Searching for (bio)chemical complexity in icy satellites, with a focus on Europa

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1. EXECUTIVE SUMMARY

Organic chemistry is ubiquitous in the Solar System. A significant repertoire of organic molecules has been detected in bodies outside the Earth (e.g., in meteorites, in cometary nuclei, on Mars or on icy moons), but none of the detected organic mixtures has enough complexity to indicate Life. There are a number of potentially habitable bodies in the solar system where water, chemical gradients and energy coexist, in particular Mars and the icy moons of the giant planets. Chemical evolution could have occurred in these bodies, and might have advanced enough to be on the cusp of forming autoreplicative and evolvable systems, or even cross the threshold to Life.

Searching for unambiguous signs of life beyond Earth is a major objective for the space science and astrobiology communities, and thus space agencies support this objective in their current programs of planetary exploration through several missions. Regrettably, the exploration of the Solar System so far has involved just one actual "search for life" mission: the Viking landers on Mars nearly 50 years ago (Klein et al., 1976). Neither the upcoming missions to Mars (ESA's ExoMars and NASA's Mars 2020) nor Europa (ESA's JUICE and NASA's Europa Clipper) or Titan (Dragonfly) are equipped with a payload capable of detecting signatures of an extant biosphere. All past and planned planetary missions that have been devoted to the detection of organics have relied on remote spectral identification or the analysis of heat-extracted, small volatile compounds. These are inefficient procedures and very often the structural integrity of the parent (bio)molecules is lost, preventing the recognition of life signatures.

We propose that in order to advance the goal of searching for evidence of life beyond Earth we must focus on the detection of large macromolecular material capable of structural and functional plasticity, as well as cell-like morphologies indicative of an extant biosphere. Here we describe this new strategy and propose a mission with the goal of revealing the different levels of prebiotic/biotic chemical and structural complexities on planets and satellites of the Solar System following a non-Earth centric approach, as well as their potential compatibility with terrestrial life. This might clarify the nature of the (bio)chemical complexity of the Solar System, both now and in the past. We prioritize Jupiter's moon Europa as the mission target due to its energetic state, activity, and the presence of liquid water and chemical elements, which all suggest it may have developed as a chemical complexity reactor. The mission emerges with the following motivating questions:

- ***Can we detect Life beyond Earth even if it is not as we know it?***
- ***What is the level of chemical complexity in the Solar System?***
- ***Could that chemical complexity be a manifestation of life?***
- ***How do planetary environments influence organic chemical evolution from prebiotic chemistry to life?***

*The mission to **Europa to find out if it can be considered a (bio)chemical reactor** imposes remarkable technological challenges, most of which have already been identified. They include issues related to radiation shielding, landing systems, communications, drilling and cryo-sampling, instrument development and new perspectives of planetary protection that deserve the attention and efforts of the planetary community.*

2. THE SCIENCE QUESTION

2.1. BASIS OF A STRATEGY TO SEARCH FOR LIFE IN THE SOLAR SYSTEM

Although a precise definition of life is still elusive, there is practical agreement on NASA's definition as "a self-sustaining chemical system capable of Darwinian evolution" (Joyce et al., 1994). Life can also be defined as a consequence of the evolution of energy and matter in the Universe (Domagal-Goldman et al., 2016). Living entities tend to be complex and highly organized, being endowed with the ability to intake matter and energy from the environment and transform it, thus allowing growth and reproduction. Therefore, two basic principles should be taken into account for defining any kind of life: (1) carbon chemistry in water-based media is the only viable option for living chemical systems, and (2) the combination of compartmentation, self-replication and metabolism is a generic requisite for all forms of life (de la Escosura et al., 2015; Ruiz-Mirazo et al., 2017) (Figure 1).

Carbon is ubiquitous in the Universe and exhibits unique capabilities to establish stable covalent bonds with other abundant elements (in particular, H, O, N, P and S), thus leading to the synthesis of millions of types of organic molecules. Water is also very abundant in the Solar System and in interstellar environments. It shows optimal performance as a solvent, plays an active role in a number of chemical reactions, offers protection against radiation, and provides a favorable environment for carbon-based chemistry to develop. Whether there are alternatives to carbon chemistry and water solvent as the universal ingredients for life has to be demonstrated (Cabrol, 2019), and would probably require geochemical environments with different physicochemical parameters (P, T, salinity, pH) where other solvent-based complex chemistries were possible. Even in such a case, this different kind of life would necessarily emerge as an increased organization level with respect to the chemistry supporting it.

