Sampling Plume Deposits on Enceladus’ Surface to Explore Ocean Materials and Search for Traces of Life or Biosignatures

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Received 2021 February 5; revised 2021 March 23; accepted 2021 March 24; published 2021 May 20

Abstract

Enceladus is unique as an astrobiology target in that it hosts an active plume sourced directly from its habitable subsurface ocean. Ice particles from the plume contain geochemical constituents that are diagnostic of the ocean conditions, and may hold traces of life and/or biosignatures, if they exist. Up to 93% of the plume particles fall back onto the surface of Enceladus. The low radiation environment and present-day activity are favorable to the preservation of any complex organics and putative biosignatures contained within these particles. Laboratory experiments and modeling suggest that plume deposits would likely be weakly consolidated and relatively easy to sample. Sampling systems like a dual rasp, under development to achieve technology readiness level (TRL) 5 in 2021, would enable a landed mission on Enceladus’ surface to acquire large amounts of surface materials, a requirement for analysis of trace constituents. A landed mission on Enceladus could greatly enhance our understanding of the chemical makeup of plume particles and the subsurface ocean, and seek traces of life and/or biosignatures.

Unified Astronomy Thesaurus concepts: Saturnian satellites (1427); Solid matter physics (2090); Laboratory astrophysics (2004); Astrobiology (74)

1. Introduction

Enceladus is the only currently known Ocean World where material from its subsurface ocean, which is thought to be habitable, is being actively ejected into space and onto its surface. Transient water vapor has been tentatively detected at Europa (Roth et al. 2014; Sparks et al. 2016; Jia et al. 2018; Paganini et al. 2020), but the presence of plumes and whether they originate from Europa’s internal ocean remain areas of active research. At Enceladus, a plume has been directly identified, and its vapor and particles have been analyzed by the Cassini mission (Dougherty et al. 2006; Hansen et al. 2006; Porco et al. 2006; Spahn et al. 2006; Tokar et al. 2006; Waite et al. 2006). A large fraction of plume particles is redeposited across Enceladus’ surface and could contain traces of life or biosignatures (Porco et al. 2017; Guzman et al. 2019; Cable et al. 2020).

Mission concepts have previously been proposed to capture particles in the plume via fly-throughs (Reh et al. 2016; Eigenbrode et al. 2018). While organic and biosignature molecules can survive and be analyzed after hypervelocity impact (Klenner et al. 2020a, 2020b; New et al. 2020a, 2020b), these concepts must mitigate small sample volumes per encounter and challenges in the contamination control of large collectors (McKay et al. 2020).

Landed mission concepts, which may be similar to the Europa Lander mission concept (Hand et al. 2017), would have their own challenges and could foreseeably be costly, however they would reduce or eliminate these risks. Critically, landed mission concepts would be able to acquire much larger amounts of plume material than plume fly-through concepts. This would allow for higher sensitivity to trace constituents, and enable a larger number of replicate analyses over a shorter time period, thereby providing more robust science results. For a detailed report on a potential flagship-class lander to address biosignature detection and other questions at Enceladus, see the Planetary Mission Concept Study entitled “Enceladus Orbilander” (MacKenzie et al. 2020).

In this article, we first present the rationale for seeking to analyze samples from plume deposit regions on Enceladus’ surface. Second, we present recent experimental results that suggest plume deposits would exhibit a low mechanical strength on Enceladus. Third, we describe a sampling system currently under development capable of acquiring plume deposit samples and transferring them to in situ instruments for subsequent analysis. Lastly, we provide a cursory description of potential analyses that may be conducted to seek the presence of life and/or biosignatures in the acquired sample(s).

