Exploration of Enceladus and Titan: Investigating Ocean Worlds' Evolution and Habitability in the Saturn System

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Abstract

We present a White Paper with a science theme concept of ocean world evolution and habitability proposed in response to ESA's Voyage 2050 Call with a focus on Titan and Enceladus in the Saturn system. Ocean worlds in the outer Solar system that possess subsurface liquid water oceans are considered to be prime targets for extra-terrestrial life and offer windows into Solar System evolution and habitability. The Cassini Huygens mission to the Saturn system (2004–2017) revealed Titan with its organic-rich evolving world with terrestrial features and Enceladus with its active aqueous environment to be ideal candidates to investigate ocean world evolution and habitability. Additionally this White Paper presents a baseline for a multiple flyby mission with a focused payload as an example of how ocean world evolution and habitability in the Saturn system could be investigated building on the heritage of the Cassini-Huygens mission and complementing the recently selected NASA Dragonfly mission.

Executive summary

Recent observations from the ground and in space have shown that Earth is not the only place in the Solar System to possess exposed surface liquid. Observations have provided evidence of subsurface liquid water oceans covered by icy shells on multiple objects in the Solar System, called ocean worlds, including the icy moons of Jupiter (Europa, Ganymede and Callisto) and of Saturn (Titan and Enceladus) as well as dwarf planets (Ceres and Pluto) (see Lunine 2017 for a review and De Sanctis et al., 2020). The Cassini-Huygens mission has shown Titan and Enceladus to be two favourable locations in the Solar System in our quest for a better understanding of the evolution of the Solar System and its habitable potential. Both Saturnian moons possess energy sources, liquid habitats, nutrients (organic compounds) and transport cycles of liquid moving nutrients and waste, all necessary ingredients for habitability (McKay, 2016; Hand et al. 2020). Titan is the only active extraterrestrial alkanological system in the Solar System (analogous to the Earth's hydrological system), including an organically rich atmosphere, hydrocarbon lakes and seas on the surface and a liquid water subsurface ocean. Enceladus has active plumes composed of multiple jets containing complex organics and water vapour and likely connected to its liquid water subsurface ocean. Along with their energy sources, these bodies are prime environments in which to investigate the conditions for the emergence of life and habitability conditions of ocean worlds in the Outer Solar System, as well as the origin and evolution of gas giant planetary systems, in a single mission.

We propose a Voyage 2050 theme of ocean worlds evolution and habitability with a focus on Enceladus and Titan in the Saturn system. Building on the heritage of Cassini-Huygens, future exploration of Enceladus and Titan should be dedicated to investigating the unique properties and the habitability potential of these ocean worlds. The proposed baseline is for a large mission (class L) and consists of multiple flybys using a solar-electric powered spacecraft (S/C) in orbit around Saturn. The proposed mission would have a focused payload that would provide high-resolution mass spectrometry of the plume emanating from Enceladus' south polar terrain and of Titan's upper atmosphere. High-resolution IR imaging would be performed of the plume and the source fractures on Enceladus' south polar terrain (SPT), and would detail Titan's geomorphology at 50–100 m resolution at minimum. In addition, radio science measurements would provide constraints on the ice shell structure and the properties of the internal ocean of Enceladus and constrain higher degree gravity field components of Titan. The baseline mission is based on the Explorer of

Enceladus and Titan (E^2T) concepts proposed as a medium-class mission led by ESA in collaboration with NASA in response to ESA's M5 Call (Mitri et al., 2018), along with several other previous proposals (e.g. TSSM, Coustenis et al. 2009; TIME, Stofan et al. 2010; JET, Sotin et al. 2011) and will complement the information provided by Cassini-Huygens, as well as the results of the newly-selected NASA Dragonfly mission.

The baseline mission can address key scientific questions regarding extraterrestrial habitability, abiotic/prebiotic chemistry, the emergence of life, and the origin and evolution of ocean worlds. Optional elements include a) an *in-situ* sea-probe to investigate one of Titan's northern seas as well as the lower atmosphere and b) an ice penetrating radar (IPR) to perform radar sounding of the subsurface of Titan and Enceladus during flybys. The *in-situ* sea-probe would open up new vistas regarding Titan's seas and lakes, the hydrological system and the possibility of prebiotic/biotic components within Titan's seas, complementing the equatorial investigations of NASA's Dragonfly, while the IPR would reveal subsurface structures and processes of Titan and Enceladus' SPT. While the baseline mission is conceived as a multiple flyby mission it can also include a final orbiter phase around Titan. The joint exploration of these two fascinating objects would potentially be performed with international collaboration and will allow us to better understand the origin of their organic-rich, liquid water habitable environment and will give access to planetary processes that have long been thought unique to the Earth. Finally, joint exploration of these ocean worlds would complement NASA's Dragonfly mission to Titan, which while unprecedented is only regional in scope exploring a low-latitude impact crater site (Selk impact crater). Thus, local observations of Enceladus' south pole, global observations of Titan and possible *in-situ* exploration of a northern sea are important science goals that remain to be addressed by a future mission to the Saturn system.

1. Introduction

1.1 Overview

The NASA/ESA/ASI Cassini-Huygens mission (2004–2017) has done much to advance our understanding of Titan and Enceladus and the Saturn system in general but also introduced new first order scientific questions for geologists, astrobiologists, organic chemists, and planetary scientists, that remain unanswered to date (Dougherty et al., 2010; Coustenis et al 2015; Nixon et al. 2018; Spilker et al. 2019). On Titan, its resemblance to primitive Earth and the presence of a rich mixture of organic material in contact with liquid reservoirs, which may be in contact with the subsurface, constitute major motivations for further exploration of the astrobiological potential of this ocean world (Coustenis and Raulin, 2015). On Enceladus, the accessibility of the contents of its subsurface ocean and hydrothermal system is an unprecedented opportunity to determine its abiotic/prebiotic potential while its comet-like composition raises new questions about the evolution of the Saturnian system and the Solar System in general. In the almost 23 years since the launch of the Cassini-Huygens mission in 1997, there have been great technological advancements in instrumentation that would enable answering key questions that still remain about the Saturnian ocean worlds.

