

Follow the plume: Organic molecules and habitable conditions in the subsurface ocean of Enceladus

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1. Enceladus: organic chemistry in a habitable ocean

Are we alone in the Universe? The search for life beyond Earth is the most compelling scientific question of our time; a positive detection would be one of the most profound discoveries ever made by humanity. Chemical evidence of habitable conditions and organic compounds make Saturn's moon Enceladus a promising lead in the search for life beyond Earth.

In 2005 Cassini's Imaging Science Subsystem (ISS) discovered a plume of gas and icy particles venting into space over the South Polar Terrain (SPT) of Saturn's icy moon Enceladus (**Fig 1**) [1–5]. The SPT is a region dominated geologically by large rifts in the icy crust, informally called 'tiger stripes.' The plume erupts along active fractures as diffuse curtains of material, with localized regions of enhanced eruption, called 'jets' [3,6,7]. Sources of jets and curtains along vents coincide with the warmest regions of the fracture system [3,6], and the plume varies in brightness with orbital position [8]; it is likely that tidal stress along the tiger stripes modulates its eruption activity with a maximum output when Enceladus is furthest from Saturn [9]. Erupted material is the source of particles that make up Saturn's E-ring [5] first observed in 1966 [10], but mantling materials over the SPT [1] point to plume fallout deposits at least several meters thick, or $>10^3$ years old considering deposition rates between 10^{-2} and 10^{-3} mm/yr [11]. The actual longevity of the plume could be $>10^4$ and perhaps $>10^6$ years, assuming the E-ring is a source of oxygen compounds in Titan's atmosphere [12], and of mantling materials on the surface of Helene .

Plume emissions consist of icy particles and vapor originated in an ocean of liquid water 10 km deep, located 30–40 km beneath the moon's surface [13–15]. Cassini flew by Enceladus 22 times, spatially resolving the structure and composition of the plume [13,16–19]. During the second flyby (E2) at high altitude (>150 km) and high speed (>15 km/s), the Ion Neutral Mass Spectrometer (INMS) detected gaseous H_2O and CO_2 [13]. During lower flybys (<50 km altitude, <10 km/s) (E5, E14, E17, E18), INMS also detected H_2 , CH_4 , HCN, methanol, formaldehyde, C_{2-4} alkenes, C_{2-5} alkanes, and benzene [13,14,19]; and the Cosmic Dust Analyzer (CDA) detected icy particles containing sodium and potassium salts [18] and refractory organics [17]. Salt-bearing particles are found to dominate the total mass flux of ejected solids ($>99\%$ by mass), but are depleted in the population escaping into the E-ring [18]. While the abundance of sodium in salt-bearing particles is fairly consistent (~ 0.5 – 2% by mass) [15,18], the abundance of total organics appears to range dramatically from a few parts per million (ppm) in some particles to 50% by mass in others [18]. The CDA also found silica nanoparticles in the E-ring that were linked to ongoing, alkaline hydrothermal activity at the ocean-sediment interface [20,21] reminiscent of hydrothermal vent systems in Earth's deep oceans. Ocean temperatures likely range from $\sim 0^\circ C$ near plume sources to $\sim 90^\circ C$ at the hydrothermal vents, and recent geochemical models of the ocean indicate an alkaline pH of ~ 11 – 12 (Glein et al. 2015), but estimates range from 6 to 12 [22–24]. Collectively, these observations are suggestive of a subsurface ocean in contact with the moon's rocky core [13,15,20,21].

Cassini provided a snapshot of a familiar, and yet alien, world that has many of the components—internal heat, an extensive liquid-water ocean, organics, and geochemical cycling—necessary to support an extant biosphere. In this white paper put forward a series of specific recommendations to the next NASA Astrobiology Strategy emphasizing key science investigation of the Enceladus plume (and any other plume discovered in the future) and the technology needed to achieve them.

