding allocated to optional programmes is solely the result of the strong ability to pitch themselves effectively to the member states. The programme of SCI is truly bottom-up, driven by scientists at ESA and decided upon by the member states. Apparently, astrobiology research has taken a place in SCI as well as in HRE, indicating that member states have shown interest in the field of astrobiology and acknowledged its relevance. European exposure biology experiments like BIOMEX have always been executed under the HRE department. Additionally, there is an education program under HRE, pointing towards an effort on outreach. However, it appears no tangible outcome is noticed from this program as the science of HRE is not communicated enough. The science journalism community in turn addressed this issue by writing an open letter to HRE and lobbied the director general, but no change has been noticed thus far. **More outreach and publicity for astrobiology research and discoveries** would undoubtedly aid in uplifting the field within the science community, incentivize industry participation and secure implementation of astrobiology roadmaps, white papers, and missions. Dr. Caplin herself shows active engagement in education and outreach of astrobiology by taking part in the ESA's series Meet The Experts: "Extreme Life", or in the RMC STORY documentary: "Sommes-nous seuls dans l'univers".

The increasing mention of astrobiology in ESA's long-term visions and the large declaration of astrobiology-related aims in ESA's Voyage 2050 vision, originates from the SCI directorate. However, ambitious astrobiology plans and missions are not a certainty yet. It still needs to be discussed during the upcoming ministerial meeting whether the Enceladus mission for instance will be followed through. There are indeed people in SCI who are pushing for astrobiology, but they are not as large a community as the people in astronomy or heliophysics. Hence, there seems to be a sociological battle between these communities, each fighting for priority. As astrobiology is gradually more exposed and popular, especially in the U.S., perhaps its voice will become louder within ESA's SCI department, leading to inspiration and a boost in this research field. Dr. Caplin and a colleague from SCI coordinated a joint HRE-SCI workshop to brainstorm about astrobiology with EANA and EAI members, attempting to draw the attention of the HRE and SCI director. This workshop was not mandated by ESA and its results were presented at the 2024 EANA conference, receiving positive feedback. However, no further action has been taken by management to actually implement the ideas discussed.

In summary, the interviews with experienced stakeholders within the domain of astrobiology in Europe revealed crucial insights into the current state of this discipline. Moreover, the public perception of key players is different from their actual organization. Circling back to the research questions postulated in this master's dissertation, the following conclusions can be made:

- **RQ1: Is astrobiology a focal point in Europe's space endeavors?**
  Various roadmaps and pan-institutional organizations have been created to stimulate astrobiology research over several decades. While these were

supported by ESA and EU policymakers, most efforts originate from bottom-up approaches. From this, it is clear that astrobiology inspires many researchers but that a more unified collaboration will be needed to enhance the impact of astrobiology research in Europe.

- **RQ2: Who are the key players in European astrobiology, and how can industry be incentivized?**
  ESA was crucial to the conception of EANA, a pan-institutional organization that brings together scientists for enhanced collaboration. From within EANA, the EAI was established to connect institutions to enable larger research projects. However, the current role of EAI seems to deviate significantly from its initial strategic position to advise ESA on a high level. Several EANA board members are active within EAI, which might have led to a conversion of both institutions to a similar strategic position. Changes in EAI leadership are thus desirable to improve the public perception on the role and interaction between EANA and EAI. Additionally, astrobiology research at ESA is divided over the mandatory SCI and the optional HRE department. Although astrobiology is emphasized in ESA's recent long-term visions, SCI is not convinced that all plans will be implemented as the astrobiology community at the SCI department are greatly outnumbered and overshadowed by other fields. Astrobiology at HRE has led to invaluable progress in the field, but outreach and communication with other European organizations lacks, even though efforts have been made to change this. In general, a strong voice for astrobiology research at ESA is required to inspire and inform researchers, delegates and the whole science community about the importance and impact of astrobiology. Eventually, this may potentially lead to incentivization of policymakers and industry to participate in the field.

6.2 The private sector can be incentivized to contribute to astrobiology

6.2.1 Economic considerations

The space sector faces significant challenges in engaging private sector participation due to the lack of a clear business case. ESA's original goal, mentioned in article 2 of the ESA Convention, was to focus on research and application development. The lack of a long-term view on space commercialization, as has been developed in the past decade in the United States, has resulted in limited industrial commitment. The absence of direct commercial returns is a major hurdle for garnering investments from private companies. In the case of astrobiology, such economic benefits are even more difficult to achieve because of its fundamental nature, complicating industrial contributions further. To date, several companies in Europe contribute to astrobiology, mainly by providing technical instruments such as spectrophotometers or robots, yet the extent of their involvement remains limited. An example is the company Leonardo Sp.A (Italy) that develops and provides robotic arms, optical and sensor technologies and/or communication systems for e.g. Mars Sample Return (Leonardo Space, 2025). Another example is the company Oxford Nanopore Technologies, which has been involved in astrobiology-related endeavours by testing their MinION sequencer as life-detecting technology on the ISS. Despite this collaboration, they do not seem to be interested in development of technology for the space sector. To get an idea of the involvement of European industry, initiatives of the American private sector regarding astrobiology, are given below.

One prominent example is the Frontier Development Lab (FDL), a research accelerator established by the Search for Extraterrestrial Intelligence (SETI) Institute (CA, USA). This initiative aims to bridge the gap between early-career researchers in astronomy and astrobiology and high-tech private sector companies, such as Intel, NVIDIA, and Google. The collaboration is mutually beneficial: companies developing artificial intelligence (AI) and machine learning (ML) algorithms require large, complex datasets to test their models, while researchers in astronomy and astrobiology increasingly face challenges managing massive datasets without sufficient expertise or computational resources (Cabrol *et al.*, 2018). FDL organizes intensive eight-week workshops where researchers and industry professionals collaborate to address significant problems, often involving astrobiology and related sciences. These workshops generate innovative solutions and promote knowledge exchange without necessitating direct financial investment from the participating companies. Instead, these firms contribute valuable resources such as computing power, hardware, and software licenses (National Academies of Sciences, Engineering, and Medicine, 2019b). Astrobiology, being a fundamental non-applied research area, means that partnerships with the commercial sector are unlikely to provide a profitable return on investment for the company. Hence, this model of partnership aligns well with the inherently multidisciplinary nature of astrobiology, making it an ideal example of how private sector expertise can be integrated into research initiatives.

Another avenue for private sector involvement in astrobiology starts with philanthropic investment. Philanthropic organizations and individuals have a history of funding space-related projects, including those tangentially connected to astrobiology. For instance, the Planetary Society (CA, USA), a citizen-funded organization, developed and launched LightSail 2. This spacecraft utilizes sunlight for propulsion, demonstrating the feasibility of solar sails. Launched in 2019, LightSail 2 successfully changed its orbit, proving the effectiveness of its design (The Planetary Society, 2025b). Moreover, they have co-funded the Lunar PlanetVac, a low-cost yet highly reliable system that acts like a vacuum cleaner to collect soil samples on planets and moons. This system was developed by Honeybee Robotics and will be delivered to the Moon by Firefly Aerospace (Ridgeway, 2025). It exemplifies how crowdfunding and public support can enable innovative space missions with industry commitment, while also highlighting the potential of public engagement in advancing scientific research.