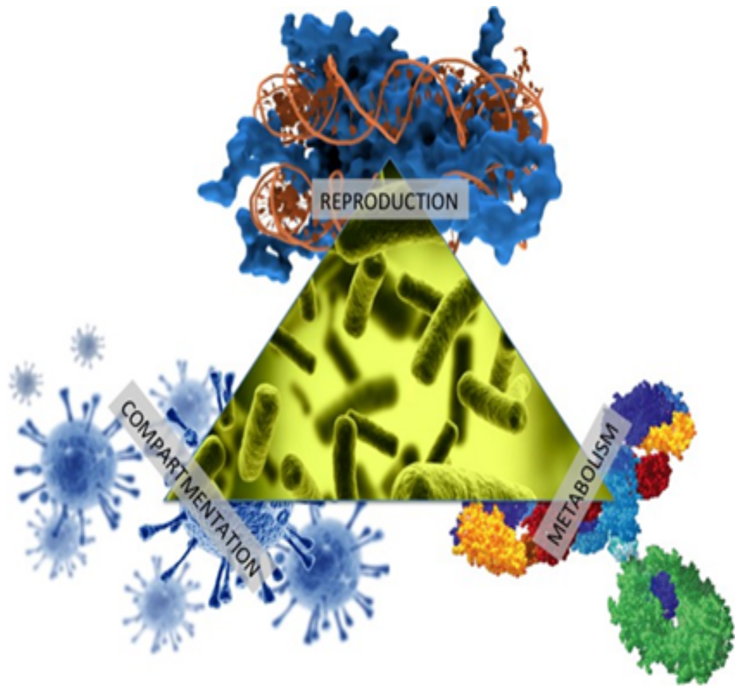

Figure 1. Although there is no consensus on the definition of life, it is commonly accepted that life is a chemical system with three features: compartmentalization, reproduction and metabolism.

Compartmentation is a process that allows concentrating chemicals into a particular niche, separated from the environment through a permanent and semi-permeable structure, which allows a far-from-equilibrium chemistry to operate inside the compartmented system. Examples of membrane-based compartments include vesicles, rods, liposomes and other cell-like structures that account for chemical organization and system individualization (Monnard and Walde, 2015). Self-reproduction of a compartmented system allows the perpetuation of almost identical features, and can be attained by complex polymers or other macromolecules showing enough conformational plasticity to allow non-covalent interactions, ligand binding and biochemical functions, eventually including self-replication (Orgel, 1992; Mansy et al., 2008). In turn, metabolism is a network of chemical reactions that allow gathering material resources and energy from the environment and transforming them to allow self-maintenance of the whole system. It requires the interconversion of a repertoire of organic molecules, which can be achieved by a complex enough prebiotic chemistry that includes catalytic species or mineral surfaces, prior to the advent of a primitive metabolism based on enzymatic activities (Peretó 2005; Ruiz-Mirazo et al., 2014). Finally, the template-based replication of an information-bearing macromolecule is also required to transmit the "blueprint of the system" to the progeny. Interestingly, the mutations and other kinds of molecular rearrangements introduced during the copying process lead to a certain degree of diversity in the offspring that will ultimately allow an open-ended evolution of the whole system (Szathmary et al., 2006; Pressman et al., 2015).

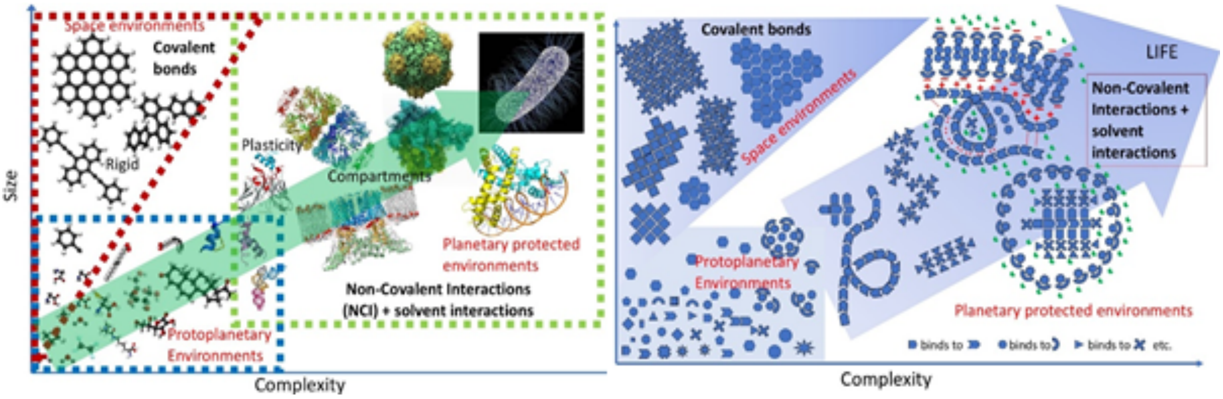

Figure 2 Size vs complexity in the molecular world leading to life. Left: The case for terrestrial life. Red triangle: Harsh space environments only permit simple, highly radiation–resistant molecules, as well as rigid poly-aromatic hydrocarbon structures. Blue rectangle: mild proto-planetary and unprotected planetary environments favor the formation and stabilization (i.e., the acquisition of a longer half-life) of biomolecules, thus increasing the complexity of the available chemical repertoire. Green rectangle: more protected and stable environments of planets or satellites allow the formation and stabilization of homo- and heteropolymers, whose 3D structure in solution, based on non-covalent interactions, confers upon them conformational plasticity and functional capabilities. This can allow the systems to undergo self-assembly and self-organization processes, including those leading to the formation of the compartments required for life. Right: The suggested case for a "generic life" involving other biomolecules that might be stable and chemically functional under different physicochemical conditions.