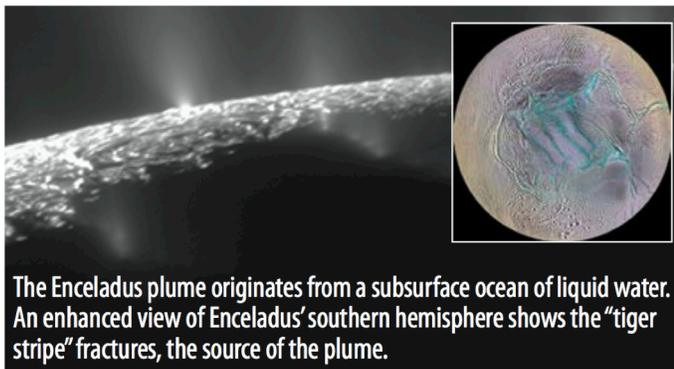


Figure 1. Enceladus has a subsurface ocean with the necessary conditions to support life. Its plume of icy particles and gas provides a unique opportunity to investigate the ocean without descending into it. Image credit: NASA/JPL

2. Science goal: The origin of organic molecules in the subsurface ocean of Enceladus

One of NASA's most immediate priority goals should be to define a science strategy to determine the origin of organic molecules in the subsurface ocean of Enceladus. Once defined, this science strategy would become the foundation on which to build mission enabling technologies in the next 10 years. Based on previous recommendations [25–30], the origin of organic molecules in a given environment is best determined through chemical and structural analyses of different classes of organic compounds, such as patterns in molecular carbon number, isotopic ratios, dominant presence of specific molecular structures, etc. However, there is limited literature and even less consensus on the range of possible chemical and structural solutions—the chemical space—expected to exist in a subsurface ocean such as Enceladus. There is also little consensus on what specific molecular patterns, isotopic ratios, structures, etc. would be indicative of biotic or abiotic sources of organic compounds. Given the likelihood of a mission that investigates the organic chemistry of the Enceladus' ocean within the next 20 years, it is imperative that the broader astrobiological community agrees upon a “set of rules” on what would constitute evidence of abiotic or biotic sources of organic compounds in the Enceladus ocean. This “set of rules” would be better formulated as a series of scientific hypotheses that can be verified or falsified by sample analyses. **We therefore recommend that the next NASA Astrobiology Strategy emphasizes the need for a hypothesis-based framework to assess the origin of organic matter (biotic or abiotic) in the Enceladus ocean.**

3. Key technological challenges

There are three foreseeable technological challenges in the study of organic molecules in the Enceladus ocean: (1) Simulations of plume formation and ejection into space; (2) Sampling the water; and (3) Providing analytical instruments with the best possible sample.

3.1 Simulations of plume formation and ejection

Enceladus is the only icy world known so far to have a sustained plume that samples a subsurface ocean, although hints of plume activity have been observed on Europa using remote imaging [31]. While our reconnaissance of icy moons in the outer Solar System has been limited to a few flythrough missions, plume activity in these bodies could be a common phenomenon. Given the relevance of plumes to investigate the interior of ocean worlds, it is important to understand how plumes form and are sustained through time, and how materials from the ocean, including organic molecules, change when they are ejected into space, due for example to rapid freezing, condensation or UV exposure. This requires both theoretical and empirical studies. Numerical plume simulations based on *Cassini* data have been used to constrain plume dynamics, particle density and particle size distribution [4,32]. We contend, however, that empirical studies would provide the most useful and reliable information, and would also provide analog samples that can be analyzed with prototype technology for future missions. But simulating plumes on icy worlds requires significant technological investment to recreate salt organic laden micrometer sized ice grains at 100 K, travelling at the spacecraft plume flythrough speeds as well as the vacuum and cold temperatures in the space environment. Current *ad hoc* solutions exist [e.g., 32], such as the use of high-speed vertical gun facilities at NASA ARC* (Fig 2), but these solutions are clearly not optimized. **Therefore, we recommend that that the next NASA Astrobiology Strategy emphasizes the need for technology funding to develop better “plume simulators”, in a way similar to efforts in the past decades to develop “planet simulators” using chambers (e.g., Mars simulation chambers).**

*[https://www.nasa.gov/sites/default/files/files/ames-vertical-gun-range-v2010\(1\).pdf](https://www.nasa.gov/sites/default/files/files/ames-vertical-gun-range-v2010(1).pdf)

3.2 Sampling the plume

In the context of Enceladus, sampling the ocean means an approach to analyze a sample—as small as a few micrograms, and scalable with probable improvements in limits of detection and/or certainty of result up to several grams—of the subsurface ocean. The plume of icy particles emanating from the South Polar Terrains provides direct access to the subsurface ocean without landing on the moon’s surface. As discussed in Section 3.1, how closely plume materials represent the composition of the subsurface ocean remains a significant knowledge gap. In addition to natural processes affecting the composition of plume materials, plume sampling technology needs to take into account the stability of organic molecules during sampling. High sampling speeds (i.e. >3-4 km/sec) would cause significant damage to molecules, which could complicate chemical and structural analyses. **Therefore, we recommend that that the next NASA Astrobiology Strategy emphasizes the need for technology funding to develop plume sampling devices, as well as investigations that seek to understand how organic molecules become altered during plume sampling.**

As an example, the ALE3D hydrocode has been implemented at NASA ARC to understand the behavior of ice grains colliding with sample collectors at high speeds. The development of “plume simulators” would be a key component in this effort. In addition, all available models of the Enceladus plume suggest that the amount of material collected after one plume flythrough could be very small (2-5 μL), and therefore microfluidic devices might be needed to handle the fluid, as discussed in the next section.

