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Topics

Exploration of Enceladus' Water-Rich Plumes toward Understanding of Chemistry and Biology of the Interior Ocean

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Enceladus is the only icy satellite known to exhibits on-going geological activity of water-rich plumes derived from the interior ocean. Here, we propose a sample return and in-situ measurement mission for Enceladus' plume materials. Depending on the cost, mission duration, and propulsion system, we propose three types of missions to Enceladus; type 1: free-return trajectory, type 2: trajectory orbiting Saturn, and type 3: trajectory orbiting Enceladus. Type 2 and 3 are preferable to type 1 in order to achieve lower encountering velocity to the plumes (> 4 km/s and 0.2 km/s for type 2 and 3, respectively) and, thus, to collect multiple and intact samples. High resolution mass spectroscopy of the gas components will provide essential information to understand the physical and chemical conditions of both the interior ocean and the solar nebula. Furthermore, detailed onboard and onshore analyses of returned samples could provide geochemical, preboplogical, and, potentially, biological context in the interior ocean of Enceladus.

Key Words: Enceladus, Icy Satellite, Outer Solar System, Sample Return, Electric Propulsion

1. Introduction

1.1. Enceladus' plumes

One of the most remarkable findings by the Cassini mission is perhaps water-rich plumes erupting from warm fractures near the south-pole region of Saturn's icy moon, Enceladus[1]. In-situ mass spectroscopy by Cassini has revealed that the gas component of the plumes consists mainly of H_2O with significant amounts of CO_2, NH_3, CH_4, and organic matter (such as, alcohols, aldehydes, and hydrocarbons)[2]. The solid component of the plumes includes H_2O ice, sodium salts, silicates, organic materials, and carbonates[3,4]. Given such geological activity and chemical composition of the plumes, Enceladus is highly likely to contain a volatile-rich interior ocean interacting with the rocky core[2-4].

Some of the large icy satellites in the outer solar system (such as Europa, Callisto, and Titan) show signs of the presence of an interior liquid ocean[5,6]. However, geological and geochemical processes occurring in the interior oceans have been largely unknown due to lack of direct measurements and sampling of the materials derived from the interior oceans. Because Enceladus is the only icy satellite known to exhibit ongoing geological activity, its plumes provide a unique opportunity for understanding chemical processes and habitability of the interior ocean.

1.2. Questions raised by Cassini

The Cassini spacecraft has revealed that liquid water persists to the present in Enceladus[2-4], however it also raises many questions regarding interior structure and geochemical processes in the ocean. The followings are a summary of questions raised by Cassini.

Geochemical processes & oceanic compositions: The chemical composition of the oceanic water and alteration minerals is essential to constrain geochemical processes occurring in Enceladus' ocean, however, these are still largely unknown. The Cassini cosmic dust analyzer (CDA) revealed the presence of sodium salts, carbonates, and silicates in the plumes[3,4], but the measurements of absolute abundances and compositions of silicate and salts are poorly constrained due to low-resolution of the mass spectrometer of the Cassini CDA. For instance, the CDA signals of Mg derived from the silicates in the plumes were largely overlapped by those of Na originated from the salts[3], leading to a large uncertainty in the detailed composition of alteration minerals in the plumes. In addition, the Cassini Ion Neutral Mass Spectrometer (INMS) cannot separate the gas species that have the same mass number. In particular, although CO, N_2, and C_2H_4 are important molecules that could reconstruct the temperature conditions of the ocean, there are still multiple interpretations for the gas composition of the plumes based on the INMS observation data[2)].

Furthermore, it will be also essential to reduce relative velocity between a spacecraft and plume during sampling. Quantitative measurements of H_2 and CO in the plume will provide clues for redox conditions of water-rock interactions and biological potential in Enceladus' ocean[7)]. However, the flyby velocity of the Cassini spacecraft is high (e.g., ~8–18 km/s), which may have induced thermal dissociation of H_2O into H_2 and CO_2 into CO during sampling[8)]. Accordingly, the H_2 and CO concentrations in the plumes and their original concentrations in the ocean are poorly constrained by the Cassini spacecraft. Reduction of the flyby velocity is also important to collect intact solid samples in future sample-return missions, because hydrated silicates and carbonates are typically decomposed around 1000 K (refs. 9 and 10), which is achieved in impacts at > several km/s. These indicate that separation of the gas species with in-situ instruments, high-resolution mass spectrometry, and reduction of the flyby velocity will be necessary in future missions to understand the chemical compositions of the oceanic water and minerals.