1.2 Titan: An organic-rich evolving world

Shrouded by a dense atmosphere of nitrogen, methane, hydrogen and haze products, Titan, Saturn's largest satellite, was once thought to host a global ocean of methane and ethane on its surface (Lunine et al., 1983). Data from the Cassini-Huygens mission uncovered a fascinating Earth-like world beneath the haze with dunes (e.g., Lorenz et al. 2006), lakes and seas (Stofan et al. 2007), networks of rivers and canyons (Tomasko et al. 2005; Soderblom et al. 2007; Poggiali et al. 2016), and mountains (Radebaugh et al. 2007; Mitri et al. 2010) and impact structures (Wood et al. 2010; Soderblom et al. 2010; Neish and Lorenz 2012; Lopes et al., 2019) within an alien landscape composed of organics and water-ice. Titan's dense, extensive atmosphere is primarily composed of nitrogen (97%) and methane (1.4%) (e.g., Bézard 2014), and a long suite of organic compounds resulting from multifaceted photochemistry which occurs in the upper atmosphere down to the surface (e.g., Israël et al. 2005; Waite et al. 2007; Gudipati et al. 2013; Bézard 2014). Titan's organic-rich dense atmosphere has provided a rich field of study with multiple models investigating the origin of its nitrogen atmosphere (e.g., Mousis et al. 2002; Miller et al. 2019), the persistence of atmospheric methane despite methane escape, and the distribution of its atmospheric components. The organics detected by the Cassini mission in Titan's atmosphere have provided tantalizing hints of the prebiotic potential of Titan's atmospheric aerosols. For example, a compelling find by Cassini for abiotic/prebiotic species is the discovery of complex large nitrogen-bearing organic molecules in Titan's upper atmosphere (Waite et al. 2007; Coates et al. 2007). Stevenson et al. (2015) suggest that membranes formed from atmospheric nitriles such as acrylonitrile could provide Titan analogues of terrestrial lipids, a component essential to life on Earth.

Since methane is close to its triple point on Titan, it gives rise to an alkanological cycle analogous to the terrestrial hydrological cycle, characterized by cloud activity, precipitation, river networks, lakes and seas covering a large fraction of the northern terrain (Figure 1) (e.g., Tomasko et al.

2005; Stofan et al. 2007; Mitri et al. 2007; Hayes et al. 2008). Titan is the only extraterrestrial planetary body with long-standing liquid on its surface, albeit hydrocarbons instead of water, likely fed by a combination of precipitation, surface runoff and subsurface alkanofers (hydrocarbon equivalent of aquifers) in the icy shell (Hayes et al. 2008). Recent work has shown that the surfaces of Titan's northern lakes and seas are on the same equipotential surface confirming the presence of subsurface alkanofers (Hayes et al., 2017; Mastrogiuseppe et al. 2019). Titan's seas and larger lakes are typically broad edge depressions while many small lakes present as sharp edge depressions often with raised ramparts (Birch et al. 2018) and some surrounded with rampart-like structures (Solomonidou et al. 2019). Observations of water-ice poor 5-μm bright material surrounding Titan's northern lakes and seas may be evaporite deposits (Barnes et al. 2011); though they are also found in the largest areal concentration in equatorial regions and if they do represent evaporites, suggest previous equatorial seas (MacKenzie et al. 2014). Experimental work in Titan conditions is attempting to reveal compounds that could form evaporites on Titan and their prebiotic and biotic potential (Cable et al., 2014, 2020).

FIGURE 1

The presence of radiogenic noble gases in the atmosphere indicates some communication between the surface and the subsurface and is suggestive of water-rock interactions and methane outgassing processes (Tobie et al. 2012), possibly associated with cryo-volcanic activity (Lopes et al. 2007; 2019). The detection of a salty ocean at depth estimated between 50 and 80 km beneath the surface (Iess et al. 2012; Beghin et al. 2012; Mitri et al. 2014b) and the possible communication between this ocean and the organic-rich surface opens up exciting astrobiological perspectives. While

Cassini has provided tantalizing views of the surface with its lakes and seas, dunes, equatorial mountains, impact craters and possible cryo-volcanoes, its low resolutions make it difficult to identify morphological features, to quantify geological processes and relationships between different geological units and monitor changes due to geologic or atmospheric activity. Determining the level of geological activity on Titan is crucial in understanding its evolution and whether this ocean world could support abiotic or prebiotic activity.

1.3 Enceladus: An active aqueous environment

The discovery in 2005 of a plume of multiple jets emanating from Enceladus' south polar terrain (SPT) is one of the major highlights of the Cassini–Huygens mission (Figure 2) (Dougherty et al. 2006; Porco et al. 2006; Spahn et al. 2006; Lunine et al. 2018). Despite its small size (10 times smaller than Titan), Enceladus is the most active moon of the Saturnian system. Although geyser-like plumes have been observed on Triton (Soderblom et al. 1990) and more recently transient water vapor activity around Europa has been reported (Roth et al. 2014, 2016), Enceladus is the only one proven to have current endogenic activity. Approximately 100 jets (Porco et al. 2014) form a huge plume of vapor and ice grains above Enceladus' south polar terrain and are associated with abnormally elevated heat flow along tectonic ridges, called 'tiger stripes'. Enceladus' endogenic activity and gravity measurements indicate that it is a differentiated body providing clues to its formation and evolution (Iess et al. 2014). Gravity, topography and libration measurements demonstrate the presence of a global subsurface ocean (Iess et al. 2014; McKinnon et al. 2015; Thomas et al. 2016; Čadek et al. 2016). Analysis of the gravity data showed that Enceladus' ice shell thickness above the subsurface ocean is likely 30–40 km, from the south pole up to 50° S latitude (Iess et al. 2014) while libration data suggest a mean thickness of 21–26 km

(Thomas et al. 2016); however recent models have shown that the variable ice shell thickness in Enceladus' south pole can be as little as 5 km (Čadek et al. 2016, 2019). This variable ice shell thickness could be the result of heat flux variation along the ice-ocean interface due to true polar wander (Tajeddine et al. 2017).

FIGURE 2

Postberg et al. (2009) and Porco et al. (2014) have shown that most of the plume material is likely not from the upper brittle layer of the ice shell but from a subsurface liquid water reservoir beneath the icy shell. Libration measurements finally confirmed the presence of a global ocean (Thomas et al. 2016). Sampling of the plume by Cassini's instruments revealed the presence of water vapor, ice grains rich in sodium and potassium salts (Postberg et al. 2011), gas and solid phase organics (Waite et al. 2009; Postberg et al. 2008, 2015). The jet sources are connected to a subsurface salt-water reservoir that is probably alkaline in nature and the site of possible hydrothermal water-rock interactions (Porco et al. 2006, 2014; Waite et al. 2006, 2009; Postberg et al. 2009, 2011; Hsu et al. 2011, 2014; Glein et al. 2015).

