Astrobiology in the outer Solar System

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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 Pa < p < 10^7 Pa and 300 < T < 500 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 any type of material may stay suspended in the "habitable" layers given the presence of strong winds and convection

Giant planets are not considered to be habitable

Life in the outer Solar System

- The outer Solar System lies far beyond the outer edge of the classic "habitable zone"
- Notwithstanding, planets and satellites of the outer Solar System have an important astrobiological potential

- Beyond the outer edge if the HZ 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

Giant planets of the outer Solar System can play a role in affecting the long term habitability of terrestrial planets

Giant planets as triggers of dynamical instabilities

Migrations of large gas giants like Saturn and Jupiter scattered minor bodies rich of water and organic material, providing a potential source of prebiotic ingredients eventually delivered to the Earth

Giant planets as protective shields

Jupiter has a role in shielding the terrestrial planets from comet impacts in the Solar System

In this sense, jovian planets may help to keep a long-term habitability for the evolution of life on Earth

Results of recent simulations (Grazier 2016) suggest that the role of "Jupiter as shield" might have been quite negligible

Life in moons and minor bodies of the outer Solar System

- Some icy moons of the outer Solar System are good candidates to search for subsurface life
- Titan, the largest moon of Saturn, is a laboratory for testing the possibility of alternative forms of biochemistry
- Minor satellites, such as Enceladus, and transneptunian objects are also being considered in astrobiological studies

Europe

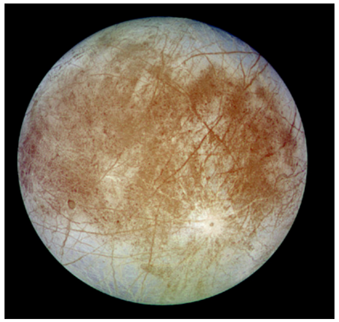
Europe has been the target of several space missions

The most detailed observations have been obtained by the "Galileo" probe

- Launched in 1989, the probe made several "flybyes" around Europe in 1997

The surface of Europe is made of H_2O 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



Europe

One of the 4 major moons of Jupiter

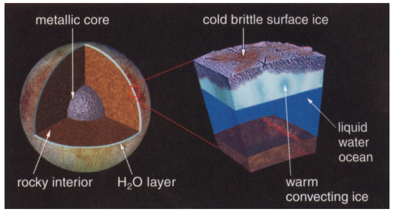
– The second one in order of distance

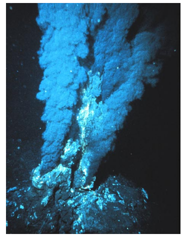
Europes' surface is not habitable

$\langle T_s \rangle = 103$ K, $p_s = 10^{-6}$ Pa

Despite the lack of surface habitability, Europe is one of the most interesting bodies in the Solar System from the point of view of astrobiology

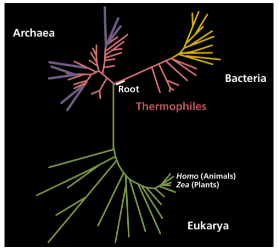
Habitability of Europe's interior

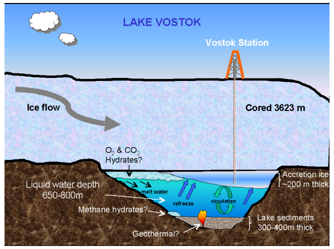




- The presence of liquid water below the surface makes Europe a candidate for studies of habitability outside the "circumstellar habitable zone" (which is defined according to the surface habitability)
- It is plausible that "hydrothermal vents", similar to those found at the bottom of the Earths oceans, 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 Anctartic 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 Europe's astrobiological studies

On the possibility of emergence of sub-surface life in icy moons

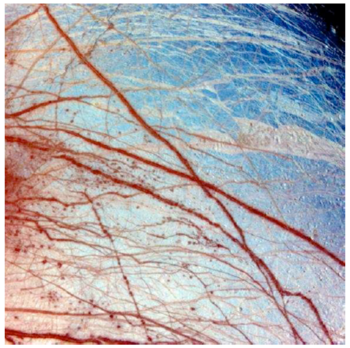
Even if the conditions of habitability are present in the subsurface oceans of Europe, it is not clear whether life could have originated in such an environment

According to some authors, the physico-chemical requirements for self-organization hardly support an emergence of life in the deep oceans of icy moons (e.g., Pascal 2016)

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 questionable in these Solar System bodies, unless additional "ad hoc" events are introduced for feeding chemical systems undergoing a transition toward life and the early living organisms

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 investigated to search for evidence of biochemical activity, if any
  - In terrestrial life, sulfur can be produced biologically, in which case the isotopic ratio $^{32}S/^{34}S$ 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