Additionally, the non-profit BoldlyGo Institute (NY, USA) responsible for the launch of Project Blue, a direct imaging space telescope designed to explore the habitable zones around Centauri A and B, focuses on capturing images of Earth-like planets. According to the BoldlyGo Institute, recent private funding in astrobiology research is driving a shift toward high-risk, high-reward missions aimed at the search for life (National Academies of Sciences, Engineering, and Medicine, 2019b). These initiatives illustrate how the quest to find life in the universe is an inspiration, fostering partnerships that accelerate scientific and technological advancements beyond what could be achieved independently.

Lastly, the potential for philanthropic funding extends beyond individual missions. A white paper by Graham and Murray discusses how philanthropic foundations can play a larger role in supporting astrobiology research. Foundations like the John Templeton Foundation (PA, USA), the Simons Foundation (NY, USA) and the Moore Foundation (CA, USA) already provide substantial funding for scientific research through competitive grant processes. These organizations have the potential to significantly impact astrobiology by supporting exploratory and high-risk research projects that might struggle to secure traditional funding (Graham and Murray, 2021).

It is important to note that the development and execution of astrobiology missions requires years to decades. This timeframe imposes various hurdles, such as patience for researchers and funding agencies as well as a certain degree of consistency within the workforce. It is thus unsurprising that several initiatives have difficulty coming to fruition, especially without the support of an agency. One example might be the Breakthrough Enceladus mission, a privately funded initiative by Russian billionaire Yuri Milner through the non-profit Breakthrough Initiatives foundation (NY, USA). Enceladus is considered a prime candidate in the search for extraterrestrial life due to its subsurface ocean and water geysers that eject material into space. This private mission aims to develop a probe capable of flying through these plumes to analyze the water for biomarkers, offering a significant step forward in astrobiology. NASA has pledged technical assistance to support the mission by signing a Pre-Phase A agreement but does not coordinate or fund the project (Anderson, 2018). The mission remains in preliminary design and feasibility assessment and since 2018, no further updates have been published about this private mission. It was estimated to take about a decade to develop this project but it seems to have lost traction compared to other missions of the Breakthrough Initiative.

Initiatives like the ones mentioned above, which involve philanthropy and the private sector, could propel astrobiology to a new level. However, most examples where industry is heavily involved and pursues incentives other than a direct financial return, take place outside Europe. To gain insight on how European companies in the space sector view astrobiology involvement, Dr. Stenuit of the Space Applications Services (SAS) was contacted. SAS is a Belgium-based private company specializing in space system engineering, operations, and software development for human and robotic exploration (Space Applications Services, 2025). The company can play a significant role in advancing the field of astrobiology by leveraging its expertise in spacecraft systems, robotics, and data analysis, which would drive the development of new instruments and technologies SAS can offer to clients. These advancements often lead to valuable terrestrial applications, enhancing our quality of life and benefiting the environment. Hence, participation in astrobiology research drives technological innovation, enhances reputation but also potentially leads to strategic advantages in securing future contracts for planetary missions, deep-space infrastructure, and Earth-based applications derived from space research. From discussions with Dr. Stenuit, who is a principal scientist at SAS, it seems that astrobiology is considered important and exciting by many, providing benefits for humans on Earth. The main hurdle for companies such as SAS, is that astrobiology research is not directly translatable to economic benefit. In general, it's noticeable that services are needed between the academic and industrial world and that astrobiology needs more time to provide a return on investment to persuade the private sector. Dr. Stenuit agrees that it would be interesting for SAS to involve astrobiology with their future *in situ* resource utilization moon rover, to get more prestige/reputation within this domain. Bringing an astrobiology project to the Moon and thereby connecting different teams and reputable individuals, such as Jim Green (NASA), would be very beneficial to the company. Moreover, **combining this prestige with *in situ* resource utilization creates an economic incentive**.

Furthermore, from discussions with dr. Rettberg, it seems that the EAI experiences difficulties with finding industrial partners. In the U.S., sponsorship by industry or hedge funds is more common, but in Europe this is clearly underdeveloped. Industry should be persuaded that astrobiology research is important and of industrial relevance. However, from discussions with Frank De Winne, industry will not likely be persuaded if there is no profit in the picture and a return to stakeholders. Hence, a strong case can be made for the upcoming domain of "**applied astrobiology**" as a possible solution. While this term is not yet broadly accepted in scientific literature, it refers to the practical application of knowledge about life's limits, adaptability, and origins to develop technologies such as bioregenerative life support systems, biomining, and synthetic biology for space missions. In addition to its relevance for space, applied astrobiology offers benefits for Earth by advancing sustainable technologies and deepening our understanding of how life interacts with extreme environments. Thus, this domain seems to connect several important fields such as biotechnology, life sciences, medicine and biomimetics, which have substantial industrial significance. Dr. de Vera agrees that applied astrobiology will lead to invaluable benefits on Earth such as new software development and miniaturized and/or portable technology, which is ideal to incentivize industry and the general public as a visible return is created.

According to Dr. Rettberg, besides the EAI experiencing difficulties in its goal to find industry partners, EAI members are reluctant to invest in the institute as well. This appears to be the case because the main activities organized by the EAI, being field trips, seminars and workshops, are less relevant for these institutions. The EAI on the other hand, cannot do more than it is doing now with the little funding it receives from its members. Tom Verbeke (BELSPO), who takes part in the Belgian delegation at ESA, agrees that Europe is fragmented in terms of budgeting for the space sector. This bottleneck indicates that space policy needs to be streamlined, also on a national level. In Germany for instance, the funding schemes for space research projects seem to be inefficient. German universities are financed by the German research association but DLR is funded by the government. If a university researcher writes a proposal for a research project to ESA and the proposal is accepted for flight, then the researcher has to write an additional proposal to the German space agency to ask for funding as ESA typically sponsors the launch and hardware for experiments but not the years of preparatory work and analysis. An additional hurdle is that the German space agency will only provide funds as soon as the researcher submits the launch date. However, if the researcher can only begin with its basic experiments from that point, little time remains to make sure the final experiment will work. This example highlights the current inefficiency of project proposals and their funding, which undoubtedly complicates industry participation. Industry is unlikely to take the lead in astrobiology research, while the academic sector lacks the necessary funding. As a result, project proposals are crucial and are primarily initiated by academic institutions. However, industry partners may be reluctant to engage if the funding decision process takes long. Companies need to be lean and able to react on market changes or opportunities, but long grant approval processes complicate a company's agility by pinning down resources and manpower.

Based on discussions with Sophie Pireaux (BELSPO), it appears that ESA is also encountering difficulties in attracting industrial participation in its Invitations to Tender (ITTs). These ITTs are formal procurement solicitations through which ESA invites industry and other eligible entities to submit proposals for the provision of services, technologies, software, hardware, or system developments within the context of ESA programs and missions (ESA, 2025j). All ITTs are governed by ESA's georeturn policy, which aims to ensure a fair distribution of contracts among member states in proportion to their financial contributions. However, large industrial players often refrain from responding to ITTs, as the technologies requested are typically highly specialized and tailored to specific space missions, limiting commercial applicability beyond the project itself. Consequently, only a single commercial unit may be produced, reducing incentives for industry to engage. While the georeturn policy is intended to foster a more balanced industrial participation across ESA member states, it may discourage some industrial engagement. Nonetheless, without such a policy, contract awards would likely be concentrated among a few major industry players, thereby disadvantaging smaller countries in the development of their space sectors. An option might be to better protect generated intellectual property (IP). As the timeframe of astrobiology missions is often years to a decade and little applications might arise for specialized instruments/technology, governments might consider protecting these inventions longer (i.e. **extended patent protection or allowing exclusivity rights**) to allow companies to recover their investment costs. This approach would be quite like IP concerning the treatment of rare disorders, for which also huge investments are made and the application potential remains limited. However, such measures would need to be initiated at a European level.

