*Sojourn – Undergraduate Research in the Netherlands* 2018
Vol. 2, no. 2, 20-25

# Enceladus: the search for life on Saturn's moon

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This paper reviews and synthesizes various studies into the geologically active moon Enceladus in Saturn's diverse satellite system. Data from the Cassini mission are the main source for these studies as they provide the chemical composition of Enceladus' famous plumes or jets which can indicate the extent of Enceladus' habitability. The hydrothermal vents responsible for Enceladus' jets are possibly analogous to early Earth as well as current examples of Earth ecosystems. Along with providing models for origins of life on Earth, the habitability of Enceladus is one of the many ways astrobiologists are exploring extra-terrestrial life. Along with that, the possibility of the survival of Earthly life, including humans, on other planets and moons in our celestial neighbourhood is one of the implications of this investigation.

## Background

Astrobiology is the field of science concerned with the search for extra-terrestrial life. In its quest, it also embraces "the origin, evolution, distribution and future of life in the universe." (Dunbar, 2017). One exciting development in this field is learning about the habitability of planets and moons in our own Solar system. Saturn's moon Enceladus has revealed itself to be one of the hotspots for the search for extra-terrestrial life. The discovery of the chemical and geological diversity of Enceladus was an unforeseen consequence of the Cassini mission, which had the aim of examining Saturn and its system of moons. This surprise brought a vast amount of solid data for astrobiologists to analyse in their quest to find extra-terrestrial life. The excitement around Enceladus and the potential for life on our own solar system echoes after the end of the Cassini mission on September 2017 as research spurs on various topics regarding the moon. The
analysis of data collected from the Cassini mission quickly grouped Enceladus with Europa, Jupiter's moon, in the category of hotspots for extra-terrestrial life.

The Cassini-Huygens's spacecraft began its journey in 1997, when it was launched from Florida on a twenty-year trip. It finally arrived at Saturn on June 2004 after making flybys of Venus and Jupiter and taking beautiful images on the way. It went on to eject its probe component 'Huygens' at another one of Saturn's moons, Titan (Matson et al., 2003). The smaller moon Enceladus, with its icy surface, comes into focus after close flyby images of its south pole reveal a complex geological surface, with deep crevasses known as tiger stripes and jets which eject water vapour into space.

These jets, referred to as geysers or plumes were analysed by taking direct samples of the ejected material, highlighting a composition of volatile gases and organic material. It was later concluded that plumes originated from hydrothermal vents in Enceladus' global ocean. (Beutel, 2017). Enceladus possesses strong indicators for life within its ocean, which is trapped between its silicone core and icy crust (JPL, 2017). These indicators include the presence of organic material, liquid water and warm temperatures emanating from a heat source. If life were to exist on Enceladus, what kind of life would it be? The importance of searching for a second

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genesis provides us with insight on how life on Earth could have emerged, even further, could certain ecological systems present on Earth tell us anything about what we might find on Enceladus in future missions? Attempting to answer all these questions is a vast undertaking as a plethora of data is still being analysed from Cassini's instruments. However, research conducted by various scientists can help answer the following question: To what extent can life emerge on Enceladus under the currently known conditions?

## Conditions on Enceladus

This section will discuss the requirements for life to evolve as well as the conditions on Enceladus that make this a possibility. In short, life requires energy (chemical or light energy) for metabolic processes, liquid water and essential elements such as carbon, hydrogen, nitrogen and sulphur. These criteria will be explored further with regards to Enceladus using data gathered from Cassini instruments.

Among the various indicators of life on Enceladus, the presence of a heat source is vital. It was discovered as scientists saw discrepancies in surface temperature of the south pole. The cracks or 'tiger stripes' are significantly warmer than the rest of the surface. The Composite Infrared Spectrometer (CIRS) measured the cracks temperature to be up to 190 K (Goddard, 2010). Secondly, Enceladus was too small to retain an atmosphere; its atmosphere must exist through an ongoing process. Finally, molecular hydrogen was detected in the plumes, which is observed in similar volcanic processes on Earth (Waite et al., 2017). These discoveries contributed to the conclusion that hydrothermal vents were behind Enceladus' plumes.