In terrestrial biochemistry, polymers of this kind include peptides and proteins, nucleic acids (ribonucleic acid, RNA, and deoxyribonucleic acid, DNA) or oligosaccharides. Polymeric macromolecules allow the exploration of a new chemical space, based on non-covalent, supramolecular interactions that include hydrogen bonds, Van der Waals forces, and electrostatic and hydrophobic interactions (Lehn, 1995). On Earth, polymers such as proteins and RNA add new properties to the chemistry of their monomers: they are flexible; they can fold and unfold based on the physicochemical features of the environment (including T, pH, ionic strength and concentration of divalent cations); they can even behave as charged polyelectrolytes; they can adopt alternative conformations as a function of the intramolecular network of weak interactions available; they can interact with other polymers (of either the same or different kind) to form macromolecular assemblies; and they can create new microenvironments that allow (bio)chemical reactions to take place by lowering the required activation energy (that is, they can become catalysts) (Benner, 2017). Therefore, polymerization of the building blocks provided by prebiotic chemistry allows the synthesis of macromolecules endowed with conformational plasticity that can interact with each other to form new structures and compartments which, in turn, allows establishment of the biochemical networks that are required for life to originate and evolve.

Planetary environments of ocean worlds can allow, in principle, chemical systems to increase in complexity regarding the molecular size, structure and functionality of the molecules, and potentially increase the number of interactions established among the individual components (Cockell et al., 2016). The search for extraterrestrial life is based on the assumption that its underlying biochemistry may be different from what we know on Earth. Thus, detection of signs of life that may be present in favorable environments in the Solar System is still an open question (Cabrol, 2018). It is relatively straightforward to detect and recognize terrestrial life (e.g., in extreme environments on our planet) because we already know its main molecular features. Therefore, the identification on other planets or satellites of any metabolite or structural component equal to those produced by living beings on Earth would be considered as compelling evidence of life. Fossil versions thereof may also be preserved in the geological history of a planet or satellite, with recognizable cell-like morphologies or other features of potential biogenicity (Hays et al., 2017; Neveu et al., 2018; but see also Van Kranendonk et al., 2019). Nonetheless, caution must be applied as certain "abiotic biomorphs" can be chemically formed in the absence of any biological process (Rouillard et al., 2018). However, it might be extremely difficult to recognize truly alien life even with state-of-the-art equipment, from which arises another set of critical questions:

- **How might we recognize other self-sustaining chemical systems capable of Darwinian evolution if their biochemistry is different from that of terrestrial life?**
- **Is there any generic physicochemical feature or set of features we can detect and measure that could shed light on its potential biogenicity?**
- **How difficult is such a task using only remote exploration on other planets and moons?**

2.2 THE SEARCH FOR COMPLEXITY

Astronomical observations and analysis of meteoritic and cometary materials reveal a common chemistry throughout the universe (Sephton and Botta 2008). Multiple and relatively large organic molecules have been detected even in interstellar space (Sewilo et al. 2018). Thus, protoplanetary disks are revealed as the substrates harboring key chemical reactions that eventually supply planets with a more or less complex primary chemistry. A multitude of proto-planetary environments would allow multiple opportunities for activating this chemistry and, perhaps, enable multiple trials for prebiotic chemistries at different evolutionary levels, both spatial and temporal. Asteroids and comets could be frozen vestiges of prebiotic reactions in the Solar System (Fayolle et al. 2017). As planets form in a given solar system, a diversity of bodies with varied sizes, compositions, and chemical complexities complexity could be generated. Planetary bodies offer mild conditions that allow simple chemicals originated in the interstellar dust to react and create stable polymers which, in turn, may adopt different types of folding (intramolecular interactions) and different kinds of interactions with other polymers. One class of such bodies are those with a size and mass large enough to create warm internal water reservoirs as a kind of precursor to ocean worlds.

The commonly accepted approach of future planned exploration missions of our Solar System involves searching for biosignatures as a combination of fundamental biological properties connected to the environment, including chemical disequilibria, distribution patterns of structurally related compounds, isotopic signatures of the dominance of catalysis in biochemistry, concentration of chemical monomers that are dictated by adaptability and utility (e.g. amino acid type, enantiomeric excess or presence of lipids, among others) (Neveu et al., 2018). We here propose that the exploration focus should switch to the identification and characterization of the eventual (bio)chemical complexity developed on the planet or satellite under study, using a non-Earth-centric approach, while also allowing the detection of different biomonomers, biopolymers and cell-like structures that are common to all known terrestrial life. Being capable of detecting this broader set of levels of chemical organization and complexity, it will be possible to infer a highly advanced and mature prebiotic chemistry or even active biochemistry operating in an extraterrestrial environment.

In a hypothetical mission designed to search for generic features of life, we propose attempting to answer the following overarching science question (Table 1):

What is the (bio)chemical evolution level that has been achieved in the Solar System, outside of Earth?

To address this question, the mission has to search for:

- Signs of higher-order organization and/or compartmentation of chemical systems.
- Complex carbon-based chemistry and signs of potential conformational plasticity of polymeric molecules based on non-covalent interactions.
- Biomolecules to compare with those of terrestrial-life.

These goals can be addressed by identifying several key parameters:

- Morphologies compatible with potentially compartmented biochemical systems, which can be recognized by optical microscopic techniques.
- Covalent bonds between carbon and other elements (C-C, C-H, C-N, C=O), and intramolecular, non-covalent forces (hydrophobic interactions, hydrogen bonds, Van der Waals forces, electrostatic interactions).
- Molecules and chemical structures belonging to the Complex Prebiotic Chemistry (CPC) or Complex Bio-Chemistry (CBC) stages.