6.2.2 Outreach and education is underdeveloped

From discussions with Frank De Winne, fragmentation in Europe is an enormous bottleneck in general, not only for space science research, but also for other domains like defense. Unlike the U.S., ESA's member states and European countries in general want to keep their sovereignty and individual priorities. As a result, there is no uniform 'European vision' to which member states can adhere or industry can contribute. For instance, in the context of the Artemis missions, ESA contributes with Gateway and service modules. Concurrently however, ESA's member states inquire at NASA individually to negotiate a potentially better agreement with them than with ESA. Hence, it seems that a **European vision** to which all member states need to adhere, might create a breakthrough by consolidating resources and clarifying ESA's astrobiology roadmap for industry. The question remains whether the member states are willing to give up their sovereignty.

Dissonance of European targets for space research and astrobiology because of different visions of member states and institutions clouds outreach to the public, policymakers and industry. Therefore, increasing visibility and awareness can also incentivize political will to fund astrobiology research. As mentioned previously, non-profit organisations like the Breakthrough Initiative Foundation and BoldlyGo demonstrate that funding does not only need to come from governments. While ESA's approach with mandatory and optional space programmes for member states will not change soon, an alternative approach to create more unisono in the European astrobiology sector might come from **appointing several astrobiology experts with great dissemination skills as public billboards for the domain**, much like Sir David Attenborough is for life on Earth (biology). These spokespersons could enhance the number of informative podcasts such as Nerdland (Belgium), documentaries, science fairs and social media pages to create more awareness, provide realistic perspectives, incentivize young adults to pursue STEAM studies, and entice the public. Eventually, when interest is maintained over a long period of time, politicians can be persuaded to prioritize astrobiology research more and unlock funds to incentivize the private sector. Moreover, Dr. Rettberg agrees that more people need to devote their time to lobbying for astrobiology funding, thereby generating public awareness and credibility.

Education presents itself as a stable and long-term outreach channel. Unsurprisingly, Article V of the ESA Convention states that education is part of the agency's mandatory basic activities (ESA, 2025i). ESA Education activities include a communications department, as well as the European Space Education Resource Office (ESERO) and ESA Academy. Some ESA directorates like HRE have their own education and outreach teams that develop tailored content and events as well. Based on discussions with Dr. Caplin, there appears to be some outreach effort from HRE, but it currently underperforms. In contrast to the United States, ESA remains less visible than NASA.

Tom Verbeke shares the opinion that outreach and education of space science at ESA and BELSPO could improve. The differences in priorities among ESA member states significantly influences educational frameworks, resulting in diverse learning objectives for each member state. The Belgian Science Policy Office (BELSPO) allocates most of its budget for space activities, ~300M€ annually, to ESA programs. However, the funding for internal space outreach initiatives is considerably smaller, amounting to ~100K€. Furthermore, education is not a responsibility at the federal level in Belgium, which restricts BELSPO's engagement in educational matters to the ESA Education program. ESERO consists of national offices across Europe that support teachers with space-related educational materials for students from the age of six to eighteen years. ESERO's activities are mandated by ESA, highlighting a discrepancy between the funding body (BELSPO) and the entities that define the expected outputs (the French, Dutch, and German-speaking communities in Belgium). Nevertheless, ESERO Belgium maintains connections with these communities to deliver space-related educational content that aligns with each community's learning objectives. On the other hand, ESA Academy is a facility based in Belgium and provides university students access to training sessions, projects, internships and mentorship by ESA professionals. ESA Academy is funded solely by ESA, but BELSPO contributed to reinforce the Belgian-based European Space Security and Education Centre (ESEC), including the ESA Academy facilities.

On a national level at BELSPO, more effort can be put in outreach, education and inspiration of the public according to Tom Verbeke, but a lack of manpower and resources hinder this. Although the space sector has long emphasized the need for enhanced outreach, this priority appears to have been overlooked, as evidenced by the consistently limited funding allocated to outreach initiatives. Recently, BELSPO together with the Belgian Olympic and Paralympic delegation visited EAC to research the (dis)similarities between athletes and astronauts. More science communication about this activity could have captured the interest of the public but remained underexploited. A few months ago, however, two spokespersons were designated at BELSPO to enhance communication with the press and exposure, showing a hopeful evolution for the future.

Tom Verbeke agrees that **education and outreach through public figures or astronauts are a way to gain awareness and visibility**. The importance of these endeavours to secure future workforce was also underpinned by Sophie Pireaux, although she recognized that it would require investment without an immediate return. Industry in Belgium typically struggles with hiring new workforce and often needs to attract them from outside of Belgium. Outreach efforts could significantly benefit academic institutions and universities by increasing awareness of the industrial competencies available within Belgium. Currently, these institutions often collaborate with foreign companies instead of engaging with capable Belgian firms due to insufficient knowledge on the capabilities of the Belgian industry. Therefore, targeted outreach aimed at enhancing visibility into specific expertise and activities of domestic companies is crucial. This does not only hold true for Belgium but should be emphasized over all of Europe. Moreover, fostering stronger links between academia and industry could be further supported by **integrating industry-oriented projects into science and engineering curricula**. Encouraging students to undertake joint projects with industry or spend part of their education engaged in industrial environments would not only enhance practical training but also promote long-term collaboration between sectors. Hence, involvement of industry in education activities is crucial. Industry engagement is incorporated within the ESERO work package, although it is not a primary focus. Nonetheless, it implies recognition of its significance. While industry stakeholders express interest in the ESERO initiative, its focus on middle and high school students, rather than university-level individuals, makes it less relevant to their immediate needs. ESA's introduction of the Junior Professional Programme (JPP), which targets individuals with 2–3 years of industry experience, reflects an institutional acknowledgment of the value of industrial experience. Conversely, industry demonstrates strong interest in candidates with ESA experience. This reciprocal interest suggests a valuable opportunity to strengthen collaboration between ESA and industry.

In summary, by reviewing literature and conversing with experts and experienced industrial stakeholders within the domain of astrobiology in Europe, the extent (or refrain) of involvement in astrobiology endeavors by the private sector could be discerned in Europe and the U.S. Additionally, several bottlenecks were identified and possible courses of action were conceived to incentivize European industry. Finally, the importance of ESA's as well as national education and outreach activities were examined. The following conclusions have been drawn, in relation to the research questions outlined in this master's dissertation:

- **RQ2: Who are the key players in European astrobiology, and how can industry be incentivized?**
  As mentioned in section 6.1, pan-institutional organizations are the main actors striving for astrobiology. European industry is not motivated to invest in astrobiology research, as it does not offer immediate applications or direct economic returns. Political will currently lacks to resolve this issue, as limited coordination and inefficient funding prevails. First of all, addressing visibility and

awareness is essential for generating the political will needed to support astrobiology research. Hence, it is suggested to designate dedicated astrobiology communicators, who engage the public through podcasts, documentaries, science fairs, and social media. Sustained awareness and interest can build public support and interest in STEAM studies, eventually encouraging political backing and funding to involve the private sector. Secondly, a solution could be to widely implement ‘applied astrobiology’, which not only advances space research, but also benefits Earth by driving sustainable technologies and innovations in fields like biotechnology, life sciences, medicine, and biomimetics. This can lead to valuable outcomes such as new software and portable technologies, offering clear returns that can attract both industry and public interest. A third suggested course of action is to better protect IP so that companies have more time to regenerate their development costs in unique technologies that are often not broadly applicable. However, this incentive should be enabled at a European level. Finally, to strengthen connections between academia and industry, incorporating industry-focused projects into science and engineering curricula is suggested.

