Astrobiology in the outer Solar System

Life in the outer Solar System

- The outer Solar System lies far beyond the outer edge of the classic “habitable zone”
- In spite of this fact, planets and satellites of the outer Solar System have an important astrobiological potential
- In principle, life could be present:
  - in subsurface regions of planets or satellites where the thermodynamical conditions are compatible with the presence of liquid water
  - in the form of organisms with the capability of suspending the metabolism at very low temperatures
  - in the form of organisms that use a medium alternative to water, characterized by a low freezing point

Astrobiological relevance of giant planets

Jupiter

Sagan & Salpeter (1976) investigated the potential habitability of Jupiter’s atmospheric layers
Some of the external atmospheric layers have pressure and temperature in the intervals
\[ 10^5 \text{ Pa} < p < 10^7 \text{ Pa} \text{ and } 300 < T < 500 \text{ K} \]
In principle, these ranges of pressure and temperature allow water to be present in liquid phase in such atmospheric layers
Hypothetical forms of life should stay suspended in those layers and resist to harsh conditions
It is very unlikely that life may have originated in such environments

Giant planets are not considered to be habitable

Giant planets of the outer Solar System can play a role in affecting the long term habitability of terrestrial planets
It has been widely reported that Jupiter has a profound role in shielding the terrestrial planets from comet impacts in the Solar System, and that a jovian planet is a requirement for the evolution of life on Earth

The results of recent simulations (Grazier 2016) provide a different view:
- The role of “Jupiter as shield” turns out to be quite negligible
- On the other hand, the results predict that in a Solar System like ours, large gas giants like Saturn and Jupiter had a different, and potentially even more important, role in the evolution of life on our planet by delivering the volatile-laden material required for the formation of life
Life in moons and minor bodies of the outer Solar System

• The icy moons of Jupiter are considered to be good candidates for the search for subsurface life
• Titan, the Saturn’s moon, is considered a laboratory for alternative forms of biology
• Minor satellites, such as Enceladus, and transneptunian objects are also starting to be considered in astrobiological studies

Europe

One of the 4 major moons of Jupiter
  – The second one in order of distance
Europe’s surface is not habitable
  \(<T> = 103 \text{ K}, \rho_s = 10^6 \text{ Pa}\)

In spite of this fact, Europe is one of the most interesting astronomical bodies in the Solar System from the point of view of astrobiology

Europe has been the target of several space missions

The most detailed observations have been obtained by the “Galileo” probe
  Launched in 1989, the probe made several "flybys" around Europe in 1997
The surface of Europe is made of H\(_2\)O ice
  The surface morphology, with relatively few impact craters, suggests that the surface is constantly being reshaped
  Different types of shallow structures can be seen on the surface
  Their presence is emphasized by differences in albedo

• A water ocean is believed to exist below the external ice layer
  The thickness of the layer is not known; likely to be between a few km and some tens of km

• The evidence for liquid water is indirect, but quite convincing
  – The fractures in the ice shield hint at presence of liquid water under the surface
  – Magnetometric measurements performed by the Galileo probe indicate the presence of an internal layer with electrical conductivity similar to that of salty water (Khurana et al. 1998)
  – Internal sources of energy are expected to exist at large depths; the heating would melt the ice from below
Europe

- **Internal heating**
  - The heat would be produced by tidal interactions with Jupiter
  - The strong effects of vulcanism found in the first moon of Jupiter (Io), suggest that also on Europe tidal effects can produce internal heating

- **Internal structure**
  The mean density, \( \rho = 3.0 \text{ g cm}^{-3} \), is similar to the value typical of silicates
  Below the layers of solid and liquid water, the interior must be rocky

Habitability of Europe’s interior

- The presence of liquid water **below the surface** makes Europe a candidate for studies of habitability outside the “circumstellar habitable zone” (which is defined according to the **surface habitability**)
- It is plausible that “hydrothermal vents”, similar to those found at the bottom of the Earth’s oceans, may exist at the bottom of Europe’s ocean
- In this case, all the main ingredients of habitability would be present:
  - Liquid water, energy sources, protection from ionizing radiations

Motivations to search for life on Europe

Connection with studies in Antarctica

The fact that Earth’s termophilic organisms found around hydrothermal vents are close to the root of the phylogenetic tree (relatively close to the origin of life), provides an argument in favour of the possible presence of life

The existence of terrestrial cryophilic organisms and the searches for life in Antarctic subglacial lakes are motivated by the similarity with Europe’s conditions

The extremophiles found in Antarctica and the technology required to carry out this type of research are all relevant for Europes’ astrobiological studies

Searches for biomarkers on Europe’s surface

The icy surface of Europe shows reddish streakes due to different compounds, such as sulfate salts and sulfuric acid

Their presence may be related to outgassing from Io, but also to an exchange of material between the surface and the subsurface layers, down to the liquid layers

The chemical pathways able to lead to the formation of such chemical compounds are currently investigated to search for evidence of biochemical activity, if any

In terrestrial life, sulfur can be produced biologically, in which case the isotopic ratio \( {^{32}\text{S}}/{^{34}\text{S}} \) tends to be higher than the corresponding non-biological ratio

Future space missions on Europe are considering the possibility of measuring the sulfur isotopic ratio on Europe’s surface, searching for evidence of a biological origin
On the possibility of emergence of life in icy moons

Even if the conditions of habitability are present in the subsurface oceans of Europe, it is not clear whether life could have originated in such environment.

According to Pascal (2016), the physicochemical requirements inferred for chemical self-organization hardly support an emergence of life in the deep oceans of icy moons.