2. Enceladus Emits Materials from a Potentially Habitable Interior Ocean, and These Materials are Largely Redeposited on the Surface

Cassini gravity data, in conjunction with surface images showing a libration (Thomas et al. 2016), indicate that Enceladus contains a global ocean beneath its ice shell (Iess et al. 2014). Cassini observed over 100 jets converging into a plume that originates from the south polar terrain of Enceladus (Porco et al. 2006), and particularly from a set of four rectilinear surface fractures dubbed the Tiger Stripes...
and CH$_4$, as well as nanograins of silica (Spitale & Porco 2007). The Tiger Stripes exhibit local thermal anomalies (Spencer et al. 2006; Howett et al. 2011) with a temperature up to 180 K (Spencer et al. 2009), while the rest of the south polar terrain is much colder, around 30–50 K (Howett et al. 2010). Intense tidal dissipation within the ice shell is likely responsible for the thermal anomalies and the existence of the plume (Nimmo et al. 2007; Spencer & Nimmo 2013). Evidence from Voyager observations and modeling from Cassini data suggest the plume is a long-lived phenomenon, persisting for decades and likely much longer (Haff et al. 1983; Hemingway et al. 2020).

Enceladus’ plume consists of vapor and particles: the particles are approximately micron-sized, mostly comprised of water ice, and feed Saturn’s E ring (Kempf et al. 2010). A subset (~40%) of the particles also contain percent-level NaCl and other salts by mass (Postberg et al. 2009, 2011), while a separate subset (~4%) contains complex organic materials, also at the percent level by mass (Postberg et al. 2018). The vapor phase of the plume includes ammonia, carbon dioxide, low-mass organics including CH$_4$, $^{40}$Ar (Waite et al. 2009), and molecular H$_2$ (Waite et al. 2017). $^{40}$Ar is formed from the radioactive decay of $^{40}$K, which suggests a direct connection between the silicate interior and the exosphere. Emissions of H$_2$ from radioactive decay of $^{40}$K, which suggests a direct connection between the silicate interior and the exosphere. Emissions of H$_2$ and CH$_4$, as well as nanograins of silica (Hsu et al. 2015), are strongly suggestive of ongoing hydrothermal activity, as they would leave the interior and escape in a short period of time. The moderately alkaline pH (8.5–9) derived for the ocean (Glein et al. 2015; Glein & Waite 2020), the presence of complex organic materials, and the abundant geothermal energy from the interior and within the south polar terrain provide evidence for habitability and the enticing prospect that life may have emerged and still be present within Enceladus (McKay et al. 2008, 2014, 2018).

Cassini observations of particles in the Enceladus plume and the E ring enabled the determination of their particle size distribution and their trajectories, and the modeling of their deposition rate back onto Enceladus’ surface. The mean radius of equivalent-sphere particles determined from imaging is $3.1 \pm 0.5 \mu$m (Ingersoll & Ewald 2011). The Cassini Cosmic Dust Analyzer characterized the vertical structure of the plume, from which a particle ejection model was established (Schmidt et al. 2008). The deposition of plume particles could then be computed as function of particle size, source location, and location on Enceladus’ surface (Kempf et al. 2010; Southworth et al. 2019). Particles in the range 0.1–5 $\mu$m are expected to dominate the plume surface deposits. The average deposition rate is on order of 1 $\mu$m yr$^{-1}$ across Enceladus’ entire surface, but can exceed 0.1 mm yr$^{-1}$ in locations close to jet sources (Kempf et al. 2010; Southworth et al. 2019). This is roughly consistent with a separate model that suggests 68%–93% of all plume particles are deposited on the surface (Porco et al. 2017).

The relatively fast deposition rate in regions close to the jet sources could be seen as inviting the direct collection of plume particles as they fall (Porco et al. 2017), rather than sample acquisition from the surface where some processing might occur between deposition and collection. However, in the subsequent sections we show that such processing is anticipated to be minimal. Furthermore, even in regions with a high plume deposition rate, collecting a sample volume large enough to enable detection of trace constituents would likely still require months. A surface mission concept with such longevity would undoubtedly benefit from analyzing samples acquired directly from the surface in tandem with the collection of plume fallout (MacKenzie et al. 2020).

3. Traces of Life and/or Biosignatures Could be Preserved in Plume Deposits

In comparison to Europa, the radiation environment of Enceladus’ surface is benign, enabling preservation of organic molecules on the surface for relatively long timescales. Both particle and ultraviolet radiation can have degradative effects on biosignatures. Uniquely on Enceladus, these effects are modulated by the continuing deposition of fresh plume particles, which scatter or absorb radiation and shield buried particles.