The existence of water vapour, amongst gases and organic material is certainly compelling. The chemical composition of the plumes provides a foundation for what processes are occurring in Enceladus', as the ejected material is the by-product of these processes. To gather this data, the Cassini Ultraviolet Imaging Spectrograph (UVIS) was used to detect the wavelengths of light emitted by the plume material, with the help of rays from the star Bellatrix as it passed by in the behind the moon, allowing light to reflect off the plumes. The Ion and Neutral Mass Spectrometer (INMS) helped in determining the chemical composition by detecting positive ions and neutral particles. (Cassini Legacy: 1997-2017, n.d.) The following table shows the results of these analyses in relation to the molecules relevant for potential life.

Table 1: Chemical composition of plumes and ice surface in the South Pole of Enceladus. (Parkinson et al., 2006)

| Molecules | Column Density[a] | References[b] |
|---|---|---|
| $N_2$ | $6.0 \times 10^{14}$ | Waite et al. (2006) |
| $H_2O$ | $1.5 \times 10^{16}$ | Hansen et al. (2006) |
| CO | $<1.3 \times 10^{14}$ | Hansen et al. (2006) |
| $CO_2$ | $<1.8 \times 10^{17}$ | this work, Yoshino et al. (1996) |
| $O_2$ | $<2.5 \times 10^{18}$ | this work, Yoshino et al. (1987) |
| $CH_4$ | $<5.6 \times 10^{15}$ | this work, Lee et al. (2001) |
| $C_2H_2$ | $<1.6 \times 10^{15}$ | this work, Smith et al. (1991) |
| $C_2H_6$ | $<4.0 \times 10^{15}$ | this work, Lee et al. (2001) |
| HCN | $<2.7 \times 10^{15}$ | this work, Lee (1980) |
| | | Nagata et al. (1981) |
| | | Nuth & Glicker (1982) |
| $NH_3$ | $<1.3 \times 10^{16}$ | this work, Cheng et al. (2006) |
| $SO_2$ | $<2.2 \times 10^{15}$ | this work, Rufus et al. (2003) |
| dust | $\sim 0.1$ m$^{-3}$ | Spahn et al. (2006) |
| electron | $\sim 100$ cm$^{-3}$ | Tokar et al. (2006) |
| $N^+$ | ~3% of total ion | Bouhram et al. (2006) |
| Organics | Detected in ice | Brown et al. (2006) |
| $CO_2$ | Detected in ice | Brown et al. (2006) |

To put this data in perspective, we can compare it to the requirements for life summarised in the following table. This can be used as a reference point of where Enceladus can be placed in terms of habitability.

Table 2: Requirements for life in our Solar System and their occurrence in our Solar System. (McKay, 2014)

| Requirement | Occurrence in the Solar System |
|---|---|
| Energy | Common |
| Predominately light | Photosynthesis at 100 AU light levels |
| Chemical energy | e.g., $H_2 + CO_2 \rightarrow CH_4 + H_2O$ |
| Carbon | Common as $CO_2$ and $CH_4$ |
| Liquid water | Rare, only on Earth for certain |
| N,P, S, Na, and other elements | Likely to be common |

Table 1 analyses the chemical composition of the plumes of Enceladus. It can be inferred that the plumes arise from the same origin source; Enceladus' sub-surface ocean. The abundance of water ($H_2O$) is due to the ocean being mainly composed of pure ice water (Parkinson et al., 2006). Carbon is an element shared by all lifeforms due to its versatility and ability to form a large variety of molecules. As seen in Table 1, it is present in the form of carbon dioxide $CO_2$ at very high densities. This could be an indication of active geochemical processes that can act as a source of energy for life. Table 2 shows an example of this with the chemical reaction in the third row. This is methanogenesis and is a process likely to be occurring on Enceladus, the relevance of this will be further explained later.