- **RQ3: What is the political landscape of astrobiology in Europe and how does it differ from the U.S.?**

  The political landscape of astrobiology in Europe is shaped by key organizations, including EAI, EANA and ESA. The EAI promotes interdisciplinary cooperation among research institutions, while EANA connects individual scientists to enhance collaboration. ESA plays a pivotal role in integrating astrobiology into its long-term strategic plans, facilitating missions aimed at investigating potential biosignatures. Interactions with member states significantly influence the effectiveness of these organizations. Each country has its own priorities and funding mechanisms, leading to a fragmented approach to astrobiology research. This decentralized structure results in varying levels of commitment, with some nations prioritizing other areas of space science over astrobiology. In contrast, the U.S. benefits from a more unified framework through NASA, which fosters collaboration between federal agencies and the private sector, creating a dynamic research environment. Focusing on Belgium, BELSPO plays a crucial role in shaping national space policy and contributes significantly to ESA projects. However, limited funding and the complexities of aligning national priorities with European goals hinder the visibility and impact of astrobiology in Belgium. Overall, the European political landscape is marked by fragmentation, contrasting sharply with the more integrated support system present in the U.S.

- **RQ4: What bottlenecks exist in astrobiology research?**
  Astrobiology research in Europe faces several significant bottlenecks that hinder progress and private sector engagement. Firstly, the lack of a unified European vision for astrobiology leads to fragmentation among member states, resulting in inefficient resource allocation and limited collaboration opportunities. This disunity creates an environment where private companies are hesitant to invest due to uncertainties regarding the direction and potential returns of astrobiology initiatives. Secondly, funding mechanisms are often inefficient, with lengthy approval processes that discourage industry participation. Additionally, the absence of immediate economic returns from astrobiology projects makes it challenging to attract private investment, as companies typically prioritize ventures with clear profit potential. Furthermore, outreach and education efforts are underdeveloped, leading to insufficient public awareness and political will to support astrobiology research. This lack of visibility limits the ability to inspire interest among potential stakeholders, including industry partners. Addressing these bottlenecks requires a concerted effort to streamline funding processes, enhance public engagement, and foster collaboration across Europe's astrobiology landscape.

6.3 Crucial aspects and technologies for astrobiology research

6.3.1 The path to research implementation is both lengthy and challenging

Increasingly sophisticated life-detection and bio-analysis technology is used on Earth as well as on the ISS and in space missions, underscoring the paramount importance of considering both current and future technological requirements in the field of astrobiology. As we advance, ESA's Topical Team Astrobiology and Astrochemistry highlights the critical need to leverage emerging platforms such as CubeSats, SmallSats, and the Lunar Orbital Gateway. These platforms present innovative opportunities to conduct experiments that address key astrobiological and astrochemical questions, thereby enhancing our capacity to search for exoplanets and biosignatures beyond our solar system, and ultimately expanding our understanding of life in the universe (Elsaesser *et al*., 2023).

From discussions with Dr. Rettberg and Dr. Caplin, there appears to be a big discrepancy between, on the one hand, identifying scientific requirements for astrobiology research in roadmaps such as AstRoMap or the 2021 white paper by ESA's Astrobiology topical team, and on the other hand, technological development or facilities to conduct experiments. ESA and the EAI acknowledge these roadmaps, but implementation is missing because of a lack of facilities. This issue seems to have a direct negative impact, namely a long hiatus between the application and implementation of an astrobiology project or experiment in space. For instance, Dr. Rettberg wrote a proposal for astrobiology experiments in 2014, which at the moment *might* fly in 2026 or 2027 on the ISS if there are no technical issues. Dr. Caplin confirms that long delays have always been there for astrobiology research in space. Projects dating from 2008 are yet to be launched. There has been a longstanding concern regarding the slow pace of development in this field. Despite ongoing discussions emphasizing the need for acceleration, tangible progress remains limited. This persistent stagnation is particularly discouraging for early-career scientists involved in these experiments, who rarely witness implementation or meaningful results. Astrobiology research in space is characterized by extensive operational planning, preparatory testing, and procedural requirements, which of course contribute to these delays. The process of getting a scientific experiment approved and implemented through ESA involves numerous stages, each of which introduces potential delays. In the case of Germany for instance, additional delays arise as researchers must apply for national funding, which is contingent on securing a launch opportunity. Even after ESA approval, further complications emerge when coordinating with industry partners to develop specialized hardware. These collaborations are often hampered by miscommunications and logistical setbacks according to Dr. de Vera, Dr. Caplin, Tom Verbeke and Sophie Pireaux. Often there is a mismatch between the expectations of researchers and the capabilities of industry. A common language needs to be found between scientists and engineers to avoid miscommunications and obtain their shared goal. Moreover, certain experiments require long-term testing, further extending the timelines. These cumulative factors significantly slow down the overall progress from concept to implementation.

The long delays mean that most of the astrobiology findings are the result of experiments in simulated space environments on Earth. These are adequate for basic tests, but not for extensive detailed research. Once more, applied astrobiology could offer a promising approach to bridge the gap between scientific requirements and practical implementation. One of the major accomplishments of astrobiology in recent decades has been the discovery of the remarkable diversity of extreme environments on Earth in which life can persist. This has coincided with growing insights into the potential habitability of extraterrestrial environments. However, accurately replicating the complex combinations of stressors found in these environments within laboratory settings remains a significant challenge. Comprehensive analysis of factors such as the toxicity of Martian regolith or the acidity of Venusian clouds necessitates the deployment of new space missions (Wordsworth *et al.*, 2025). Besides research into habitability on celestial bodies, access to space is imperative for experiments in prolonged microgravity and its complex radiation field, which cannot be reproduced on Earth. ESA's 2024 HRE workshop in Warsaw, Poland, consisted of 30 sessions, of which only one related to astrobiology named “Origins & Limits of Life / Exposure & Astro-bio – Extremophiles”. During this session, recommendations from the former ESA Topical Team Astrobiology and Astrochemistry were communicated. They emphasized that the execution of space exposure experiments necessitates the utilization of appropriate platforms, which are designed to facilitate the attainment of elevated levels of radiation and modified gravitational forces. The location of the platform is a critical factor in determining the duration of the mission, the level of radiation exposure, the feasibility of sample return, and the necessity of in situ measurements (Billi, 2024). During the wrap-up discussion of the ESA-HRE workshop, it was emphasized once more that (astro)biology experiments currently lack platforms. A new opportunity has arisen, however, with the Exocube project, part of the European Space Exposure Platform (EXPO), which will conduct *in situ* experiments on microbial survival and organic molecules in low Earth orbit. Exocube is designed with two main experiments: ExocubeChem, which studies organic molecules using infrared spectroscopy, and ExocubeBio, which focuses on microbial responses, particularly to radiation. ExocubeBio integrates advanced microfluidics and miniaturized fluorescence and absorbance systems, making it the first platform to combine real-time measurements with sample return capabilities for post-flight analysis. Set to launch in 2026 aboard the ISS, Exocube aims to explore how space radiation, microgravity, and other conditions affect microbial growth, metabolism, and cellular integrity. The project will also study the mechanisms behind microbial survivability, with a focus on radiation biology and space exploration (Burr *et al.*, 2022).

