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Potential habitability of the Jupiter system: deep aqueous environments in Europa, Ganymede and Callisto

O. Prieto-Ballesteros[1], L. J. Bonales[1,2], and V. Muñoz-Iglesias[1,2]

[1] Centro de Astrobiología INTA-CSIC. Ctra. Ajalvir km. 4. Torrejón de Ardoz, 28850 Madrid. Spain
[2] Facultad de Químicas. Universidad Complutense de Madrid. 28040 Madrid. Spain

Abstract

The three large icy satellites of the Jupiter system, Europa, Ganymede and Callisto have different geophysical and geological characteristics but in common the possible presence of an internal ocean. The confirmation of the existence of deep aqueous reservoirs and their physical characterization are critical actions to find out if there are habitable environments in these satellites. A comparative study of these three bodies will be performed by the JUICE (Jupiter and Icy Moons Explorer) space mission in the near future. It will be key to evaluate the parameters, apart from the liquid water, that restrict the potential habitability in this planetary system and in the Universe. Once the habitability is ratified, the exploration of these icy moons should go further to search for biosignatures and life.

1 Introduction

The presence of liquid water in a planet has been related to the existence of life since 50s, when the early discussions about the regions in the Universe where life could exist were published. The concept of planetary habitability has evolved since then, but the importance of liquid water is kept as one of the essential parameters for life. The precise meaning of habitability varies depending on the point of view of each scientific discipline. Classically, astronomers have used the term to identify the zone around a star where liquid water is possible to exist on the surface of a planet as a result of direct solar heating. Consequently, icy satellites like Europa, Enceladus or Ganymede that have liquid water oceans due to the tidal heating of the moon, lie far outside the habitable zone. Actually, the discovery of global oceans inside icy satellites has expanded the astronomical concept of habitability to deep environments. On the other hand, for biologists, habitability is referred to the set of conditions necessary to life existence in an active form. Astrobiology has adapted these two perceptions, concluding that habitability implies a general analysis directed toward determining whether an environment appears to provide what life requires. So, it is accepted that the habitable planetary environments are those which permit the formation, develop, and the evolution of life.

The concept of habitability is based in the only life that we know that is from our planet. Moreover, terrestrial life is used to extract the common features and basic elements essential for the organisms, and to determine the physical chemical limits for the life. Thus, when we look for planetary habitability, we are taking into account the minimal requirements established for terrestrial life, including those observed in extreme environments, and arguing similar conditions for other planets in order to become them habitable. Ultimately, there are four broad requirements for habitability:

- Liquid water. The biological affinity for this liquid is due to its intrinsic properties. The main one is that the substance is in the liquid phase in the appropriate range in which many of the reactions associated to life occur. This makes that it may function as a reactant substance, be used as a solvent medium, be an efficient medium for transportation, control the temperature changes, and other utilities for life. In addition, it has the advantage of its abundance in the Universe.
- Building block chemical elements for life, such as carbon, hydrogen, nitrogen, phosphorous and sulfur, in addition to ions like sodium, magnesium, potassium, calcium, iron, manganese, cobalt or copper, that are major elements for life [17]. These elements can be taken from minerals of the rock fraction of the planet (e.g. silicates, carbonates, sulfides). The organisms may use them in structural macromolecules or to produce energy as in electron transfer chains.
- Energy for maintaining the metabolism. The usual processes for cellular metabolism in terrestrial environments are respiration, fermentation and phototrophy, which use chemicals or light as sources of energy. Organisms living in deep environments, where light is prohibited, may obtain the energy from alternative sources such as the geothermal flux, tides, or disequilibrium chemistry [16].
- Time. The above-cited conditions should be maintained during appropriated periods of time to let the potentially habitable system evolve, including the complex chemistry.

The assessment of the habitability of some bodies of the outer Solar System is prioritized in the road maps of the main space agencies around the world. Search for deep habitable environments and their characterization are goals for the space missions of the near future. Nevertheless, the presence of the habitable conditions does not imply that the environment is inhabited. The conclusive detection of life elsewhere in the Universe is difficult to achieve. From the experience of the Mars's exploration we have learnt that in situ observations are needed in order to have more probability to find any biosignature. In addition, the detection of more than one biosignature is needed to be conclusive in the results. Our improving understanding about the life from terrestrial extreme environments helps us to determine what could be used as a reliable biosignature and as a specific and definite biomarker. Searching of life includes the development of new technology capable to work in the utmost conditions of the surface/subsurface of the icy satellites (e.g. under strong radiation in the surface or high pressure at deep).

