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Mémoire

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Master in Space Sciences
Professional Focus

Design and Justification of a Partial Gravity Centrifuge for Simulating Europa and Enceladus Gravity Conditions in the ICE Cubes Facility

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FACULTY OF SCIENCE

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In the framework of my Master thesis, I completed a five-month internship at the ICE Cubes Service (Space Applications Services), in the Business Development Department. While working on projects revolving around biosciences and biotechnology, I gained substantial insight into the space industry and experiments conducted in microgravity. Evolving in this environment helped me identify the gap in the experiments sent to the ISS regarding astrobiology and inspired me to develop a new payload dedicated to that. By working at the Noordwijk office, in the Netherlands, I had the opportunity of being very close to the Business Development team that helped me understand the complex intersection of scientific research and payload integration for LEO and the Engineering Department, whose members guided me tremendously in the conception of my experiment hardware.

Special thanks to the whole ICE Cubes Service Team for their trust in me during my internship and their support to my thesis. Thank you to Alexei Ofitserov, Jacopo Carra and Luca Facciolati for their help on the technical aspects. Many thanks to Miguel Ferreira and Andrei Sapera for their input, patience and uplifting energy, to Hilde Stenuit for her support during my internship. I am also very grateful to Tristan Margottin for the intern camaraderie.

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To improve the clarity and readability of this thesis, language editing tools including Grammarly and OpenAI’s ChatGPT were utilized for proofreading and refining the writing style. All scientific content and technical decisions remain the original work of the author. Software such as Canva and Fusion 360 have been used for original illustrations.

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1. Context

1.1. Background & Motivation

For millennia, humanity has wondered about the meaning of its existence. One of the fundamental pieces of this puzzle is questioning whether we are alone in the Universe. Is there life elsewhere in our Solar System, in our Galaxy, in the Universe? Are we unique? Or is all this merely a coincidence of nature, a phenomenon that could have occurred, or may occur, elsewhere in spacetime?

Apart from physics and philosophy disciplines, the field addressing this question is astrobiology. These studies aim to characterize what is common to living beings, how to define life, how to determine whether a location is habitable, and where we might find other life forms beyond Earth.

Aside from Mars, other places in our Solar System have been identified by astrobiologists as potential sites for traces of life or, even better, existing life forms. These locations include the icy moons of gas giants such as Jupiter and Saturn. This work will primarily focus on Europa, a natural satellite of Jupiter, and Enceladus, a natural satellite of Saturn, which possess the most favorable conditions for hosting life.

In order to study these bodies and prepare for future missions there, a goal set by European Space Agency's Voyage 2050 Science Objectives [1], further research is needed to understand if life could thrive in Europa and Enceladus's conditions. If research suggests it is possible, what would its characteristics be, and how could we refine our instruments and scientific methods to effectively detect it, assuming it exists? To achieve this goal, it is important to test extremophiles (organisms that thrive in extreme conditions) in environments simulating those of Europa and Enceladus. This is accomplished on Earth through studying analog environments, reproducing conditions in laboratories and numerical simulations [2]. Additionally, platforms in Earth's orbit are utilized to assess life's resistance to harsh environments, and orbital experiments serve as preparation for future orbiters and landers. However, there is a very limited number of examples of such experiments.

Given their mass, these moons have a gravitational acceleration approximately ten times lower than that of Earth, which can affect the behavior of living organisms. By studying life forms in low gravity, hypergravity and microgravity, scientists have discovered that various aspects of cell functioning depend on gravitational pull [3].

On Earth, we experience an acceleration of 9.81 m/s^2, which is considered to be 1g as a reference. Higher g can be achieved through speed acceleration, with short arm human centrifuges like the one at the German Space Agency (DLR) in Cologne for example, while 0g may be reached on Earth through parabolic flights and drop towers or during extended periods in space, on board orbital stations, where the conditions are those of microgravity. One method to simulate partial gravity is to use a centrifuge in microgravity. By starting from 0g, the rotating motion creates a centrifugal force that can accelerate samples to 0.1 g, for example. This activity has already been conducted on board the ISS to simulate 0.33g [4], resembling Mars-like gravitational conditions and Moon-like 0.13g.

1.2. Research Objectives & Questions

The goal of my Master thesis is to conceptualize experimental hardware that can simulate the gravitational conditions of Europa and Enceladus to further facilitate the study of potential life there and to prepare for in situ missions. The objective is to design a centrifuge to be sent to the ISS to achieve partial gravity. The envisioned platform, called CAMINO (Centrifuge for Astrobiology in Microgravity and INvestigations of Ocean-moons), will be designed to fit in a cube-like box, a practice that has been widely used in current facilities onboard the ISS for easy compatibility. It will carry samples containing microorganisms and will have the capability of transmitting real-time data from cameras, along with the possibility of directly interacting with the hardware by changing conditions from the ground.

The design of this mission involves access to a commercial service for an orbital station. This is in tune with the current evolution of the space sector and makes the project more accessible by facilitating its implementation. The development occurs within the framework of using the ICE Cubes Service, a service provided by Space Applications Services. This service includes access to a facility onboard the ISS, inside the European module Columbus, referred to as the ICE Cubes Facility, or ICF. This facility can host multiple experiments and provide them with power and data connections, allowing their scientific investigators to monitor and interact with them in real time.

For all the reasons mentioned above, the goal of this work is to develop experimental hardware that simulates the icy moon conditions of Europa and Enceladus to research how life forms react to them. The study will focus on the project's relevance, the feasibility of creating this type of hardware, its potential design, its advantages and disadvantages, and its accessibility if fully developed.

Research question:

What are the scientific, technical, and operational justifications for implementing a centrifuge to simulate Europa and Enceladus gravity levels within the ICE Cubes Facility, and what are the key design requirements and constraints for such a system?

1.3. CAMINO

Before diving into the introduction, context for the name and mission patch will be provided. This will facilitate project management and can later be useful for marketing and press.

As mentioned previously, the centrifuge project is called CAMINO. It is an acronym for Centrifuge for Astrobiology in Microgravity and INvestigations of Ocean-moons. It also means “chimney” in Italian, which is a suitable reference to the hydrothermal vents that are supposed to exist at the bottom of Europa and Enceladus's sea-beds, similar to the black smokers we have here on Earth. Furthermore, it also references Kamino, an ocean planet from the Star Wars Universe.

The mission patch represents a planet with the shape of Saturn and the colors of Jupiter, symbolizing the host planets of both Europa and Enceladus. It spins to reflect the rotating motion of the centrifuge. The wave, inspired by "The Great Wave off Kanagawa" by Hokusai, represents the oceans beneath the icy shells of the moons. There are six stars, each representing one year of my university journey, celebrating the culmination of my higher education, which is this Master's thesis.

Figure 1: CAMINO Mission Patch [Credit: Ioana Dimitrova]

2. Introduction

In order to create an experimental platform that could serve astrobiology, it is essential to have a clear understanding of what this branch of science studies and why. In the first part of this literature review, we will focus on the reasons Europa and Enceladus are of interest by reviewing criteria for habitability, definitions of habitable zones, and the characteristics of these two celestial bodies.

Next, we will review different types of astrobiological experiments that are possible to conduct, with a particular focus on those carried out in microgravity by analyzing the different experimental factors that this environment entails. Additionally, we will reference examples of previous missions and experiments to reflect on what has already been accomplished and how. In this section, we will introduce the concept of centrifuges for generating artificial partial gravity and discuss other centrifuges that currently exist in orbit.

In the third and final part of the literature review, I will introduce the ICE Cubes Service. I will describe what the service is, how it differs from traditional agency services, and why it is interesting to imagine this experiment implemented through their platform.

2.1. Astrobiology in the Solar System

First, we will focus on what astrobiology is and why it is interesting to study. Next, the commonly accepted criteria for life will be listed, the definition of a habitable zone will be presented, and lastly, specific locations in our Solar System will be covered, where we can expect to find interesting places that could provide us with clues to understanding life better.

2.1.1. Why Astrobiology?

Astrobiology can be defined as follows: “It is the science that seeks to understand the story of life in our universe”. It is the study of the emergence of life, the conditions necessary for it, and the places where we may find these conditions. It also covers how life as we know it may survive in other locations and attempts to investigate the fundamental human question of “Are we alone in the universe ?” [5].

Why is this so important? This question is part of many humans’ quest for answers and has even given rise to a new branch of psychology called *exopsychology*, which explores how humans imagine extraterrestrial life. According to Charles Cockell, a very renowned astrobiologist, humans not only have an interest in finding life for scientific curiosity but also because it gives their own life context. “The only answer I’ve been able to come up with is the ineffable sense of wonder aliens offer us. It’s a heady mixture of the familiar, the idea of living things, like us, grappling with their situation in the universe and the problems of existence, with the ethereal, the excitement of something unexpected, different, new, maybe a frisson of trepidation.”, he shares in the Saturday Evening Post

[6]. In this article, he also discusses how thinking about other forms of life gives us a form of hope, an escape from mundane life, and that perhaps just the mere thought of thinking about them, without having to actually encounter them, is enough to keep our minds excited. Similarly, Graham Lau, an astrobiologist from the Blue Marble Space Institute of Science in Seattle, compared this effect to the "Overview Effect". This term describes what some astronauts have reported feeling after coming back from space: a renewal in their vision of the world and a revival of hope and awe about humanity. He writes that by looking from the inside out rather than the outside in, one senses a similar feeling that he calls "the panzoic effect". The feeling of awe and wonder towards outer space and the existence (or not) of other forms of life brings hope for unity and compassion among us here on Earth and incites care for ourselves and our planet. "Considering alien life is a means for considering ourselves" [7].

It also investigates further about the past, present and future of our Universe. Has life existed before? Will it always exist? Drake's equation tackles this problem in a very straightforward manner. It combines the rate of formation of stars in the Galaxy (R_*), the fraction of stars with planetary systems (f_p), the number of planets that have life bearing conditions(n_e), the fraction of those planets that actually host life (f_e) , the fraction of those planets that have intelligent life (f_i), the fraction of civilisations that have technology to contact other civilisations (f_c) and finally, the length of time during which they are potentially sending signals (L). At the end we obtain the number of technologically advanced civilizations (N) in the Milky Way galaxy.

$$N = R_* \times f_p \times n_e \times f_e \times f_i \times f_c \times L \tag{1}$$

The numbers for N have ranged from 10 to several million because some of these factors are very difficult to calculate. Scientists have been working on refining them and have revised the results over the decades. At the end of the line, the recent discoveries of around 5,000 exoplanets show us that if the probability is actually 0, that means that other civilizations are incapable of connecting to us due to a lack of technological advancement, or for some reason, unwilling, or maybe life is just unique to this planet. Given the age of our Universe, if life had existed somewhere, it would have had the time to evolve and find us. This discrepancy between the lack of evidence of advanced extraterrestrial life and the likelihood of its existence, is known as the Fermi paradox [8] [9] [10].

If we were to actually be alone, what does that say about us? Does this mean we are special, here with a specific goal? How does that put our daily actions into perspective? On the contrary, if we are not alone, how does that affect our actions? How would we want to be perceived? How does this impact our belief system and religion? How do we psychologically accept that we are just a coincidence? The questions are endless.

The potential for finding life elsewhere is also linked to the possibility of our own species surviving in other parts of the Universe. Could our terrestrial life survive on another planet? Could we engage in space travel beyond our local neighborhood? If one day our planet were doomed, would we, as a species, be saved? Could we expand into a multi-planetary civilization? The abundance of sci-fi movies and books reflects the fascination humans have with this idea, as do the contemporary missions planned and the direction humankind has taken over the last 100 years in relation to space.

On a more scientific note, since a few thousand years, humans have developed new set of tools to this quest. Their curiosity about nature has led to philosophical realizations, but most importantly, it has spurred advancements in technology, improving our experience of life. By studying astrobiology, we increase our knowledge about our own form of life, which can positively impact our society. If humans had never wondered about sparks, we would never have mastered fire. If they had never wondered how birds fly, we would never have had planes [11].

This curiosity also opens doors to exploring the most inhabitable places on our planet, leading to discoveries and the exploration of Earth, which we still do not fully understand. This can have implications for our knowledge of different species and the discovery of biological processes unknown today. It can uncover solutions to climate change, on how to mitigate extreme living conditions, and contribute to our wonder of the nature surrounding us [11].

2.1.2. Definition of life

To study astrobiology, which aims to explore the history of life in our Universe, one must first define life, a task that is not easy. In fact, life on Earth is so diverse that the boundary between living and non-living has often been debated.

The most widely accepted definition is the one proposed by NASA/Joyce (1994): "self-sustained chemical system capable of Darwinian evolution" [5].

In order to arrive to such a definition, scientists have gathered an ensemble of characteristics that are common to most living organisms:

- Phospholipids that form the membrane
- Genetic information (DNA, RNA)
- Proteins that manage the cell (created by translation of the genetic code)
- Ordered structure
- Reproduction
- Growth and development
- Utilization of energy
- Response to the environment
- Homeostasis (regulating the inside environment unregarding the outside one)
- Evolutionary adaptation

A tricky candidate to position is the virus because it meets most of the criteria, but it cannot reproduce without infecting a host. It also doesn't utilize energy, respond to the environment, or maintain homeostasis. This indicates that many examples meet part of the criteria but not all. Therefore, viruses are not considered living forms.

In the context of astrobiology, we want to define life to provide search criteria when we scan the Universe for other life forms. By understanding how living things are characterized, we can better decide where to investigate further and determine whether a potential candidate is actually living [5].

It is essential to underline that we only know about the type of life that exists on Earth, which is carbon-based. It is not excluded that other types of life may exist somewhere else in the Universe, based on other molecules and functioning in different ways. This type of potential life is commonly called *"weird life"*. Some scientists have speculated that the most likely other base for life would be silicon, due to its resemblance to carbon, a fundamental brick of life, in the many compounds it can produce. Similarly, ammonia has been proposed as an alternative solvent to water due to its similar properties to methane, especially in the context of Titan, a moon of Saturn, which will be discussed further in Section 2.1.4 [12] [13].

What we know for sure is that Earth-based life has common characteristics across all species. The origin of this is still uncertain, as it could be because these characteristics are common to all life in the Universe or because all Earth-life shares a common ancestor and thus inherits its traits. Nevertheless, starting from what we know best simplifies the search and gives us a basis for conditions and criteria to search for [5].

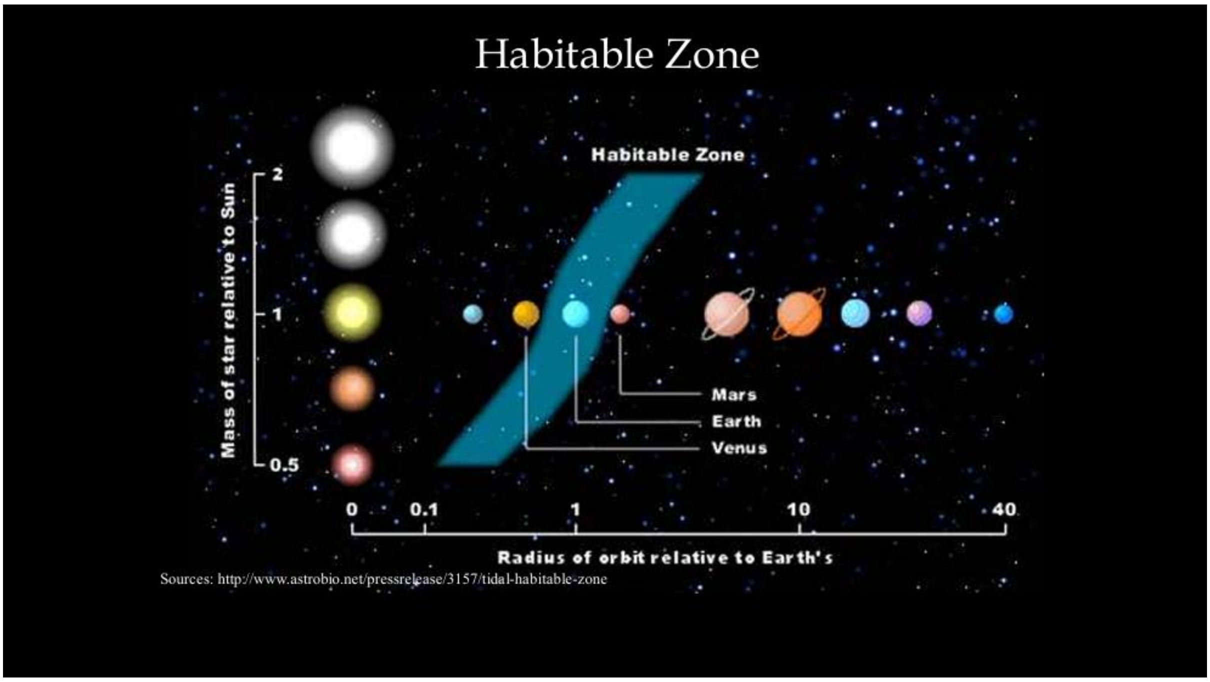
2.1.3. Habitable zone

With that in mind, the next question to ask is, what are those conditions? What kind of environment does life as we know it survive or thrive in? This way we can try and investigate areas with similar criteria in our Universe, in order to eventually find other life forms or understand why in fact we do not find them [5].