The flux of magnetospheric particle radiation at Enceladus is relatively low. While detailed studies on the particle irradiation at Enceladus are not available to date, we can use the radiation environment of Saturn’s neighboring moon Mimas as a worst-case analog for Enceladus. Indeed, Mimas is the major moon of Saturn that is most subject to irradiation (Paranicas et al. 2012, 2014; Nordheim et al. 2017). At the most irradiated location on Mimas’ surface, the time to reach a 100 eV/16 amu electron dose accumulation (a standard unit representing a chemically significant dose) is about 100,000 yr at a depth of 1 mm (Nordheim et al. 2017). In comparison, at the same depth on Europa, such a dose would be accumulated in only 100–1000 yr (Nordheim et al. 2018). Thus, shallow material in regions of plume deposition at Enceladus will be minimally processed by charged particle irradiation. Galactic cosmic rays deliver radiation doses that are many orders of magnitude lower than that from magnetospheric particles (Nordheim et al. 2019), thus do not need to be considered as a degradation mechanism on the short timescales appropriate to Enceladus’ continually deposited plume particles.

Solar ultraviolet irradiation can also degrade organic biosignatures. Generally, the most damaging radiation is in the vacuum ultraviolet (VUV), with wavelengths shorter than approximately 150 nm. Light at these wavelengths has absorption lengths (the distance light travels before its intensity decreases by a factor of $e$) of less than 0.1 $\mu$m in a single crystal of water ice (Warren 1984; Warren & Brandt 2008). This indicates that organic molecules embedded within micron-sized plume particles will be almost entirely shielded from damaging VUV radiation. Continuous deposition of plume particles on the surface would provide additional shielding. For the purposes of this article, we set a limit of 10% degradation in order to state that the original quantity was “preserved”; this would allow the faithful reconstruction of molecular abundance patterns (fatty acids, amino acids) that could provide evidence of biologic activity.

Longer-wavelength ultraviolet radiation is also damaging to organic molecules. The electronic absorption spectrum of these large molecular species overlaps with the solar spectrum in most cases, leading to photolysis (breaking covalent bonds). Laboratory experiments have explored the degradation rate at these long wavelengths for amino acids in ices at low temperatures (Orzechowska et al. 2007; Johnson et al. 2012). For example, the photolytic half-lives of the amino acids glycine and phenylalanine are 6.5 and 4.5 yr at 206 nm, and 5 and 1 yr at 254 nm, respectively, under solar flux levels representative of Europa’s surface (Johnson et al. 2012).

Extrapolating these wavelength-dependent photolysis rates to the solar spectrum, one can convolve the photolysis spectra
with the photon spectrum at Enceladus over time and predict the degradation of these organics at Enceladus’ surface. Figure 1 shows an example of such a calculation for glycine, made with the following assumptions. An average solar photon flux of $8 \times 10^{12} \text{ cm}^{-2} \text{ yr}^{-1}$ over the 100–320 nm range is used, as expected at 60°S latitude. The ice is only composed of water and glycine at a 1000:1 ratio in this simple simulation. This calculation does not account for plume redeposition. Despite these conservative assumptions, the degradation rate of glycine appears to be less than 10% at 100 μm depth over one year.

These results suggest that, at locations on Enceladus where deposition rates are high (0.01–0.1 mm yr$^{-1}$ and higher), the deposition of plume particles would effectively shield amino acids from photolytic degradation. Broadly, we expect that most other organic molecular biosignatures would have photolytic half-lives of the same order of magnitude as amino acids, but this warrants further work to identify any particularly important but susceptible families of molecules. Furthermore, the preliminary calculations shown in Figure 1 do not include scattering by ice particles, which is anticipated to further reduce the penetration depth of UV photons (Johnson et al. 2012). Future modeling work may bring additional constraints on the topic by including more complex effects and more relevant molecules to elucidate the longevity of biosignature molecules at various locations on Enceladus.