SCIENCE QUESTION 2050	OBJECTIVE	INVESTIGATION	OBSERVABLES	MISSION
WHAT IS THE CHEMICAL COMPLEXITY IN THE SOLAR SYSTEM	Determine the inventory of diverse organic chemistry	Measure the composition of the materials that show evidence of connections with the liquid water reservoirs, from the subsurface to the liquid layers	Spectral signatures of pristine samples in endogenic geologic settings	To: **EUROPA** ENCELADUS TITAN MARS CERES
	Search for complex macromolecules capable of conformational plasticity	Recognize polymers with high level of structural complexity that exhibit weak bonds	(Bio)chemical affinity Spectral signatures of weak bonds	Contact with unaltered samples is needed
	Detect organization/ compartmentation features	Identify patterns that suggest any kind of organic matter organization	Microscopic structures	

Table 1 Traceability matrix of the mission to discover the chemical complexity in the Solar System

3. THE SPACE MISSION STRATEGY

3.1 MISSION DESTINATION: EUROPA

The ocean worlds of the Solar System are recommended targets for the coming astrobiological exploration era because they have current or relic liquid water reservoirs. Special attention is applied to those showing evidence of having energy to both maintain the aqueous environment through time and to promote interactions between the water and silicate layers. Thus, they might have developed a (bio)chemical reactor, so would therefore answer the science question we propose.

When considering the celestial objects that could be active as (bio)chemical reactors, early Mars was the most similar to Earth early in its history. Furthermore, nearing the frost line, an ancient water ocean could have been present within Ceres in contact with a hot core, where (bio)chemical evolution was potentially feasible, based on recent observations from the Dawn mission (Nathues et al. 2015). Beyond Jupiter, there are many moons with large volumes of liquid water in their interiors. Unfortunately, the level of knowledge we have of most of them is scarce due to the very few missions that have explored them. Europa and Enceladus stand out as encouraging destinations to search for life since they achieve the bio(chemical) reactor requisites, and show features that highlight the link between the ocean and the surface.

Europa is the closer, most promising object in the Solar System that may host an ecosystem irrelative to terrestrial life at present. The seafloor could include a hydrothermally active rock basement providing energy and a plethora of chemical species to the potential organic reactor (Schulze-Makuch. and Irwin 2002, Irwin and Schulze-Makuch 2003, Lowell and DuBose, 2005). The internal aqueous ocean is protected against damaging surface radiation by a water ice crust. This is highly affected by active ice tectonics, and the material ascending facilitates exchanges between layers at different depths, as well as continuous cycling of chemicals. Recently, evidence of plume ejecting materials have been detected (Roth et al. 2014, Jia et al., 2018). Previous missions to the jovian system have shown that the surface composition of Europa is dominated by water ice plus other dark albedo materials, identified as hydrated salts (Carlson et al., 1999; McCord et al., 1999, Dalton et al. 2005, Trumbo et al 2019). These salts are associated with tectonic and cryovolcanic features, suggesting that they have a subsurface origin linked to aqueous reservoirs. Endogenic materials are strongly affected by the surface radiation environment (Dalton et al. 2013, Hand and Carlson 2015). Moreover, some volatiles are detected (e.g., CO_2, H_2S, SO_2) as ice phases mixed with water ice, trapped as inclusions between crystals, or forming hydrate clathrates (Prieto-Ballesteros et al. 2005). There are three recognized terrestrial analogs that are considered as good locations in which to better understand the geochemistry and potential habitability of Europa: aphotic systems, deep cold brines, and subglacial liquid-water environments (Painter et al., 1982). Additional laboratory experiments and field work are required to better anticipate and understand what we can find on Europa. This research will allow us to determine different levels of prebiotic/biotic chemical and structural complexity, using aqueous solutions that resemble the melted endogenous materials enriched in varying concentrations of sulfates, sulfuric acid, and chlorides, and also which may be doped with different concentrations of the target biomolecules to be detected (e.g., antibiotics, peptides, proteins, lipids or whole cells).

Studies on selected Mars (Fairén et al., 2010) and Europa (Prieto-Ballesteros et al., 2003; Lorenz et al., 2011) analogs on Earth show that, generally, in extreme environments we should expect chemolithotrophic metabolisms and a very low biomass of cells, which are in most cases also very small in size. This is so because the stability and functionality of the biomolecules of most organisms (and, thus, their viability) are strongly affected by extreme physico-chemical parameters like acidity and redox state. Therefore, the sensitivity of astrobiology-dedicated instruments must be high enough to guarantee the detection of a limited number of cell-like morphologies as well as low concentrations of biomolecules. In any case, additional work on terrestrial analogs deploying instrument suites is critical to better understand what kind of morphological and biochemical diversity could be expected on other planets and moons of the Solar System.