The three keystones for life, based on our understanding today, are access to liquid water, building blocks for life (Carbon, Hydrogen, Nitrogen, Oxygen, Phosphorus, Sulfur, also known as CHNOPS), and some form of energy. It is widely accepted that for life to thrive, meaning for a place to be habitable, these three elements must be present. A habitable body does not mean there is necessarily life on it. It means that life could be sustained there, whether it originates from that celestial body or is brought to it otherwise [12].

Based on this definition of habitability, most scientists have defined liquid water as the first criterion that should be searched for since it depends on planet temperatures, which are dependent on primary energy sources, such as stars. Keep in mind that if liquid water were to be detected on a celestial body, that does not necessarily mean that life exists there [14].

To sustain liquid water, not only does the temperature need to be exactly right, but atmospheric conditions must be met as well. This brings us to the concept of the habitable zone, defined as "the circumstellar region where liquid water may exist on the surface without triggering a runaway greenhouse effect" [15]. The location of this zone depends on a star's mass, which affects its luminosity (energy radiated by the star) and, in turn, the temperature at different distances. For hotter, more massive stars, the habitable zone is farther out, while for cooler stars, it is closer in, as seen in Figure 2.



Sources: http://www.astrobio.net/pressrelease/3157/tidal-habitable-zone

Figure 2: Habitable zone in function of the star mass, comparison with the Solar System [15]

The greenhouse effect plays a key role in maintaining surface temperatures. Certain gases in a planet's atmosphere, such as water vapor, carbon dioxide, and methane, absorb heat from the surface and re-radiate some of it back to the ground, trapping warmth in a feedback loop. This process keeps planets like Earth warm enough for liquid water. However, if this effect becomes too strong, as suspected to have happened on Venus, it can lead to a "runaway greenhouse effect", where excessive heat causes more evaporation, increasing greenhouse gases and further intensifying warming [16].

A planet's distance from its star influences this process. If a planet is too close, high temperatures can cause rapid water evaporation, accelerating the greenhouse effect until the planet overheats and loses its water. Conversely, if a planet is too far, it receives too little energy to sustain liquid water. Thus, the balance between stellar energy, atmospheric composition, and the greenhouse effect determines whether a planet remains habitable or undergoes runaway heating or deep freezing [16].

Scientists have long studied the question of habitable zones and have defined a habitability zone in our own Solar System (discussed in the next section), as well as in distant stellar systems. One of the most revolutionary discoveries in terms of exoplanet discovery is the TRAPPIST-1 system, found by the Trappist telescope in Oukaimenden, Morocco, by a team of astrophysicists at the University of Liège. The seven planets found within the star's habitable zone represent a groundbreaking number and, to this day, the system contains the most habitable exoplanets found in a single stellar system [16]. (see Figure 3)

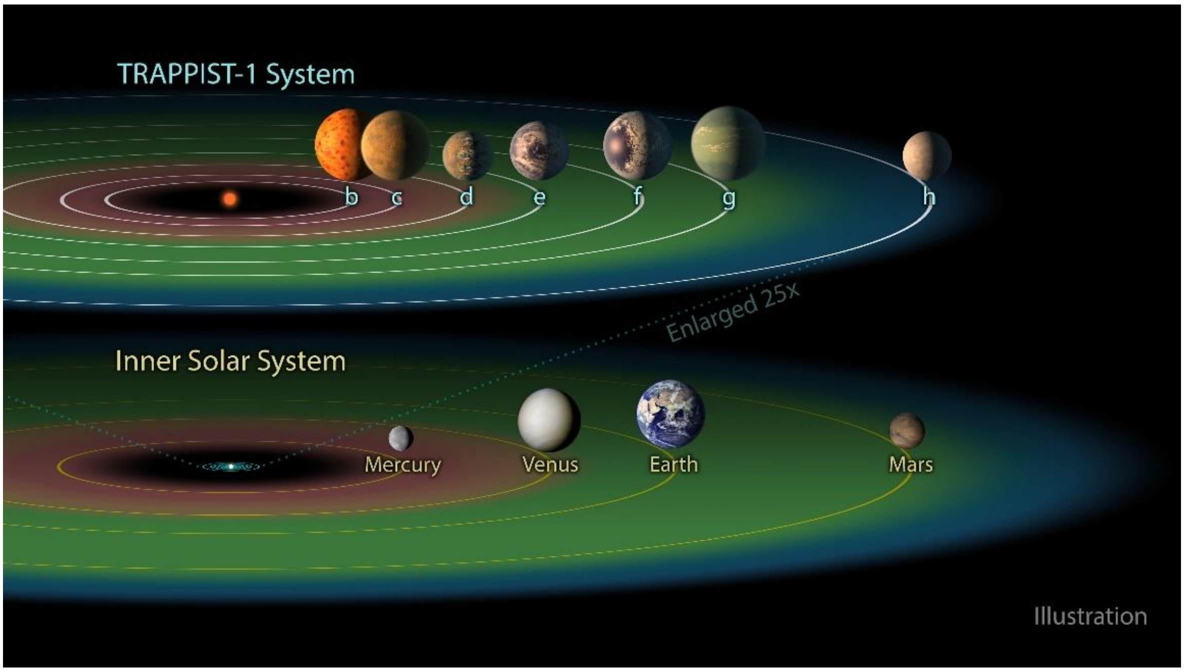


Figure 3: Habitable zones (Green) of TRAPPIST-1 System and Solar System [16]

This particular definition of habitability is for "surface" habitability. It may apply to planets but also to natural satellites. In comparison, "subsurface habitability" targets bodies that have oceans beneath their surface, unlike Earth, with the life conditions mentioned earlier, that could host life. It has the following criteria: the surface must be frozen, and there should be sufficient internal heat to allow liquid water to exist underneath this surface. Thus, in this case, compared to surface habitability, the energy heat source does not come from the star but from the internal heat of the natural satellite, which actually derives from its interactions with its host planet [17].

These interactions can be of different types, such as tidal, radiogenic, electromagnetic, etc. Tidal heat, for example, comes from the orbital energy between the two bodies. They exert mutual gravitational attraction, resulting in orbital damping. The shape of the orbiting body is stretched and compressed due to the gravitational pull exerted by the more massive body. The stretching and compression generate energy dissipation as heat within the moon's interior, thereby warming the body. This phenomenon is particularly pronounced when the orbit is eccentric, meaning that the orbit of a body is more elongated, as it creates big differences in the intensity of the pull, leading to increased flexing (see Figure 4) [12] [18].

Systems affected by orbital resonance are particularly prone to tidal heating. In celestial mechanics, orbital resonance occurs when two bodies' orbital periods can be expressed as a ratio of two integers. For example, Neptune and Pluto are in a 3:2 resonance, meaning that for every three orbits Neptune completes, Pluto completes two. Gravitational interactions in resonant systems occur at predictable intervals, exerting periodic tugs that reinforce perturbations rather than cancelling them out over time. This sustains an orbit's eccentricity because, instead of tidal forces gradually circularizing the orbit (as they would in non-resonant systems), the periodic gravitational tugs maintain or even enhance orbital elongation. As a result, systems in orbital resonance tend to experience more tidal heating, as is the case for Europa and Enceladus, which are described further [17] [19] [20] .

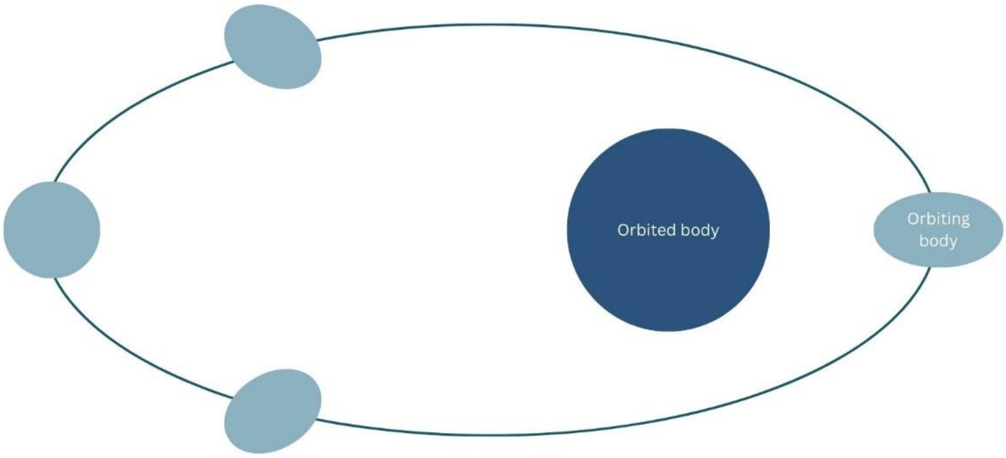


Figure 4: Deformation of the orbiting body in eccentric orbit depending on its orbital position, leading to tidal heating. Image adapted from [20]

There is still much to learn about these heat-producing phenomena, which expand habitability to "subsurface habitability", also helping us look further into exomoons, moons orbiting planets in stellar systems other than the Solar System [17]. In the same way this paper is focusing on moons of gas giants because of their potential habitability (to be discussed below), scientists suppose that exomoons may also be life hubs. They are challenging to detect due to their proximity to their planets, making discerning the signal challenging. Nevertheless, scientists have found a couple of them around gas giants near our Solar System, such as WASP-49 Ab and have speculated that they might be habitable [21].

2.1.4. Habitable zones in the Solar System

If we concentrate on what is reachable and most easily observable, we must remain within the limits of our Solar System. This is also the area where we are most likely to find life, as it is the home of our planet, Earth.

In our Solar System, as seen in Figure 2, Venus and Mars are just outside the limits of our habitable zone, and Earth is completely in it. But has it always been that way? The habitable zone is shifting and expanding into the solar system with time because of the Sun's evolution. The Sun, like every other star, follows its own evolution path. Given the mass of our star, it will most likely evolve into a Red Giant, a different type of star, in a couple of billion years from now, and by then, the habitable zone will shift, as illustrated in Figure 5. This means that Venus was likely in a past habitable zone and that it would have been slowly edged out of our current one. Regarding Mars, some studies consider it to be outside of the habitable zone, and some consider it to be on the border [22] .

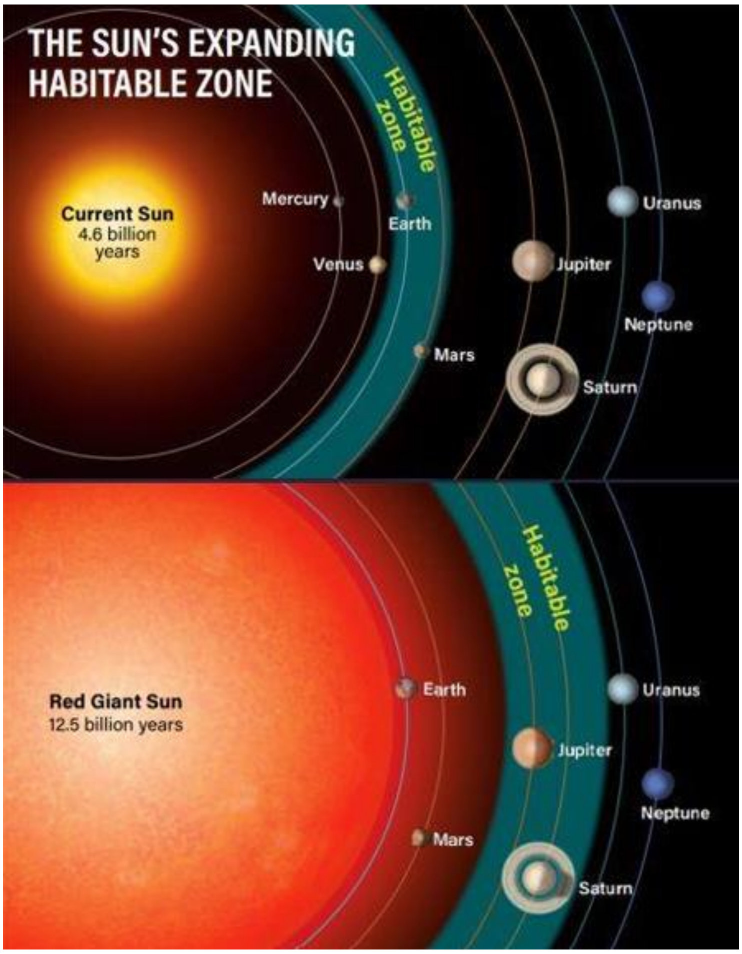


Figure 5:The shift of the habitable zone of the Solar System with the evolution of the Sun [23]

a) Venus

Venus is a fascinating yet hostile planet. Currently, it is inhospitable due to extreme heat, the absence of a magnetic field, and a lack of liquid water. The runaway greenhouse effect is believed to be the main reason Venus became unhabitable. Carbon dioxide built up to such high levels that it trapped heat, causing the oceans to boil away. However, there is debate about whether Venus was ever habitable. Some hypotheses suggest that its thick sulfuric acid (H_2SO_4) clouds may have originated from volcanic eruptions, which could have temporarily cooled the planet by reflecting sunlight. Alternatively, Venus may have always had a dense atmosphere, but whether it was ever cool enough for liquid water remains uncertain [23] [24].

A recent, controversial discovery of phosphine in Venus' atmosphere has sparked discussion because biological processes typically produce phosphine. However, this finding needs further validation, and non-biological sources (such as volcanic or chemical reactions) could explain its presence. Additionally, while volcanic eruptions could have contributed to Venus' thick atmosphere, they are unlikely to have produced significant oxygen, so any oxygen detection should not necessarily be considered a sign of biological life [16].

Venus remains a mystery, and further research is essential to determine whether it was ever habitable and to understand how planets could lose their habitability over time.

b) Earth

Earth is the only place where we know life exists. It serves as the foundation upon which we establish the criteria for searching for life elsewhere. Is it special? We don't know. Habitability changes over time and space, and we understand that life can adapt to various conditions. Species that existed thousands of years ago, during the Archean, (first traces date back to 3.5 billion years ago), when temperatures were much higher, cannot survive today, and we certainly cannot endure the conditions of that era. The main change occurred around 2.7 to 2.4 billion years ago, when there was a shift in the plate tectonics regime due to the cooling of our planet. This tectonic activity resulted in increased crustal recycling, which in turn altered the geochemical composition of our oceans. The anoxic life forms that existed at that time, such as bacteria and archaea, gradually began to oxygenate the ocean and subsequently the atmosphere. The change in atmospheric composition led to new biochemical cycles, and life as we know it today began to flourish [22] [25].

c) Mars

Mars has a good chance of having been habitable in the past. This reason, combined with the proximity of our red neighbor, is the main motivation for the extensive efforts made on the numerous missions we send to Mars. The conditions there at present do not readily allow for humans to thrive, though there might have been life on Mars in the past. We have not found any proof of its existence, but scientists are investigating traces and signs of past habitable conditions in hopes of finding some indication that life used to survive there. A discovery of this type would revolutionize astrobiology, the study of life in the universe, and motivate us to further explore space. Would this life have originated on Mars? Was it independent of the life on Earth, or did Earth's life come from there? What caused its extinction, and could this phenomenon happen on Earth as well? All these secondary questions would arise in the event of such a discovery, further advancing us in the fundamental quest to understand the meaning of humanity's existence.

Mars does have water frozen in its ice caps, it also has traces of methane, which is interesting because methane is primarily produced by life forms here on Earth. Additionally, it can arise from other phenomena, such as hydrothermal vents, water and rock reactions, or methane clathrate. The idea of life forms existing on the red planet is not extraordinary, considering Mars is relatively close to the habitable zone. It is believed that in the past, during its Noachian period (from 4.1 billion to 3.5 billion years ago), Mars had an atmosphere, and there are many signs of liquid water, including oceans, lakes, and rivers. It likely also had a stronger magnetic field, and its dimming was probably responsible for the gradual decline in habitability. What is certain is that today, Mars is not habitable; it has a very thin atmosphere and no liquid water. Nevertheless, it remains an excellent place to study how planets transform and what may have existed in the past [15] [26] [27].

In conclusion, no traces of life apart from terrestrial ones have been found yet in the vicinity of the habitable zone of the Solar System. However, what should not be forgotten is the "subsurface habitability" that was mentioned earlier. This region is not easily definable in relation to the system's star, and it does not necessarily correspond to the "surface habitability".

As mentioned before, the three keystones for life, based on our understanding today, are access to liquid water, building blocks for life and some form of energy. Several worlds have the first two criteria: Ganymede, Callisto, and Europa (all natural satellites of Jupiter), Enceladus and Titan (natural satellites of Saturn), and Pluto, a dwarf planet on the outskirts of our Solar System. As shown by Figure 6, only Europa, Enceladus, and Titan have the third condition met as well. There is not enough knowledge yet for Triton (a Neptunian moon) and Mimas (a Saturnian moon) [12].

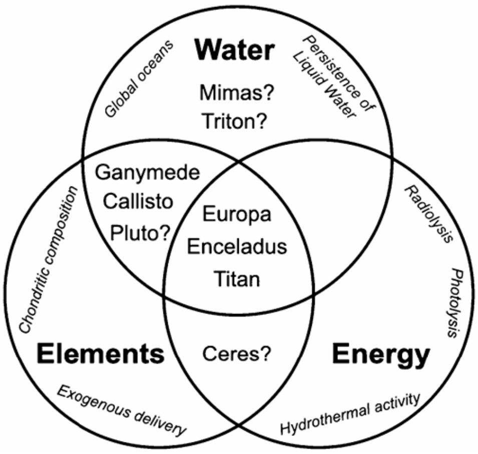


Figure 6: Keystones for the habitability of life and the placement of ocean worlds of the Solar System [12]

Titan's atmosphere is rich in organic molecules and has an icy crust with a liquid ocean beneath it. Its surface is too cold for life to exist on it, but if the organic molecules can travel between the methane atmosphere, its icy surface, and its subsurface ocean, maybe the ocean underneath can be habitable. "*Weird life*" based on another molecule instead of carbon is more expected there because of the lack of oxidants [12] [28].