Early solar system & isotopic compositions: Isotopic compositions of C, N, O, and H of primordial volatiles would provide information on physical properties at the Saturn-forming region in the solar nebula. According to the recent planetary disk models, it is suggested that primordial volatiles had different isotopic ratios in the pre-solar molecular clouds and/or outer regions of the solar nebula[11-13)]. In the outer region of the disk, these pre-solar isotopic values would have been preserved due to low temperatures. But, in the inner, higher temperature regions, isotopic exchanges would have occurred. There are some models that calculate the isotopic exchanges in the early solar system, but the results largely depend on the disk temperature, gas viscosity, and timing of gas dissipation[11)]. Thus, if the profile of isotopic compositions of primordial volatiles can be determined as a function of distance from the sun, it would be useful to constrain these parameters of the solar nebula, which is critical for planetary formation theory.

Although the Cassini INMS has found that D/H ratio of H_2O of Enceladus' plume is close to those of comets[2)], the isotopic compositions of other major volatiles, such as NH_3, CO_2, and CH_4, have not been reported. In particular, nitrogen in the solar system is not isotopically uniform[14)]. In the Saturn-forming region in the solar nebula and Saturnian subnebula, NH_3 is the predominant source of N trapped in icy planetesimals[15)]. Because Enceladus' plumes contain significant amounts of NH_3 (ref. 2), its nitrogen isotopic values would provide primordial values at the Saturn-forming region and/or in the Saturnian subnebula, which is useful to constrain the conditions of the solar nebula and the Saturnian system[16)].

To measure isotopic compositions of the gas, separation of the gas species and high-resolution mass spectrometry/infrared spectrometry will be required. Detailed analyses of returned samples will provide more direct and precise data on the isotopic compositions of the plume materials.

Internal structure: Information of the interior structure and surface features of Enceladus are essential for understanding its thermal history and heating mechanisms that sustain liquid water in Enceladus. The results of crater counting on Enceladus by Cassini indicate a wide range of surface ages, suggesting remarkable differences in geological activity between regions[1)]. The northern heavily-cratered plains show surface ages as old as ~4.2–1.7 billion years, whereas the south-pole terrain, where warm fractures are located, exhibits very young ages (i.e., < 0.1 billion years) (ref. 17). Such a hemispheric north-south asymmetry may reflect a local liquid ocean beneath the icy crust near the south-pole region[18)]. Alternatively, a global ocean may be necessary to cause large tidal deformation, which in turn maintains a liquid water reservoir over long periods[17)].

In addition to the location of the ocean, the depth of a water reservoir in Enceladus is also poorly understood. If Enceladus possesses a warm core[18)], its plumes would have been originated from water-rock interface in the deep interior. Matson et al. [2012] propose that the plumes would have come from water chambers near the surface along with warm fractures, where pressure-driven circulation from the deep oceans sustains liquid water[19)]. On the other hand, shear heating at the surface by tidal stress could have melted or sublimated ice in the crust, which produce the plumes[20)]. To summarize, the size, location, and depth of the ocean are still controversial, which induce large uncertainty in the persistency and thus habitability of the ocean.

Magnitude and pattern of surface displacement in response to tidal stress is very sensitive to the location and volume of a liquid-water reservoir. Additionally, if the plume sources are located near the surface, thermal emission anomalies would be observed from extensive areas near from the warm fractures of Enceladus[19)]. In future missions, high-priority measurements will commit to high spatial resolution imaging and thermal emission mapping, combined with measurements of surface displacement and gravity, by a spacecraft orbiting Enceladus.