The ISS is currently the main platform for astrobiology-related experiments in LEO, until its retirement at the end of 2030. From discussions with Dr. Stenuit, research taking place on the ISS, currently focuses on studying chemical processes in microgravity, but also biofilm formation and the interaction of microorganisms with abiotic material like rocks and regolith. An experiment on dust physics in vacuum is also being done in relation to planetary formation. Hence, it seems that many experiments are conducted on the ISS, including through ICE cubes, which relate to certain aspects of astrobiology. Moreover, from communication with Sophie Pireaux, it appears that astrobiology researchers typically piggyback on other research or missions to retrieve relevant astrobiology data. For instance, ESA research on asteroid impacts, which falls under the domain of space safety and security, is also useful for astrobiology researchers to obtain data on asteroids.

6.3.2 Technological and infrastructural needs for LEO and Mars missions

To know where we are with astrobiology today and what the future holds, it is important to understand the limits of current technology, the constraints of the implementation of novel instruments as well as the long-term goals. From discussions with Dr. Stenuit and Dr. de Vera, technology demands a high investment of time and money to be ready for use on the ISS or other celestial bodies in terms of robustness and radiation hardness. This implies that most of the current analysis and diagnostics technology on the ISS is outperformed by new technologies on Earth. Hence, it is crucial to address this bottleneck by promoting the quick implementation of new technologies on the ISS and beyond. SAS is actively involved in mitigating this bottleneck by developing capabilities to replace technology easily and swiftly on the ISS from the moment it is developed on Earth.

Technological requirements for future astrobiology research were discussed with Dr. Stenuit, Dr. Caplin and Dr. de Vera. Regarding experiments on the ISS and future space platforms, **improved temperature control** is imperative next to **miniaturization**, **microfluidics** and **robotics** allowing for autonomy. Investing in *in situ* science and measurements is essential for the future of space exploration. These aspects have been strongly recommended by the astrobiology topical team in their white paper and during the ESA-HRE workshop, highlighting its value across a wide range of scientific disciplines, platforms, and destinations. The integration of microfluidics with *in situ* technologies is especially promising and has been identified as a key advancement. In astrobiology, this capability is crucial for addressing major scientific questions and conducting planetary protection studies. Moreover, its relevance extends to broader biology communities, including Earth-based applications in human health and organ-on-chip research, aligning with many of ESA's strategic objectives. This reinforces why Exocube as an astrobiology exposure platform will be invaluable (Kish and Elsaesser, 2024). Furthermore, there seems to be a clear evolution towards the implementation of **artificial intelligence** (AI). For instance, in the ICE cubes facility designed by SAS, an AI box was installed quite quickly, including a camera to study crew wellbeing based on face recognition. It also serves to investigate how AI can be used operationally in space stations. Extensive research is still needed to identify the optimal balance between biological systems and machines for supporting science and exploration in space. As the space economy grows more complex and machines gain the ability to perform tasks beyond human capabilities, the roles and functions of robots and AI in space will continue to evolve (Wordsworth *et al.*, 2025).

Furthermore, spectroscopy is a critical technology for astrobiology research because it enables the detection, identification, and analysis of chemical compounds, both remotely and *in situ*. Dr. Stenuit said that it would be interesting to have a handheld Raman spectrometer tested on the ISS, to assess its potential for *in situ* research on the moon or Mars. From discussions with Dr. de Vera, the importance of combining different spectroscopy techniques became clear. Using one spectroscopy technique allows for clear identification of a limited set of molecules. However, in the search for remnants of life on Mars, it's necessary to combine different spectroscopes to be able to detect all molecule groups forming a cell, thereby obtaining significant unambiguous results. Hence, Dr. de Vera is inquiring and advocating the procurement of a **multi-spectrometer**, to have a better chance at investigating and detecting (remnants) of cells. This insight into the necessity of combining more spectroscopy techniques was strengthened by Curiosity's recent finding of large aliphatic molecules. Curiosity uncovered these most likely thanks to improved technology as well as a better idea of where to search for biosignatures on Mars. Now, samples are analyzed in much more spectrometer ranges, using Raman, IR and UV spectroscopy. On the other hand, samples are searched in specific interesting areas, particularly in deposits, where accumulations of material can be found over long timescales. ExoMars is a large European project for Mars that has been running for decades, and soon the Rosalind Franklin rover will be launched with the help of NASA. Then, biosignatures will be looked for in the Martian subsurface, much deeper than where Perseverance is collecting samples at the moment, and for which novel instruments were carefully chosen.

Tom Verbeke communicated that the launch date for the Rosalind Franklin rover is set for 2028, but that NASA still needs to deliver some crucial parts for the mission. The current political shifts in the U.S. have brought about much uncertainty about priorities in the space sector and planned missions, such as the Mars Sample Return mission. This uncertainty is likely to incentivize NASA to maintain its collaboration with ESA on the ExoMars mission, as it represents the agency's most secure opportunity to remain actively engaged in Mars exploration in the foreseeable future. Wordsworth *et al.* confirm that Mars Sample Return, NASA's flagship mission, is currently undergoing re-evaluation due to rising costs. Increased involvement from the private sector is being considered as a potential part of the solution (Wordsworth *et al.*, 2025).

From discussions with Dr. Rettberg, Frank De Winne and Dr. de Vera, the development of **curation facilities for sample return missions** is a big discussion point for Europe. The first returned unsterilized samples of the Mars Sample Return will be analyzed in a facility in the U.S., which is currently being built. NASA is actively developing optimal methodologies for the containment and analysis of Martian samples, with particular attention to preventing any potential risk to Earth's biosphere in accordance with established planetary protection protocols. While the likelihood of harm is considered extremely low, it is not zero, and the mission continues to prompt concerns among some members of the scientific community and the public. However, Europe will unlikely develop facilities to receive and analyze unsterilized extraterrestrial samples in the near future. The political will in Europe, necessary to unlock the large funds (>150 million euros) for these facilities, lacks among the member states.

The distribution of the sterilized samples will be based on the best science, entailing that researchers need to write a detailed proposal to the international committee to prove that their science will be valuable and their lab certified clean enough to avoid contamination. As this process takes years, European research groups should engage now to be certified and trained for handling extraterrestrial samples on time. Within ESA, sample curation is regarded as a strategic priority, grounded in the belief that the future of space exploration will increasingly rely on sample return missions. To support this trajectory, specialized curation facilities capable of handling materials from the Moon, Mars, icy moons and asteroids will be essential. However, the development of such infrastructure is both highly specialized and costly, raising questions about the extent to which ESA member states are willing to invest in it. While some member states, such as France and Germany, recognize the prestige and scientific value of such facilities and are interested in contributing, others are more hesitant. The way forward remains uncertain and is expected to be a central topic of discussion at the upcoming ministerial conference. The goal is not to reach a definitive yes-or-no decision, but rather to explore various options, such as identifying which countries are interested in hosting or contributing to these facilities, whether a distributed network of smaller-scale facilities could be more feasible, or if a single large-scale center should be established. In the latter case, decisions around location and associated prestige will also need to be carefully negotiated.

ESA has developed a Sample Return Plan (SRP), which is currently under discussion with its member states. Under existing agreements, Europe is theoretically entitled to access up to 50% of the returned samples. Consequently, ESA is engaging with both member states and NASA to address how European scientists can secure this access, particularly if the primary curation facility is in the U.S. This includes exploring mechanisms for facilitating the transfer of samples to European laboratories. This issue remains a significant topic of negotiation, both within Europe and in transatlantic discussions. The scientific framework for the Mars Sample Return mission has not yet been fully defined, although there is still time to develop it, as the samples are not expected to arrive on Earth until between 2035 and 2038. Presently, efforts remain focused on the engineering aspects of the mission, such as the development of rockets and landers for sample retrieval, rather than the subsequent scientific analysis. Additionally, political developments, including decisions by the current U.S. administration, may also influence the course of these plans.