Nitrogen ($N_2$) is a vital ingredient for life as it is a component of amino acids which make up proteins in living organisms. There needs to be an abundant amount of $N_2$ for nitrogen fixation to occur. Nitrogen fixation is an anaerobic process integral to life as it turns the relatively inert nitrogen gas to a chemically reactive molecule ammonia ($NH_3$) that can bond with other elements to form various molecules such as DNA. One study focuses on the possibility of a nitrogen cycle on Enceladus. This process was relatively more effective in early Earth's environment which had lower oxygen levels. Hence, it is likely to occur on Enceladus given the amounts of $NH_3$ detected by INMS and the anoxic conditions on the icy moon. (Taubner, 2012). The presence of a nitrogen cycle would greatly increase the likelihood of life on Enceladus.

The requirement for light energy in Table 2 applies to photosynthetic life. We can deduce that organisms relying on this metabolic pathway have a low probability of emerging on Enceladus (Taubner, 2012). This is because a sufficient amount of sunlight is unlikely to reach the moon's ocean, which is trapped beneath a thick layer of ice. However, this does not eliminate the chances for other forms of life to emerge. Microbes can derive energy from geothermal activity present due to the active seafloor. This is a possible metabolic source for life on Enceladus' ocean.

A compelling discovery was the prevalence of methane ($CH_4$) on Enceladus. The moon's plumes are surprisingly methane-rich (Table 1). The exact reason for the abundance of methane in the plumes is still uncertain, but research points to hydrothermal processes in the ocean floor as a viable cause. Serpentinisation is a metamorphic geological process occurring in volcanically active regions which has been shown to result in the production of methane in deep sea vents. This process produces molecular hydrogen ($H_2$) which then reduces $CO_2$ into methane (Russell et al., 2010). The chemical equation for this process is as follows:

$$H_2 + CO_2 \rightarrow CH_4 + H_2O$$

The abundance of $CO_2$ indicated in the Table 1 makes it a possibility that this process is currently oversaturating Enceladus' ocean with methane that is then ejected along with other plume material into space. Serpentinisation is thought to be an indicator for early life on Earth and even on the terranes of Mars (Schulte et al., 2006).

An accompanying explanation for the abundance of methane is the existence of methanogenic bacteria in Enceladus. Methanogens are a particularly unusual group of archaebacteria with coenzymes not typically found in other microbes (Woese, 1978). Methanogens' metabolic reaction, methanogenesis, involves the reduction of $CO_2$ into methane and the release of water as a by-product (Zeikus, 1977). This is exactly the process described by the equation above, but now occurring within a living organism. Despite their difference in metabolic processes to photosynthetic life, methanogens are not uncommon on Earth as they are found in various extremely low or high temperature ecological systems as well as deep sea oceans. A study of the deep glacial ice in Greenland found methanogenic bacteria to be the source of excess methane trapped beneath about 3 kilometres of ice (Tung et al., 2005).

Hydrothermal vents, similar to those on Enceladus, can be a hotspot for methanogens as they provide an abundance of $H_2$, which is needed for methanogenesis. The hydrothermal field known as Lost City is a system of oceanic vents discovered in the mid-Atlantic Ocean on December 2000 (Kelley, 2005). It presents a great example of a serpentinite-hosted system on Earth that generates the necessary conditions for large amounts of archaebacteria, including methanogens, to thrive.

Such geochemical systems have intrigued biologists as they provide substantial models which enable further study into the 'Primordial Soup' theory. This is a possible explanation for the emergence of life on Earth theorized by scientist A.I Oparin in 1924 (Fry, 2006). It was later reinforced by Stanley Urey and Harold Miller's experiment, which demonstrated that organic compounds can arise from inorganic chemicals (Miller & Urey, 1959). The experiment involved the simulation of early Earth conditions; an anaerobic atmosphere, inorganic material such as hydrogen, methane and ammonia. Electrodes were also used to simulate lightning. At the end of the experiment, various organic compounds such as amino acids were found.