2. Mission Concept and Scientific Goals

To summarize, there are three major questions raised by Cassini; that is, the chemical composition of the oceanic water and alteration minerals, isotopic compositions of the plume materials, and interior structure of Enceladus. These will be the high-priority observation targets in future missions. As discussed above, the key challenges to answer the questions are separation of gas species, high-resolution mass spectrometry (and infrared spectrometry), and reduction of flyby velocity between the spacecraft and the plumes. If possible, sample return would provide more precise and direct information on the chemical and isotopic composition of the plume materials. To understand the size and location of the ocean, measurements of surface displacement and gravity of Enceladus are essential.

We propose a sample return and in-situ measurement mission for Enceladus' plume materials with aims at understanding "habitability" of the icy moon. More particular, the mission goals include to understand the chemical composition of and geochemical processes in the interior ocean, constrain the physical and chemical conditions of the protoplanetary disk, and investigate the potentially biological signature in the plumes.

2.1. Trajectory

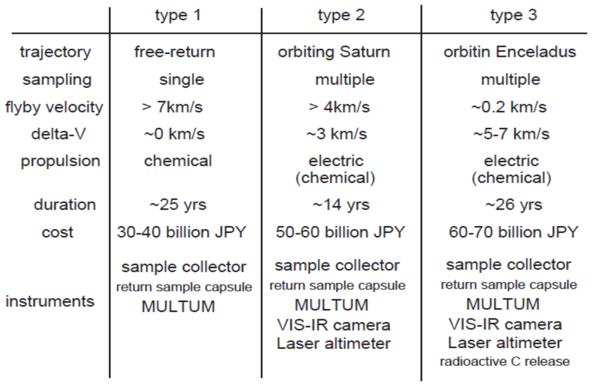
Depending on the cost, mission duration, and propulsion system, we consider three types of trajectories for the mission; type 1: free-return trajectory, type 2: trajectory orbiting Saturn, and type 3: trajectory orbiting Enceladus. The type 2 mission is similar to another sample return mission for Enceladus

(LIFE: Life Investigating For Enceladus) independently proposed by others[21].

Table 1 summarizes the comparison of these three types of mission to Enceladus. To achieve low flyby velocity (> ~4 km/s and ~0.2 km/s for type 2 and 3, respectively: Table 1) and, thus, to collect multiple, intact samples from the plumes, type 2 or 3 are preferable to type 1 (see below in Sec. 3.2 for more detail). Figure 1 shows an example of trajectory for the type 3 mission. In type 2, the total mission duration is estimated ~14 years. It will take ~8 years to arrive at the Saturnian system with both a Venus-Earth-Earth gravity assist and Jupiter gravity assist. The mission delta-V for type 2 is estimated to be ~3 km/s (Table 1). In type 3, the mission duration become ~26 years, which depends on the spacecraft weight and the trajectory to Saturn. It will take ~12 years are required to arrive at the Saturnian system with a Venus-Venus-Earth-Earth gravity assist. The total mission delta-V is estimated to be ~5–7 km/s for type 3 (Table 1).

Given the sample return mission to Enceladus at ~10 AU, there are two possible propulsion systems. First is a combination of a radioisotope generator with chemical propulsion, which can be used for type 1 mission. The other is electric propulsion with a solar power sail system[22]. To achieve the relatively large mission delta-V and to acquire an adequate mission payload for the instruments shown below, electric propulsion, such as a solar power sail system[22], will be preferable for type 2 and 3. Electric propulsion will be used during the SOI (Saturn orbit insertion) phase and every small delta-V maneuver between gravity assists with satellites, and will contribute to reducing the fuel consumption for the large delta-V. Currently, solar power sail for Jovian Trojan asteroid exploration is being studied based on the technology demonstration results of small solar power sail spacecraft "IKAROS[22]." Further development of solar power sail such as extending the sail area and improving the solar power generation efficiency will enable type 2 and 3 missions in the Saturnian region.