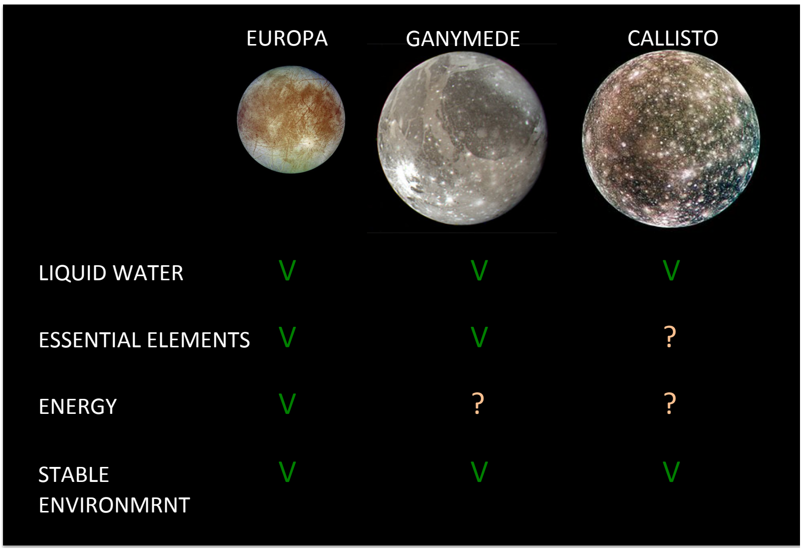
JUICE will be the next mission to visit the Jupiter system. This mission, led by the European Space Agency, will have two main goals: 1) to determine the appearance of habitable worlds around the giant planets and 2) study the Jupiter system as archetype of an extrasolar gas giant system [3]. The combination of the proposed instrumentation for JUICE (e.g. radar sensor, VIS-IR spectrometers, magnetometers) will allow characterizing the deep environments. It will be the beginning of the astrobiological exploration of the outer Solar System.

2 The astrobiological scenario of the Galilean satellites that is known at present

The deep aqueous environments of the icy satellites are hidden to most of the remote sensing instruments used in the space exploration performed until now. The study of the surfaces of the moons complimented with some geophysical measurements of their interiors has shown enough indications of the presence of some potentially habitable environments in icy satellites of the Solar System. Using these observations, the simulation experiments and theoretical models may also provide some insights about the chemistry of the unrevealed aqueous systems. The direct astrobiological characterization will have to wait to the future space missions coming.

The information that we have about the Jupiter system mainly comes from the space missions Voyager and Galileo, which were launched in the late 70s and 80s respectively. Remote sensing data from these missions revealed that the Jupiter system may be considered as a mini solar system in some ways, where several characteristics depend on the distant to the giant planet. In fact, there are some gradients that decrease from the inner to the outer system: the radiation flux, the proportion of rock of the orbiting bodies, or the geological activity. The occurrence of geological structures on the surface is symptomatic of the accumulated energy inside the satellite, which is in part produced by the tidal forces and is maximum near Jupiter. From the four Galilean satellites, Europa, Ganymede and Callisto are considered as icy objects because water ice is the main composition of their crusts. All the three seem to have developed environments at depth that achieve some of the requisites of habitability already discussed in the introduction section (liquid water, essential elements, energy and stability). They show evidences to harbour global aqueous oceans below the icy crusts, but each one has different physical, chemical and geological characteristics which balance their respective scenario of habitability (Fig. 1).