In summary, through discussions with experts in the European space sector and in the field of astrobiology, scientific and technological requirements as well as bottlenecks were discerned. The scope encompassed experimental research on the ISS and current and future missions to other bodies in the solar system. Additionally, the political context in Europe around the Mars Sample Return mission was discussed as well. The following conclusions have been drawn, in relation to the research questions outlined in this master's dissertation:

- ❖ **RQ5: Which crucial technologies or facilities are missing in Europe for the next big leap in astrobiology?**
  Several bottlenecks hinder the progress and implementation of astrobiology experiments in space. Earth-based space analogs are an adequate platform for basic tests but lack crucial parameters such as prolonged microgravity and complex radiation. Hence, the development of new appropriate platforms and facilities is crucial to conduct experiments in the space environment, especially with the retirement of the ISS approaching. Additionally, technologies of paramount importance for future astrobiology research include microfluidics, highly temperature-controlled and miniaturized hardware, robotics and multi-wavelength spectrometers. Investing in cross-cutting technologies and hardware offers strong returns, as these tools can be leveraged across multiple applications. Fluidics, in particular, play a vital role on the human, microbial, and

molecular level, making it a critical area for investment. It has been recognized as an essential component for platforms in space, such as the Gateway, and for use in extreme environments on Earth. As for Earth-based facilities, curation laboratories are considered key for the future of space exploration and highly necessary for the upcoming Mars Sample Return. While the U.S. is currently building one to receive unsterilized samples, Europe does not have the political will and means to do the same. However, European research groups should invest in certifying laboratories for the analyzation of sterilized samples, to ensure access to 50% of samples and involvement in the research. Moreover, the training of staff to handle extraterrestrial samples should also begin. As the process of proposal writing, certifying labs and training staff takes a significant amount of time, action should be taken now. ESA internally is highly interested in the development of curation facilities, but the member states are divided.

6.4 Metrics to monitor the evolution of astrobiology

In context of the first research question of this master's dissertation: "Is astrobiology a focal point in Europe's space endeavors?", metrics were sought to assess the evolution of astrobiology in Europe. The number of publications on astrobiology and the annual budgeting data for astrobiology of ESA were investigated. After inquiring about these metrics during the interviews with experts in the space domain, no knowledge or data appeared to be present or available about this subject. In the future, a study focusing on the evolution of astrobiology in Europe, using the above-mentioned metrics for instance, would provide valuable insights for both the scientific community and the broader space sector. Demonstrating a positive trend would underscore the growing significance of astrobiology over the past decades and could serve to encourage increased investment from ESA member states and other stakeholders. Such support would be instrumental in addressing current bottlenecks that are limiting progress in the field.

While the proposed study extends beyond the scope of this master's dissertation, preliminary insights are presented in section 6.1.1, which examines the increasing integration of astrobiology-related missions within ESA's long-term strategic plans. Furthermore, a search for the terms "astrobiology", "biosignature" and "extremophile" in the Web of Science database yielded data on the number of publications related to astrobiology research from 1997, the year it was officially recognized by ESA, until 2024. The resulting data for various terms were analysed and compared to mitigate semantic bias. The analysis indicates a distinct upward trend in astrobiology-related research over the past 27 years (Figure 12). A more comprehensive examination of astrobiology-related publications in Europe, including specific areas of focus and their implications for science and society, is warranted. Additionally, further research into supplementary metrics is necessary to thoroughly evaluate the evolution of this field in Europe.

Furthermore, insights from discussions with Tom Verbeke and Sophie Pireaux have shed light on the relative role of astrobiology within ESA's broader space activities. Notably, the Rosalind Franklin rover, part of the ExoMars mission, accounts for roughly one-third of the activities within ESA's HRE directorate. The HRE department encompasses disciplines such as human spaceflight, robotic exploration, space systems and technology, scientific research, mission planning and exploration strategy. ESA's SCI directorate covers, among others, Earth observation, planetary science, astrophysics, and space science. Some astrobiology-related efforts also originate from this directorate, such as the CHEOPS mission and smaller experiments conducted aboard the ISS. However, these activities remain significantly outnumbered by initiatives in other domains, such as Earth observation. Consequently, while astrobiology is an important area of interest, it represents a relatively small portion of the overall activities within the domains of both directorates.

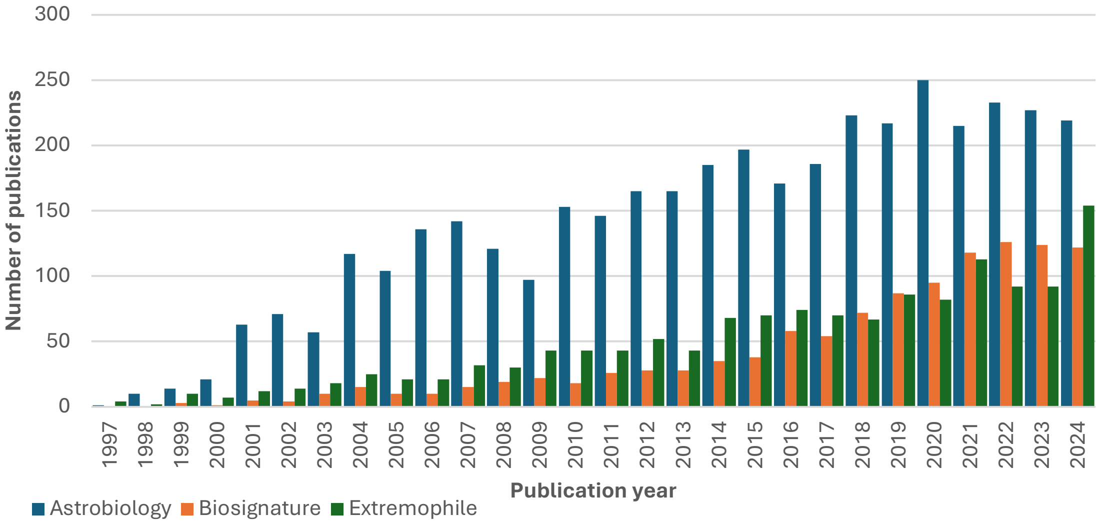
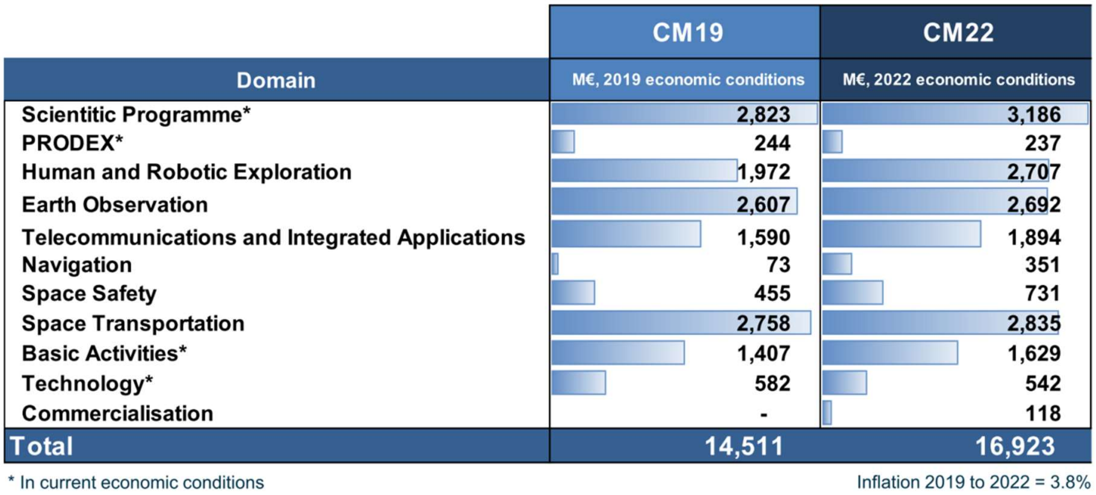


Figure 12: Plot of the number of publications related to the term "astrobiology", "biosignature" and "extremophile" from 1997 until 2024. A clear rising trend in research related to astrobiology is visible. Source of data: Web of Science.