4. Plume Deposit Regions on Enceladus’ Surface are Likely to be Weakly Consolidated, Even after Extensive Periods of Time Postdeposition

Plume deposits are expected to consist initially of fine-grained ice particles loosely in contact, forming a granular and unconsolidated material. This material would then slowly thermally sinter over time and become more consolidated (Blackford 2007; Molaro et al. 2019). Understanding the mechanical properties of plume deposits and how they evolve over time is critical to the design, development, and testing of landing, sampling, and mobility systems aiming to explore Enceladus’ surface.

A recent laboratory study (Choukroun et al. 2020) investigated the evolution of mechanical resistance upon sintering of fine-grained ice particles with diameters comparable to Enceladus’ plume particles. Cone penetration resistance measurements were obtained as a function of time and at different temperatures (Figure 2(a)). An Arrhenius analysis of the strengthening rates yielded an activation energy of $24.3 \pm 3.3 \text{ kJ mol}^{-1}$, which was then used to predict the strength evolution of plume deposits under Enceladus and Europa’s surface conditions (Figure 2(b)).

A second laboratory study explored in a preliminary manner the unconfined compressive behavior of porous sintered ice. The samples consisted of ice microspheres sintered at 193 K for 436 days (Choukroun et al. 2020). Cylindrical-shaped specimens (~20 mm diameter × 25 mm height) were extracted via coring of a large sample, then uniaxially compressed at constant strain rates ranging from $3 \times 10^{-4}$ to $3 \times 10^{-2} \text{ s}^{-1}$ using an MTS model 810 servo-hydraulic loading system housed within a cold room held at 248 K at Dartmouth’s Ice Research Laboratory. Photographs of the samples and stress–strain curves are shown in Figure 3.

When shortened at the lower rates, first by 14% at $3 \times 10^{-4} \text{ s}^{-1}$ followed by fast unloading and then by shortening an additional 15% at $3 \times 10^{-3} \text{ s}^{-1}$, the ice exhibited ductile behavior marked by barreling (Figure 3(b)) and strain-rate hardening (Figure 3(e)). Also, density increased from 675 ± 5 to 734 ± 5 kg m$^{-3}$, accounting in part for the apparent strain hardening during the first stage of deformation. At the higher rate of $1 \times 10^{-2} \text{ s}^{-1}$, the ice behaved in a transitional manner, marked by a maximum in strength, by a slow fall to zero in load-bearing ability (Figure 3(e), red curve) and by failure via axial splitting (Figure 3(d)). From these compressive test results, we interpret that a ductile-to-brittle transition occurred at a strain rate around $10^{-2} \text{ s}^{-1}$, from ductile behavior at lower rates to brittle behavior at higher. At the highest rate of $3 \times 10^{-2} \text{ s}^{-1}$, the ice disintegrated (not shown). Ductile behavior was characterized by strain-rate hardening where the flow stress scales as a strain rate to the power of 0.28. The transition in behavior was evident from the appearance of the deformed ice and from the stress–strain curves (see Figure 3). The transition strain rate is about two to three orders of magnitude higher than that of pore-free, coarsely-grained (~6 mm) ice at the same temperature (Schulson & Duval 2009), owing principally to the finer microstructure of the Enceladus-like material, as expected from theory (Schulson 1990).

The compressive stresses applied on the samples to sustain the range of imposed strain rates are within the range ~2–8 MPa. This range of values of compressive strength is commensurate with the cone penetration resistance of sintered ice samples of that age, also on order of a few megapascals. Similarly, in weakly consolidated snow of <1 MPa cone penetration resistance, McCallum (2012) reported unconfined compressive strength values of the same magnitude. Taken together, these results suggest that cone penetration and unconfined compressive strength of porous granular ice are of the same magnitude and evolve in a similar manner upon sintering. Future studies are needed to verify and further characterize this relationship between the two properties.

Based on these results, plume deposits on Enceladus are expected to be weakly consolidated. It would take plume
deposits at least 100 Myr to develop a resistance of 1 MPa under Enceladus’ nominal surface conditions. Deposits near the Tiger Stripes, where strengthening rates would be much higher due to the higher surface temperature, would also be covered by fresh unconsolidated particles at a rate up to ~1 mm yr⁻¹ (Kempf et al. 2010; Southworth et al. 2019). Therefore, near the most active regions of Enceladus’ surface, the surface material is likely to be weakly consolidated and exhibit both a cone penetration resistance and a compressive strength below 1 MPa.