In this work, we will only focus on Europa and Enceladus because they have more plausible habitability cases, because they are more similar to one another, and also because some ongoing missions are on their way to Europa.

These worlds have outer shells made of ice, a couple of kilometers thick with liquid oceans under their surface. Even though they are very far away from the "surface habitable" zone mentioned above, the gravitational activity related to their host planet gives them sufficient energy source to maintain a liquid ocean, making them potentially "subsurface habitable". It is believed they have a rocky core, which is in contact with the subsurface ocean, and could lead to interesting chemistry and a possible heat source. This possible geothermal activity on the ocean floors gives chemical conditions that may be similar to what we can find on the bottom of the Earth's oceans, where we find life. The characteristics of these celestial bodies fill most of the habitability conditions and have the highest probability of finding life elsewhere in the Solar System [29].

In recent years, two important missions dedicated specifically to their study have been sent there. JUICE and Europa Clipper (further discussed in Section 2.1.5) will spend time studying Europa, orbiting it and collecting more precise data. If the results are promising, the imagined icy moon landers will have even more reason to be sent there. Even in the event that no traces of life are found, it will be intriguing to explore the reasons life hasn't formed there and whether any kind of life is capable of surviving in that environment. This will further refine our understanding of life on Earth and advance our comprehension of where, or if, other life forms could be found [15].

Studying icy moons is one of the priorities for ESA's scientific objectives set for the upcoming years. The new objectives are called VOYAGE 2050 and have the following scientific subjects as study goals [1]:

- Moons of giant planets
- From temperate exoplanets to the Milky Way
- New physical probes of the early universe (Cosmic Microwave Background, gravitational waves…)

2.1.5. <u>Europa and Enceladus</u>

The focus will now be on two of the most favorable candidates. The ocean's sub-surface is key here. As we know, life on Earth most likely emerged in its oceans first. So, it is interesting to follow that lead and see how these similar conditions may or may not have given rise to the same existence of life.

a) <u>Europa</u>

Europa, as seen in Figure 7 is one of Jupiter's four Galilean moons, the largest moons of the planet, which are quite easily visible through a telescope in the night sky. This is how they were discovered by Galileo Galilei in the past. Europa is the smallest and also the brightest of these moons. Here are its characteristics:

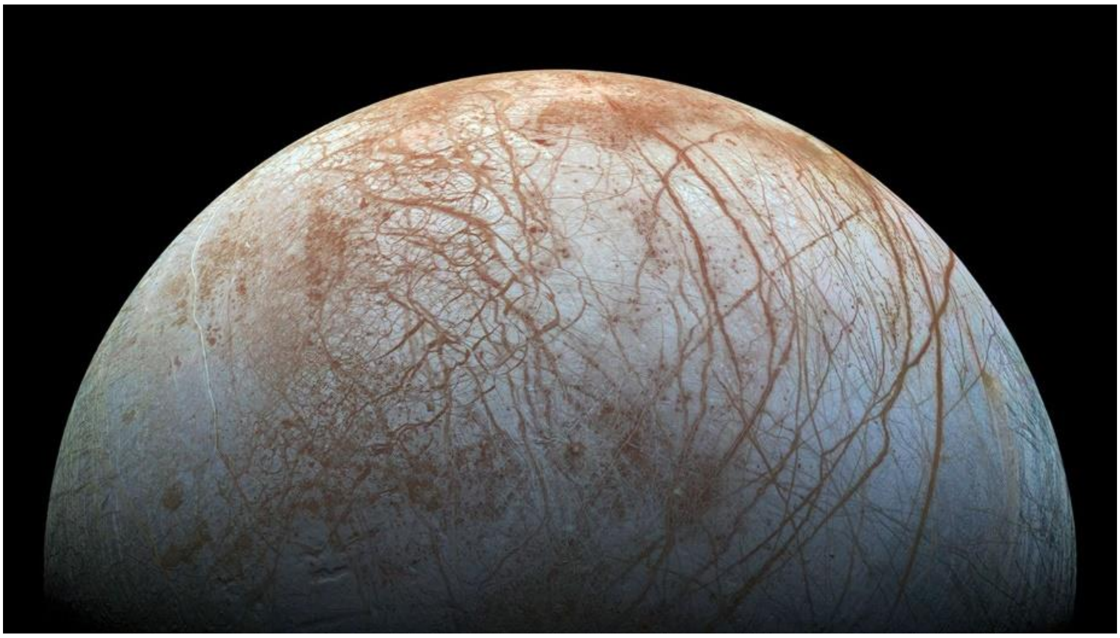


Figure 7: Europa as captured by Galileo spacecraft in the 1990s [30]

- Ephemeris:

Europa is one of Jupiter's largest moons and is similar in size to Earth's Moon. It is located approximately 671,000 km from Jupiter and 780 million km from the Sun. Europa completes one orbit around Jupiter in about 3.5 Earth days [15].

- Structure:

Its internal structure includes a metallic core, a rocky mantle, and an outer ice shell, which is believed to be a few kilometers to 30 km thick [15]. Figure 8 shows that beneath the ice shell lies a global salty ocean, potentially as deep as 100 km, making it deeper than Earth's oceans. The ocean is kept in a liquid state primarily through tidal dissipation due to Europa's elliptical orbit around Jupiter, although this alone might not be sufficient to maintain it. Radiogenic heating and historical tidal activity may also contribute to preventing the ocean from freezing entirely. The way the liquid ocean was discovered (detailed in the next paragraph) was when Galileo detected variations in the magnetic field that suggested the presence of a conductive layer beneath the surface, interpreted as a global salty liquid ocean [31] [32].

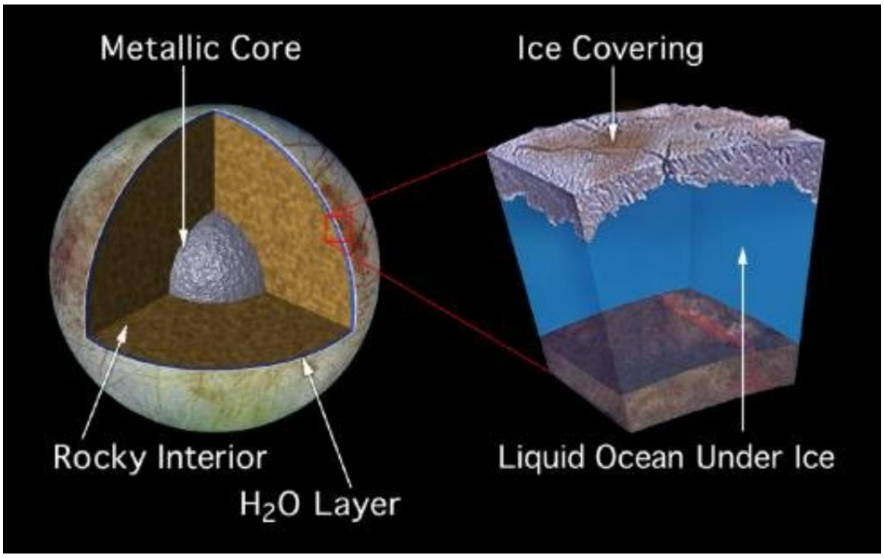


Figure 8: Structure of Europa [15]

- Energy source:

Though less dramatic than Enceladus's plumes (expulsion of material through the ice shell) that will be discussed further, Europa has geological features such as ridges and fractures, which suggest ongoing tectonic or cryovolcanic activity. Hubble Space Telescope observations hinted at possible plume activity, indicating the ice shell may allow occasional material exchange with the surface.
Europa lies within Jupiter's magnetic field, and Galileo's data showed variations in the induced magnetic field, which could only be explained by the existence of a conductor.

According to Faraday's law, if a magnetic field moves past a conductor, it induces an electric current. The current in return, will generate its own magnetic field, which is Lenz's law. Since Europa seems to react magnetically to Jupiter's field, it must have conducting material that puts Faraday and Lenz's laws into action. That is how scientists understood that there was a subsurface layer of salty, conductive liquid water [31]. Models of tidal dissipation, measured as power dissipated over a surface, at Europa's seafloor range between 8 mW/m^2 and over 100 mW/m^2, comparable to Earth's average of 80 mW/m^2, and even 200 mW/m^2 in tectonically active regions. This supports the plausibility of hydrothermal systems [32].

- Temperature:

Europa's surface temperature ranges from -223°C to -160°C, with predictions for the subsurface ocean at approximately -13°C near the ice-water interface and up to 90°C at the seafloor, particularly near potential hydrothermal vents. The water remains liquid below 0°C freezing due to salinity, although the exact concentration still needs clarification [32].

- Composition:

Europa's surface is water ice, and its subsurface ocean is rich in salts, though its exact composition remains uncertain due to the lack of direct sampling. Carbon was also recently found and is suspected to have come from the sub-surface up to the surface. More research is needed, and Europa Clipper will contribute to that. Similar to Cassini's Dust Analyzer (NASA mission that flew by Jupiter in 2000), Europa Clipper has the Surface Dust Analyzer on board. It will capture material from plumes if they exist, as imagined in Figure 9 Figure 9: Model of possible plumes at Europa with surface fractures ,and if not, it will hopefully capture material lifted up from the impact created by micro-meteorites that bombard Europa frequently [29] [33].

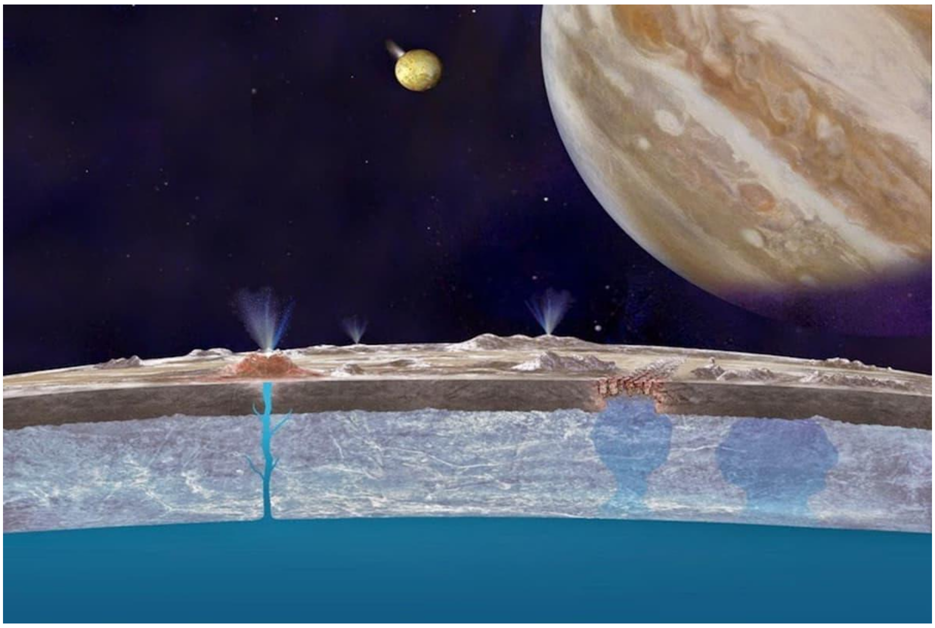


Figure 9: Model of possible plumes at Europa with surface fractures [15]

- Pressure:

Ocean pressure is predicted to be around 110 MPa at the sea floor, comparable to Earth's Mariana Trench. There is not enough data to have more precise estimations. Hopefully, the ongoing missions will bring more information [33].

- Habitability:

Europa may host electron gradients from seafloor interactions, providing energy for potential life (like hydrothermal vents on Earth). Additionally, oxidants (loss of electrons) may be produced on the icy surface due to Jupiter's intense magnetic interaction with Europa, bombarding its surface with particles. If there were chemical reactions at the seabed, they would be reduction (gain of electrons) reactions, which are a key factor in life on Earth. However, current salinity levels and the extent of energy gradients are not fully constrained, and it is unclear if they support life's origin or merely its survival. If life is found, it is expected to be relatively straightforward. If oxygen created on the surface can penetrate into the ocean, then maybe more complex forms of life, such as fish, could exist, since oxygen is a big factor that helped life develop extensively into complex creatures here on Earth. Big civilizations are not expected to be found because we would probably have detected such activity already from afar [29] [32] [33] [34].

b) Enceladus

Enceladus is one of Saturn's hundreds of moons. It is covered in ice and, as seen on Figure 10, has some very recognizable "tiger stripes", which are fractures in the crust. Scientists believe these stripes create plumes, places where thermal energy escapes, kind of like geysers. Water jets are expelled from these cracks, enabling missions to collect samples by flying through them, like Cassini, mentioned previously. Here are its characteristics:

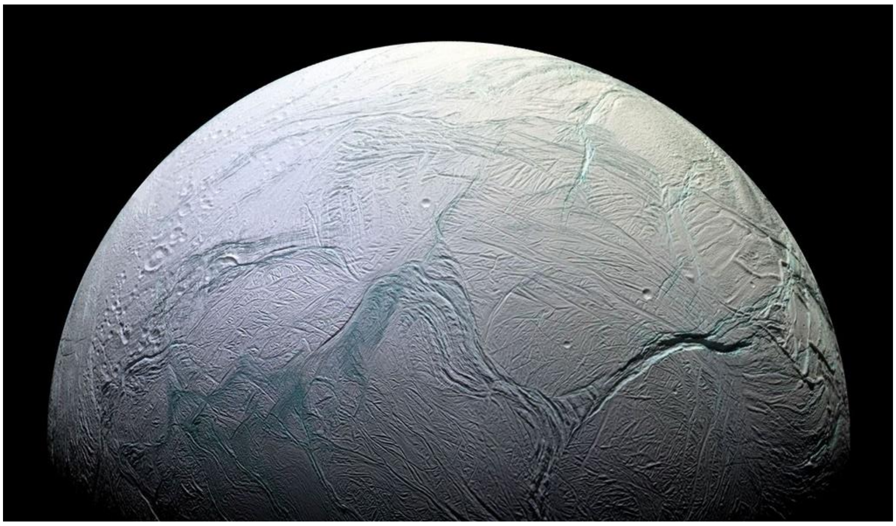


Figure 10: Mosaic of images of Enceladus taken by Cassini fly-by in 2008 [35]

- Ephemeris:

Enceladus has a semi-axis of 148,000 km, with respect to Saturn, and is located some 890 million km from the Sun. Its orbit around Saturn lasts 1.37 Earth days. Enceladus and Saturn are tidally locked, as described in the previous section, meaning only one side of the natural satellite faces the host planet, just like our own Moon and Earth [35].

- Structure:

Due to the way Enceladus rotates and the analysis of these jets coming out of the moon, scientists believe that beneath its shell of ice, the moon's composition is liquid. As visualized in Figure 11, the ice shell is estimated to be around 20km deep on average but is believed to be as shallow as 1-5km in its south pole. The bottoms of the ocean might be around 45km deep, as predicted by Cassini [35].

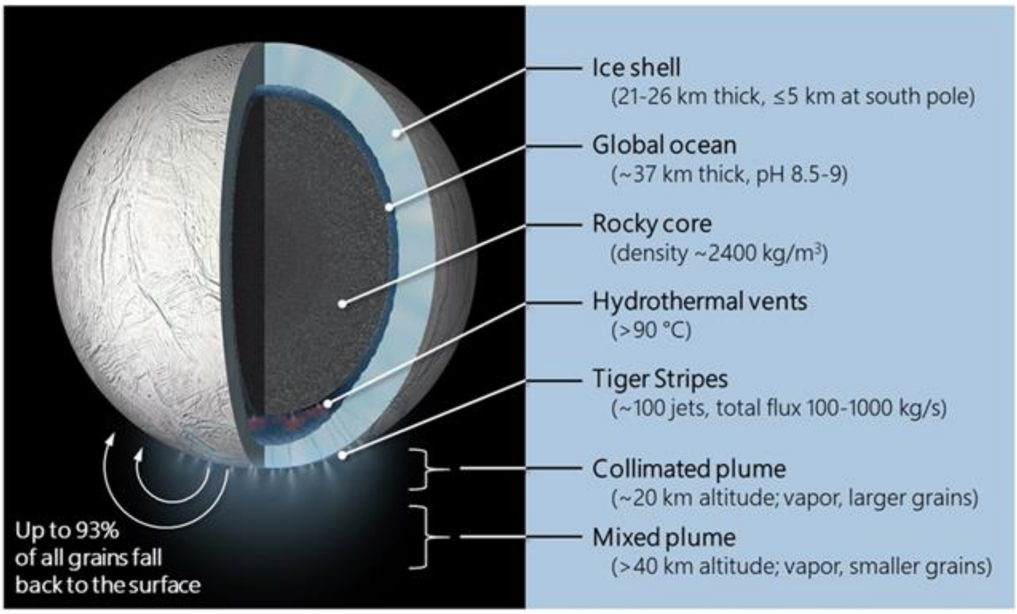


Figure 11: Characteristics of Enceladus [36]

- Energy source:

If there really is a liquid ocean beneath the ice crust, then there must be an energy source maintaining a warmer temperature in this cold, distant region of the Solar System. The prominent tiger-like stripes indicate thermal activity, suggesting that a viable energy source likely exists. Some observations imply that tidal dissipation is the source of energy, just like for Europa [33]. As explained earlier, this is due to the gravitational interactions between two bodies, such as a moon and its host, generates friction and heat. This phenomenon causes the moon to deform, creating heat and keeping an ocean in a liquid state. This tidal energy likely translates into geothermal activity at the bottom of the ocean, similar to what occurs on Earth, where the primary energy source is the molten core of our planet.