Following on from this framework, the geochemical setting in which the primordial soup begins to form organic compounds seems to be hydrothermal vents not dissimilar to those found on Enceladus. The mechanism that allows this to occur can be explained through the iron-sulphur world theory by Günter Wächtershäuser, which hypothesises that life began to emerge near hydrothermal vents on iron sulphide surfaces (Wächtershäuser, 2008). Since Enceladus seems to contain chemically rich fluids from its silicone core, as well as hydrothermal vents in its ocean floor which supply chemical energy in the form of hydrogen, the emergence of life would likely be chemotrophic. (Taubner, 2012). If such life is to be found on Enceladus, it could provide evidence for the aforementioned theories about the origins of life on Earth.

**Stability**

The emergence of life requires stability. While astrobiologists agree that Enceladus delivers excellent conditions for life to arise, research onto Enceladus' formation reveals an unstable past it shares with the rest of Saturn's midsized moons. Though much of their history remains uncertain, those moons appear to have formed from a debris disk which was the product of the disruption of a previous generation of similar midsized moons. Furthermore, the disk was hypothesized to be short-lived and the study concluded that Saturn's midsized satellite system is still very young (Ćuk et al., 2016). The exact timespan that Enceladus has remained stable is unknown, but this can be further studied with upcoming missions. Enceladus' future, however, may not be as unstable as its past. Another study highlights that the global ocean and seafloor geological activity can be sustained for "tens of millions to billions of years", under the condition that a heat power of greater than 20 billion watts is maintained. Heat power of greater than 10 GW is hypothesized to be generated in Enceladus and sustained in the future, keeping its ocean warm enough to host life (Choblet et al., 2017). Hence, even if there was not enough time for life to evolve, there exists potential for its emergence under the assumption that extra-terrestrial life will share the same biochemistry, and therefore require the same amount of time to evolve as life on Earth.

**Conclusion and Implications**

The conditions on Enceladus seem to be an active geological environment with an abundance of water and molecules that could indicate at least microbial life, one of which is methane. Certain organisms such as methanogens could potentially thrive on Enceladus. The subsurface geological activity is akin to that of early Earth as well as current environments such as Lost City. If life were to be found on Enceladus, it could provide evidence for the Primordial Soup theory as well as the iron-sulphur world theory, as Enceladus can be viewed as a model for early Earth's subterranean ecosystems. Furthermore, the past instability of Enceladus lowers the chances of currently finding life. However, geothermal power from volcanic activity is the main enabler for the ideal warm temperatures within Enceladus' ocean. This warmth is likely to be maintained to sustain life in the future if it has not yet emerged.

The compelling data gathered from the Cassini mission has prompted further study into Enceladus' atmosphere, surface, ocean and plumes. The Enceladus Life Finder (ELF) is another Saturn orbiter mission that has been proposed by NASA for the purpose of providing enough data to conclude whether Enceladus hosts life. The mission aims to determine the sources of organic material on Enceladus and to further analyse its plumes. The instruments of the ELF will have higher sensitivity, resolution and mass range than those on Cassini (Lunine et al., 2015). If NASA confirms the mission, it will launch on either 2020 or 2021 (Wall, 2015). ELF will fly on a solar-powered journey to provide more substantial evidence for the potential of life evolving elsewhere in our Solar system.

All analyses of conditions on Enceladus with regards to the emergence of life fall under the assumption that extra-terrestrial life is predictable and analogous to terrestrial life in metabolism and biochemistry. If such life is observed on Enceladus, it could hint at 'Solar System panspermia', the theory that life was carried in interstellar dust and incorporated into the nebula which gave rise to our solar system. (McKay et al., 2008). This would have resulted in all emergent planets or moons coming to have the potential for a homogenous biochemistry of life. This infers the scenario of other planets and moons being habitable even for human life. As reminiscent of science fiction as it seems, this is a possibility being explored by astrobiologists and other scientists today for future generations of humans on Earth, who may experience a lack of resources due to climate change, for example.

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