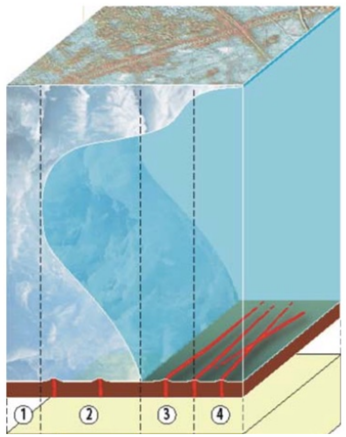
The large icy moons of Jupiter: Ganymede and Callisto

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 (case 2 in the figure)

Moreover, Ganymede and Callisto probably undergo lower tidal heating than Europe since they lie at larger distances from Jupiter



Lammer et al. (2009)

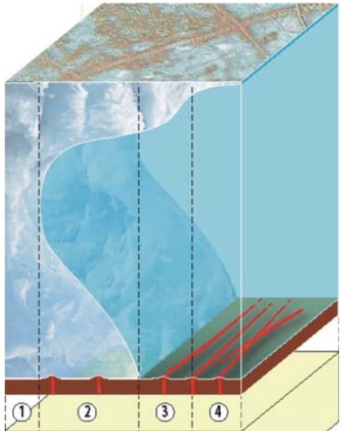
The large icy moons of Jupiter: Ganymede and Callisto

Case 2 in the figure:

The bottom of the oceans is not exposed to hydrothermal vents

The problem of energy sources and of finding proper conditions for the origin of life is by far more complicated than in the case of Europa

This type of situation is expected to be present also in exoplanets with complete ice covers and large radii



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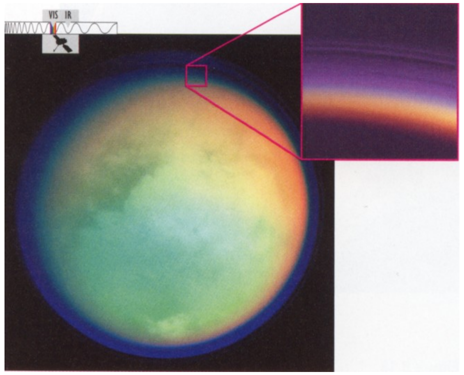
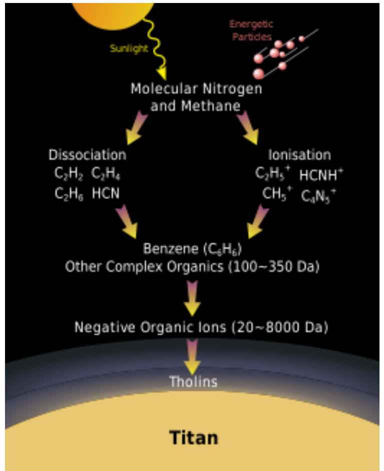




Titan's atmosphere

The most abundant molecule is N_2, as in the Earth's atmosphere

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

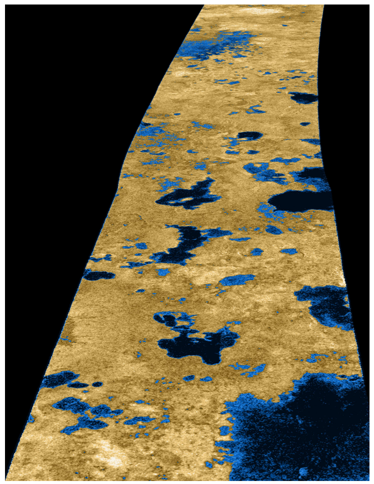
Tholins: organic compounds obtained from the processing of simple organic molecules photo-dissociated and photo-ionized

Titan

- Largest satellite of Saturn
  - Radius 40% of Earth's radius
  - Non habitable surface:
  - $<T_s>=94$ K $p_s=1.47\ 10^5$ 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 surface

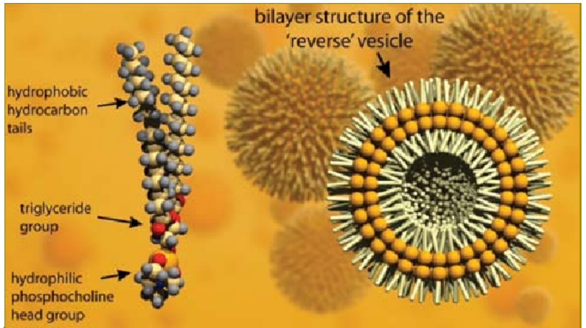
- The surface pressure is comparable to that of the Earth (50% larger)
  - $p_s=1.47 \times 10^5$ Pa
- What makes particularly interesting Titan is the presence of large amounts of organic molecules in liquid phase, forming surface lakes of hydrocarbons
  - Mainly methane (CH_4) ed ethane (C_2H_6)
    - 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 Titan's atmosphere have shown the possibility of formation of prebiotic material, including aminoacids 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 the viability of an alternative biochemistry with a non-polar medium is far from being demonstrated

According to some authors, hypothetical 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



4: "Reverse" vesicle structures (right) consist of spherical bilayers of close-packed surfactant molecules (such as phosphatidylcholine, shown on the left). The hydrophilic groups (orange spheres) are packed into the centre of the bilayer, with the hydrophobic chains of hydrocarbons (pale yellow sticks) extending inwards and outwards. The phosphatidylcholine molecule shown on the left is ~25Å in length.