Table 1. A summary of trajectory, sampling velocity, propulsion system, total delta-V, mission duration, approximate mission cost, and spacecraft instruments for type 1–3 missions to Enceladus. The total delta-V and mission duration shown here are one example of our deliberation. The mission cost is estimated based on those for other spacecraft missions with a similar spacecraft size and instruments onboard.



	type 1	type 2	type 3
trajectory	free-return	orbiting Saturn	orbitin Enceladus
sampling	single	multiple	multiple
flyby velocity	> 7km/s	> 4km/s	~0.2 km/s
delta-V	~0 km/s	~3 km/s	~5-7 km/s
propulsion	chemical	electric (chemical)	electric (chemical)
duration	~25 yrs	~14 yrs	~26 yrs
cost	30-40 billion JPY	50-60 billion JPY	60-70 billion JPY
instruments	sample collector return sample capsule MULTUM	sample collector return sample capsule MULTUM VIS-IR camera Laser altimeter	sample collector return sample capsule MULTUM VIS-IR camera Laser altimeter radioactive C release

2.2. Science of sample return and in-situ measurement

The spacecraft instruments include a capturing and retention system of plume materials, return sample capsule, and a high-resolution mass spectrometer for the three mission types (Table 1). In addition to the above, a laser altimeter and visible infrared camera will be included in the spacecraft instruments for type 2 and 3. In type 3, biological investigation, such as carbon assimilation experiment, will be performed by release of radioactive ^{14}C-labeled carbon to the collected samples. The spacecraft instruments and prospective observations for each type mission are summarized in Tables 1 and 2, respectively.

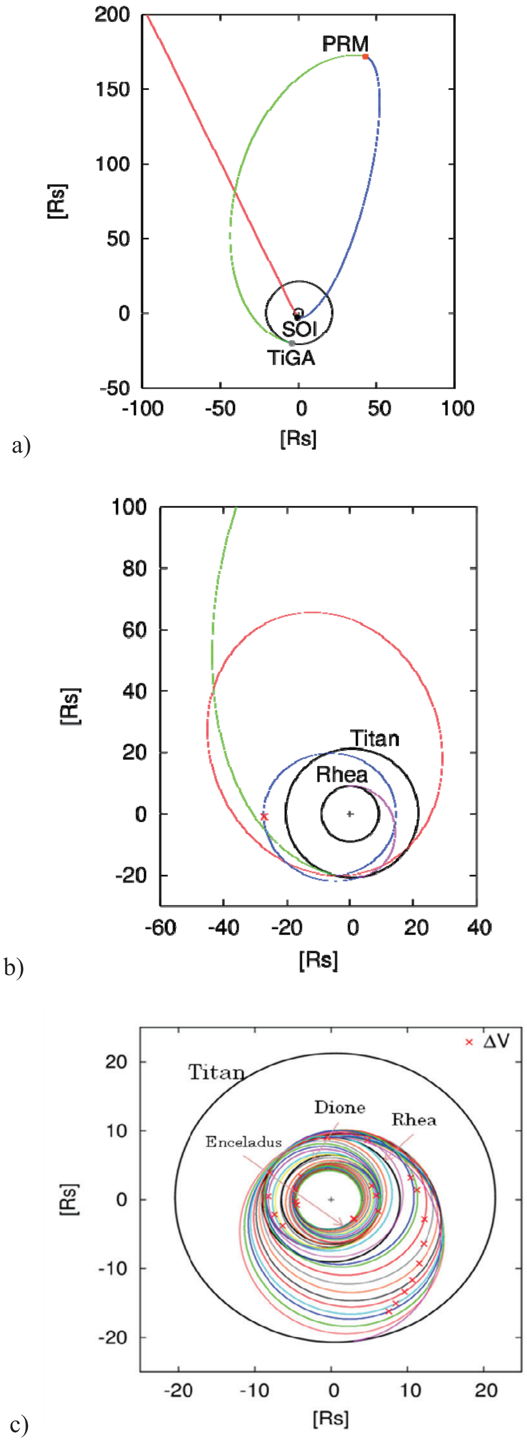


Fig. 1. An example of trajectory of type 3 mission. The symbol R_s in the diagrams is Saturn's radius. A diagram of a) Saturn orbit insertion (SOI) and Periapsis raising maneuver (PRM), b) Titan gravity assist trajectory to target Rhea, and c) multiple gravity assist trajectory from Titan to Enceladus using Saturnian satellites. Rhea, Dione, and Enceladus are used for gravity assists in order to achieve low delta-V trajectory.