The co-existence of organic compounds, salts, liquid water and energy sources on this small moon provides all the necessary ingredients for the emergence of life by chemoautotrophic pathways (McKay et al. 2008) – a generally held model for the origin of life on Earth in deep sea vents, such as the Lost City hydrothermal field located in the Mid-Atlantic Ridge. The eruption activity of Enceladus offers a unique possibility to sample fresh material emerging from subsurface liquid water and to understand how exchange processes with the interior control surface activity. It provides us with an opportunity to *in situ* study phenomena that have been important in the past on Earth and throughout the outer Solar System.

2. Science case after the Cassini-Huygens mission

While Cassini-Huygens and its extended missions have revealed much about Enceladus and Titan (Dougherty et al. 2010; Lunine et al. 2018), the S/C was not equipped to search for life or constrain the evolution of these ocean worlds and many open questions remain. *In situ* measurements by Cassini at Enceladus and Titan revealed a wealth of chemical complexity of neutral and positively charged molecules. However, analysis was restricted by mass spectroscopic instruments, which were limited by their low sensitivity, mass range, and resolution and subsequent inability to resolve high-mass isobaric molecular species, neutral and positive ions. For example, in Enceladus' vapor plume an unidentified species with a mass-to-charge (m/z) ratio of 28, which is thought to be either CO, N_2, C_2H_4 or a combination of these compounds was detected. Determining the abundance ratio between these different species is essential to constrain the origin of volatiles on Enceladus and to assess whether they were reprocessed internally. The evidence of high temperature hydrothermal activity (Hsu et al. 2015) within Enceladus' subsurface ocean provides strong incentive to test the plume for prebiotic and biotic signatures using high-resolution spectrometers. Further, putative exothermic water-rock interactions on Enceladus could be further constrained by quantifying H_2 in the plume. On Titan, higher resolution spectroscopic instruments would enable better constraints on complex organic processes and components occurring in Titan's atmosphere, particularly those with prebiotic and biotic potential.

The geology and morphology of both Titan and Enceladus has been revealed by Cassini Visual and Infrared Mapping spectrometer (VIMS), Imaging Science Subsystem (ISS) and RADAR SAR imagery but only at low to moderate resolutions. Additionally, imaging of the surface was also constrained on Titan by scattering of atmospheric aerosols and absorption that limited SNR. A future mission to Titan can provide images in the mid-IR range at or around 5 μm since images at these wavelengths are subject to minimal scattering (Soderblom et al. 2012; Barmes et al. 2013) enabling diffraction limited images that are extremely sensitive to composition (Clark et al. 2010; Barnes et al. 2014) with spatial resolutions an order of magnitude better than Cassini observations (Clark et al. 2010; Soderblom et al. 2012; Barnes et al. 2014). A high-resolution map would enable a vastly improved investigation of Titan's geology, hydrology, and compositional variability and would enable the detection of morphology not evident from Cassini data, quantify geological processes and relationships between different geological units and examine alterations due to geologic, atmospheric or seasonal activity. Recently an ice-rich linear feature of bedrock, covering 40% of Titan's circumference was discovered using statistical analysis of 13,000 Cassini VIMS images (Griffith et al. 2019); it is likely many features with weaker spectral signatures remain to be discovered. High-resolution imaging of Enceladus' SPT will provide new detail of the tectonically active surface, constrain characteristics of the hydrothermal system by investigating the composition and kinematics of Enceladus' jets and plumes. Further IR imaging will view thermal emission from Enceladus' hot spots and constrain the presence of anomalous heat signatures in the SPT (Le Gall et al. 2017) at resolutions comparable to ISS observations of the SPT.

TABLE 1

TABLE 2

TABLE 3

Gravity field measurements are powerful tools to constrain the interior structure and to assess mass anomalies, providing information on the internal dynamics and evolution. Gravity measurements of Enceladus' south pole can be used to find a local solution of the SPT gravity field and its time-variation (using along-track data) rather than a global solution. In the south polar region, we expect a larger time-variation of the gravity field with respect to the global solution of the time variation of the gravity field due to the fact that the ice shell thickness is expected to be locally thin at the SPT. A radio science experiment that will determine the local solution of the gravity field of Enceladus at the SPT will allow the determination of the thickness variation at the south polar regions and constraints on the mechanical properties (viscosity) of the ice overlying an outer ice shell. The expected tidal deformation is characterized by a pattern more complex that the standard degree-two pattern, with a strong amplification of the tidal fluctuation in the SPT (Brzobohaty et al. 2016). Should a final Titan orbiter phase be included in the baseline mission, higher degrees of gravity coefficients, up to at least degrees twelve could be obtained as well as an estimation of the real and imaginary parts of Titan's k_2 with an accuracy of 0.0001 (Tortora et al. 2017). The characterization of the global gravity field of Titan and/or Enceladus might also be significantly improved through a pair of companion small satellites, to be released by the mothership around either moons. This element may complement the science observations of the larger spacecraft, through a combination of Satellite-to-Satellite Tracking (SST) between two smallsats or between one smallsat and the mothership. Preliminary simulations have shown that in just three months this technique would allow to estimate the static gravity field up to at least degree thirteen (for Titan) and degree twenty (for Enceladus), while the real and imaginary part of k_2 can reach an accuracy of about 0.08 for Titan and 0.002 for Enceladus (Tortora et al. 2018a, Tortora et al. 2018b). This optional element may be studied in parallel to the more consolidated Options a) and b) listed above. The subsurface processes and structures of both Titan and Enceladus can be further investigated with an ice penetrating radar (IPR), which uses microwaves to penetrate through the surface to examine subsurface characteristics. Structural, thermal and compositional profiles of subsurface structures and thickness of the regolith layer can be used to characterize the surface and subsurface structures and determine their correlation to each other. Further determination of the ice-ocean interface at Enceladus' SPT and the brittle-ductile interface within Titan's ice shell can constrain evolutionary and thermal processes. Radar sounding instruments have been used in multiple space missions on Mars and the Moon (e.g., Heggy et al. 2006; Seu et al. 2007; Picardi et al. 2004; Ono et al. 2010) and will be used to examine Europa and Ganymede in the Jupiter system in ESA's upcoming JUICE mission (Bruzzone et al. 2013, 2015). The upcoming NASA mission, Europa Clipper, will radar sound Europa during a series of multiple flybys while in orbit around Jupiter (Blankenship et al. 2009).