L. H. Norman, A D. Fortes, *Astronomy & Geophysics* **2011**, *52 (1)*, 1.39-1.42
doi:10.1111/j.1468-4004.2011.52139.x

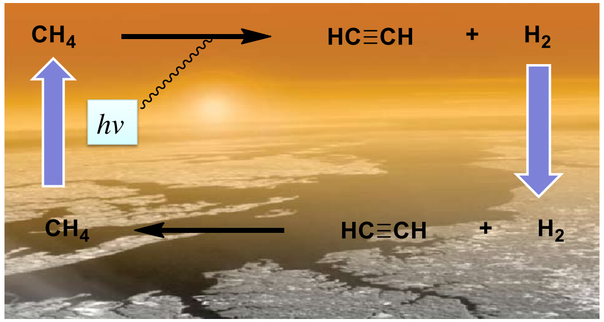
Titan possesses an atmospheric "hydrocarbon cycle": acetylene and hydrogen form in the troposphere and rains to the surface

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" 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 alternative type of life that consumes acetylene and hydrogen to sustain itself

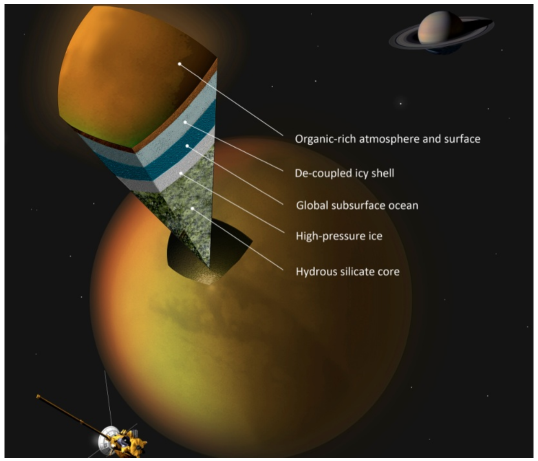


Titan as a laboratory of astrobiology

Liquid water is believed to be present in underground layers in Titan

Indirect evidence for the presence of sub-surface water are accumulating, in line with the known abundance of volatiles in the outer Solar System

The exchanges between the hydrocarbons on the surface and the subsurface ocean provide extremely interesting astrobiological conditions in the subsurface layers of Titan

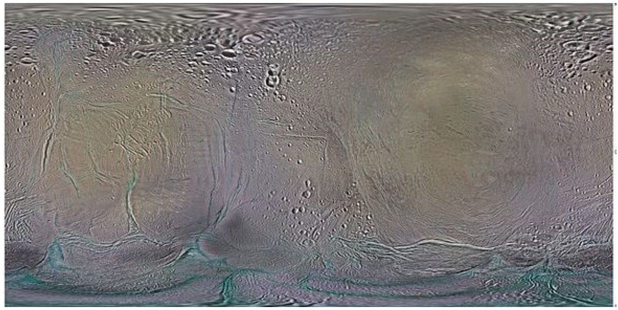


Small moons of Saturn: Enceladus

Enceladus is a moon of Saturn with radius ~250 km

Its mean surface temperature is extremely low (~ 75 K) not only because 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 performed multiple close flybys of Enceladus, revealing its surface in detail; the surface shows old, heavily cratered regions, as well as young, tectonically deformed terrains

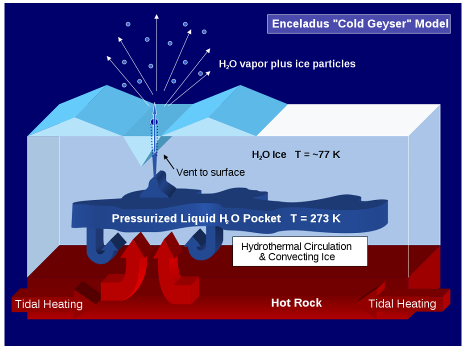


Enceladus

Enceladus is trapped in an orbital resonance with Dione; this resonance excites its orbital eccentricity, which is damped by tidal forces

The geophysical 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

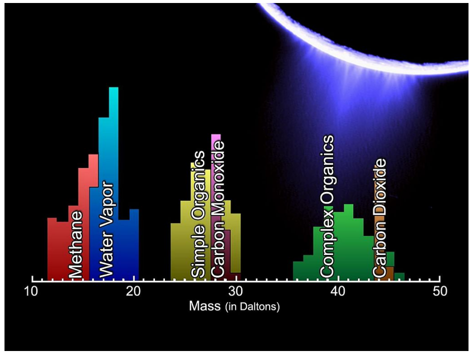


Enceladus

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, CO_2 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



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 then Saturn system, also in light of the lower costs

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