- Temperature:

Due to its considerable distance from the Sun, temperatures are very cold, -220°C at night and -190°C during the day on the surface. However, these temperatures are not guaranteed to be the same in the sub-surface ocean. There is evidence of silica found in the E ring of Saturn which is created by the ejections of Enceladus. Silica is created thanks to interactions between rock and liquid water at high temperatures, at a minimum of 90°C. Subsurface temperatures are not known in detail, but it is assumed that, because of the evidence of this silica and the supposition of geothermal activity, the maximum temperature is at least 90°C and the minimum temperature should be about -0.15°C, just under the ice crust [33].

- Composition:

By analyzing what comes out of the plumes, as captured in Figure 12, thanks to Cassini's Chemical Dust Analyzer, an instrument abord the spacecraft, scientists have detected water vapor, carbon dioxide, methane, salts, and silica. They predict that the composition of the ocean is water ice, sodium, potassium, bicarbonate, and sodium carbonate. Traces of ammonia and molecular hydrogen are also found. Based on the plume composition, the latest models of the ocean composition predict a pH of [7.95 – 9.05] [37], quite similar to Earth, which has a pH of around 8. CHON atoms were detected with Cassini, but sulfur and phosphorus were missing from the CHNOPS essential building blocks, mentioned in Section 2.1.2. Sulfur levels were ambiguous in the samples, but it was deduced that if hydrothermal activity was active, theoretically it should exist in up to 5 times the quantity needed for sustaining life [36]. Phosphorus was then the only component missing from completing CHNOPS. In 2023, scientists discovered the presence of sodium phosphates in Saturn's E ring, which, as mentioned previously, is filled up by ejections from Enceladus's oceans. These scientists have further studied analog environments of the ocean and found that it makes sense that phosphate would be dissolved in the liquid ocean and that the potential geothermal activity combined with the alkaline ocean, makes it inevitable to find phosphorus. Phosphorus is important because it can be found in phospholipids that form cellular membranes and energy-yielding bonds of ATP [32] [38].

Figure 12: Jets coming out of Enceladus captured by Cassini in 2010 [35]

- Pressure research:

Predicted pressures range from 3.6–5.3 MPa, depending on location and assumed depth of the seafloor (35–50 km). Evidently, further data is needed to have more precise measurements [33].

- Habitability:

Habitability levels are similar as for Europa. Interactions between Enceladus's Ocean and rocky core are thought to drive water-rock reactions, creating molecular hydrogen, an energy source for microbes. This mirrors chemosynthetic ecosystems near Earth's hydrothermal vents. The rest of the criteria, such as temperature, composition and acidic level, also give arguments as to why Enceladus is potentially a habitable icy moon [33].

c) Comparison between Europa and Enceladus

In summary, if we return to the three conditions that define a place as habitable: energy source, liquid water, and nutrients, Europa and Enceladus can both be suggested as habitable and confirmed with more confidence thanks to future data. Evidence supports liquid water subsurface oceans, containing salts and nutrients and kept at a liquid temperature by tidal or magnetic interactions with their host planet. A recap and comparison of the icy moons' characteristics previously presented can be done by examining the data in Table 1.

Table 1: Comparison table of Europa and Enceladus characteristics

	Europa	**Enceladus**
Host planet	Jupiter	Saturn
Gravitational acceleration	1.3m/s^2	0.11m/s^2
Ice shell thickness	1km – 30km	~20 km (1–5 km at poles)
Ocean depth	~100 km	~45 km
Surface temperature	-223°C to -160°C	-220°C to -190°C
Subsurface temperature	-13°C to 90°C	-0.15°C to 90°C
Seafloor pressure	~110 MPa	3.6 – 5.3 MPa
Energy Source	Tidal, radiogenic, magnetic	Tidal
Material detection	Salty water	Water, CH_4, CO_2, NH_3, H_2, salts, sodium phosphates
Plumes	Probable	Confirmed
pH	Unknown	7.95 – 9.05
Radiation level in subsurface ocean	Unknown but higher than Enceladus due to Jupiter's belt	Unknown but lower than Europa

2.2. Partial gravity studies

We have established that moons such as Europa and Enceladus have compelling characteristics that could support life. The next logical step is to explore how such environments might influence biological processes. While studies of their geophysical and chemical conditions are ongoing, one critical factor often overlooked is gravity. These moons possess only a fraction of Earth's gravity (Europa: 0.13g and Enceladus: 0.01g), yet the role of gravity in supporting or constraining life is not fully understood. Understanding how life as we know it responds to such gravitational conditions is essential not only for refining our definitions of habitability but also for preparing future life-detection missions. This section explores existing experimental approaches used to study gravity's effect on life and the rationale for developing simulation platforms to address this gap.

2.2.1. Effects of gravity on life

It is well known that gravity influences life. The direction of plant growth and animal weight distribution are just two examples of biological features that have evolved under the constant constraint of Earth's gravity. When humans travel to the International Space Station (ISS), where microgravity conditions prevail, their bodies undergo significant physiological changes. These include decreased bone density, muscle atrophy, and adaptations in the vestibular system. Altered fluid behavior impacts cardiovascular function, and astronauts' eyesight problems have been investigated because of this, among other changes [39].

Plants have also been investigated, with *Arabidopsis thaliana* being a standard model. Studies have explored how gravity affects root growth and light cycles, notably using facilities like the European Modular Cultivation System (EMCS) (discussed further in Section 2.2.3), which includes onboard centrifuges for controlled gravity experiments [40].

Since gravity affects complex organisms such as humans and plants, on a smaller scale, microorganisms are also affected. Research has shown that microbes can sense and respond to mechanical forces, a phenomenon known as mechanotransduction. In microgravity, the absence of convection currents leads to low fluid shear, altering the environment in which cells are exposed. While the precise mechanisms through which cells convert mechanical cues into chemical responses are still not fully understood, microgravity and ground-based analog experiments suggest this ability is universal to cellular life [3].

For example, studies have shown that *Escherichia coli* strains cultured under simulated microgravity, lunar gravity, and Martian gravity using clinostat devices (described in Section 2.2.2) demonstrated increased bacterial growth rates [41]. Others have found no significant differences in final bacterial concentrations across the different gravity conditions. An experiment studying three bacterial species, *Sphingomonas desiccabilis*, *Bacillus subtilis*, and *Cupriavidus metallidurans* investigated their growth under microgravity, simulated Mars gravity, and Earth gravity conditions aboard the International Space Station over several weeks. The results suggested that gravity variations did not affect the ultimate bacterial growth outcomes in this context [42]. The contradiction of these results shows that there is still much to learn.

Additionally, some results suggest changes in bacterial membrane characteristics. A 2012 investigation focused on the effects of modeled reduced gravity (MRG) (described in Section 2.2.2) conditions on the morphology and physiology of *Escherichia coli* and *Staphylococcus aureus*. Using low-shear modeled microgravity environments, researchers assessed parameters such as total protein concentrations, biovolume, membrane potential, and membrane integrity during exponential and stationary growth phases. The findings indicated that bacterial membranes were more energized under MRG conditions. An "energized membrane" refers to the bacterial cell membrane's ability to maintain a voltage difference across it, known as the membrane potential. A heightened state of the membrane in this way, leads to enhanced nutrient accessibility and metabolic activity [43].

Microbiology is especially important in the context of astrobiology, since microorganisms represent the most likely form of life that we might detect elsewhere. More specifically, extremophiles (microorganisms that survive in extreme conditions on Earth) are of particular interest. Investigating how organisms that survive extreme conditions, like those we can find on icy moons, respond to partial gravity, could offer vital insights into what potential life might look life there, and how we might go about detecting it.

This type of research has been done before. Extremophiles such as *Haloferax mediterranei* and *Halococcus dombrowskii*, salt-tolerant archaea, were grown under simulated microgravity conditions using a rotary cell culture system (described in Section 2.2.2). The study aimed to understand how microgravity affects the viability and survival of these extremophiles. Observed responses included aggregation of cells and changes in pigmentation and alterations in the composition of the proteome, which has similarly been described for *Salmonella* bacteria grown in the same conditions. The haloarchaea was also found to be one of that fastest growing microorganisms in the rotary cell culture system, making it a good model for future studies [44].

Together, these findings reinforce the idea that gravity is not merely a background condition but a key variable in how life functions and evolves. If gravity plays such a critical role here on Earth, it likely influences the potential for life elsewhere. Since extremophiles are most likely to resemble potential life surviving in conditions similar to Earth's extreme environment on Europa and Enceladus, it would be interesting to observe their behavior in partial gravity, their colony size, morphology changes, and biofilm production [45]. This is why the focus of this payload concept is to study different types of microorganisms.

2.2.2. Existing partial gravity experiments

Now that we have established why studying microorganisms in different gravity conditions is important, how can we create simulation models? Different techniques exist, some of them have already been mentioned in the previous section, they are presented below and illustrated in Figure 13:

- A) **Clinostat:** device that rotates samples around one or two axes to negate the effects of the gravitational vector, simulating microgravity.
- B) **Random Positioning Machine (RPM):** device that constantly changes the orientation of the sample in 3D space to negate the gravitational vector.
- C) **Rotating Wall Vessel (RWV) / Rotary Cell Culture System (RCCS):** device that rotates slowly, keeping samples suspended in liquid, simulating microgravity.
- D) **Drop tower:** very tall facility with vacuum conditions which allows for dropping samples from the top in order to achieve free-fall, which is the same as microgravity.
- E) **Magnetic levitation:** use of strong magnetic fields to keep some diamagnetic samples in levitation, creating weightlessness.
- F) **Centrifuge:** centripetal acceleration caused by rotating samples mimics gravitational acceleration, it can be used for hypergravity or for partial gravity if used in space.
- G) **Parabolic flight:** aircraft following a parabolic trajectory creates moments of free-fall, simulating microgravity.

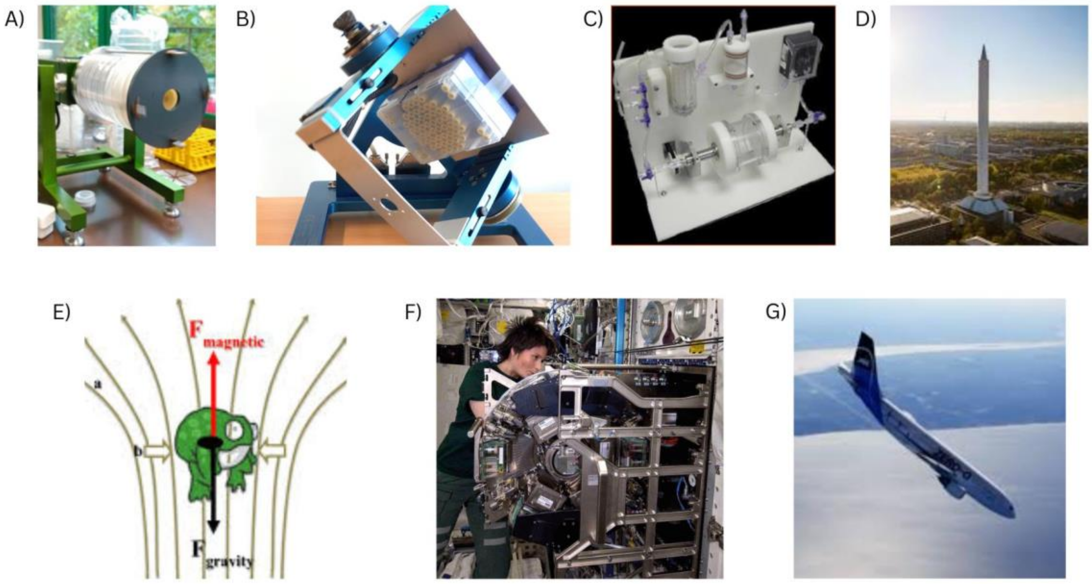


Figure 13 : Microgravity and partial gravity simulation techniques. A: [46], B: [47], C: [48], D: [49], E: [50], F: [51], G: [52]

2.2.3. Space centrifuges

The work of this Master's thesis will be focused on one of these examples: the centrifuge. This choice will be justified in the Methodology section. In this sub-section, the centrifuge theory will be explained, and examples of existing space-centrifuges will be given.

a) How does a centrifuge work?

A centrifuge relies on centripetal force, which is the force that keeps an object moving in a circular path. Imagine spinning a ball tied to a rope like a lasso; the tension in the rope provides the centripetal force, constantly pulling the ball inward and keeping it on a circular trajectory, as illustrated on Figure 14. Meanwhile, due to inertia, the ball wants to move in a straight line (tangentially), and if the rope were cut, it would fly off in that tangential direction.

Now, consider a person in a car making a turn. From the outside (inertial frame), the person continues in a straight line (inertia), while the vehicle turns underneath them. The car door provides the centripetal force that changes their direction and keeps them inside.

From inside the car (a non-inertial frame), it feels like there's an outward force pushing the person toward the door. This is the centrifugal force, a fictitious force that appears in rotating frames to account for the sensation of being pushed outward. It's not a real force but a result of observing motion from an accelerating frame, such as inside the car. By adding this force, you can explain why the person in the car is not moving, sliding toward the outside of the vehicle. Without this additional force, Newton's first law would seem violated: no net force equals no net acceleration. The reality is that what keeps you balanced is the constraint of the car door, which prevents you from moving outside; this is the centripetal force.

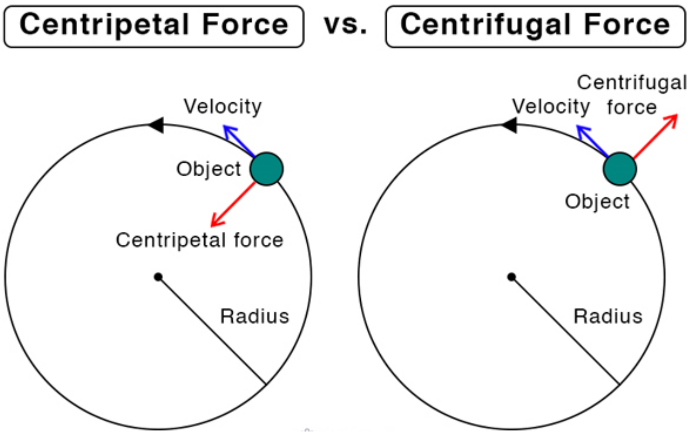


Figure 14: Centripetal force vs Centrifugal force [53]

What you feel as a push is Newton's third law of action and reaction: the car seat pushes you inward (centripetal), and you move outward on the seat as a reaction.

The same principle applies in a centrifuge: the rotating habitat pushes inward on a sample (centripetal force), and it feels pressed outward. That outward "push" can mimic the force we associate with gravity. Though it's not real gravity (which results from mass bending spacetime), the acceleration of the centripetal force simulates the feeling of weight and can be adjusted to match Earth's gravity, or lower, like on Mars or the Moon.

To summarize, the gravitational acceleration is simulated by the centripetal acceleration associated to the centripetal force. It is calculated by the following formula. a is the centripetal acceleration (or the gravitational acceleration required to achieve), r is the radius and w is the angular velocity of the centrifuge:

$$a = r \, . \, w^2 \qquad (1)$$

b) <u>Examples of existing space-based centrifuges</u>

In order to give a context of what kind of space-centrifuges already exist, this part will focus on examples and characteristics of the current landscape in this domain. The findings are recapitulated on Figure 15.

Several centrifuge systems have been developed and deployed in space to simulate partial gravity and study its effects on biological systems. **The European Modular Cultivation System (EMCS)**, operated aboard the International Space Station (ISS) until 2018, was designed explicitly for plant biology experiments and included dual centrifuges to provide gravity levels from 0.001g to 2g. It allowed researchers to study gravitational effects under tightly controlled light and atmospheric conditions, especially on model organisms like *Arabidopsis thaliana,* a small plant, widely used for genome sequencing [40].

KUBIK, a compact and versatile incubator developed by European Space Agency (ESA), has been extensively used for small-scale biological experiments. It is managed by the Bioreactor Express Service provided by Kayser Italia. Capable of simulating gravity from 0.2g to 2g, it accommodates up to eight samples in its centrifuge and sixteen in non-rotating control slots. However, one of KUBIK's operational limitations is that it does not currently support direct communication between the facility and the experiments. Manual intervention is required to change parameters, and the settings are pre-programmed or adjusted through physical buttons [54].

The **Biolab** facility, located in ESA's Columbus module, provides advanced capabilities. It supports real-time command and data acquisition of individual samples, enabling experiments at gravity levels ranging from 0.001g to 2g. Biolab can process up to six samples simultaneously and features advanced environmental controls (temperature, humidity, light exposure, atmospheric gas composition), making it suitable for a wide variety of biological investigations [4].

Beyond large-scale facilities, smaller centrifuge platforms have also been tested. For instance, **SporeSat** was a NASA mini-satellite that included three lab-on-a-chip centrifuges to investigate how microgravity affects calcium-ion signaling in plant cells, which is critical for understanding plant adaptation and mechanosensing [55].