While Cassini has provided stunning imagery of Titan's lakes and seas (e.g. Stofan et al. 2007) and VIMS and RADAR data have been used to constrain their composition and bathymetry (Brown et al. 2008; Mastrogiuseppe et al., 2014; Lopes et al., 2019), open questions regarding their formation, particularly smaller sharp edge depression lakes, the extant of subsurface communication, composition of the lakes and seas and the evaporites that often surround them as well as paleolakes in the south pole and possible presence of lakes or empty lake basins outside the polar regions still remain (e.g. Nixon et al. 2018). The combination of high resolution remote sensing and *in situ* measurements can answer many questions. In addition, *in situ* studies of one of Titan's seas would complement data obtained by the Dragonfly mission, which was recently selected by NASA as part of its New Frontiers program as an upcoming mission to be launched in 2026 and arrive at Titan in 2034. The Dragonfly mission while unprecedented is only regional in scope exploring the low-latitude Selk impact crater region with a flying rotorcraft drone. Thus *in situ* exploration of a northern sea and global observations of Titan are important science goals that remain to be addressed by a future mission to the Saturn system.

Science goals to be resolved by a future baseline multiple flyby mission to Titan and Enceladus, based on the E^2T mission proposed for ESA M5 study (Mitri et al. 2018) are shown in Table 1. Additional science goals that can be investigated with the option #1 of *in situ* exploration of a northern sea and/or the option #2 of radar sounding of the surface of Titan and Enceladus SPT during multiple flybys or Titan's orbiter are described in Table 2 and Table 3 respectively.

3. Missions scenarios

3.1 Baseline mission scenario

The proposed baseline mission concept consists of a solar-electric powered spacecraft performing multiple flybys of Titan and Enceladus while in orbit around Saturn. The proposed baseline mission is based on the Explorer of Enceladus and Titan (E^2T) proposed as a medium-class mission led by ESA in collaboration with NASA in response to ESA's M5 Call (Mitri et al. 2018). The proposed baseline mission concept for this White Paper is for a large class ESA mission (class L). The evaluated cost from ESA review for E^2T is 950 M€ that fit in a large mission budget constraint.

FIGURE 3

The baseline payload would consist of three scientific instruments: two time-of-flight mass spectrometers and a high-resolution infrared camera, while the telecommunication system would be utilized to perform gravity science. The baseline interplanetary transfer, cruise and flyby phases are all based on a proposed launch in 2029–2030 and therefore are included only as example trajectories. After the launch, the S/C will transfer from geosynchronous transfer orbit (GTO) to a hyperbolic escape trajectory and would pursue a gravity assist flyby of the Earth to help propel itself to the Saturn system. The cruise phase from Earth to Saturn would be 6 years long. After the arrival in the Saturn system, the mission is divided in a first Enceladus science phase and in a second Titan science phase. The S/C should perform at least 6 flybys of Enceladus above the south polar terrain (SPT) and at least 17 flybys of Titan. To prevent contamination of Enceladus science by Titan's organics, E^2T S/C will perform close flybys of Enceladus at the beginning of the tour (Enceladus science phase); distant flybys of Titan will be performed during the initial tour phase.

FIGURE 4

After the main Enceladus phase, close flybys of Titan with atmospheric sampling will be performed (Titan science phase). During the Titan science phase, the S/C will provide *in situ* sampling of the upper atmosphere at a minimum altitude from Titan surface as low as 900 km using mass spectrometers. At the closest approach the velocity of the S/C with respect to Titan's surface will be ~7 km/s. Imaging data would be collected during inbound and outbound segments of each flyby. The duration of the tour from its arrival in the Saturn system to the end of the 17-

flyby Titan phase is about 3.5 years. Figure 3 shows a proposed interplanetary transfer to Saturn and Figure 4 shows a proposed sample tour. Both Figures 3 and 4 are based on a proposed E^2T launch of 2029–2030 (Mitri et al. 2018). Figure 5 shows the proposed configuration of the S/C for the E^2T project. While the baseline mission is conceived as a multiply flyby mission it can also include a final orbiter phase around Titan similar to the final orbiter phase of the JUICE (JUpiter ICy moons Explorer) spacecraft around Ganymede in the upcoming ESA JUICE mission.

3.2 Option 1: Titan sea lander

The S/C will carry a scientific payload consisting of remote sensing instruments and experiments aforementioned while if Option #1 is utilized the S/C will also carry an Entry, Descent and Landing (EDL) module containing a sea lander equipped with an instrument suite capable of carrying out *in situ* measurements of one of Titan's north polar seas. Figure 6 shows a proposed sea lander and entry vehicle. During the descent, the probe will make *in situ* measurement of the atmosphere. Once a successful splashdown has been achieved, the sea probe will be taking measurements sampling both the liquid of the seas and the atmosphere above. Previous analysis for a mission that considered the exploration of Titan using an orbiter, a lake-probe and a balloon demonstrated the feasibility of such mission (the Titan Saturn System Mission Study TSSM, Coustenis et al. 2009) as did the study of the Titan Mare Explorer (TiME) (Stofan et al. 2010) which was a lake lander only mission to *in-situ* investigate one of the large north polar mare on Titan. In addition, Mitri et al. (2014a) presented the science case for the exploration of Titan and one of its seas with an orbiter and a lake probe. If Option #2 is utilized, the S/C will carry a nadir-looking ice penetrating radar sounder (IPR).

The sea lander will sample Titan's atmosphere obtaining temperature, wind, humidity and composition profiles during its descent. Once the sea lander is in the Titan sea, it will make a number of measurements including bulk and trace composition of the sea and lower atmosphere, and bathymetric and shoreline profiles; additionally, the shoreline of the sea can be imaged during the descent. Possible instrument suite utilized by a sea lander with associated science goals and measurements is shown in Table 4 (Mitri et al. 2014a).

The sea lander will relay data to the S/C, which will serve as the communications link between the probe and Earth. Direct-to-Earth (DTE) communication of the sea lander is a possible complementary communication method. Lorenz and Newman (2015) have found that the seasonal geometry at Titan's north pole allows DTE from the seas until 2026 and after 2040. Given the opacity of Titan's atmosphere, the use of a solar powered generator for the sea-probe is infeasible if its operations need to last more than a few hours. The sea lander portion of the proposed mission will be short-lived due to technical constraints. Current technology dictates that the use of batteries will only provide power to the sea lander on the order of hours; though this technology will likely improve. The sea lander will not have propulsion capabilities rather it will propelled around the lake by winds and possible tides; Lorenz and Mann (2015) have studied the wind and wave conditions that a floating Titan sea lander might encounter. Testing of a scale model of the proposed Titan Mare Explorer sea lander capsule has revealed important data regarding potential science operations and lander-lake dynamics (Lorenz et al. 2015; Lorenz and Cabrol 2015). Recent work proposes that a sea-lander could possibly not only float but also be able to propel itself utilizing mechanical tensegrity structures (Gebara et al. 2019). The use of a radioisotopic power generator for the sea probe could be requested using technology, which could significantly reduce the amount of plutonium fuel. The Advanced Stirling Radioisotopic Generator (ASRG), based on Stirling power conversion technology, offers a four-fold reduction in the amount of plutonium fuel compared to radioisotope thermal generators (RTG) used in previous interplanetary missions (Stofan et al. 2010); while NASA has ended funding for in-flight development of ASRG technology in 2013 due to budget cuts, research continues on this technology and other radioisotope power systems in NASA (Oriti and Schmitz 2019). Additionally, the development of radioisotopic power using Americium (^{241}Am) currently being developed by ESA since 2008 is another possible option (Barco et al. 2019).