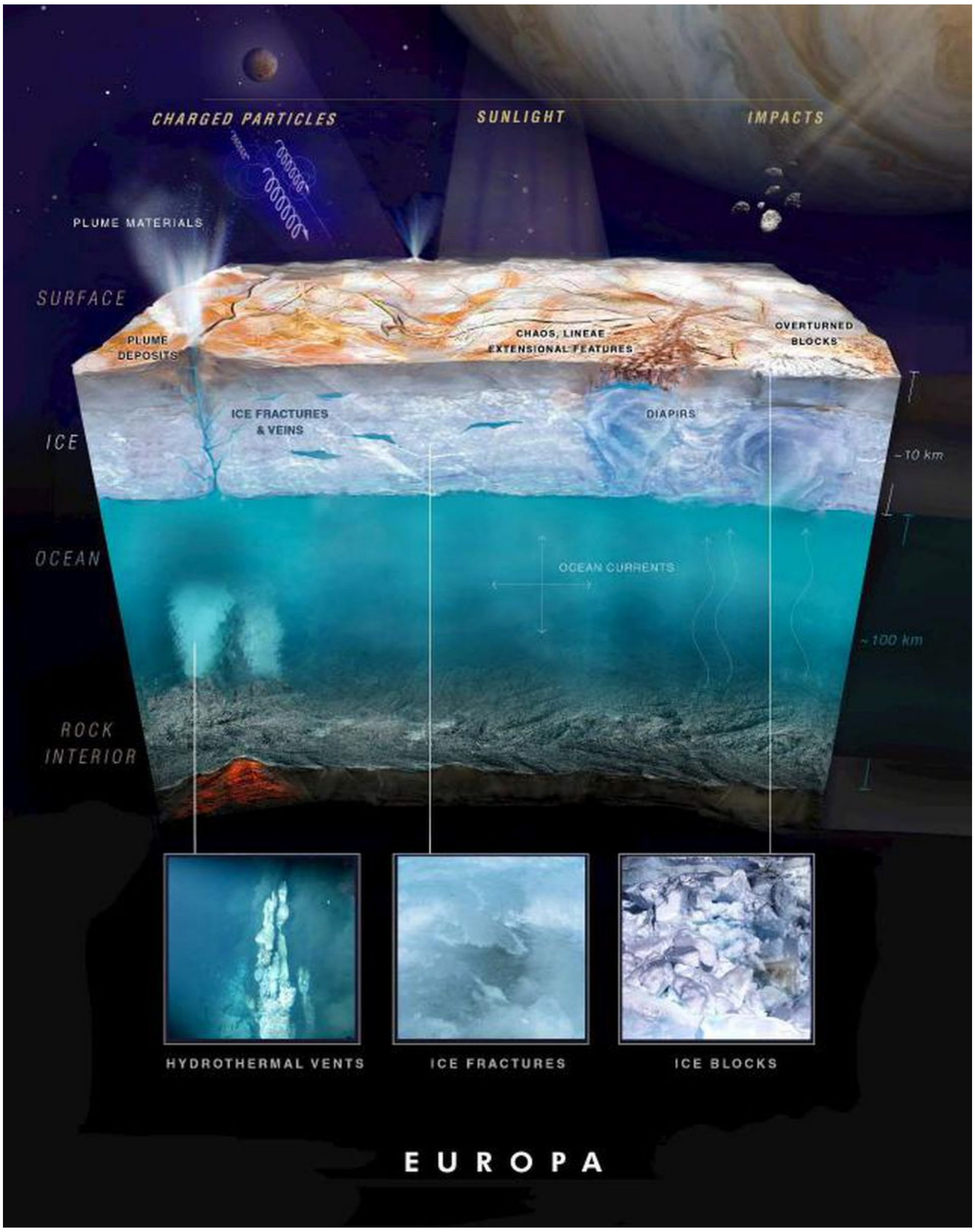

Figure 3 Artist impression of the internal structure of Europa. The interaction between the silicate mantle and the liquid water ocean may promote the evolution of the organic chemistry. Credits: NASA/JPL-Caltech

Recently, Sherwood et al. (2018) proposed that future exploration of the ocean worlds should occur in steps with increasing risks and technological challenges, including the return of samples from different layers: 0) Europa Clipper and JUICE will map and characterize the surface, providing arguments for future landed missions; 1) access the endogenous material deposited near and on the surface of confirmed ocean-surface exchange zones where future missions could land; 2) explore the diverse material composition and the local geology of the exchange site using some mobility capacity; 3) subsurface access in search of more pristine materials; 4) examination of samples from such sites in terrestrial laboratories, i.e. sample return; 5) deep access, i.e. drilling the ice shell into the ocean below, for in situ sampling and/or sample acquisition for return; 7) under-ice exploration of the top of the ocean; and 8) submarine exploration of the open ocean including potential seafloor hydrothermal activity.

3.1.1 Main elements of the mission

To find answers to the posed scientific questions, contact with and analysis of samples is required. Thus, we propose a program of in situ Europa missions based on four elements: orbiter, lander, jumper and ocean explorer.

In the mission program, some elements are essential for determining geological and geochemical context. However, we give more emphasis to those related to the scientific questions proposed.

Europa orbiter (EO)

Europa orbiter science will provide global geophysical information of the moon. Information about chemical composition, topography, ice crust characteristic (thickness and morphology) and all the data required to confirm a landing place for the Europa Lander will be collected, as well as determining the zone of interest for a number of jumpers.