The requirement for an energy source of sufficient potential (equivalent to the potential of visible light) to drive the emergence of life could be absent in the interior of icy moons.

The presence of life is unlikely on these Solar System bodies, unless additional highly improbable events are introduced for feeding chemical systems undergoing a transition toward life and the early living organisms.

The large icy moons of Jupiter: Ganymede and Callisto

The ice layers are expected to be thicker in the large moons Ganymede and Callisto.

The possible internal structure of these moons is sketched in the left of the figure (1 or 2), where internal pressures are sufficient to allow for the formation of high-pressure ice-phases.

Oceans—if they exist—should be enclosed between thick ice layers.

Moreover, these moons undergo lower tidal heating than Europe since they lie at larger distances from Jupiter.

Given this situation, the presence of life in Ganymede and Callisto is considered to be unlikely.

Titan

- Largest satellite of Saturn
  - Radius 40% of Earth’s radius
  - Non-habitable surface: 
    - \( T > 94 \text{ K} \)
    - \( p_s = 1.47 \times 10^5 \text{ Pa} \)
- Main observations from space missions
  - NASA Pioneer 11, Voyager 1 and 2 between 1979 and 1982
  - Mission NASA/ESA Cassini-Huygens, since 2004
  - Close up maps obtained by Cassini
  - Landing of the Huygens probe in 2005

Titan’s atmosphere

The most abundant molecule is \( \text{N}_2 \), as in the Earth’s atmosphere.

The highest atmospheric layers are characterized by a haze of tholins.

Organic compounds obtained from the processing of simple organic molecules photo-dissociated and photo-ionized.
Titan’s surface

- The surface pressure is comparable to that of the Earth (50% larger)
  \( p_s = 1.47 \times 10^5 \) Pa
- What makes particularly interesting Titan is the presence of large amounts of organic molecules in liquid phase, forming surface lakes of hydrocarbons
  Mainly methane (\( \text{CH}_4 \)) and ethane (\( \text{C}_2\text{H}_6 \))
  The lakes have been discovered by the Cassini probe and, with higher detail, in the landing site of the Huygens module

Titan as a laboratory of astrobiology

- The presence of large quantities of organic material makes it possible the formation of complex organic molecules on Titan
  Laboratory simulations of Titian’s atmosphere have shown the possibility of formation of prebiotic material, including amino acids and nucleic acids
  Horst et al. (2010)
- Titan is an ideal laboratory to understand whether a biochemistry based on a liquid different from water, such as methane and ethane, can be possible
  However, methane and ethane molecules are not polar
  Some authors have considered the possibility that non polar liquids may give rise to some type of alternative biochemistry (Schulze-Makuch & Irwin 2004)
  The possibility of generating membranes in non polar hydrocarbons has been investigated, but an alternative chemistry is controversial

Titan biota that are hydrocarbon based may adopt a modification of the arrangement of surfactant molecules in the cell membrane, forming a so-called “reverse” vesicle structure

Titan possesses an atmospheric “hydrocarbon cycle”: acetylene and hydrogen form in the troposphere and rains to the surface
Acetylene is available as a nutrient and energy source for hydrocarbon-based life forms, e.g. by recombining with hydrogen
There is a lack of hydrogen on the surface, i.e. something on the surface of Titan “breathes” \( \text{H}_2 \) and might use it to hydrogenate acetylene producing energy
This “something” could be:
- a catalytic metal species able to drive this reaction under the icy conditions
- an organism that consumes acetylene and hydrogen to sustain itself

Titan as a laboratory of astrobiology

Liquid water might exist in underground layers in Titan.

There are no direct evidences, but it is plausible.

If liquid water is present, the exchanges between the organic material and the liquid water may yield extremely interesting astrobiological conditions in the subsurface layers.

Small moons of Saturn: Enceladus

Enceladus is a moon of Saturn with radius ~250 km.

Its mean surface temperature is extremely low (~75 K) not only because of the low insolation, but also because of the very high albedo of its surface, which is mostly covered by fresh ice.

In 2005, the Cassini spacecraft started multiple close flybys of Enceladus, revealing its surface in detail; the surface shows old, heavily cratered regions, as well as young, tectonically deformed terrains.

The astrobiological interest of Enceladus arises from the discovery of geyser-like jets of water vapor venting from the south polar region.

In addition to water vapour, the jets contain methane, CO, CO₂ and organics. The geyser observations, along with the finding of escaping internal heat and the lack of impact craters in the south polar region, show that Enceladus is geologically active today.
Enceladus

Enceladus is trapped in an orbital resonance with Dione; this resonance excites its orbital eccentricity, which is damped by tidal forces. The geological activity is probably driven by tidal heating of its interior. The existence of liquid water and organics in an ambient with internal energy and temperature gradient makes the interior of Enceladus a potentially habitable environment.

Next mission to the outer Solar System

Missions to the outer Solar System are extremely expensive. The next large ESA mission of astrobiological interest, JUICE, will be focussed on the Jupiter system, rather than Saturn system, also in light of economical considerations. JUICE (JUpiter ICy moons Explorer) will be the first large-class ESA mission. Planned for launch in 2022 and arrival in 2030, it will spend at least three years making detailed observations of Jupiter, Ganymede, Callisto and Europa. For Europa, the focus of the mission will be on the chemistry essential to life, including organic molecules, and on understanding the formation of surface features and the composition of the non water-ice material. JUICE plans to provide the first subsurface sounding of Europe, including the first determination of the minimal thickness of the icy crust over the most recently active regions.