FIGURE 6

TABLE 4

3.3 Option 2: Radar sounder

The ice penetrating radar, following the heritage of JUICE RIME and Europa Clipper REASON, would be capable of both shallow and deep sounding to characterize the subsurface with a depth of 9 km and ~30 m vertical resolution at minimum. Both RIME and REASON are to operate at a HF band with a center-frequency of 9 MHz and possess bandwidths between 1 and 3 MHz while REASON operates at an additional VHF frequency with a center frequency of 60 MHz (Bruzzone et al. 2013; Grima et al. 2015). An IPR can characterize structural, compositional and thermal variations occurring in the subsurface providing data that can correlate surface and subsurface features and processes, deformation in the upper ice shell, as well as global and local surface age. In addition, an IPR can also investigate the ice-ocean interface at Enceladus' SPT and brittle-ductile transition on Titan constraining the thickness and thermal evolution of the ice shells. An additional option for radar architecture could be a multi-mode radar design suitable for both sounding and imaging to be operated in two modes: a vertical sounder mode with similar capabilities as described above though with different architecture, and a Synthetic Aperture Radar (SAR) imaging mode, similar to Cassini (Elachi et al., 2004), but with a higher resolution at tens of meters. The additional SAR mode could be used for high-resolution imaging of the surface, complementing the IR imaging, as well as for creating three-dimensional high-resolution bathymetric maps of Titan seas and lakes and could permit investigation of any possible compositional variation in space and time of the hydrocarbon liquid and/or sea floor properties.

4. Science case for the baseline mission scenario

In this section we discuss the science goals and themes for the proposed baseline mission based on the E^2T mission submitted to ESA in response to the M5 Call (Mitri et al. 2018). Discussion of the science themes of the proposed mission options is discussed in Section 5.

4.1 Origin and evolution of volatile-rich ocean worlds, Enceladus and Titan

The origin of volatiles currently present on Titan and Enceladus is still being debated. New data are needed to determine if the volatile inventory is primordial, originating in the solar nebula or

Saturnian subnebula possibly altered during the accretion process or else were produced in some secondary manner is still being debated (e.g., Atreya et al. 2006). How photochemical processes on Titan and aqueous alteration on Enceladus have affected the initial volatile inventory remains unknown. Given that a late accretion scenario may explain the mass distribution and ice/rock ratio of the mid-sized moons in the Saturn system, Enceladus may have formed less than 1 billion years ago, while Titan may have accreted early. This may have resulted in significant differences in their initial volatile inventory and their subsequent evolution.

By combining *in situ* chemical analysis of Titan's atmosphere and Enceladus' plume with observations of Enceladus' plume dynamics and Titan's surface geology, a future mission can provide constraints on how these ocean worlds acquired their initial volatile inventory and how it was subsequently modified during their evolution (Lunine et al. 2018); these investigations can improve our understanding of the nature of Saturn subnebula formation conditions and its subsequent evolution as well as the conditions of the early solar nebula, the nature of cometary and giant impacts, all of which might also help to predict the physical and chemical properties of terrestrial planets and exoplanets beyond the Solar System.

4.2 Chemical constraints on the origin and evolution of Titan and Enceladus

The origin and evolution of Titan's methane still needs to be constrained. Whether Titan's methane is primordial likely through water-rock interactions in Titan's interior during its accretionary phase (Atreya et al. 2006) or else delivered to Titan during its formation processes (Mousis et al. 2009) or by cometary impacts (Zahnle et al. 1992; Griffith and Zahnle 1995) is a key open question. On Titan, the Huygens probe detected small argon abundance (^{36}Ar) and a tentative amount of neon (^{22}Ne) in its atmosphere (Niemann et al. 2005, 2010), but was unable to detect the corresponding abundance of xenon and krypton. The presence of ^{22}Ne ($^{36}Ar/^{22}Ne \sim 1$) was unexpected as neon is not expected to be present in any significant amounts in protosolar ices (Niemann et al. 2005, 2010) and may indicate water-rock interactions and outgassing processes (Tobie et al. 2012). The non-detection of xenon and krypton supports the idea that Titan's methane was generated by serpentinization of primordial carbon monoxide and carbon dioxide delivered by volatile depleted planetesimals originating from within Saturn's subnebula (e.g., Atreya et al. 2006). Xenon and krypton would both have to be sequestered from the atmosphere to support a primordial methane source. While xenon is soluble in liquid hydrocarbons (solubility of 10^{-3} at 95 K) and could potentially be sequestered into liquid reservoirs, argon and krypton cannot (Cordier et al. 2010). Therefore, the absence of measurable atmospheric krypton requires either sequestration into non-liquid surface deposits, such as clathrates (Mousis et al. 2011), or depletion in the noble gas concentration of the planetesimals (Owen and Niemann 2009). Unlike Cassini INMS, which was developed in the 1990s, current and future spectrometers have the mass range and sensitivity to accurately measure xenon. Measurement of the abundance of noble gases in the upper atmosphere of Titan can discriminate between crustal carbon sequestration and carbon delivery via depleted planetesimals.

The longevity of methane in Titan's atmosphere is still a mystery. The value of $^{12}C/^{13}C$ in Titan's atmosphere has been used to conclude that methane outgassed $\sim 10^7$ years ago (Yung et al. 1984) and is being lost via photolysis and atmospheric escape (Yelle et al. 2008). It is an open question whether the current methane rich atmosphere is a unique event, whether it is in a steady state where methane destruction and replenishment are in balance (Jennings et al. 2009), or else is a unique transient event and is in a non-steady state where methane is being actively depleted or replenished. Indeed, the possibility that Titan did not always possess a methane rich atmosphere seems to be supported by the fact that the amount of ethane on Titan's surface should be larger than the present inventory (this is further discussed in the geological processes section below); though Wilson and Atreya (2009) contend that missing surface deposits may simply be reburied into Titan's crust and Mousis and Schmitt (2008) have shown that it is possible for liquid ethane to react with a water-ice and methane-clathrate crust to create ethane clathrates and release methane. Nixon et al. (2012), however, favor a model in which methane is not being replenished and suggest atmospheric methane duration is likely between 300 and 600 Ma given that Hörst et al. (2008) demonstrated that 300 Ma is necessary to create Titan's current CO inventory and recent surface age estimates based on cratering (Neish and Lorenz 2012). Mandt et al. (2012) suggests that methane's presence in the atmosphere, assumed here to be due to outgassing, has an upper limit of 470 Ma or else up to 940 Ma if the presumed methane outgassing rate was large enough to overcome $^{12}C/^{13}C$ isotope fractionation resulting from photochemistry and escape. Both the results of Mandt et al. (2012) and Nixon et al. (2012) fall into the timeline suggested by interior models (Tobie et al. 2006) which suggests that the methane atmosphere is the result of an outgassing episode that occurred between 350 and 1350 Ma.