5. A Dual-rasp Sampling System Could Acquire Large Sample Volumes from Plume Deposit Regions and Transfer Them to In Situ Analytical Instrument(s)

Due to the continuous resurfacing via the deposition of plume particles, a future landed mission to Enceladus would likely have unique sampling requirements compared to previous missions targeting other destinations. The sampling system of an Enceladus surface mission should be capable of acquiring plume deposit material from a potentially wide range of strengths in the low, 1% Earth gravity vacuum environment. Given the expected plume...
deposit strength of <1 MPa (Choukroun et al. 2020), and allowing for strength uncertainty and need for mission robustness, the sampling system should be able to sample from surface material up to about 10 MPa cone penetration strength. In addition, it is likely be preferred that the sampling system acquire shallow surface material in the top few centimeters, since this would be the freshest plume material that has fallen to the surface. Fresh material is less likely to have been altered by VUV radiation, impact gardening, or other processes, and is more likely to be representative of the current state of Enceladus’ subsurface ocean. A sampling system capable of collecting various sample volumes up to tens of cm³ would provide versatility for multiple instruments and enable detection of trace (sub-ppb) constituents. These unique sampling requirements drive the need to design a new sampling system for potential future Enceladus missions.

Prior sampling systems were designed for different applications and requirements that make them less suited to Enceladus’ environment. Samplers developed solely for use in loose material could potentially be adequate for fresh plume deposits, however they may not be suitable for the entire range of possible material strengths. The OSIRIS-REx mission’s TAGSAM (Touch-And-Go Sample Acquisition Mechanism) was developed for the loose surface material of an asteroid (Beshore et al. 2015). The Pneumatic Sampler for the Japanese Aerospace Exploration Agency’s Martian Moons eXploration (JAXA MMX) mission is being designed for the loose surface of Phobos (Zacny et al. 2020b). The Rosetta mission’s Philae lander rotary drill, SD2 (Sampler, Drill, and Distribution), was designed to acquire a subsurface comet sample (Finzi et al. 2007) so would not be ideal for acquiring shallow surface material. The planned NASA Dragonfly mission’s DrACO (Drill for Acquisition of Complex Organics) sampler was designed for sampling in the relatively high-gravity and high-atmospheric-pressure environment of Titan (Zacny et al. 2020a). The Mars Phoenix ISAD (Icy Soil Acquisition Device) scoop with rasp was designed for the relatively high Mars gravity environment (Bonitz et al. 2008) for capturing samples in the scoop and transferring them to instruments.

The Dual-Rasp sampling system provides the capabilities needed to acquire surface samples for an Enceladus-landed mission (Backes et al. 2020). The low 1% Earth gravity environment of Enceladus limits the allowable reacted load from the sampling activity to a lander to less than about 8 N (Badescu et al. 2019). At Mars, the Phoenix rasp acquired icy samples while it only applied a 6 N preload against the surface (Bonitz et al. 2008), demonstrating the capability of rasps to sample strong materials while imparting very low reactive forces. Other sampling tools such as drills and scoops require higher reacted loads, even to acquire samples from a 1 MPa cone penetration strength material.

The Dual-Rasp sampling system has been developed to technology readiness level (TRL) 4 (Figure 4(a)) and is under development to achieve TRL 5 in 2021. The sampler has counterrotating rasps that break apart surface material and throw it up between them for capture in a collection cup (see Figure 5(a)). The rasps are able to acquire a wide range of weak to strong materials with a low sampling preload.