The EO should be a highly radiation-tolerant spacecraft that will be the carrier of the lander and jumpers. It will have an instrumentation payload for the remote observation of the surface, as well as ground penetrating radar for collecting data of the deep subsurface. Also, it will act as a repeater for data transmission from the surface to the Earth. A polar orbit will allow visitation of most of Europa's surface.

Europa Lander (EL)

The Europa Lander (EL) and the Ocean Explorer will be in charge of collecting data addressing the core scientific questions, and thus the EL will need to explore the surface and subsurface, and be capable of deploying a probe to explore the subsurface ocean.

The EL will be part of the Europa Lander Module (ELM), which will constitute the Descent Module and the EL itself. Once the landing site is selected, the ELM separates from the orbiter and starts a descent trajectory controlled by a propulsion system and guided in its last stage by radar and an autonomous system for landing site selection based on images captured during the descent. At a few meters above the surface, the EL separates from the ELM and touches down, controlled by thrusters activated with inert gas. To avoid surface contamination by the propulsion gases of the ELM, the ELM will land far enough away to avoid any perturbation to the EL.

Once the Lander has verified its initiation status and commissioning phase, the mission will start with its threefold objective: surface recognition, subsurface sample analysis and deep drilling (Ocean Explorer). The EL will have three elements: a deployable mast, a robotic arm and a drill system. The mast will have cameras and remote spectrometers. The robotic arm will be equipped with a sampler for taking several ice samples. The instrument payload is protected from radiation by the lander body. The deep drill could be based on heat drilling with an element composed of two parts: drill bit and the Ocean Explorer.

One possible configuration of the lander is: a central structure to protect all key electronics, and legs to isolate from ice and stabilize the lander, a propulsion module for the last phase of the landing; a communications unit to link with the orbiter; a power unit based on solar panels or more likely on some kind of RTG; a mast with an actuator for deployment; a robotic arm with at least four degrees of freedom; and the drill system. Part of the payload is situated inside the central structure for radiation isolation and to maintain a temperature-controlled environment under operational conditions.

Europa jumper (EJ)

The goal of the jumpers will be to undertake geochemical and geological reconnaissance of the context around the lander at a local scale. Jumpers will not include their own descent modules, but will be ejected from the ELM along its trajectory and will have to survive the impact. Each one will analyze the physicochemical properties of the local ice, taking some images during descent. Once the jumpers end their analytical phase, they will be kept active to record potential seismic signals.

Jumpers will be ejected from the lander to a distance of several meters. Jumpers will maintain power and communication links by umbilical cables. They will be capable of making short jumps in order to explore different spots.

Europa Ocean Explorer (EOEx)

Exploration of the ocean with a submersible module is required to have access to direct samples of the (bio)chemical reactor. It implies a remarkable technological challenge, which would be preceded by the development of a descending probe to allow reaching the upper part of the sub-ice liquid water ocean.

Once the drill bit is in contact with the liquid water ocean, the EOEx will delivered. The EOEx will include a wire-controlled unit to communicate with the lander. The EOEx should be equipped with microsensors to measure the physicochemical properties of the water and microspectrometers to evaluate its level of chemical complexity, performing analysis every several meters to evaluate temperature variations and chemical gradients. A microcamera recording images will help to understand the environment. A microsampling system will also be part of the unit. Also, the development of new sensors based on a multiparameter configuration to analyze the environmental geochemistry by means of wet chemistry is envisaged (similar to Kounaves et al. 2009).

3.1.2 Exploration of the plumes

The plume activity detected to be emerging from moons such as Europa, Enceladus, or Triton, facilitate access to materials derived from deep layers. The architecture for a mission just to investigate the (bio)chemical complexity of the ejecting material would perfectly apply to Enceladus, where this process seems to be relatively continuous at present. The concept is that the EO would have the capability to modify its orbit once a geyser is detected, and make fly-bys at different heights collecting particles (perhaps of organic nature) for analysis with appropriate instrumentation, which could be similar to those implemented in the EL, as detailed in section 4.5.

3.2 THE MISSION IN A WORLDWIDE CONTEXT

A mission to Europa has already been considered a priority in the past programs of the main space agencies (e.g. Cosmic Vision 2015-2025 and Planetary Decadal Survey 2013-2022). To be launched in the 2020's, JUICE and the Europa Clipper will start to characterize Europa's habitable environments, performing investigations on habitability from several flybys.

Following program recommendations, Europa missions with orbiters and landers have been analyzed and proposed in several ESA calls (e.g. EJSM-Laplace -L1, JEM -M5). Nevertheless, a compelling answer to questions about life requires dedicated missions and instruments that are not implemented yet, so objectives regarding the search for life have been postponed.

Although the Europa lander was not included in the last NASA decadal survey program, in 2017, the NASA Europa lander study report was published (Hand et al. 2017). The report shows that NASA lander science is focused on looking for signs of life in the icy surface material of Jupiter's moon Europa. Three main goals are proposed for the mission to be launched in 2025: 1) Search for evidence of life, 2) assess the habitability of Europa via in situ techniques, and 3) characterize the surface and subsurface to enable future robotic exploration. The mission would complement the objectives of Europa Clipper and JUICE missions, providing local information from the ground. At present, the NASA lander mission is still under study, having funding for continuing concept studies.