Europa is the icy satellite with higher density of the Solar System. Geophysical measurements have evidenced that it has a differentiated structure in several layers, which include a metallic core, a silicate mantle and a water-rich crust. The melting and movement of the inner materials is promoted by the energy of the body. The liberation of this energy has also



	EUROPA	GANYMEDE	CALLISTO
LIQUID WATER	V	V	V
ESSENTIAL ELEMENTS	V	V	?
ENERGY	V	?	?
STABLE ENVIRONMRNT	V	V	V

Figure 1: Ranking of the parameters of habitability for the Galilean satellites at present. The V symbol in green indicates high probability for the parameter to be present in the moon. The question mark in orange means moderate probability for the parameter to be present. Modified from [3]

generated the geological features observed on the surface, like fractures, chaotic terrains or the particular lenticulae areas. The resurfacing has occurred until recent times or may be happening at present, taking into account the crater counting analysis [18]. The remote spectroscopy at the Galileo's resolution has revealed that the surface composition is dominated by bright water ice and dark materials, which are a combination of hydrated salts, mainly sulfates of magnesium and sodium, and hydrates of sulfuric acid [9, 2]. These materials are often associated to tectonic/cryomagmatic features, which indicate their possible endogenous origin [10]. It has been hypothesized that a liquid water layer is currently in contact with the rocky mantle. This scenario produces the key difference with respect the other satellites that also have global internal oceans. The rocky substrate is probably geothermally active, which stimulates the interaction between water and minerals, and could provide both the nutrients and chemical energy sources to support the habitability of Europa. The environment would be similar than the terrestrial sea floor, which is an environment biologically exuberant. Actually, terrestrial hydrothermal systems have been proposed as relevant analogues to Europa environments.

The scenarios that we recognize concerning the liquid water reservoirs are different in Ganymede and Callisto than in Europa. The magnetic signatures induced by the oceans indicate that the liquid layer is present in all the satellites, and that they contain electrolytic ions. However, the larger satellites have the ocean sandwiched between solid water ice at different crystal phases. Internal differentiation is significant in Ganymede, which has the metallic core, the silicate mantle and the water layer separated as Europa. In Callisto, although an aqueous layer has been predicted, the differentiation state is still under discussion.

Presumably, the source of the oceanic solutes of the larger satellites is also the rocky fraction, as in Europa. Nevertheless, this enrichment would had happened during a period when the state of the interior was less differentiated or by rising melted plumes from the interface rock-water produced during pulses of heat. In addition to the induced magnetic signature, Ganymede also has an intrinsic magnetic field. This is unusual for icy satellites, which makes that the magnetospheric interaction between Ganymede and Jupiter be unique in the Solar System. The chemistry observed by Galileo of the surfaces of both giant satellites is mainly composed by water ice, carbon dioxide and sulfur dioxide ices, and some amounts of silicates and organic materials. The salt hydrates are also present in the surface of Ganymede. Although an oceanic origin has also been proposed for these salts [10], links between the liquid layer and the surface are not obvious because the current thickness of the crust is too much and the cryovolcanic features are infrequent. However, resurfacing has occurred by faulting presumably during periods of high tidal flexing activity and heating, which resulted in the visible dichotomy of dark and bright terrains. During those heating periods the mentioned rise of deep melt plumes into the Ganymedes ocean [1] may also be produced. On the other side, the resurfacing in Callisto is scarce, being its surface the oldest among the Galileans.

We still do not have any direct evidence of the current characteristics of the liquids at depth, nor how they have evolved to the current planetary scenarios described above that are potentially habitable. Both, laboratory experiments and modeling of cryomagmatic processes may provide some clues. The study of the cryomagmatism is highly relevant to Astrobiology because it includes all the processes that happen to the water-rich systems in the icy moons (e.g. chemical, dynamical). Thus, some possible situations for the aqueous reservoirs may be envisaged from this study: 1) the aqueous environment could be stored as a stagnant layer, or 2) it could be heated from interior sources promoting its convection, or 3) it could change their structural level taking advantage of fractures in the crust. The result is that there might be more aqueous layers in the crust, apart from the global ocean [15]. In some favorable situations, the liquids may react with the solid layers (with silicates in the case of the Europa's seafloor, or with ices if warm liquids are formed by partial melting of the crust or have been moved to this layer from deeper reservoirs). They also may interact with other liquids in the same manner that magmas may mix in the Earth. In the case of Europa, it is possible that this activity has been maintained until now. The aqueous cryomagmas may crystallize in situ, or during its movement, and this process may occur by fractional precipitation in a magma chamber or by flash frozen in the surface [12]. Anyway, the chemical composition of the liquid solution, including the concentration in essential elements for life, will be the result of these cryomagmatic events. Aqueous solutions may include organic compounds delivered from the mantle or from an exogenous source. Special attention should be paid to the salts mentioned earlier. The high concentration of salts in the aqueous solutions determines the presence of life, as it occurs in the extreme environments on the Earth. Some studies indicate that high amounts of sodium chloride may inhibit the synthesis of some oligomers, and subsequently this could affect the origin of life [11]. Nevertheless, there is no data concerning sulfates, and we do not know many details about the prebiotic reactions nor the origin of life.