FIGURE 7

On Titan, both simple (methane, ethane and propane) and complex hydrocarbons precipitate out of the atmosphere and onto the surface. Measuring the isotopic ratios ($^{14}N/^{15}N$; $^{12}C/^{13}C$; D/H; $^{16}O/^{18}O$) and abundances of the simple alkanes (e.g., methane, ethane and propane) will constrain the formation and evolution of the methane cycle on Titan. Further measurements of radiogenic noble gases such as ^{40}Ar and ^{22}Ne, which are typically markers of volatile elements from Titan's interior can constrain outgassing episodes. Detection of ^{40}Ar and tentatively ^{22}Ne in the atmosphere has provided circumstantial evidence of water-rock interactions and methane outgassing from the interior (Niemann et al. 2010; Tobie et al. 2012). Measurements of the composition and isotopic ratios of Titan's upper atmosphere in a future mission can be used to determine the age of methane in the atmosphere and characterize outgassing history.

On Enceladus, Cassini measurements by INMS (Waite et al. 2006, 2009) and UVIS (Hansen et al. 2006, 2008) showed that plume gas consists primarily of water vapor with a few percent other volatiles (Figure 7). In addition to H_2O as the dominant species, INMS was able to identify CO_2 (0.6% ± 0.15%), CH_4 (0.23% ± 0.06%), and NH_3 (0.7% ± 0.2%) in the vapor plume as well as an unidentified species with a mass-to-charge (m/z) ratio of 28, which is thought to be either CO, N_2, C_2H_4 or a combination of these compounds. The low mass resolution of Cassini INMS is insufficient to separate these species, and the UVIS measurements can only provide upper limits on N_2 and CO abundance. Determining the abundance ratio between these different species is, however, essential to constrain the origin of volatiles on Enceladus and to assess whether they were reprocessed internally. A high CO/N_2 ratio, for instance, would suggest a cometary-like source with only a moderate modification of the volatile inventory, whereas a low CO/N_2 ratio would indicate a significant internal reprocessing.

In addition to these main volatile species, during some Cassini flybys, the INMS data also indicated the possible presence of trace quantities of C_2H_2, C_3H_8, C_4, methanol, formaldehyde and hydrogen sulfide. Organic species above the INMS mass range of 99 u are also present but could not be further constrained (Waite et al. 2009). The identification and the quantification of the abundances of these trace species remains very uncertain due to the limitations of the mass spectrometer on board Cassini.

Except for the measurement of D/H in H_2O on Enceladus (which has large uncertainty, Waite et al. 2009), no information is yet available for the isotopic ratio in Enceladus' plume gas. The baseline mission would determine the isotopic ratios (D/H, $^{12}C/^{13}C$, $^{16}O/^{18}O$, $^{14}N/^{15}N$) in major gas compounds of Enceladus' plume as well as $^{12}C/^{13}C$ in organics contained in icy grains. Comparison of gas isotopic ratios (e.g., D/H in H_2O and CH_4, $^{12}C/^{13}C$ in CH_4, CO_2, and CO; $^{16}O/^{18}O$ in H_2O, CO_2, CO; $^{14}N/^{15}N$ in NH_3 and N_2) and with Solar System standards will provide essential constraints on the origin of volatiles and how they may have been internally reprocessed. Simultaneous precise determination of isotopic ratios in N, H, C and O-bearing species in Enceladus' plume and Titan's atmosphere will permit a better determination of the initial reference values and a quantification of the fractionation due to internal and atmospheric processes on both moons.

Noble gases also provide essential information on how volatiles were delivered to Enceladus and whether significant exchanges between the rock phase and water-ice phase occurred during Enceladus' evolution. The detection and quantification of ^{36}Ar and ^{38}Ar will place fundamental constraints on the volatile delivery in the Saturn system. A low $^{36}Ar/N_2$ ratio, for instance, would indicate that N_2 on Enceladus is not primordial, like on Titan (Niemann et al. 2010), and that the fraction of argon brought by cometary materials on Enceladus is rather low. In addition to argon, if Ne, Kr, and Xe are present in detectable amounts, the baseline mission would be able to test whether primordial noble gases on Enceladus were primarily brought by a chondritic phase or cometary ice phase, which has implications for all the other primordial volatiles. The $^{40}Ar/^{38}Ar/^{36}Ar$ as well as $^{20}N/^{21}Ne/^{22}Ne$ measured ratios will also allow for testing of how noble gases were extracted from the rocky core. Abundance ratios between Ar/Kr and Ar/Xe, if Kr and Xe are above detection limit, will offer an opportunity to test the influence of clathration storage and decomposition in volatile exchanges through Enceladus's ice shell.

The origin of methane detected in Enceladus' plume is still uncertain. Methane, ubiquitous in the interstellar medium was most likely embedded in the protosolar nebula gas. The inflow of protosolar nebular gas into the Saturn subnebula may have trapped methane in clathrates that were embedded in the planetesimals of Enceladus during their formation. Alternatively, methane may have been produced via hydrothermal reactions in Enceladus' interior. Mousis et al. (2009) suggests that if the methane of Enceladus originates from the solar nebula, then Xe/H_2O and Kr/H_2O ratios are predicted to be equal to $\sim 7\times10^{-7}$ and 7×10^{-6} in the satellite's interior, respectively. On the other hand, if the methane of Enceladus results from hydrothermal reactions, then Kr/H_2O should not exceed $\sim 10^{-10}$ and Xe/H_2O should range between $\sim 1\times10^{-7}$ and 7×10^{-7} in the satellite's interior.