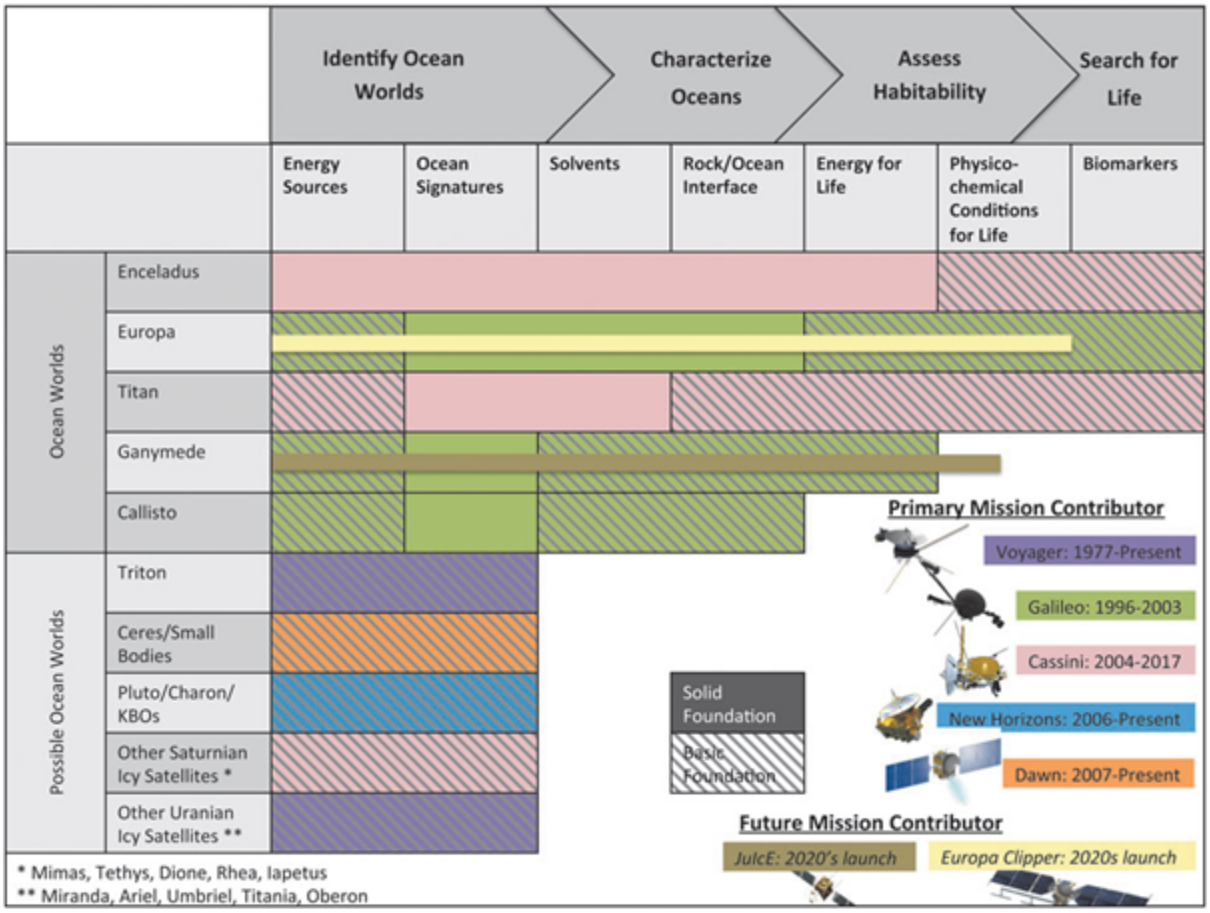

Figure 4. Ocean worlds roadmap (Hendrix et al 2019). The solid color or hatched areas for each mission represents the evaluation on how well each target is understood regarding the science objectives, solidly or basic respectively.

Since the planetary science community is highly sensitive to the importance of ocean world exploration for understanding the distribution of life in the Solar System, a roadmap has recently been developed and published (Hendrix et al. 2019). Confirmed ocean worlds from geophysical measurements are Europa, Enceladus, Titan, Ganymede, and Callisto. The document maintains that all ocean worlds are potential targets; however, the question of whether some ocean worlds are better suited to have developed chemical complexity than others emerges.

Given the dimensions of the mission program proposed herein, international collaboration is demanded. Such collaborations in the past, like the Cassini-Huygens mission, have been very successful and provide enormous benefits to the planetary community.

4. TECHNOLOGICAL CHALLENGES

The Europa mission program, by its complexity, has plenty of technological challenges in all the orbiter, lander and jumper components, as well as in the instruments payload. For this reason, if the main elements fly at the same time, we believe the mission should be framed as a L-type mission.

4.1 Europa Orbiter

JUICE and Europa Clipper will explore Europa (JUNO for only part of its mission) in the coming years, and therefore the lessons that will be learned in terms of environmental conditions (radiation) and operation could be leveraged for future missions. But we advance here that the main issue is to survive the large radiation levels existing in the Europa space environment. Electronics capable of surviving this challenge will need to be developed.