During the 2022 ESA Council at the ministerial level in Paris, BELSPO presented a report titled "Follow-up and Debriefing to the Belgian Space Actors." This report compared the budgets allocated to various domains for the years 2019 and 2022 (Figure 13) (BELSPO, 2022). Notably, the two domains in which astrobiology plays a minor role, the Scientific Programme and HRE, experienced a significant increase in funding over the three-year period. In contrast, the increase in investment for large domains such as Earth Observation and Space Transportation was comparatively smaller. However, it remains unclear to what extent astrobiology contributes to the overall SCI and HRE departments, as well as how the increases in funding specifically relate to astrobiology endeavours. Therefore, a dedicated study is warranted, ideally following the upcoming ministerial council of 2025, to evaluate the role and evolution of astrobiology within ESA and Europe.



	CM19	CM22
Domain	M€, 2019 economic conditions	M€, 2022 economic conditions
Scientitic Programme*	2,823	3,186
PRODEX*	244	237
Human and Robotic Exploration	1,972	2,707
Earth Observation	2,607	2,692
Telecommunications and Integrated Applications	1,590	1,894
Navigation	73	351
Space Safety	455	731
Space Transportation	2,758	2,835
Basic Activities*	1,407	1,629
Technology*	582	542
Commercialisation	-	118
Total	**14,511**	**16,923**

* In current economic conditions

Inflation 2019 to 2022 = 3.8%

Figure 13: Comparison of budget allocations for various domains within the European Space Agency (ESA) for the years 2019 and 2022, highlighting changes in funding across different sectors. Credits: BELSPO.

7. Legal, ethical and philosophical considerations

In contrast to the United States, Europe places explicit emphasis on the legal and ethical dimensions intrinsically associated with astrobiology. This commitment is exemplified by the establishment of a dedicated working group focused on "Historical, Philosophical, Societal, and Ethical Issues in Astrobiology," reflecting a comprehensive and interdisciplinary approach to the field (EAI, 2025d). The potential existence of microbial life beyond Earth indeed necessitates a legally and ethically responsible approach to space exploration. Compliance with international space law, particularly the Outer Space Treaty, requires stringent planetary protection protocols to prevent harmful biological contamination. Astrobiologists bear a legal and moral obligation to develop and implement rigorous measures that prevent both forward contamination (the transfer of Earth life to other celestial bodies) and backward contamination (the introduction of extraterrestrial life forms to Earth's biosphere) (Berliner *et al.*, 2024). In this context, the importance of planetary protection protocols is becoming increasingly evident, particularly with ambitious missions such as the Mars Sample Return.

Since the early 1960s, planetary protection measures have evolved significantly, grounded in peer-reviewed scientific research and reflected in the recommendations of the Committee on Space Research (COSPAR). The COSPAR Panel on Planetary Protection (PPP) plays a pivotal role in advising on strategies to prevent organic and biological contamination caused by space missions. The Panel is responsible for the development and oversight of the COSPAR Policy on Planetary Protection, a voluntary non-binding framework intended to assist spacefaring nations in adhering to Article IX of the 1967 Outer Space Treaty. This article obliges countries to take appropriate steps to avoid harmful contamination of celestial bodies and adverse changes to Earth's environment from extraterrestrial material (COSPAR, 2025). The widespread ratification of the Outer Space Treaty demonstrates a global consensus on the importance of preventing contamination of extraterrestrial environments. As a result, planetary protection has effectively evolved into a norm of customary international law.

Furthermore, these protocols are not only crucial for upholding the integrity of scientific investigations into the origins and distribution of life but also for ensuring the safety and health of astronauts and Earth's environment. Astrobiologists are also tasked with monitoring and controlling biological spacecraft burdens, ensuring spacecraft do not harbor or spread potentially pathogenic microorganisms. Their work plays a pivotal role in maintaining ethical standards, legal compliance, and biological safety in humanity's pursuit of knowledge beyond our planet (Berliner *et al.*, 2024).

Astrobioethics, defined as "the study of ethical questions in connection with astrobiology", is an emergent and interdisciplinary field that aims to examine the ethical implications of astrobiology research and exploration (Persson, 2023). As astrobiology advances in its exploration of life beyond Earth, astrobioethics becomes increasingly essential for framing the philosophical and moral questions that arise from these scientific endeavours. On the global stage, its importance is reflected in initiatives such as the founding of the International Working Group on Astrobioethics and discussions at major scientific congresses. Astrobioethics addresses planetary protection and considers the broader consequences of space exploration for ecology, technology, and human responsibility (Chon-Torres, 2018). Especially for the upcoming Mars Sample Return mission, it is essential to determine how Martian samples will be securely contained, how contamination will be prevented, and how the samples should be analysed. While the goals of planetary protection and astrobiology may appear to align, they are not without conflict. Complete sterilization of astronauts or robotic systems is unachievable. As a result, absolute prevention of both forward and backward contamination may not be guaranteed. Therefore, it is crucial to address the ethical and legal implications of these challenges, consider established strategies, and carefully evaluate the trade-offs between the search for extraterrestrial life and the responsibility to protect existing life (Persson, 2017). Rooted in the critical and reflective nature of philosophy, astrobioethics encourages consensus among scientific communities and offers guidance on legal, ethical, and social dimensions of astrobiology activities (Chon-Torres, 2018).

8. The interdisciplinary character of astrobiology

The nature and goals of astrobiology research undeniably require many disciplines to come together. Astrobiology inherently is multidisciplinary in content and interdisciplinary in implementation. Besides its scientific aspect, it also has a strong focus on society, education, and public outreach (Race *et al.*, 2012). Research and advancements in solving fundamental questions about life have tremendous impact in many fields. On the one hand, they provide more insight into (bio)chemistry, (micro)biology, (geo)chemistry, astronomy, biophysics, bioinformatics etc. On the other hand, our society and human philosophy are significantly influenced as well. Thanks to the many disciplines contributing to astrobiology research, science and other related aspects are put in perspective, modern technologies are developed, and our understanding of Earth can develop (De Mol, 2023). The interdisciplinarity of astrobiology becomes evident when reviewing the different scientific working groups of the EAI, established by EANA. Their foci vary greatly and include: the origin and evolution of life and habitability, life under extreme conditions, the detection of biosignatures and habitable planets, but also the historical, philosophical, societal and ethical issues in astrobiology (EAI, 2025d).