The deep aqueous environments are protected by the icy crust from the strong radiation that dominates the surface of icy satellites, mostly in Europa. From the astrobiological point of view, the presence of a strong radiation on the surface may be positive or negative. On one side, radiation generates oxidants by photolysis that may be useful for life as a source of energy. The oxidants of the surface could be moved to the interior, promoting the habitability of the deep environment [7]. On the other side, the radiation environment is a handicap for life and for searching biosignatures, because it produces the alteration and even the destruction of the materials once they are exposed. The stability of the organics and minerals under the radiation of the Europa's surface is poorly known, and more laboratory experiments are needed to understand the alteration processes.

3 Strategies to explore the habitability of deep environments

The direct study of the deep aqueous reservoirs is not feasible at present because of the uncertainties about the location and the extension of these liquid layers, and their inaccessibility. The first step in the astrobiological exploration of the Jupiter system will be to confirm these ambiguities. As we have seen, some important information about the habitability may be obtained from the remote sensing measurements of future space missions like JUICE [3]. Especially important observations will be those from the radar sounder in combination with the spectroscopy data and imaging because they will reveal the subsurface structure of the geological features that are visible in the surface, and consequently potential links with liquid environments. In the particular case of Europa, even the analysis of endogenous materials and the biosignatures searching could be approached if some connection between the liquid reservoirs and the surface is confirmed. The study of the materials coming from rising aqueous cryomagmas will help to understand the environmental properties (salinity, temperature, acidity) and the composition of the deep water reservoirs [12].

The JUICE mission is conceived to perform a detailed analysis of Ganymede using several orbits around it. In addition, it will do some flybys over Europa and Callisto in order to obtain information about the main satellites with oceans [3]. This plan is configured to minimize the risks produced by excess of the radiation doses tolerated for the spacecraft and the instrumentation payload. The limited observations that are permitted over Europa have obligated to prioritize several regions to be studied. These regions have been selected analyzing the potential to find any biosignature on them. Searching for biosignatures is not easy from remote sensing. Remote observations would be useful just in the case the detection is absolutely clear and definitive, and this only occurs if the biosignatures are in high abundance or they are explicitly biological (eg. biomolecules such as pigments).

Some geological criteria have been used to propose the areas of Europa with highest potential to find biosignatures [4]: A) Evidence of the material mobility from the interior of the satellite. The upward transport can support the connection between the internal liquid layers and the surface. B) Concentration of the non-water ice components. These materials can provide essential elements or/and energy for the microorganisms. If they are salts, they could be an evidence of internal aqueous reservoirs. C) Relative youth, which increases the chances for finding preserved biosignatures due to less time of exposure to the radiation environment. D) Textural roughness, because it can be useful for shielding against radiation. This is not a good parameter if the area be considered as a landing site in the future. E)

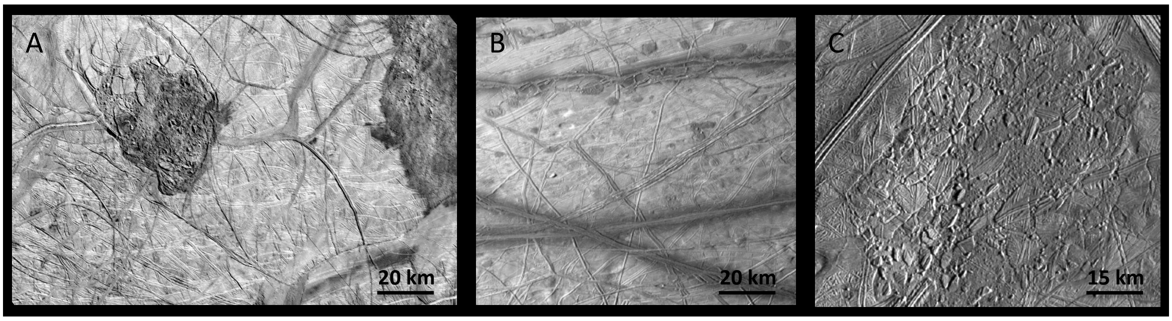


Figure 2: Images from the Galileo mission of A) Thera and Thrace maculae, B) lenticulae features associated to Minos, Udaeus and Cadmus lineae, and C) Conamara chaos region.