Some heritage from past missions (e.g. Cassini-Huygens as an example of orbiter-lander separation, and Moon missions and examples of landing in low gravity bodies) can help mitigate the risk associated to the landing

4.2 Europa Lander

The Europa Lander is very challenging from a technological point of view, with a long list of risky areas such as:

- Landing. Due to the complexity of the mission, a heavy system should be delivered over a likely rough surface. This has been accomplished in the past on the Moon, but in this case the level of autonomy should be absolute (like on Mars) but perhaps with a lower level of terrain knowledge.
- Power. The mission could last several months, and the Jupiter system is very far from the Sun; therefore, solar panels are not a realistic option. An RTG power system seems to be the best solution.
- Mass. A large effort in miniaturization should drive the design of all subsystems, both to optimize mass and to allow better protection from radiation.

- Radiation and low temperatures. All electronics and electromechanical components should work in an extremely difficult environment, out of the space standards. Materials, components and processes should be selected to be operative under such conditions.

- Planetary protection. Due to the goal of the mission, the level of chemical and biological cleanliness should be quite high and with a very good knowledge of the potential contaminants.

- Validation. Special facilities should be developed for testing in Europa-like conditions.

4.3 Europa Ocean Explorer

While landers have been successfully deployed in the past in Moon, Mars, Venus and Titan missions, the Ocean Explorer would be a pioneer spacecraft: nothing similar has been done before in space or in Earth studies, and therefore plenty of technological challenges await, such as:

- Drilling system. It looks like an electromechanical system is not a good option due to the hardness of the ice at Europa temperatures. Thermic drilling appears to be a more promising option. But there are a number of associated problems to ponder, including keeping the borehole open at a distance of up to kilometers.

- Drilling guidance. The borehole should be orthogonal to the surface, otherwise it would be impossible to find liquid water.

- Communications. The link between the drill bit and the lander should be kept open. Wired communications appear more realistic but for long distances could be a problem. For example, wire-guided missiles that can hit a target in the range of several kilometers is one type of possible technology.

- Sampling. EOEx will require a microfluidic system for taking a water sample, circulating it through all instrumentation and pumping it out at the end of the process.

- Power. A power line will be needed during drilling and water exploration. The main issue is the distance, but also the cable jacket should be manufactured with a material able to avoid sticking to the borehole wall ice.

- Borehole delta pressure. If the borehole is maintained open at the moment of contact with the target water, the different pressures between the open-space surface and the liquid water ocean may trigger the formation of a water jet, a geyser. That event could be catastrophic for the probe; therefore a drilling process should be designed to avoid this delta pressure at the end of the drilling phase.

- Instrument miniaturization. A large effort for volume, power and mass reduction will be required for the instrument inside the Ocean Explorer, as well as for operability at low temperatures. Conversely, radiation is not expected to be a problem beneath the ice.

4.4 Europa Jumper

In the past, some impactor and penetrators prototypes (Gowen et al. 2011) have been developed for Mars, the Moon and even for Europa. In addition to this heritage, it will be necessary for specific designs to adapt the jumper to surface conditions and also to the specific payload for Europa. To maintain a minimum operability, power management is quite important as well as communications. As in the case of the EJ, a large effort in miniaturization should be undertaken in the jumper design.

4.5 Key instrumentation

In addition to the instrumentation required for analysis of geological and geochemical context (i.e., camera, infrared spectrometers, magnetometer, wet chemistry), some other instruments will constitute the very core of the investigation proposed. We have identified these key instruments below (see Fairén et al., 2019; Fairén et. al. submitted).

Microscope

The microscope should be able to detect structures that are 0.5 microns in diameter or larger, based on cell-size distribution of microbial life in Earth's ocean and polar brines that show a range between 0.2 and 3 microns. This size of 0.5 microns is also the average diameter of Ross Sea bacteria and archaea sizes (La Ferla et al., 2015). Nonetheless, it should be noted that ultra-small cells have been reported in Antarctic lakes as a result of environmental stress or life cycle-related conditions (Kuhn et al., 2014).

The main goal would be to collect as much information as possible from the images of the sample, ideally with infinite resolution and contrast sensitivity. Limitations are self-evident, especially for an instrument in space, as performance comes at a cost with respect to complexity and size. Furthermore, augmenting the instrument imaging resolution may not be sufficient, as information on chemical composition, growth or dynamics would be necessary for a more definitive conclusion on the detection of life. In this context, the main performance requirements for the microscope would be to be able to provide information on size, shape and mobility of the detected particulates.

Raman Spectrometer

A Raman Spectrometer in the range of 15-1800 cm-1 can detect signatures of organic molecules of different sizes and complexities, including the presence of non-covalent bonds in biopolymers and their aggregates. Within this range, Raman can detect bands depending on inter- and intra-molecular effects, and therefore primary, secondary and even tertiary polymer structures could be detected. A reference is the spectrometer developed for ExoMars (Rull, 2017).

Complex molecules detector

The goal of a biomarker detector would be to screen for chemical structures such as prebiotic universal molecules and others that are equal or highly similar to molecular biomarkers from terrestrial-like life (Johnson et al. 2018). The SOLID concept (Parro et al., 2011) is a good example of an instrument proposed to detect non-volatile and large complex organic molecules, either free or as part of supra-macromolecular structures (vesicles, membranes, nano-micro particles) in liquid suspensions. With the SOLID concept, a set of up to 200 molecular probes (antibodies + aptamers) can interrogate for the presence of a similar number of compounds including prebiotic molecules, biochemical, and microbial markers.

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