The Dual-Rasp sampling system could be deployed from a lander by a two degree-of-freedom robotic arm which would allow for sampling in an arc in front of the lander (Figure 4(b)) while enabling pneumatic sample transfer through rigid pneumatic tubes. Cuttings created by the rasps and thrown up into a guide are directed into the sample collection cup. The guide is shaped as an ellipsoid with the rasps at one focus and the second focus at the entrance of the sample collection cup. After the desired sample volume (initially designed for up to 5 cm³, but adaptable for larger sample volumes) has accumulated in the sample cup, the cup would be covered and compressed gas from a tank on the deployment arm would lift and transfer the sample. The sample would travel from the collection cup through a rigid tube into the deployment arm and through passive pneumatic joints at the arm base to arrive at a sample handling system for science instruments on the lander. Optical sample flow measurement in the pneumatic transfer tube would be used to determine if a sufficient sample volume has been transferred. An example sample flow measurement sensor is the Honeybee Robotics Beam Breaker for the JAXA MMX mission sampling system (Zacny et al. 2020b).
6. Concept-specific Instruments Could Subsequently Analyze the Composition of the Sample(s) and Seek Traces of Life and/or Biosignatures

A detailed description of the suite of analyses that might be conducted on the acquired sample(s) to determine the presence of life and/or potential biosignatures goes beyond the scope of this article. Indeed, each mission concept may develop its own approach for analyzing the organic content and determining the presence of extinct and/or extant life in the sample(s) while accounting for concept-specific resource availability constraints (mass, power, total energy, payload accommodation volume, data storage and downlink capabilities, cost, etc.).

In general, life- and habitability-seeking mission concepts include multiple independent tests for life, following the “Ladder of Life Detection” strategy (Neveu et al. 2018). Aside from typical organic chemistry analyses, it is anticipated that the presence of life may be inferred, for example, from the observation of motile organisms, and/or isotopic signatures of potentially biological metabolic products, and/or distribution of chiral amino acids, and/or presence of molecules that achieve specific functions essential to biological activity. Depending on the instrument sensitivity and estimated putative biomass the Enceladus ocean might support (Cable et al. 2020), some payload elements might require sample volumes on the order of 1–10 cm$^3$ or greater to reach limits of detection better than 1 cell ml$^{-1}$. The Dual-Rasp sampling system would provide a sufficient volume of fresh surface material to achieve such science objectives.

7. Conclusions

Plume deposit regions on the surface of Enceladus could provide an opportunity for planetary missions to investigate the composition of another solar system ocean and determine if life exists and potentially originated independently of Earth. The plume deposits likely reflect and preserve the composition of the internal ocean and could contain possible traces of life and biosignatures.

The Enceladus surface environment presents unique, but not insurmountable, challenges for sampling including low gravity, vacuum, cryogenic temperatures, and a science preference for shallow (and therefore young) surface samples. The novel Dual-Rasp sampling system uniquely provides the capabilities necessary to acquire the required surface samples and transfer them to an in situ analytical chemistry instrument (or suite thereof) to evaluate the habitability potential of Enceladus and seek potential traces of life and/or biosignatures. The Dual-Rasp sampling system is under development to achieve TRL 5 in 2021 to make it available for an Enceladus-landed mission in the next decade.

Plume deposits on Enceladus’ surface may provide the most direct access to large amounts of well-preserved ocean materials, thereby enabling one of the most promising ways to search for traces of life and biosignatures in the outer solar system. Until an in situ mission concept is selected and developed for flight, recent research efforts provided first insights into the feasibility of such a concept.

Laboratory experiments have placed important bounds on the range of mechanical properties of ice plume deposit analogs, and future studies will continue to refine these values. More specifically, these experiments provided the first indications of the impact of sintering state on cone penetration resistance and unconfined compressive strength of plume deposits. A more refined understanding of these properties, their interrelations, and other properties such as flexural strength and fracture toughness, is needed to fully predict the interactions of landing and sampling elements with surface plume deposits.

Along the same lines, the photolytic degradation of organic molecules is a vast research topic, and future studies are needed to improve our understanding of the UV degradation of relevant types of organic molecules, particularly under Enceladus-like conditions and as a function of location on the surface. Such future research endeavors could make an important contribution to a program dedicated to the exploration of Ocean Worlds.

Part of this work has been conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. The authors are grateful to two anonymous reviewers for their comments on this manuscript. Support by