General stability. The environment should be geologically stable or change gradually in order to preserve the signatures coming from the interior. According to these geological criteria, the potential for the presence of biosignatures associated to the main features is maximize in areas with young bands, chaotic terrains and lenticulae features. Other features like ridges have moderate interest, although they could be intriguing in order to look for active plumes similar than the observed ones in the south pole of Enceladus. The smooth plains have high the index of potential biosignature and are also suitable for future landing. Craters could be interesting if subsurface material were raised during isostatic rebound. JUICE's flybys will explore in detail some of these areas like Thera and Trace maculae, the chaotic terrains north of Comamara chaos or the lenticuae-rich area near the Minos' prominent band [3] (Fig. 2).

In any case, the endogenous materials could be affected and/or completely destroyed by the strong radiation environment in the surface environment of Europa, even in the younger terrains. Therefore, the expected astrobiological analysis farther than the searching of the habitability requirements, would be more efficient if the instruments might access to the subsurface to sample fresh materials. Studies focused to detect biosignatures on extreme environments on the Earth show that biosignatures (e.g., isotopes, organic molecules, specific bio-induced minerals) usually appear in very low concentration, so their detection need both direct sampling and concentration of the materials. This is only possible if some in situ explorer element reaches the subsurface samples. The option of having a penetrator or lander for a future mission to the icy moons is a step further in space exploration. They will provide more reasonable opportunities in searching for life, extant or extinct. These options are already under study: a consortium of several institutions at UK is developing a penetrator module for a mission to Ganymede or Europa. Details of the current penetrator concept are described in [5], where some instrumentation dedicated to study the astrobiology of the Galilean satellites is included in the payload. The development of the lander option is considered for some space agencies such as Roscosmos [19, 8] or NASA. Several configurations of landers are taken into account, from a full-equipped heavy lander similar than Exomars to mini-landers with limited life span [6]. If a lander is involved in a mission, the characterization of the astrobiology should include 3 levels of measurements concerning: physical chemistry and geology of the context, biosignatures, and life.

1. Environmental measurements to constraint the geology and chemistry at the local context of the lander. Information about mineralogy, radiation doses, physical-chemical properties of melted ices (acidity, redox) should be obtained. Sampling of the subsurface by drilling or/and melting of the ice is required in order to avoid the upper layer affected by radiation. Simple sensors packaged in an environmental station as part of the lander payload would be very useful as it has been already proposed for the penetrator [5].

2. Measurements for the detection of potential biosignatures. They include the organic molecules characterization, volatiles detection, analysis of the ratios of several isotopes, and examination of potential biological structures. Some techniques are relevant for these purposes such as Raman, infrared and fluorescence spectroscopy, GCMS, and optical microscopy. Imaging of the context from where the chemical analysis is made, and the comparison between data from the orbiter and the lander are mandatory.

3. Biological measurements. A lander for Europa should include biological measurements of potential extant life. Interesting techniques to have into account are the "inmuno arrays" [14]. In the case of the icy moons, specific protocols and devices should be developed due to the duration of the trip to the Jupiter system and the extreme radiation environment of the surface. Immuno arrays sensor is a biochemical test that is able to state the presence as well as concentration of certain compounds, by using the reaction of antibodies to its corresponding antigens. This essay takes advantage of the specific binding of an antibody (typically monoclonal) to its antigen. An instrument based on this technique is SOLID [14, 13] that has been designed and built for the detection and identification of biochemical compounds by in situ analysis of samples.

The most farther step envisioned in exploration of the deep environments will be the in situ study of the aqueous oceans. This will imply a big challenge in the space exploration of the outer Solar System.

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