Capturing system and return sample analyses: As mentioned above, the solid plume particles contain H_2O, sodium-rich salts, silicate, carbonates, and organic matter. For intact collection of hydrous silicate, carbonate, and organic matter, the sample capturing and retention system will consist of a silica aerogel collector, which was used in the Stardust mission[23]. Because the size of the solid particles in the plumes is typically less than 1 μm (refs. 3 and 4), a metallic plate collector system also will be used to collect solid samples. This is because it is usually difficult to find and collect sub-μm-sized particles captured in aerogel. According to the previous results of the laboratory experiments on hypervelocity impacts[9,10,16,24], hydrous silicates, carbonates, NH_3-bearing materials, and refractory organic matter will be able to collect without significant thermal alterations during capturing in type 2 mission (i.e., sampling velocity of ~4 km/s) (Table 2). In type 3 (i.e., sampling velocity of ~0.2 km/s), even soluble organic matter, including life-related organic materials, also could collect without significant alterations with the metallic plate collector (Table 2).

Detailed organic/inorganic, mineralogical, and isotopical analyses will be performed for the retrieved solid samples (Table 2). From the point of view of planetary protection and back-contamination[25], the returned sample capsule will be landed and collected on international water with a large research vessel[26]. Given biological potential of returned samples, initial handing will be performed offshore on a research ship, which will possess a laboratory to higher bio-safety level 4 standards[26]. After initial handing and declaration of the safety statement, the detailed analyses will be performed onshore with various instruments for microprobe analyses, including a nano-SIMS (Secondary ion mass spectrometer), TOF-SIMS (Time of flight secondary ion mass spectrometer) ^{13}C-/proton- NMR, and synchrotron radiation facility. The detailed compositions of salts and hydrous silicates will provide answer for the oceanic pH and redox conditions of Enceladus' ocean. Isotopic investigations of three oxygen isotopes (^{16}O, ^{17}O, and ^{18}O) for silicates, carbonates, H_2O, and CO_2 will be important to understand the solar nebular chemistry and interior processes. Isotopic fractionation of carbon between CO_2, carbonate, and organic matter will be a proxy for reconstructing temperature conditions and biological potential in the interior. The detailed chemical composition and structure of high-weight organic molecules in the returned samples also will be analyzed, together with approaches in molecular chirality[27,28,29]. The results will be compared with those of organic materials contained in meteorites and asteroids retrieved by future sample return missions, such as MarcoPolo-R, Osiris-REx, and Hayabusa 2. These results will allow us to discuss more concrete reaction pathway of chemical evolution in the solar system.

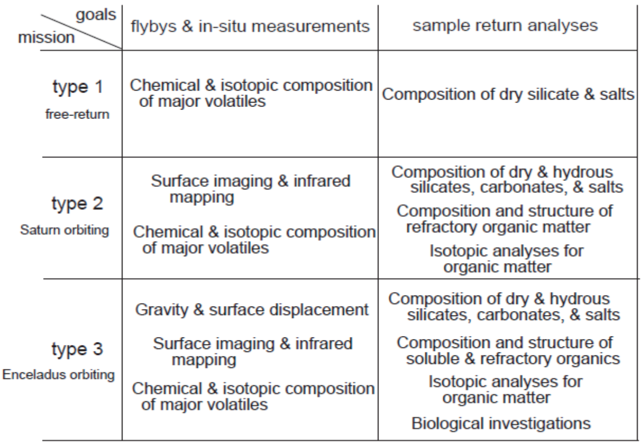
In-situ analyses: High-resolution gas analysis for Enceladus' plume will be performed with a multi-turn time of flight mass spectrometer (MULTUM)[30,31]. The MULTUM's mass range is 2–1000 amu with mass resolution of 10000–50000 (refs. 30 and 31). Thus, separation of N_2, CO, and C_2 hydrocarbons is possible. The MULTUM will be combined with a gas-chromatograph with micro-total analysis system[32], which focuses to separate major gas components, such as H_2O, CO_2, NH_3, CH_4, and other light hydrocarbons (Table 2). For detailed isotopic analyses, including ^{17}O, a high-resolution infrared spectrometer would be required to measure the three isotopic ratios of oxygen with high accuracy. A possible candidate of the infrared spectrometer is the tunable laser spectrometer aboard Curiosity[33]. This laser spectrometer is capable of measuring the carbon and oxygen isotopic ratios of water vapor and CO_2 (ref. 33).