Scientific endeavors aside, the societal aspects of astrobiology are given much attention and importance. The fundamental questions about life to which astrobiology attempts to find answers are intertwined with almost all cultures and societies. As astrobiology has this impact on human philosophy, politics and society, research topics on these aspects are posed as well. They include, amongst others, the way in which astrobiology influences the significance and meaning of life, the exploration of societal issues regarding the origin and evolution of life, how to approach planetary protection, and the relationship between humans, Earth and (extraterrestrial) life (Race *et al.*, 2012). Furthermore, astrobiology presents educational opportunities, being an inspiring and visionary field that garners significant public interest. The study of life's origins and the possibility of extraterrestrial existence sparks curiosity. This sense of wonder, combined with the opportunities associated with astrobiology, space exploration and space-related endeavors, motivates young people to pursue STEAM studies (Sephton, 2014).

It is however important to note that the interdisciplinary nature of astrobiology poses some challenges. The impact of astrobiology on society and the potential impact of society on astrobiology need to be considered consistently and collectively by experts in all related fields. Moreover, astrobiology discoveries and interpretations should be communicated to different audiences by identifying both areas of agreement and disagreement, as these can influence how scientific findings are understood and accepted. Ongoing support for astrobiology may depend on having credible experts from a range of complementary fields who can place these findings within broader contexts (Race *et al.*, 2012).

9. Conclusions and future perspectives

This master's dissertation has comprehensively examined the current state of astrobiology in Europe, analyzing both its scientific achievements and the policy landscape that shapes its development. Through extensive literature review and in-depth interviews with key stakeholders across academia, industry, and space agencies, this research provides crucial insights into Europe's position in the global quest to understand life's origins, distribution, and future in the universe. The investigation revealed that astrobiology has evolved significantly since ESA's formal recognition of the field in 1996, as indicated by the rising number of publications related to astrobiology over the last decades (Figure 12). From its early focus on exobiology to today's comprehensive interdisciplinary approach, European astrobiology has contributed groundbreaking discoveries through missions like Rosetta, which provided evidence supporting panspermia theory, and the ongoing ExoMars mission searching for biosignatures on Mars. The establishment of pan-institutional organizations, EANA in 2001, AbGradE in 2005 and EAI in 2019, demonstrates Europe's commitment to fostering collaboration and advancing the field. However, these organizations face challenges in coordination and strategic alignment, with overlapping roles creating confusion rather than synergy.

Addressing the research questions, this study found that while astrobiology increasingly features in ESA's long-term visions, it has not yet achieved focal point status in Europe's space endeavors (RQ1). The field remains driven primarily by bottom-up initiatives from passionate researchers rather than top-down strategic prioritization. The key players identified include ESA's SCI and HRE directorates, EANA, EAI, and national research institutions like DLR, though industrial participation remains minimal (RQ2). This limited industry engagement stems from astrobiology's fundamental nature, which offers few immediate commercial applications or economic returns. The political landscape analysis (RQ3) revealed that Europe's fragmented approach contrasts with the more integrated U.S. model. While American philanthropists and private companies actively support astrobiology through initiatives like the Breakthrough Foundation and Frontier Development Lab, European industry remains hesitant without clear profit incentives. This disparity is compounded by inefficient funding schemes that create bureaucratic hurdles between proposal acceptance and implementation, often resulting in decade-long delays. The research identified several critical bottlenecks hindering European astrobiology's progress (RQ4). These include impractical funding mechanisms that discourage industry participation, insufficient public visibility limiting political support, extensive delays between experiment approval and spaceflight implementation, and Europe's inherent fragmentation preventing unified vision and strategy. Additionally, the approaching ISS retirement in 2030 creates urgency for developing alternative platforms for astrobiology experiments in space. Technological gaps (RQ5) present both challenges and opportunities. Europe lacks appropriate platforms for long-duration space exposure experiments, curation facilities for extraterrestrial samples, and cutting-edge instrumentation like multi-wavelength spectrometers and microfluidic systems. The Mars Sample Return mission exemplifies this challenge as Europe will theoretically access 50% of returned samples, but no European facility exists to handle unsterilized extraterrestrial material, limiting analysis capabilities to sterilized samples.

To address these bottlenecks, this research proposes several solutions. First, developing "applied astrobiology" could bridge the gap between fundamental research and commercial viability, attracting industry through tangible Earth-based applications in biotechnology, medicine, and sustainable technologies. Second, dedicated science communicators should be designated to enhance public awareness through diverse media channels, building the political will necessary for increased funding. Third, extending patent protection for astrobiology-related innovations could incentivize industry investment by ensuring an adequate return on newly developed, specialized technologies. Fourth, strengthening the connection between industry and academia could be enhanced by incorporating industry-focused projects into science and engineering curricula. Lastly, improved coordination between EANA and EAI, possibly through leadership changes and clearer role delineation, would eliminate redundancy and strengthen Europe's unified voice in astrobiology.

Looking toward the future, European astrobiology stands at a crucial juncture. Novel platforms like Exocube, launching in 2026, promise new capabilities for real-time biological experiments in LEO, while the Rosalind Franklin rover's 2028 launch will search for subsurface biosignatures on Mars. Voyage 2050's priorities include investigating icy moons and characterizing exoplanet habitability, which position astrobiology prominently in ESA's future missions. The field's inherent interdisciplinarity, combining expertise from biology, chemistry, physics, geology, and engineering with philosophical and ethical considerations, makes it uniquely positioned to address humanity's most profound questions. This research emphasizes that astrobiology's relevance extends far beyond the search for extraterrestrial life. Understanding life's limits and adaptability informs biotechnology development, inspires new materials and processes for extreme environments, and provides crucial knowledge for future human space exploration. Moreover, astrobiology serves as a powerful tool for science education and public engagement, inspiring the next generation of STEAM professionals.

To conclude, European astrobiology possesses exceptional scientific talent, ambitious goals, and growing recognition within space policy frameworks. However, realizing its full potential requires addressing structural bottlenecks through enhanced coordination, strategic funding reforms, increased industry engagement, and sustained public outreach. Only through such comprehensive reforms can Europe secure its position as a global leader in humanity's quest to understand our place in the universe and answer the fundamental question: Are we alone? As we stand on the brink of potentially transformative discoveries, from Mars sample analysis to the exploration of icy moons, the decisions made today will determine whether Europe merely participates in or actively shapes the future of astrobiology.

10. Contribution statement

This master's dissertation is the result of a collaborative journey, and I would like to express my sincere gratitude to all those who contributed to its development.

I am especially thankful to my promotor and supervisor, Maarten, whose guidance has been invaluable throughout this process. From the very beginning, we developed the core concept of this master's thesis together, and his support was crucial in shaping its direction. Furthermore, Maarten facilitated contact with many of the individuals I interviewed and provided valuable support in preparing for the discussions with them. His constructive feedback refined my critical thinking and analysis, significantly contributing to the depth of the thesis.

The conducted interviews formed the foundation of this research, and I am deeply grateful to Dr. Rettberg, Dr. Caplin, Dr. Stenuit, Frank De Winne, Dr. de Vera, Tom Verbeke and Sophie Pireaux for their willingness to share their time, experiences, and expertise. Their insights were essential in developing the core arguments and conclusions of this thesis.

I am also profoundly grateful for the opportunity to pursue the Master of Space Studies. The program has been interesting, inspiring and deeply rewarding. I would like to thank all the professors and guest speakers for their engaging and insightful courses, as well as Dr. Clio Gielen, who was always there for the students, answering every question and organizing excursions that enriched our learning experience beyond the classroom. Lastly, I want to thank my classmates, who became my friends. Their support, encouragement and camaraderie were an important part of this journey and made it all the more meaningful.

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