4.3 Compositional variability in Enceladus' plume

The detection of salty ice grains (Postberg et al. 2009, 2011), the high solid-to-vapor ratio (Porco et al. 2006; Ingersoll and Ewald, 2011), and the observations of large particles in the lower part of the plume (Hedman et al. 2009) all indicate that the plume of Enceladus originates from a liquid source likely from the subsurface ocean rather than from active melting within the outer ice shell. However, the abundance of the major gas species observed by Cassini suggests some contribution from the surrounding cold icy crust should also be considered. Cassini observations show that the plume is made up of ~100 discrete collimated jets as well as a broad, diffuse component (Hansen et al. 2008, 2011; Postberg et al. 2011; Porco et al. 2014). The majority of plume material is found in the distributed diffuse portion of the plume while only a small portion of gas and grains are emitted from the jets (Hansen et al. 2011; Postberg et al. 2011). The saltiness of the ice grains and recent detection of nanometer sized silica dust particles in E-ring stream particles (Hsu et al. 2011, 2015) all indicate their origin is a location where alkaline high temperature hydrothermal reactions and likely water-rock interactions are occurring.

Although the Cassini (Cosmic Dust Analyzer) CDA has constrained knowledge of plume compositional stratigraphy, measurements of the absolute abundance and composition of organics, silicates and salts are poorly constrained given the low spatial resolution (10 km), low mass resolution and limited mass range of the CDA. The Cassini INMS provided only plume integrated spectra and is not able to separate gas species with the same nominal mass. However, current high mass resolution, spectrometers have a resolution that is 50 times larger than that of Cassini INMS, and would allow for the separation of isobaric interferences, for example separating ^{13}C and ^{12}CH and CO and N_2. Determining high-resolution spatial variations in composition is crucial to establish whether the jets are fed by a common liquid reservoir or if jet sources are disconnected, and if the local liquid sources interact with a heterogeneous in the icy shell. Variations in composition between the solid and gas phases as a function of distance from jet sources can also provide information about how the less volatile species condense on the grains, thus constraining the eruption mechanisms.

4.4 Geological constraints on Titan's methane cycle and surface evolution

As discussed above, there is an open question on whether Titan's methane-rich atmosphere is being actively replenished, or if methane is being lost and Titan's methane may eventually be depleted (Yung et al. 1984). Cryovolcanism has been suggested as a mechanism by which methane and argon can be transported from Titan's interior to its surface (e.g., Lopes et al. 2013). Cryovolcanic activity may also promote methane outgassing (Tobie et al. 2006); while methane clathrates are stable in Titan's ice shell in the absence of destabilizing thermal perturbations and/or pressure variation, variations in the thermal structure of Titan's outer ice shell during its evolution could have produced thermal destabilization of methane clathrates generating outgassing events from the interior to the atmosphere (Tobie et al. 2006; see also Davies et al. 2016). A number of candidate cryovolcanic features have been identified in Cassini observations (Lopes et al. 2013). High-resolution color images from the proposed baseline mission would provide the data needed to determine the geneses of these features. Stratigraphic relationships and crater counting will provide a means by which the relative ages of these features may be constrained.

A related question to the age of Titan's atmosphere is whether Titan's climate is changing. At present, most of the observed liquid methane is located in the north polar region (Aharonson et al. 2009). There have been suggestions, however, that organic seas may have existed in Titan's tropics (Moore and Howard 2010; MacKenzie et al. 2014), and/or in broad depressions in the south (Aharonson et al. 2009; Hayes et al. 2011). Models suggest Titan's methane distribution varies on seasonal timescales (e.g., Hayes et al. 2010; Turtle et al. 2011) or Milankovitch timescales (Aharonson et al. 2009). Alternative models suggest that methane is being depleted and Titan's atmosphere is drying out (Moore and Howard 2010). High-resolution images of the margins and interiors of these basins will allow us to determine whether they once held seas. Identification of impact features or aeolian processes within these basins will help to constrain the timing of their desiccation.

In addition to their inherent scientific interest, Titan's dunes also serve as a witness plate to climatic evolution. Larger dune forms take longer to form than smaller dune forms. In Earth's Namib desert, these differing timescales result in large, longitudinal dunes that adhere to the overall wind conditions from the Pleistocene 20,000 years ago, while smaller superposing dunes (sometimes called rake dunes, or flanking dunes) have responded to the winds during our current interglacial and orient ages accordingly. On Titan, a high-resolution infrared camera could resolve these potential smaller dunes on top of the known longitudinal dunes and will therefore reveal if Titan's recent climate has been stable or if it has changed over the past few Ma. Titan's geology is unique in that liquid and solid organics likely play key roles in many of the observed processes. As these processes play an important role in the modification of organics on Titan, both physically and chemically, understanding them is crucial for determining the complex chemistry that likely occurs on this moon. Furthermore, study of Titan's geology allows us to investigate processes that are also common on Earth, but in drastically different environmental conditions, providing a unique way to gain insight into the processes that shaped the Earth and pre-Noachian Mars.

Observations of Titan suggest the landscape is significantly modified by liquid organics (e.g., Burr et al. 2013). Fluvial erosion is observed at all latitudes, with a variety of morphologies suggesting a range of controls and fluvial processes (Burr et al. 2013). High-resolution color imaging will provide insight into the nature of this erosion: whether it is predominantly pluvial or sapping in nature and whether it is dominated by mechanical erosion or dissolution. Dissolution processes are suspected to control the landscape of Titan's labyrinth terrains (Cornet et al. 2015) and may also be responsible for the formation of the polar sharp-edged depressions (Hayes et al. 2008), though a new model suggests that the sharp-edged depressions with raised rims may be craters formed by explosions of subsurface pressurized nitrogen during colder methane-depleted periods in Titan's past (Mitri et al., 2019). High-resolution imaging will allow direct testing of these hypotheses in the proposed baseline mission.

Both fluvial and aeolian processes likely produce and transport sediments on Titan. Dunes are observed across Titan's equator (Radebaugh et al. 2008; Malaska et al. 2016) while a variety of fluvial sediment deposits can be identified in SAR data (Burr et al. 2013; Birch et al. 2016). Detailed imagery of the margins of the dune fields will allow us to determine the source and fate of sands on Titan. High-resolution images will also help determine whether the observed fluvial features are river valleys or channels (cf. Burr et al. 2013) providing key information in obtaining accurate discharge estimates needed to model sediment transport (Burr et al. 2006) as well as provide insight into the primary erosion processes acting on crater rims, which are likely composed of a mixture of organics and water ice (Soderblom et al., 2007; Neish et al. 2015, 2016). Finally, improved imaging will provide insight into the nature of erosion that exists in Titan's mid-latitudes, a region that shows little variability in Cassini observations.