The space company Yuri has an upcoming capability called **Science Taxi**, which is an incubator and centrifuge, capable of carrying up to 38 samples to space and bringing them back to Earth on a return mission. It can reach temperatures up to 40°C and centrifuge up to 16 samples with gravity simulation from 0 to 1g [56].

BioServe Space Technologies has a centrifuge which is more focused on achieving hypergravity levels called the "Variable Gravity Machine" which has capabilities up to 7g and can carry 6 sample cartridges at a time. It can be controlled from the ground via their Payload Operations Control Center (POCC). They also have another model, the **BioServe Centrifuge**, which carries 12 samples and can be used inside the Life Science Glovebox [57].

The **Rhodium Variable Gravity Simulator** simulates the partial gravities of the Moon and Mars. It was developed by Rhodium Scientific and is accessible through commercial partnerships. It can handle 36 samples, and in addition to its centrifuge capabilities, it also has incubation options [58].

EMCS centrifuge KUBIK Biolab centrifuge SporeSat

ScienceTaxi BioServe Centrifuge Rhodium Variable Gravity Simulator

Figure 15: Examples of centrifuges in space. From left to right, top to bottom: [59], [60], [61], [62], [56], [63], [64]

2.2.4. ICE Cubes Service

Some of the examples presented above are not commercial services; instead, they are supported or funded by national agencies. This makes sense given that the space industry has historically been driven by government initiatives and national space programs. The origins of space exploration trace back to the Cold War in the 1950s, which sparked the space race and led to the launch of the first satellites and crewed missions. This momentum continued through the 1980s, culminating in international collaborations such as the construction of the ISS, in the late 90s.

However, over the past couple of decades, a gradual shift toward commercialization has occurred in the space industry. This transition aligns with broader trends in Western free market economies. The reduction of NASA's budget, the rise of private companies such as SpaceX, and the anticipated retirement of the ISS have all accelerated the entry of private actors into the field. Today, hundreds of companies are developing new commercial launchers, space stations, and services, transforming space into a competitive and increasingly accessible market.

Private companies are now offering services that were once the exclusive domain of national space agencies. Launch providers, for example, allow agencies and commercial clients to purchase launch capabilities on-demand, without maintaining in-house infrastructure. This fosters competition, drives innovation, and reduces costs. Some companies also offer access to the ISS through commercial partnerships, enabling researchers to conduct space-based experiments without going through lengthy and complex governmental processes. Scientists can now bypass some of the traditional agency programs' administrative and financial hurdles. Commercial platforms often offer shorter development timelines, modular payload opportunities, and cost-sharing through multi-user flights. This shift brings more frequent access to space and greater flexibility. Therefore, actors such as universities, startups, and individual researchers can launch and operate payloads.

One such example is the International Commercial Experiment Cubes Service (ICE Cubes Service), a commercial offering provided by Space Applications Services, a Belgian aerospace company established in 1987. The company supports astronaut training, develops advanced space systems, and provides a variety of spaceflight services. It is headquartered in Zaventem, Belgium, with additional offices in Noordwijk, The Netherlands, and Houston, USA [65].

ICE Cubes facilitates access to the International Space Station through a commercial platform called the ICE Cubes Facility (ICF) (see Figure 16), housed in Columbus, the European science module aboard the ISS. The ICF provides 20 internal slots designed to host Experiment Cubes, modular payloads that support a broad spectrum of research, technology demonstrations, and educational initiatives. These Cubes vary in size and are powered and interfaced via the ICF's onboard systems. They can be custom-built by engineers at Space Applications Services or adapted to meet specific investigator requirements.

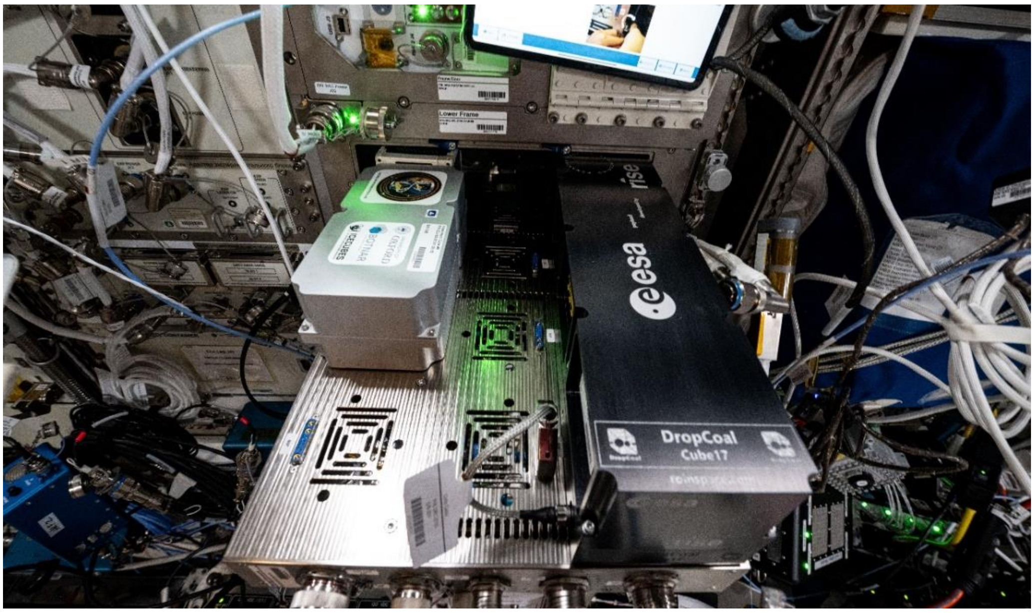


Figure 16: ICE Cubes Facility in Columbus module on the ISS (Credit: ESA/NASA)

Several in-house Cubes have been developed based on typical market needs and are available for use by scientists (Figure 17). The Science Cube is a biological payload that allows incubation at 37°C with continuous video monitoring; it is typically returned post-flight for analysis. The AI-Box is a sensor-equipped computing unit capable of receiving software updates from Earth. Less cube-like, the Media Set is a communication system featuring a camera, speaker, and microphone for interactive or recorded sessions between the ISS and Earth. Another example is the Calliope mini, a small, programmable computer used for STEM engagement and student-led projects.

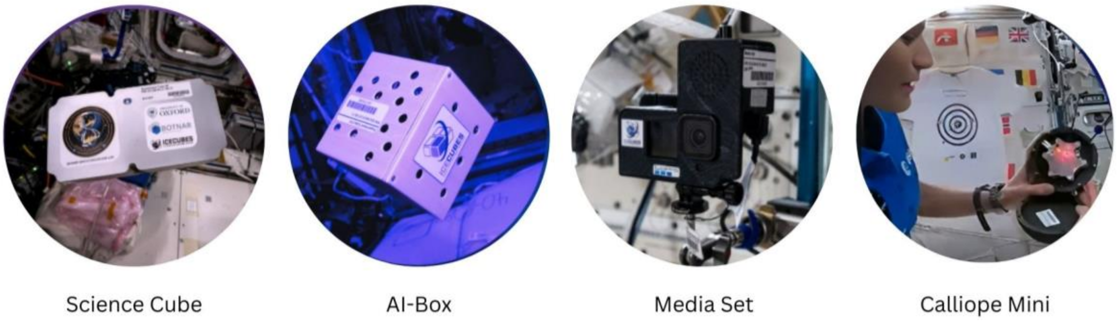


Figure 17: Examples of ICE Cubes assets [66]

In addition to hardware, ICE Cubes offers end-to-end services, including payload design, integration, launch logistics, certification, and optional return of hardware or samples.

The uniqueness of this service is the real-time monitoring and commanding that scientists can do from the ground. They can do this via the User Home Base, a ground-based interface that enables principal investigators to monitor and interact with their experiments in near real-time, from their own labs or institutions. This capability distinguishes ICE Cubes from most other commercial access services. Researchers are not limited to passive observation but can actively control their experiments throughout the mission. This is particularly valuable for sensitive biological, environmental, or dynamic systems where timing and adaptability are critical [66].

The service attracts users from various backgrounds. As more commercial space stations and platforms become operational in the coming years, prices are likely to decrease, allowing a broader range of scientific and educational projects, including astrobiology and fundamental research, to engage in space exploration.

3. Methodology

Now that we have established that the effect of gravity on living organisms must be studied further to advance astrobiology research, I will propose an experimental solution to this problem: a centrifuge for microgravity.

In this section, an overview of the whole maturation process of designing a centrifuge will be provided. Before starting to design such a system in detail, it's important to start by carrying out preceding systems engineering activities. Given that the idea of this thesis is not to professionally build this platform, but to assess its feasibility and think about the factors going into it, some parts of the process will be more detailed than others.

The section will be divided into three sub-sections, which drive the design process of the system.

- **Mission analysis**: Here, what will be discussed is the problem the system is trying to solve, what kind of business/funding opportunity will drive the mission, and what gaps in the market/science community remain.
- **System requirements**: In this section, the needs of the stakeholder and the criteria that the system should meet to respond to, will be listed.
- **System architecture definition:** The different factors to be considered, the various options to choose from, and how this is tackled.

3.1. Mission analysis

The motivation behind the development of this platform is justified by the literature review in the first part of this thesis. The centrifuge is designed to advance research in astrobiology, helping to understand the origin of life, the uniqueness of life, and preparing us for future missions and investigations.

Next, it is important to determine how we will progress in partial gravity research. While this has partly been accomplished by reviewing the existing solutions in the introduction, we still need to justify the choice of the centrifuge.

All the methods introduced previously have both positive and negative aspects, which are summarized in the table below (Table 2).

Table 2: Comparison of gravity simulation methods for microorganisms

Simulation Method	**Type**	**Gravity level**	**Duration**
A: Clinostat	Ground-based	Simulated microgravity	Continuous
B: RPM	Ground-based	Simulated microgravity	Continuous
C: RCCS	Ground-based	Simulated microgravity	Continuous
D: Drop tower	Ground-based	Real microgravity	Milliseconds to seconds
E: Magnetic levitation	Ground-based	Simulated microgravity	Continuous
F: Centrifuge	Ground-based or space-based	Hypergravity on ground and partial gravity in space	Continuous
G: Parabolic flight	Flight-based	Real microgravity, hypergravity and partial gravity	25 seconds per arc

Most experiments simulating reduced gravity are conducted on the ground because they are more practical, less expensive. The issue is that they don't accurately represent the gravity levels of Europa and Enceladus since some of them can only simulate microgravity and not partial gravity. The only other type of experiment that resolves this problem, apart from centrifuges, is parabolic flights. However, these flights do not allow for extensive data collection as the flight arcs last only a couple of seconds. This makes the centrifuge to be the most appropriate solution for our scientific objectives.

Rotational motion causes centrifugal force and is employed to create hypergravity on the ground, training astronauts or fighter pilots, for example. By using the centrifuge, one can experience higher g-forces. If you start with 1g, like on Earth, you can't achieve partial gravity; however, by beginning in 0g on an orbital station, you could reach any gravitational acceleration you desire. Nowadays, some centrifuges in space are already used to simulate partial gravity, like Moon or Mars levels (see Section 2.2.3).

Initially, centrifuges were placed into orbit to establish a 1g reference. By comparing the results obtained on the ground with those obtained in space, we cannot determine if the differences observed are solely due to the difference in gravity or if they are also due to other factors such as radiation. Centrifuges on board simulating 1g act as controls and are used to prove that gravity is a factor affecting the behavior of the study subjects [67].

Now that the mission's motivation and the centrifuge's choice have been explained, why is a commercial service, such as ICE Cubes Service, a good implementation method for this project?

Services like ICE Cubes represent an ideal platform for a scientific mission like the one defended in this thesis. Building a centrifuge to add to their portfolio of available assets could help them broaden their capabilities, give new possibilities to researchers such as astrobiologists and make them competitive against other companies.

By developing commercial services, platforms such as the ICF will become more accessible and less expensive, enabling space scientists, who typically have less funding than large companies, to access microgravity for their research.

A centrifuge like CAMINO is designed with microorganisms in mind but it could even help support other types of research such as studies on plants, regenerative medicine, space farming, organoids etc. [68]. Of course, to accomplish this, the sample accommodation in the centrifuge may need to be adapted with adequate feeding systems, plant growing capabilities, exhaust collection functionalities and other, depending on the type of application desired.

Additionally, as the entire space sector undergoes commercialization, opting to build a payload through a private company enhances the project's competitiveness and prevents it from being tied to a specific country or station (currently, the ICF is on the ISS, but in the future, it could theoretically be installed on any station). This approach opens up more opportunities for scientists from various backgrounds to access microgravity.

3.2. System requirements

In order to design a system, it is important to establish a list of requirements essential for the stakeholders and the goal of the project. Once these criteria are defined, we can start designing the payload to meet those requirements, and ultimately, we can revisit them to assess the progress made.

Thanks to the market analysis in Section 2.2.3, we have identified similar centrifuge projects with different capabilities, such as incubation, handling numerous samples, and real-time command from the ground. Consequently, we have also noted a lack of real-time monitoring of samples in commercial space centrifuges. Real-time monitoring can help scientists adapt the setup if needed and analyze some results before or without having to return them. Using this gap in the commercial offering, we can ensure that our payload remains competitive. This already establishes a couple of requirements.

To study extremophiles as outlined in the scientific objectives, it is important to identify what specific aspects we want to explore about them. As we aim to observe how their behavior may change in partial gravity, examining macroscopic changes such as colony size and growth rate is a practical starting point.

Additionally, by choosing to implement this project via the ICE Cubes Service, we must comply with the requirements of the ICE Cubes Facility (ICF) (Figure 18). All relevant information regarding the facility and its compliance rules can be found in the Interface Requirements Documents (IRD), available on the ICE Cubes Service website [69].

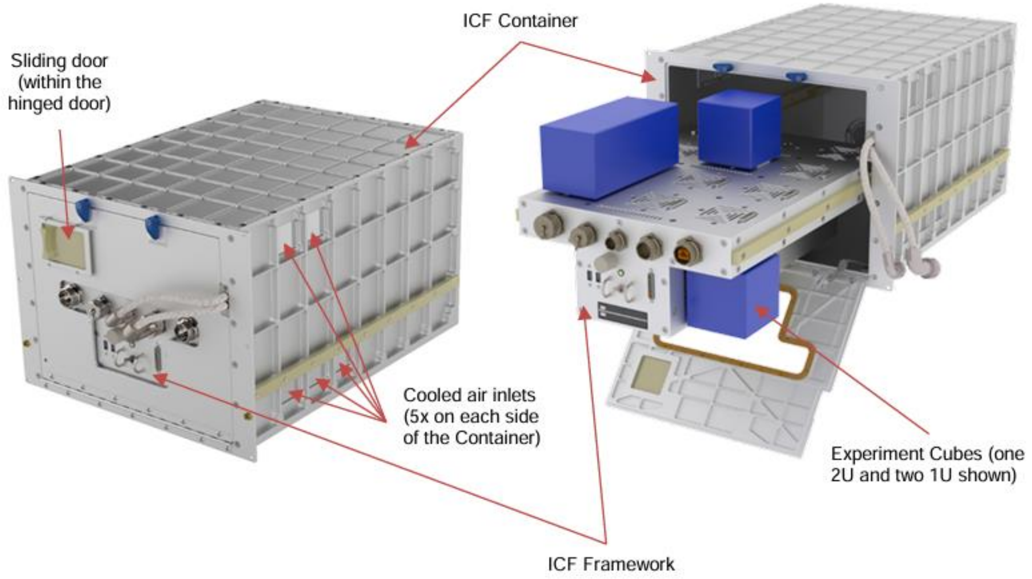


Figure 18: ICE Cubes Facility: Open and closed views [69]

Here is the list of the most important System Requirements:

- The system shall comply with the interface requirements outlined in the IRD.
- They shall be capable of generating centrifugal acceleration to gravity levels from 0.01g to 1g.
- The system shall support biological sample containers that do not require active thermal regulation or nutrient delivery.
- The system shall provide visual monitoring of the samples.
- The system shall allow the rotational speed of the centrifuge to be remotely adjusted via ground control commands.

3.3. System architecture definition

Concerning the technical details, first, we will list the different components of the system to provide an overview of the minimum parts we should consider including. Then, we will summarize the requirements outlined in the IRD, which recapitulates what is needed to make a payload function in the ICF and incorporate the constraints added by the specific requirements of the CAMINO project, cited in the System Requirements, here above.

Given the scope of this thesis, I will only cover the most important aspects of the design in a high-level manner, corresponding to Phase A of a project, according to ESA guidelines (see Section 5.2). This will be a preliminary design activity and thought process for the project.

3.3.1. Components

Before examining the specific requirements, let's list the minimum needs for the science objectives we have in mind. If we are to create a centrifuge, we need to accommodate samples, make them spin, and control the speed specific to the partial gravity we would like to simulate. As discussed previously, to make the system competitive, we want real-time monitoring; therefore, cameras are needed along with light to illuminate the samples. We also mentioned that this footage should be streamed to and controlled by ground control, which requires a micro-processor to manage the entire system. Additionally, to fit inside the ICF, an external cube-like structure and an interface adapter are needed.