3.3 Provide analytical instruments with the best possible sample

The 2015 Astrobiology Strategy singles out certain techniques that in retrospect are relevant to the investigation of organic compounds in the Enceladus ocean, including melting and filtration of ice, followed by ultra-sensitive analysis using various chemical techniques such as immunoassays, lab-on-a-chip methods using capillary electrophoresis and laser induced fluorescence and ultra-sensitive mass spectrometry. However, it obviated the fact that in the case of plume samples, instruments must be able to handle tiny sample volumes (2-5 μL), and these sensitive analytical tools often require different sample handling and preparation functions, including: (1) Integrated pumping, metering, valving, and control of flow rate and pressure; (2) Filtering non-soluble particles by size; (3) *In-situ* measurement and adjustment, up or down, of both ionic strength (conductivity) and pH; (4) Admixture of reagents such as dyes, stains, and fluorescent labels; (5) Degassing and trapping of bubbles; (6) Distributing appropriately preprocessed sample aliquots to analytical instruments at the appropriate flow rate and total fluid volume, with repeat aliquots for redundant analyses that will increase the statistical power of the results.

Technology for handling and preparation of small liquid samples in the environment of space is still incipient. Over the past decade, NASA ARC has developed, space qualified, and operated a range of



Figure 2. The Ames Vertical Gun Range (AVGR) is typically used to simulate high-speed, celestial body impacts on a small scale, and recently it has been adapted to simulate plumes emanating from icy moons [33].

bioanalytical / bioprocessor systems that comprised the payloads of multiple nanosatellite missions to study living biological organisms in Earth orbit [34–37]. More development is needed to adapt these existing technologies, or invent new ones, for long-term Astrobiology missions to investigate plumes in the outer Solar System. **Therefore, we recommend that that the next NASA Astrobiology Strategy emphasizes the development of front-end microfluidic technology to handle and prepare small volumes of liquid samples, with the goal of maximizing the performance of back-end analytical systems.**

3.4 Contamination Control

Due to the low organic abundances expected in the Enceladus ocean [38], any mission that seeks evidence of life in plume materials must implement stringent cleanliness and contamination control protocols at all mission levels to prevent a false positive results. Here, contaminant material refers to any organic compound classes that are targeted by the mission, such as amino acids, which were not originated in the Enceladus ocean, and include terrestrial sources as well as other possible sources between Earth and Enceladus. We note that the required contamination plan will likely have to go beyond standard planetary protection requirements that are concerned with the transfer of viable terrestrial organisms, since non-viable terrestrial organisms could still be a source of organic material and cause a false positive result. **We recommend that that the next NASA Astrobiology Strategy emphasizes the need to define an adequate contamination control strategy to sample and analyze the Enceladus plume and also captures the need to fund and develop the technology necessary to implement that strategy.**

4. Summary of recommendations

-We recommend that the next NASA Astrobiology Strategy emphasizes the need for a hypothesis-based framework to assess the origin of organic matter (biotic or abiotic) in the Enceladus ocean.

-We recommend that that the next NASA Astrobiology Strategy emphasizes the need for technology funding to develop better “plume simulators”, in a way similar to efforts in the past decades to develop “planet simulators” using chambers (e.g., Mars simulation chambers).

-We recommend that that the next NASA Astrobiology Strategy emphasizes the need for technology funding to develop plume sampling devices, as well as investigations that seek to understand how organic molecules become altered during plume sampling.

-We recommend that that the next NASA Astrobiology Strategy emphasizes the development of front-end microfluidic technology to handle and prepare small volumes of liquid samples, with the goal of maximizing the performance of back-end analytical systems.

-We recommend that that the next NASA Astrobiology Strategy emphasizes the need to define an adequate contamination control strategy to sample and analyze the Enceladus plume and also captures the need to fund and develop the necessary technology to implement that strategy.

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