In type 1 and 2 missions, icy particles would evaporate during the capture on the metallic plate collector due to relatively high sampling velocities (> ~4 km/s for type 2 and > ~7 km/s for type 1) (Table 1). These volatiles will be collected in a cold trap in the collector system and be analyzed with the MULTUM through step-wise heating. Pyrolysis-MULTUM also will be performed in the spacecraft for organic matter collected on the metallic plate collector. McKay et al. [2008] suggest that because life on Earth uses only a few discrete molecules to build the main structures[7], possible life on Enceladus also might be expected to select certain molecules. Because intact capturing of plume materials is possible in type 3, the MULTUM can test the above hypothesis by obtaining a wide range of mass spectra for organic matter in the plumes (Table 2). Furthermore, the high-resolution mass spectroscopy would enable to discuss the compositional similarity of the icy planetesimals of the Saturnian system to long- and short-period comets based on the isotopic compositions of major volatiles (Table 2).

Camera and laser altimeter: During orbiting Enceladus in type 3 and flybys in type 2, the detailed observations of surface features and materials on Enceladus will be conducted with a laser altimeter and infrared mapping camera. Enceladus orbits around the Saturn in ~1.5 days; accordingly, surface displacement in response to tidal forces by gravity of Saturn and Dione will be able to measure in the mission duration.

Biological experiments: During the return flight to Earth in type 3, a biological investigations will be performed by release of radioactive carbon. In the isotopic labeling experiments, a part of the return samples will be exposed with ^{14}C-labeled inorganic carbon, such as $^{14}CO_2$ or ^{14}CO, or organic carbon, such as ^{14}C-glucose. The detailed analyses of ^{14}C assimilation for the retrieved samples will be performed during the return flight or after the return to Earth. Furthermore, sensitive isothermal calorimetry will be conducted for the return samples to test biological activity.

Table 2. A summary of prospective observations by type 1–3 missions to Enceladus.



goals mission	flybys & in-situ measurements	sample return analyses
type 1 free-return	Chemical & isotopic composition of major volatiles	Composition of dry silicate & salts
type 2 Saturn orbiting	Surface imaging & infrared mapping Chemical & isotopic composition of major volatiles	Composition of dry & hydrous silicates, carbonates, & salts Composition and structure of refractory organic matter Isotopic analyses for organic matter
type 3 Enceladus orbiting	Gravity & surface displacement Surface imaging & infrared mapping Chemical & isotopic composition of major volatiles	Composition of dry & hydrous silicates, carbonates, & salts Composition and structure of soluble & refractory organics Isotopic analyses for organic matter Biological investigations

3. Conclusions

The Cassini spacecraft has discovered water-rich plumes erupting from the south-pole region of Enceladus. Given the geological activity and chemical constitutes of the plumes, Enceladus would have possessed an interior ocean where active geochemistry might have occurred. However, Cassini was unable to reveal the detailed chemical and isotopic compositions of the plume materials, which are essential to understand the physical and chemical conditions of the ocean and to constrain the solar nebular chemistry. The sample return and in-situ measurement mission for Enceladus' plume materials proposed by the present study will provide direct and essential observational data on geochemistry and habitability of the icy moon. Key technology for the mission will be separation of gas species, high-resolution in-situ measurements, and reduction of flyby velocity. To achieve low flyby velocity for intact collection of the plume materials, type 2 or 3 mission, possibly with electric propulsion, is more preferable than type 1.

The Jupiter icy moons explorer (JUICE) by ESA will arrive at the Jovian system in 2030 and would make detailed observations of surface materials on the large satellites, Europa, Ganymede, and Callisto. Furthermore, the sample-return missions from C-type asteroids will provide detailed information on chemical reactions among water, organics, and minerals occurred in the early stage of the solar system. The sample-return mission to Enceladus, together with the results of the JUICE mission and asteroids sample return missions, will allow geochemists, geologists, and life scientists to be involved in planetary and icy satellite sciences, as the recent Mars missions have done for the last 10 years. Such a research at the interactions of interdisciplinary fields is required to understand the habitability and potential for life in the solar system.

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