From now on, the system will be referred to in two distinct parts that are *in fine* connected, the external cube and the rotating structure:

- **The external cube**:
  - **Motor** (part that rotates the sample-holding structure)
  - **Micro-processor(s)** (to manage data and power for the system)
  - **H-bridge** (to connect the micro-processor to the motor)
  - **External structure** (to assemble everything)
  - **Interface with the ICF** (the plug to connect to the facility and transfer power and data)
  - **Additional elements** (depending on the type of coupling or electrical system)

- **The rotating structure:**
  - **Sample holder** (rotating structure that holds the samples)
  - **Micro-controller(s)** (to control the speed)
  - **Cameras** (to monitor the samples)
  - **LEDs** (for sample illumination)

3.3.2. Interface Requirements applied to CAMINO

This section will follow the order of the Interface Requirements Document (IRD), focusing on high-level constraints to be taken into account when choosing the design of the CAMINO payload in the Results part of this thesis, Section 4.

a) Mechanical and structural constraints

- Connector: From the IRD, we learn that the Experiment Cube should have a specific DW13W3P connector (Figure 19), to ensure the transfer of power and data from and to the payload. Each slot offers 5V and 12V of power. Depending of the power needs of CAMINO, it might need one or several connectors. The measurements and specifications of the connector are detailed in the IRD.

Figure 19: DB13W3P male plug [69]

- Size: Next, we learn about the standard dimensions of Experiment cubes. They range from 1U, which is 10cmx10cmx10cm, to 4Ux3U [69]. In the case of CAMINO, different sizes can be foreseen. The size must be optimized to collect as many samples as possible by having the smallest mass since the uploading of the mass gets more expensive the heavier it is. To choose the optimal size, a number of tests are to be made to study the best configuration. The initial idea is to account for have a cube-like volume dedicated to the centrifuge rotating system and additional volume providing space to host the rest of the components.

- Motor: The motor needs to be able to rotate fast enough to attain the right gravitational acceleration. The required RPM to achieve the acceleration levels stated in the systems requirements is calculated here below, given the experiment cube sizes mentioned in the previous paragraph.

  The centrifuge simulates gravitational acceleration by centripetal acceleration like explained in Section 2.2.3.

  To find the rotation per minute (N), Equation 1 must be solved for the angular velocity and then transformed through the following way:

$$N = \frac{w.60}{2\pi} \tag{2}$$

  In the system requirements, the required gravitational accelerations are from 0.01g to 1g, so we will examine those minimum and maximum, and the radiuses are the ones of the possible sizes of cube-like experiment boxes (Table 3).

Table 3: RPM range in function of size

	a=0,1m/s^2	a=9,18m/s^2
1Ux1U (r = 4cm)	14,3 RPM	144,9 RPM
2Ux2U (r = 8cm)	10,9 RPM	99 RPM
3Ux3U (r = 15cm)	9 RPM	79,6 RPM

We consider that if the volume of the rotating system lies is 1Ux1U, 10cmx10cmx10cm, we give some margin to the rotating system, so that it can rotate without touching the walls. That is how we obtain the 4cm radius that is assumed to be for the rotating system.

Calculating the necessary RPM could limit the size of the cube if the RPM needed becomes too high to produce by a standard motor. But in this case, all of the scenarios are acceptable, since a standard rotating motor goes up to an average of 150 RPM, according to what can be found on the market [70].

- Audible noise: In terms of audible noise, the limit of 31dBA when measured at 64cm is a limit to not be surpassed [69]. For CAMINO, the only source of audible noise may come from the motor and the moving components, so that is to be considered with further testing in future steps of the project.

- Vibrations: It is important to consider the vibrations that the system might create. To not disturb other projects on the ISS, the vibration created by CAMINO must stay in the specified range, for attenuated and unattenuated random vibrations, communicated in the IRD [69]. Vibration tests with shakers must be made to determine what the vibration of the system is and how much it needs to be mitigated.

  One way of mitigating these vibrations is by using magnetic coupling instead of mechanical coupling (Figure 20). Magnetic coupling transfers torque without physical touch between the motor shaft and the rotating structure. It is mostly useful when the rotating structure is filled up with liquid and limits the risk of leaks. In our case, it may help reduce vibrations but it is more complicated to install [71].

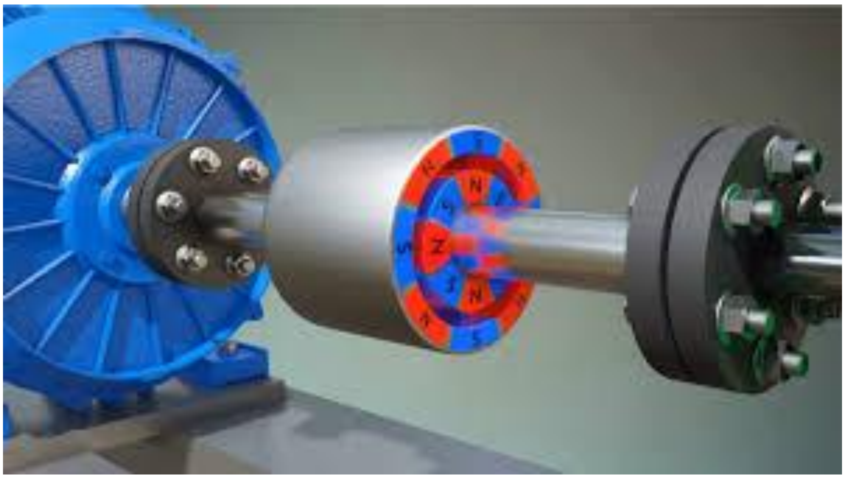


Figure 20: Model of magnetic coupling [71]

Another solution to limit vibrations would be to use magnetic bearings for support instead of classic ball bearings. They are essentially sets of permanent magnets that achieve full levitation combined with some sensors and electronics to create a feedback loop. These bearings can be used in combination with mechanical couplings and will help keep the centrifuge on axis and in place without adding additional vibrations. Additionally, they don't create wear and compensate automatically when the system is out of balance. It is important to keep note that they are power-consuming and more complex but are a good alternative if classical ball bearings are causing too much vibration, noise or contamination.

Maintaining system stability also contributes to vibration mitigation. It also is important so the centrifugation of the samples can be done properly, and the partial gravity levels attained for each sample in the same way. To maintain equilibrium, the system must be completely radially symmetrical in terms of mass and geometry. The center of mass should align with the rotation axis of the centrifuge's rotating system. Complications may arise because nothing can ever be perfectly symmetrical, and the presence of liquid samples may further complicate this symmetry. The extent of acceptable asymmetry will be studied in greater detail during later phases of the project.

- Temperature: The possible range of temperatures the payload could be submitted to is between 5°C and 46°C, including the temperature on board the station and the possible launcher environment [69]. Once on board, the ICF maintains a temperature between 16°C and 30°C, but averages mostly around 22°C. CAMINO does not foresee having any experiments needing temperature control, as it focuses mainly on the partial gravity factor. The heating up of some parts due to the rotation should be studied to prevent overheating of the system, but this should be tackled with thermal testing to be done during the project's next phases.

  If samples are to be returned, they could be frozen, but this will be done via another service, provided by a national agency or another company, not via CAMINO. The ICE Cubes Service can provide access to a freezer on-board such as ESA's Minus Eighty-Degree Laboratory Freezer for ISS (MELFI) at -80°C to return the samples frozen.

  What could be interesting for the scientific research is to add temperature sensors to the samples to detect at what temperature they are at a certain point in time and see how that relates to the partial gravity. These temperature sensors should be put as close as possible to the samples to get their true data, but also not touching other surfaces which could influence their measurement. The feasibility of using these temperature sensors will be considered further, when discussing the electrical wires constraints of the system.

- Sample holders: The number of sample holders will depend on the electrical constraints. Since the system requirements mandate that the samples be monitored continuously, which implies one camera per sample and a lighting system to ensure good visual conditions, the number of wires connecting everything must also be considered. This also affects the shape and size of the sample holders.

What is certain is that to have a clear visual image, one of the sides of the sample holders must be transparent. To keep the rotor balanced, they should be placed radially symmetrically around the center and the samples themselves must be symmetric for stable centrifugation. They should be adapted to study extremophiles or bacteria, which are the most studied species in astrobiology studies [72] and the focus group of our scientific objectives. This also requires a certain level of containment, discussed in a further section on safety. The best type of sample holder should be selected after a series of tests to determine the ideal configuration and shape for effective centrifugation results.

b) Electrical constraints

- Power: As mentioned earlier, the Cube should have the correct interface plug to connect to the facility. The facility provides power at 5V at 1A (5W max) or 12V at 3.1A (37.2W max), corresponding to the 2 power lines available. The maximum power delivered to the Cube also depends on its capacity to dissipate heat. This heat dissipation requires the right choice of material and specific testing done at a later stage.

- Wires: It is important to consider that both main parts, external cube and rotating system, should be connected to power and additionally to each other to transfer data and commands. The cameras, LEDs, and possibly temperature sensors should be installed inside the rotating structure. This creates a problem if the connection system uses wires because the spinning parts connected to the non-spinning parts will create wire entanglement. This means that the components should either be connected wirelessly or utilize a slip ring, which is a system with brushes that helps connect wires between rotating and non-rotating parts.

  The issue with the slip ring is that its mechanism does not allow for many lines, the small models go up to 24 lines. Let’s review the number of lines in our system:

    - USB Camera: 4 lines
    - LED: 2 lines, one for power and one for ground
    - Temperature sensor (optional): 2 lines

  This means 8 lines per sample. Given that the slip ring models go up to 24 lines, it limits the number of samples to 3 if we include the temperature sensors and 4 if not.

One solution to decrease the number of wires passing through the slip ring would be to install a micro-processor in the rotating frame. This means that the only wires going through the slip ring would be the ones connecting the cameras to the micro-processor, totaling 4 per sample, which includes the data provided to the micro-controller and power lines. This sums up to 20 lines instead of 24, which is an improvement, but still limits us to only 4 samples.

In this case, it might even be better to have the micro-processor inside the frame but have the power and data connection be wireless. The disadvantage of this is that for it to work best, the data transfer would be asynchronous, meaning that data updates would be done at a certain interval of time. It also means testing if charging a rotating system wirelessly works as well as a non-rotating one. Studies tackling this issue have been done but are still at a preliminary stage [73].

Another solution is to install a USB port instead of a microprocessor inside of the rotating frame. It allows the footage from all cameras to be centralized inside the spinning part, and will need only 4 lines to connect to the micro-processor attached to the external cube wall. The ideal solution is to be assessed by further testing.

- Light: To use a camera for monitoring samples, one must illuminate them. Since the aim is to study how extremophiles react to partial gravity on a macroscopic level, transmission light passing through a transparent sample holder suffices. A LED light is sufficient to track the growth curves of bacteria, visually observe biofilm formation, and track morphological changes when naturally or genetically modified fluorescent extremophiles are used, or alternatively, metabolic indicator dyes, such as those used in BioSentinel, a 2022 NASA mission to study radiation effects on microorganisms [74].

  According to the IRD, a maximum of 10,000cd/m^2 is allowed for the light source, and it should be optically contained if exceeding this limit [69]. A possible mitigation for this constraint could be choosing the right coating for the centrifuge materials.

  Since the light source also has some wiring constraints, further testing should investigate the optimal lighting method. For example, can a single light be used to illuminate all samples if positioned in the middle? Tests of the optical setup, light, sensor, and lens are needed to answer this question.

There are many considerations to be taken into account regarding the various electric and magnetic fields radiated by the payload, the capacitor levels, etc. Because the focus is more on preliminary conceptual design, this is the extent at which these points will be covered, but they need to be studied in detail if the project is to advance to the next level.

c) <u>Safety</u>

- <u>Hazards:</u> Potential hazards should be identified beforehand and mitigation strategies should be put in place to reduce the risk of them affecting the safety of the payload. NASA has issued a document called "ISS Safety Requirements" [75] which goes over every scenario and what type of testing or solution it may require. This document will be the one to read when looking to comply with ISS safety regulations and making sure that CAMINO does not cause harm to the ISS environment.

  As for CAMINO's own safety, this type of documentation should be written by the CAMINO project team once the design is fully determined, since they are responsible for the equipment safety. It should include the instructions on how the payload should be handled to maintain its functionality and mitigation to potential risks similar to what is specified in Section 3.3.3.

- <u>Containment:</u> Hazardous samples must be contained to avoid contamination between samples, to the facility or to astronauts. The level of containment refers to the number of physical walls between the sample and the outside environment, the level number increasing with the danger of contamination. The level of containment is chosen with respect to the biosafety level of the bacteria studied and the respective table is figured in the ISS Safety Requirements document.

  The most commonly studied species for astrobiology studies are extremophiles (such as *Deinococcus radiodurans*) or cyanobacteria (such as *Anabaena spp.*) [32], so the system must be adapted for this type of bacteria. They are usually considered to be BSL-1 (Biosafety Level 1), which is the safest kind. In order to prevent leaks and potential damage to other components, two levels of containment are required for this biosafety level.

d) <u>Software</u>

- <u>Interface</u> : Software systems must be developed to have monitoring and control over the system. In the ideal scenario, the customer/scientist will have a User Home Base, an interface in his laboratory that will enable him/her to connect with the payload. The UHB and ground control center work with the YAMCS server which is system built by Space Applications Services for easy managing of control centers. This is what is used by the ICE Cubes Service for connection with the ICE Cubes facility and their payloads. A simple interface screen will be developed with easy commands already integrated such as:

    - Start and stop of the rotation
    - Setting the speed and thus the partial gravity level
    - Changing the light intensity
    - Control of the video recording.

  The interface should be designed once the controls are decided upon permanently.

- Programming language: The Raspberry Pi is the most commonly used microprocessor for this kind of payload, and Python is the main programming language. Python works well for tasks like sending and receiving data (telemetry and telecommands), running automation, and saving information. To make the system work properly, several Python scripts are needed. One script runs automatically when the payload is turned on. It handles basic setup tasks, such as turning on communication systems and setting up the experiment components with their default settings. Another script is used to respond to specific commands sent by scientists from the User Home Base (UHB).

  However, Python has some limits, especially when it comes to demanding tasks like streaming live video. Because Python is slower than some other languages like C or C++, and it can't easily do many things at the same time, it may struggle when trying to handle several video feeds at once. Also, the Raspberry Pi has limited memory and processing power, which makes it even harder to manage live video smoothly.

  These limitations become even more important when you consider that the ISS regularly experiences Loss of Signal (LOS), times when communication with Earth is interrupted. During these periods, the system must store all data locally and send it later. Since handling full live video streams would be too much for Python and the hardware, one practical solution is to reduce the video load. Instead of streaming continuously, the system can save one frame every few seconds, which is much easier to manage and still provides useful visual data.

- Signal path: The signal is transmitted via a K/Ku band between the ground and space. The ICE Cubes Mission Control Centre in Zaventem sends commands to the ESA Columbus Command Centre in Germany which in turn will communicate with the NASA ISS Control Centre in Houston. Finally, the signal will be sent via the White Sands TDRSS Control and relayed to a Tracking and Data Relay Satellite which will transfer the signal to the ISS. Once on the ISS, the signal will be sent to the right IP address. Each power/data port has its own IP address which enables the signal to know to whom it is addressed. The same path works for telemetry and is visible on Figure 21.

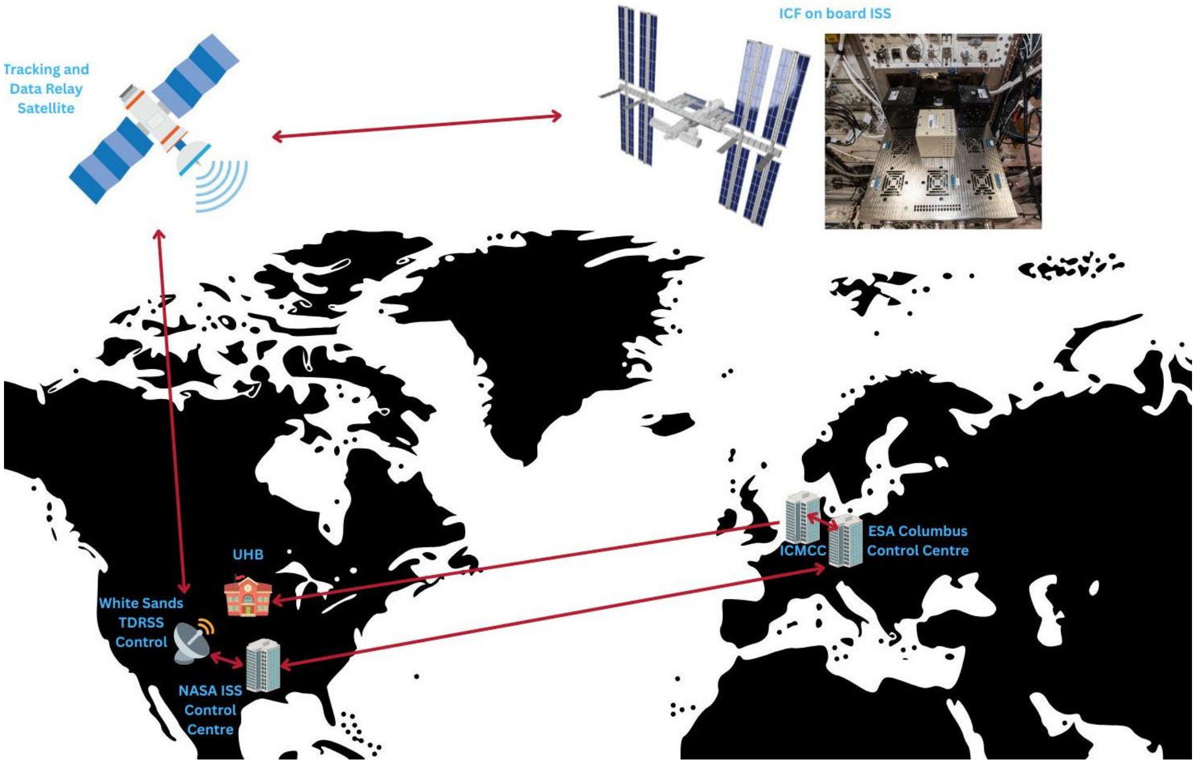


Figure 21: Data flow between payloads in the ICF and ground

e) Astronaut interaction

- <u>Operations:</u> Based on previous ICE Cubes Service experiment processes, a good operations plan for the CAMINO project would be to launch it and keep it onboard, allowing samples to come up and down when needed. This approach reduces the cost of the experiment by minimizing the mass upload, while also shortening the timeframe required to prepare the uploaded material (only samples instead of an entire machine). However, this necessitates that astronauts unpack the samples and place them into the centrifuge, then remove them once the experiment is complete. Crew time is usually difficult to obtain and expensive.

  This task cannot be entirely avoided even if we were to send a whole CAMINO sealed with the samples each time, as the astronaut would still need to unpack it and install it in the ICF. Nevertheless, when astronauts directly manipulate the samples, extra time and additional safety considerations are required.

  Here is the timeline of the proposed service operations:
    - Pre-launch sample preparation
    - Launch and activation aboard the ISS
    - Continuous monitoring of biological survival
    - Data collection throughout mission
    - Experiment conclusion and sample return if needed (could be refrigerated)

> With this process in mind, and to facilitate the manipulation of the astronaut, CAMINO should have an easy mechanism for opening the Cube and inserting/removing the samples. This imposes certain constraints on having a lid, how the wiring should be placed and how the elements should be attached to the external cube walls.

As expected, at this stage, it is difficult to define every detail of the system because most choices require their own dedicated study and testing. For this phase of the project, we make assumptions about some high-level design choices based on what theoretically would be best for the system and propose a few alternatives. However, after further testing and in-depth studies, additional solutions to the challenges may be discovered, and other difficulties may also arise.

3.3.3. Technical risks

With all of these considerations in mind, it is essential to assess the potential risks of the project before developing the payload, to include mitigation strategies in the choice of components and structure, and to integrate them into the design. The following non-exhaustive table (Table 4) summarizes the most mission-critical risks and their potential mitigations.

Table 4: Technical risks regarding the functioning of CAMINO

Risk Number	Risk Description	Likelihood	Severity	Mitigation Strategy
R-1	Rotor imbalance due to asymmetric mass distribution	Intermediate	High	Design for axial symmetry
R-2	Liquid causes imbalance during rotation	Intermediate	Intermediate	Use sealed and symmetric sample containers
R-3	Slip ring wear or contact loss over time	Intermediate	High	Use high-quality slip rings
R-4	Failure of the micro-controller	Low	High	Use radiation-tolerant micro-controller
R-5	LED lighting failure	Intermediate	Intermediate	Use space-rated LEDs, add redundancy
R-6	Non-consistent downlink	Intermediate	Intermediate	Add onboard video storage
R-7	Sample containment	Low	High	Use double containment

4. Results

As mentioned in the Methodology section, it is difficult to obtain a model that is fully defined at this stage of the project. Most decisions should be made based on tests and validated through in-depth studies. Nevertheless, it is possible to predict and assume that some decisions might be best for the system and begin designing what the system would look like. This helps with visualizing the payload and may lead to new thoughts and emerging questions or challenges that we would not have considered without visualization.

Based on all the factors discussed in the previous section, the next step is to combine them and envision a model of the system that incorporates all the best elements. This is a preliminary model, meaning that after testing and further study in the next phases of the project, it will be revisited and refined or modified.

First, the justification of some design choices based on the thought process mentioned in the Methodology section, will be discussed. Afterwards, we will show the 3D rendering of the system and detail its architecture. Finally, the technical design with precise dimensions will be demonstrated on Figures 28 and 29.

4.1. Design choices

The technical design has been made with design choices that are based on the concerns and alternatives discussed in the Methodology section.

- Size: In the methodology section, we discussed the reasons for wanting a parallelepiped shape, but the most optimal solution would be to maximize the space surrounding the rotating structure, which is why for this initial design, everything will be accommodated in a square paralepidid structure.

  We also considered the rotation frequency of the motor, which did not constrain us from choosing a specific size. Objectively, choosing a bigger size will give us space to put bigger or multiple samples per sample holder. It also comes with higher costs, especially for initial manufacturing. This is why we have chosen the middle option, 2Ux2U, to balance out the positive and negative aspects, for this particular design version. Since the only difference between the versions would be the proportions, this can always be adapted at a later stage.

- Connector: According to a brief study of motors on the market, it is possible to find motors that can respond to our requirements of reaching 99 RPM (see Table 3), that function with under 12V of power, which is the maximum available power for one single connector. The rest of the components will also require power, but less than the motor. A comprehensive study must be done to assess how many connectors are needed given the power needs of each component. For this reason, the connector has not been included in the design. It is assumed to be on the bottom side of the external cube for the simple reason that given the 2Ux2U size, the only space CAMINO could be accommodated in would be the top of the ICF, where the interface connectors are at the bottom (see Figure 18: ICE Cubes Facility: Open and closed views .

- Wiring: If we insert a USB hub into the rotating frame, we can use the slip ring, which is the most reliable solution to date. This means that camera data acquisition will be local and will be transmitted to the micro-processor through 4 wires passing in the slip ring. Same goes for the LED lights, which will be centralized and consist only of 2 wires. This leaves us with plenty of space to add temperature sensors as well.

  If in the future, there is reliable technology that enables wireless charging of rotating frames, then it could be a good solution to replace the slip ring that may have some wear and tear. The assessment of magnetic and electric fields in this case should then be tested extensively.

- Vibration: Since it is very important to avoid high vibration levels, the best choice would be magnetic coupling and magnetic bearings, but this technology is to be tested. It does not impact the final design much, which is why the initial technical design shown further can be valid for both types of coupling.

- Temperature sensors: Since we know the range of temperatures of the ICE Cubes Facility environment and given the strong resistance of extremophiles to temperature, temperature sensors are not the most crucial element to the scientific objective. Given the currently chosen electrical configuration, these can be added without too much of a burden in the next steps of the project if needed but have not been considered in this initial technical design.

- Sample holders: Given the symmetrical constraints mentioned earlier and the necessity for extremophile accommodation, the ideal shape for the sample holders would be cylindrical cuvettes or Petri dishes. The best solution is to be determined with further testing. For this design, we assume a rectangular Petri dish. Given the size of the cube, the wiring design choice, and the power requirements, the number of 6 samples has been chosen to be a good compromise, even though with further adjustments, 8 samples may be accommodated.

- Containment: As discussed previously, two levels of containment will be needed to accommodate the bacteria. This is why individual sample holders have been created. Their idea is to accommodate a sealed box, such as a cassette, already containing the samples inside of them. This way the transfer is easy for the astronaut manipulating them, and the two levels of containment requirement are covered.

- Light: For better optimization of space and resources, a ring-like LED light strip that illuminates all samples simultaneously has been envisioned. It would be placed on the internal cylindrical wall of the rotating system, shining through the samples and reaching the cameras at the center. Further testing would have to study if that solution is viable, as it may create disturbing reflections or unwanted effects.

  The color of the centrifuge rotating part has been chosen to be rather opaque to mitigate any possible reflection that could make observing the samples more difficult and also stay in the brightness limit mentioned before, to ensure safety to the crew and other payloads.

- Cameras: The type of cameras are still to be chosen. It would be a possibility to make the whole hexagonal shape in the center of the rotating system modular, so that the type of cameras could be easily changed in the case of failure. This system could also be used to expand the observational capabilities of the cameras, by using cameras of different fields of view or in the case the scientists would like to use different spectra, such as thermal cameras, observing in the infrared. The distance between the cameras and the samples is to ensure the successful focus of the cameras.

- Lid: To facilitate astronaut manipulation, the cube will have a lid that remains attached to the main structure, preventing it from being lost in the station. It will provide access to the main rotating structure, but not to the section containing the components. This way, only the necessary parts are exposed to a different environment, minimizing the risk of inadvertently disturbing the system.

- Software: As discussed earlier, the system may have trouble streaming six live footages in exact real-time. Given that the observed biological processes are expected to be slow, if the footage consists of capturing a frame every couple of seconds, it allows for a compatible compromise within the scientific objective. This is still to be studied further and has not impacted on the design at this stage.

4.2. 3D Model

The following 3D models (Figures 22 to 29) have been made with Autodesk Fusion 360, CAD (computer aided-design) modelling program, by the author of this thesis. They are useful for visual representation and later can be analyzed further thanks to the program's structural and thermal analysis tools.

The CAMINO payload consists of an external 2Ux2U Cube. It has a rotating structure and other components. These other components are the micro-processor (Raspberry Pi), the H-bridge to connect it to the motor, the motor itself and the rotational velocity sensor. This sensor will help control the speed of the rotation and keep it in line with the required level. It is placed underneath where it will measure the velocity by detecting some black and white indications painted on the bottom of the rotating structure.

The rotating structure consists of a cylindrical box with 6 sample holders and a central hexagonal cylinder structure. Each face of this structure hosts a camera, each pointed at the sample holder across from it. The center of this hollow hexagonal cylinder will hold the USB port collecting data from all 6 cameras. On the internal wall of the rotating cylinder, a ring of strip LED lights will be placed to illuminate the samples.

Each sample holder has a lid which will have some mechanism to keep it attached to its holder. This has not been represented in this design since the best attachment strategy is still to be decided upon, but it is important to keep the astronauts from losing them in the station. The same goes for the external lid closing the whole payload which will also need some bearings to facilitate the easy rotation of the rotating structure.

Figure 22: 3D rendering of CAMINO, with external cube and lid

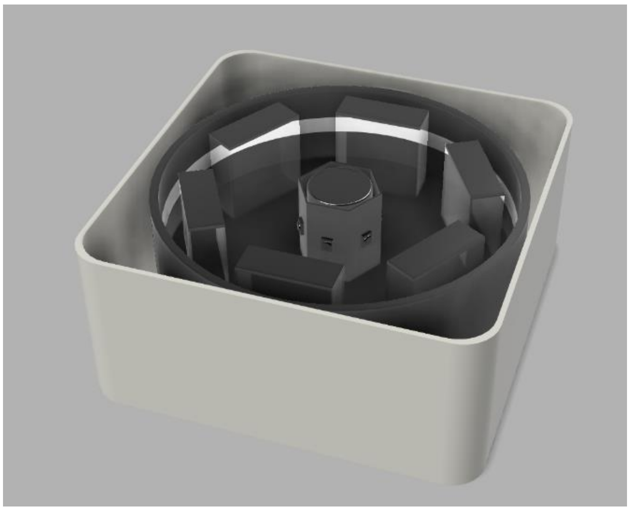


Figure 23: 3D rendering of CAMINO rotating structure and external cube, without the lid

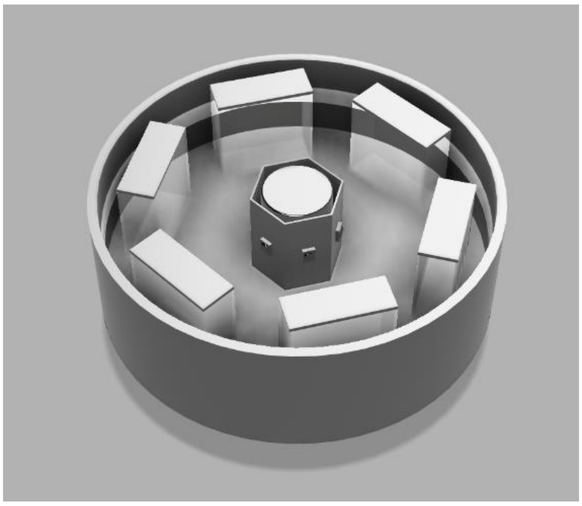


Figure 24: 3D rendering of CAMINO rotating part, top view without the lid and external cube

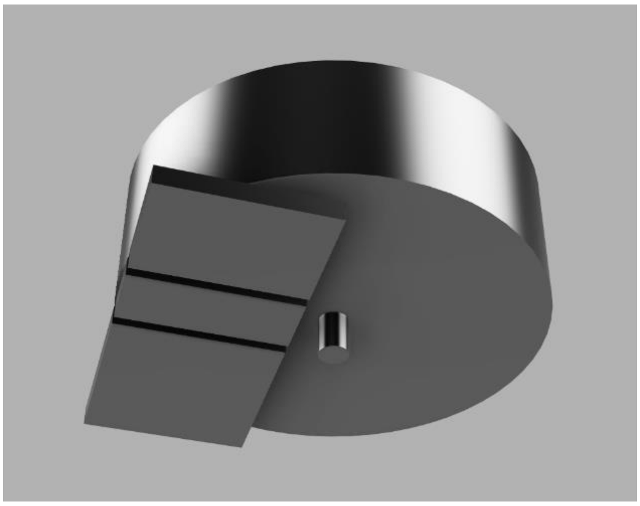


Figure 25: 3D rendering of CAMINO, bottom view of rotating part and non-rotating elements in the cube, without the external cube structure and lid

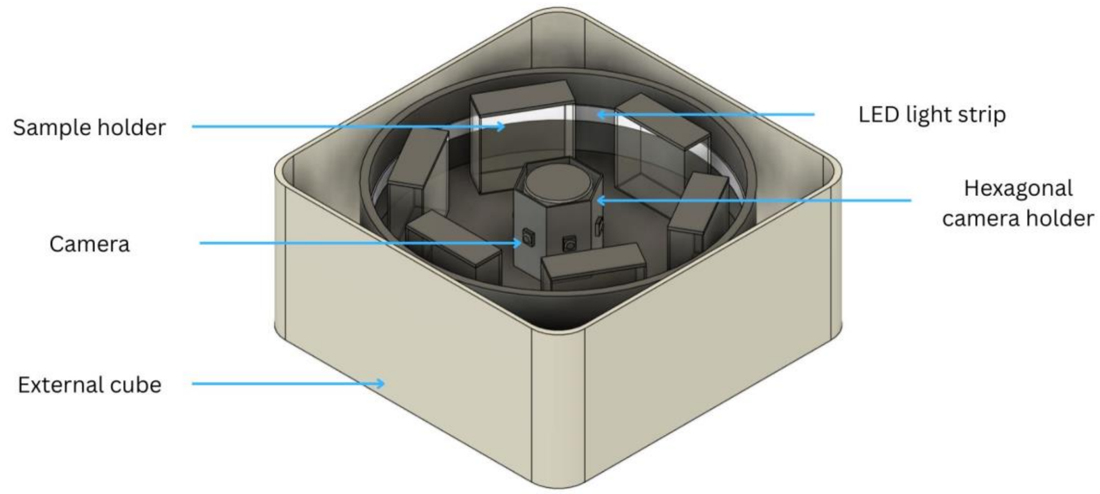


Figure 26: CAMINO architecture - Top view of rotating structure with external cube, without the lid

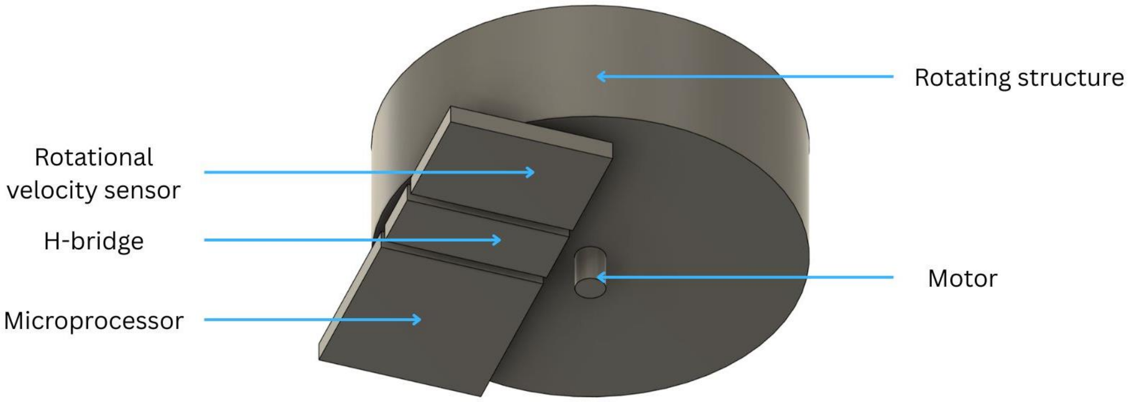


Figure 27: CAMINO architecture - Bottom view of rotating part and non-rotating elements in the cube, without the external cube structure and lid

4.3. Technical design

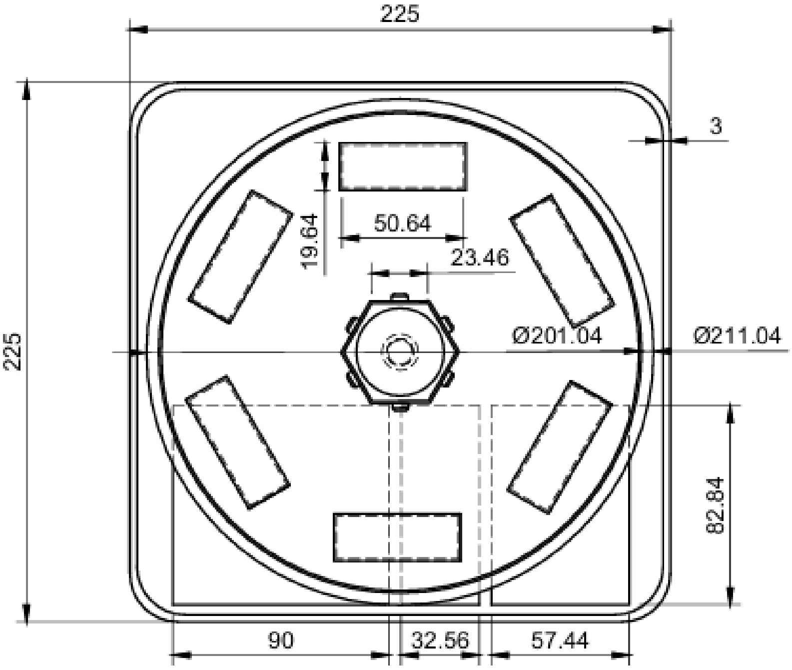


Figure 28: Top view of 2D technical design of CAMINO with dimensions

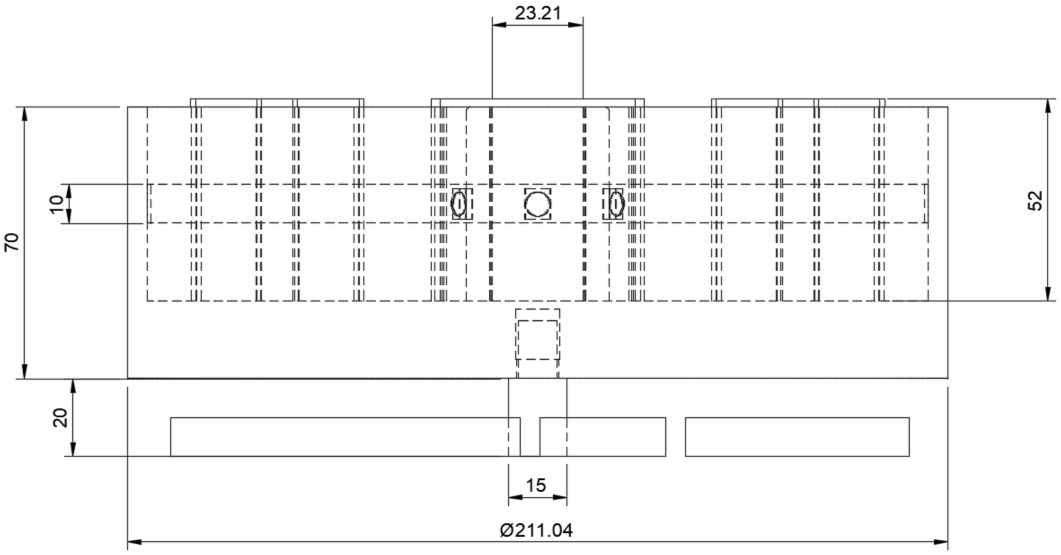


Figure 29: Side view of 2D technical design of CAMINO with dimensions

5. Discussion

5.1. Limitations & Technical Challenges

Now that we have a tangible model to work with, let’s analyze its weaknesses and identify areas that need further consideration.

First, we can examine the system requirements outlined in Section 3.2 and reflect on how closely they have been met. Real-time monitoring has been desired, but managing six live feeds with the microprocessor and Python language utilized presents some challenges. This implies that monitoring may need to be adjusted to a delayed state, necessitating a revision of the system requirements. We could also consider altering the microprocessor system, but this would require adapting the entire ground control center and the current software engineering methods for a single payload.

Second, the way the lights have been installed, on the internal wall of the rotating cylinder, may create unwanted reflections. This may be mitigated by painting some sides of the sample holders with anti-reflective paint, but this solution has yet to be tested.

The slip ring is a good solution to our wire entanglement issue, but still needs to be tested extensively as its wear and tear may cause some complications that cannot be solved easily from the ground.

An aspect that hasn’t been discussed in this work is ventilation, which is crucial in preventing the system from overheating. The amount of ventilation and the placement of the necessary components are factors that need to be addressed. Although it may change the configuration and design slightly, it is not expected to greatly impact the design.

The lid attachment style is also another point of uncertainty. Will the sample holder lids have the same type of attachment as the external cube lid? Will it be made with joints or a sliding system? On which side? These are all questions that still require further study and assessment.

Having 6 samples is good, and expanding to 8 would be even better, but it is not as extensive as that of other competitors (see Section 2.2.3), which can host tens of samples. Of course, a certain trade-off must be made between the number of samples and the added value of the monitoring; however, it would still be beneficial to find a way to increase the number of samples by alleviating the electrical and software constraints, which are currently the limiting factor. This would mean either reducing the frequency of imaging even further or recording the footage on an SD card instead of sending it live.

The last challenge to address is the cost of this project, which may affect the sustainability of both the project and the service. This will be discussed in Section 5.3.

5.2. Future steps

The work completed in this Master's thesis represents the first part of a mission project: the thought process that begins with defining a scientific goal, setting the requirements, and envisioning a preliminary design along with its various implications.

If the project continues, it will need to pass through multiple steps before being flown to space. The ESA Payload Development life cycle has phases going from A to F, with different steps and certifications to comply with different criteria [76].

Phase 0/A focuses on Mission Definition and Feasibility. It involves identifying mission needs, science performance goals, and operational constraints. Initial technical designs are produced, risks are evaluated, and management plans are defined. The work done in the scope of this thesis covers most of the activities typically done in Phase 0/A of a project. The technical design is not done by a professional engineer, so further verification and refining must be done. The only part that is completely lacking from a typical Phase A is an organization of the work plan and all of its management aspects, which is irrelevant for the moment since this project has not been assigned to be developed by any entity.

The next steps would be:

Phase B: Preliminary Definition involves finalizing the high-level plans and beginning the prototyping process. This includes defining the system architecture, manufacturing breadboard models (which serve as early functional prototypes), and preparing the initial technical documentation. The main objective of this phase is to achieve the Preliminary Design Review (PDR), which ensures that the preliminary system design is robust, meets mission requirements, and is feasible to develop further.

Phase C: Detailed Definition focuses on refining the engineering design and expanding documentation. During this phase, the design is finalized, and a Science Reference Model is developed, which defines the scientific objectives and data expectations of the mission. User manuals and operation guides are also prepared, and methods for hazard control verification are identified to ensure system safety. The culmination of this phase is the Critical Design Review (CDR), which confirms that the system design is complete and ready for fabrication.

Phase D: Production and Qualification/Verification marks the transition from design to construction and testing. Hardware for both flight and ground operations is built, and rigorous qualification testing is performed to ensure the system can withstand operational conditions. This phase concludes with two critical milestones: the Flight Acceptance Review (FAR), which validates that the hardware is ready for mission deployment, and the Certificate of Flight Readiness (CoFR), confirming that all safety and readiness criteria have been met.

Phase E: Operations and Utilization includes launch, in-orbit commissioning, flight operations, crew activities (if applicable), and ongoing ground support. It represents the active mission phase during which the system fulfills its intended function and scientific data is collected and analyzed.

Phase F: Return or Disposal addresses the end-of-life stage of the system. Depending on the mission, this may involve de-orbiting, safe disposal, or returning components to Earth. Post-mission activities also include final data archiving, system decommissioning, and preparation of summary reports.

5.3. Cost

The feasibility of the project greatly depends on the accessibility of the service. If scientists cannot use the platform in a financially viable manner, then the service will not be used optimally, and the building project CAMINO will lose its significance. The purpose of using a commercial implementation partner, such as ICE Cubes Service, is to facilitate administrative burdens and lower costs; however, developing the payload, constructing it, and uploading the mass into space involves significant expenses and should also account for the required manpower to accomplish all of this.

To estimate the cost of the project, we have broken down the price that the ICE Cubes Service would require to build the project as one of their own assets. The following activities are the ones that will need financing:

- Management
- Service Engineering (documentation, technical support, testing facilities...)
- Product assurance & Safety
- Operations
- Design, Development, Test
- Materials and External Services
- Travel costs
- Fees for transport and in-orbit services (mass upload and download, real estate, thermal conditioning, crew time...)
- Risks and commercial margin

This price, estimated by the ICE Cubes Service Business Development Department for building this project, is to be a minimum of 300,000 €.

This is a significant price. It could be developed as part of a company investment, a collective funding effort, or a grant award. Once the project is built and sent to the ISS, the scientists will be able to send their samples to travel to and back from space. This is done at a lower cost and is more important since the principal investigators need to be able to afford the service for it to work.

The same criteria as mentioned above should be considered in the pricing scenario of the service. The estimated cost would be significantly less than the aforementioned price, but it will depend on the number of samples, the duration of stay at the station, and market pricing. It is estimated to be in the tens of thousands of euros. For comparison, sending samples to KUBIK, a similar service, has a starting price at 160,000€ for one experiment container, which is equivalent to one sample holder for CAMINO [77].

5.4. Viability & Future Applications

5.4.1. Future Low Earth Orbit accommodations

An important factor to consider is that the ICE Cubes Service, which is considered to be the Implementation Partner in this work, currently only has access to the ISS, like many others. The ICE Cubes Facility (ICF), located in the Columbus module, is still operating in 2025. It is foreseen to continue operations until as late as possible, but its future is compromised since the ISS will be decommissioned in 2030 [78].

The ICE Cubes Service, along with most organizations leading science in Low Earth Orbit (LEO), will need to shift their business to another LEO station and adapt to the changes if they wish to continue their activities. Currently, various companies are competing to develop new LEO platforms to secure market presence and provide an alternative to the ISS. The industry has seen many start-ups spearheading projects for new inhabited stations, alongside the introduction of free-flyers (uncrewed satellites with return capabilities), new LEO manned and robotic stations, and return capsules. Some solutions provide a combination of these functions.

The ICE Cubes Service is currently exploring new ways to adapt to the demise of the ISS. Many options are available. If they were to partner with another LEO space station, a new version of the ICF would have to be built, and the service would be reproduced on a new platform. They could also change their model by focusing more on their payload development skills and acting solely as a payload developer service without managing an on-board facility.

The future remains uncertain, and tendencies change with each new signed agreement and test flight. It remains to be determined how the ICE Cubes Service will integrate into this evolving landscape. If a project like CAMINO were to be implemented in the future, it would most likely be able to adapt to other LEO platforms, especially at this early design stage when interfaces can still be modified. A more significant issue arises if it is developed as a payload intended to remain onboard, as envisioned in this thesis, similar to how the KUBIK centrifuge operates through the Bioreactor Express Service. For the time being, its destination would then be the ISS, but with a short accommodation duration. If the ICE Cubes Service installs a new facility in another station, then CAMINO could also be installed there.

If the service is implemented on a free-flyer, for example, which goes to space and returns after a short duration, it will change the business plan since CAMINO is anticipated to be a unique reusable payload. To make it financially feasible, this necessitates a partnership with the specific free-flyer company to allocate a slot for CAMINO when needed, by providing the centrifuge in-kind, or by having a subscription price to the launching service.

In the contrary case, where the payload is disposed of each time or if CAMINO's mass upload must be paid for at each launch, the business model of CAMINO must be revised, since paying for the development of each CAMINO or its mass upload every time is very expensive.

5.4.2. Other research possibilities

The CAMINO centrifuge project has been initiated to study the effect of partial gravity on extremophiles, but the platform could also be used for other research goals.

A study focusing on the needs of future astrobiological space platforms concluded that more platforms are necessary to investigate the combined effects of altered or microgravity with high radiation levels. To contribute to this, CAMINO can be conceptualized as being hosted by a Moon, Mars, or icy moon orbiter, where radiation levels are elevated, to study the additional impact of radiation on microorganisms in partial gravity [79]. Free-flyers may also be a good alternative for LEO destinations as they will have less shielding due to them being unmanned.

Apart from studying what potential life on the icy moons would look like, experiments more focused on planetary protection could be carried out. With potential landers planned for in situ exploration of Europa or Enceladus, it will be important not to contaminate the moons with our own biological specimens. By studying how living forms behave in partial gravity, scientists can further predict the potential risks of contamination and develop strategies to mitigate them.

CAMINO could also be used to create other partial gravities, apart from those of Europa and Enceladus. To accommodate experiments for future space exploration research, the levels of gravity can be adapted to Mars, Moon and other gravitational accelerations. This has already been done in some centrifuges such as KUBIK for biomining experiments such as BioRock [80].

Aside from astrobiological studies, the setup can be used for any space experiment that requires a 1g control. This is valuable for any kind of biological experiment that needs to isolate the experimental factor of microgravity, to deduce its actual effects on the studied sample [67].

A variety of biological experiments are already being conducted on board the ISS. "Ageing in microgravity", a study on ageing led by the University of Oxford, sends musculoskeletal cells to the ISS to study the effect microgravity has on them. This study could be extended into the future by exposing the same types of cells to lunar gravity in preparation for long duration missions [81].

Organoids are another focus of microgravity studies. Microgravity conditions allow for higher quality organoid testing because it provides a platform for 3D cell culture in vitro systems. These small bundles of cells try to mimic organ functions in the best way. They are a groundbreaking way to test drugs and pharmaceutical products on realistic systems whilst avoiding animal testing. They can also contribute to the development of personalized medicine, making tailor-made pharmaceutical solutions for particular patients. The ICE Cubes Service is developing a new payload solely dedicated to this purpose, called M4PM [82].

“Space Volcanic Algae” is an experiment flying with the Axiom-4 mission, led by polish scientists, that studies how extremophiles can be of help for extensive missions thanks to their many characteristics such as oxygen production [83].

Although all three of these examples use different payloads for their implementation, they are all hosted inside of the ICE Cubes Facility. In the future, the experiments could be extended by studying the same problematics in partial gravity conditions or by validating their results by having 1g controls in orbit. This could then be done by using CAMINO in addition to their own payload or by upgrading CAMINO to include the necessary components to maintain cell cultures, such as nutrition and exhaust systems.

6. Conclusion & Recommendations

6.1. Summary of findings

This thesis presents the design of the CAMINO payload, a small centrifuge system designed to study extremophile microorganisms under partial gravity conditions similar to those on the icy moons Europa and Enceladus. These moons were chosen because their subsurface oceans and potentially habitable environments make them key targets in the search for life beyond Earth. Understanding how microbes respond to such partial gravity conditions is essential for astrobiology.

A centrifuge was selected as the most accurate way to recreate these gravity levels. This method is one of the few that offers partial gravity simulation levels and provides significantly better control than other alternatives, making it ideal for long-term biological experiments in orbit. It also allows precise, adjustable simulation of reduced gravity inside a compact, reusable payload suitable for space.

The design features a rotating cylindrical structure that holds six sealed sample holders, a central hexagonal camera array to monitor the samples, and LED lighting around the inner wall to ensure even illumination. Magnetic coupling and bearings were proposed to reduce vibrations, which are critical to protecting experiment integrity; however, these technologies require further testing. Temperature sensors were deemed less crucial due to extremophiles' tolerance, but could be added later. Six samples balance size, wiring, and power constraints, with the possibility to increase to eight with further work.

Cost estimates indicate that this project requires a significant budget, but collaborating with commercial partners like ICE Cubes can lower barriers and make the payload more accessible to a broader range of researchers. The design aligns with ESA's payload development phases but needs additional refinement before flight.

6.2. Final assessment of feasibility and areas for improvement

While the CAMINO design is promising, several areas require further study and improvement before the payload is ready for space. The magnetic coupling and bearings require extensive testing to ensure that vibration levels remain low and stable in orbit. The lighting setup, especially the ring of LEDs, must be optimized to avoid reflections that could affect camera images. Anti-reflective coatings may help, but their effectiveness needs validation.

The system's data handling capabilities, particularly streaming six live video feeds, are challenging with the chosen microprocessor and software. This might require reducing image frequency, switching to onboard storage, or improving software performance. The attachment mechanisms for lids, both for sample holders and the external cube, need to be finalized to prevent loss or contamination in space.

Ventilation and thermal management were not fully addressed and require further study to prevent overheating. Expanding the number of samples beyond six would improve scientific output, but requires solving electrical and software constraints. Finally, the overall cost and long-term sustainability require careful management to ensure the project is financially viable.

6.3. Broader future evolution and research opportunities

Looking ahead, CAMINO's design can evolve to fit future space platforms beyond the ISS, especially as new Low Earth Orbit stations, Moon, Mars, and icy moon orbiters or landers are developed. The flexibility of the centrifuge payload makes it well-suited for integration into these next-generation facilities, enabling experiments under various gravity conditions and radiation environments.

Incorporating AI and onboard data processing could revolutionize how biological data is collected and analyzed in space, reducing the need for constant live data transmission and enabling more autonomous monitoring of experiments. Expanding CAMINO's gravity simulation capabilities to mimic those of Mars, the Moon, or other celestial bodies would open new research frontiers in space biology.

Partnerships with commercial space providers and adapting the business model to new launch and platform realities will be essential for long-term sustainability. By continuously evolving, CAMINO can become a versatile and valuable tool for astrobiology and other space life sciences for years to come.

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