Of great interest in understanding the evolution of Titan's surface is determining the nature of the observed geologic units, including their mechanical and chemical properties. Fluvial processes, the degree to which mechanical vs dissolution dominates and the existence of sapping, reflect the material properties of the surface and therefore can be used as a powerful tool to investigate the properties of the surface. The baseline mission imaging would also allow us to investigate the strength of the surface materials by constraining the maximum slopes supported by different geologic units. High-resolution detailed color and stereo imaging of the boundaries of units will also allow investigation of the morphology, topography, and spectral relationship across unit boundaries.

4.5 Habitability and potential for life in ocean worlds, Enceladus and Titan

Ocean worlds, such as Titan and Enceladus, are objects of wide astrobiological interest because water is one of the key prerequisites for life, in addition to nutrients and energy. Additionally, the organic surface environment of Titan provides an ideal, and in many ways unique setting to investigate the prebiotic chemistry that may have led to the emergence of life on the Earth. Water on ocean worlds in the outer Solar System is found underneath the surface of insulating ice shells, which regulate heat and chemical transport.

The dissipation of energy from tidal flexing, combined with radiogenic energy from these moons' interior provide the energy to sustain these oceans. The presence of antifreeze elements, such as salts or ammonia, suggested by mass spectrometric measurements on Titan and Enceladus (Niemann et al. 2005; Waite et al. 2009) and accretion models (Lunine and Stevenson 1987; Mousis et al. 2002) may also play an important role in sustaining these subsurface oceans. Subsurface oceans are known to exist on both Titan and Enceladus based on Cassini-Huygens mission gravity, shape and libration data (Iess et al. 2010, 2012, 2014; Mitri et al. 2014b; McKinnon 2015; Thomas et al. 2016), compositional *in situ* measurements and thermal evolution models (Tobie et al. 2005, 2006; Mitri and Showman 2008). Enceladus is unique in that communication of this water is known to exist between the surface and the subsurface and, quite conveniently, this water is ejected into space for easy *in situ* sampling. Titan provides its own unique environment in which a rich array of complex organics exists on the surface and may interact with the subsurface ocean via cryovolcanic activity or, alternatively, with transient liquid water at the surface following impact events.

Because the presence of a subsurface ocean decouples the interior from the outer ice shell, there is a much larger ice shell deflection and thus enhanced tidal heating and stresses in the shell; therefore tectonic features are much more likely on ocean worlds (Mitri et al. 2010; Nimmo and Pappalardo 2016) than on icy satellites without subsurface oceans. Surface geological activity may also lead to transport of surface organic material emplaced via precipitation from the atmosphere (e.g. Titan) or lodged in the surface as a result of cometary impacts into subsurface oceans. Titan's alkanological cycle and the associated meteorology creates a global distribution of trace species, evident in the formation and dynamics of clouds and an extensive photochemical haze in Titan's atmosphere, which affects the dynamics of how, when and where organic material settles on the surface and possibly interacts with the subsurface as seen in Figure 8.

FIGURE 8

In addition, cometary impacts could deliver key organics such as glycine, the simplest amino acid which has been detected on both comet 67P/Churyumov-Gerasimenko from *in situ* sampling by ESA's ROSETTA's mission and on comet 81P/Wild-2 from samples returned by NASA's Stardust mission. Neish et al. (2010) suggested that transient liquid water environments, created by impact melts could be an incubator for the deposited aerosols to create prebiotic chemistry. Further it is likely that such impact melt pools could be stable for 10^2–10^4 years (O'Brien et al. 2005).

This process could be circular; Tobie et al. (2012) suggests that some of the species now present in Titan's atmosphere may have originally been dissolved in the subsurface. On smaller ocean worlds such as Europa and Enceladus, the ocean may be in direct contact with the silicate core providing a means of water-rocks interactions (Mitri and Showman 2005; Iess et al. 2014). Recent detection of nanometer silica dust particles in Saturn's E-ring is indicative of an origin where alkaline high- temperature water-rock interactions is occurring (Hsu et al. 2015). The enormous heat output in the south polar terrain, associated with liquid water in contact with rocks, favors prebiotic processes, providing both an energy source and mineral surfaces for catalyzing chemical reactions.

Titan and Enceladus have already demonstrated remarkable astrobiological potential as evidenced by observations of Titan's complex atmosphere and methane cycle, analogous to Earth's water cycle, and Enceladus' cyrovolcanic plume spewing rich organics from the subsurface out into space. Studies of the nature of these organics could tell us whether or not they are biogenic. For instance, part of the CH_4 detected in the plume of Enceladus may result from methanogens analogous to those occurring in anaerobic chemosynthetic ecosystems on Earth (Stevens and McKinley 1995; McKay et al. 2008). A powerful method to distinguish between biogenic and abiogenic CH_4 is to analyze the difference in carbon isotope, $^{12}C/^{13}C$, between CH_4 and a potential source of C, most likely CO_2 on Enceladus and Titan, and to analyze the pattern of carbon isotopes in other hydrocarbons, such as C_2H_6, C_2H_4, C_2H_2, C_3H_8 etc. (Sherwood et al. 2002; McKay et al.

2008). The abundances of other non-methane hydrocarbons relative to methane could also be used to distinguish between biological and other sources (McKay et al. 2008; McKay 2016). The detection of amino acids could provide additional evidence for active biogenic processes. Even though amino acids can be produced, both biologically and via aqueous alteration of refractory organics, their distribution pattern can confirm if they are of biological origin (Dorn et al. 2011). Indeed, low molecular weight amino acids, such as glycine and alanine, are kinetically favorable and therefore dominate mixture of amino acids synthesized by abiotic process, whereas amino acids resulting from biotic process show a more varied distribution dominated by the protein amino acids in roughly equal proportions (Dorn et al. 2011).

By searching for abnormal isotopic ratios and mass distribution of organic molecules, including amino acids, the proposed baseline mission can determine what chemical processes control the formation and evolution of complex organics on Titan and will test whether biotic processes are currently occurring inside Enceladus. The analysis of salts and minerals embedded in icy grains and their possible distribution throughout the plume will also provide crucial constraints on the nature of hydrothermal activity occurring in Enceladus' deep interior and on how it connects with the plume activity. The observations of Titan's surface will also reveal if active exchange processes with the interior is currently occurring and whether complex organics are potentially in contact with fresh water.

4.6 Evidence for prebiotic and biotic chemical processes on Titan and Enceladus

Unlike the other ocean worlds in the Solar System, Titan has a substantial atmosphere, consisting of approximately 95% nitrogen and 5% methane with trace quantities of hydrogen and its by-products such as hydrocarbons (e.g. ethane, acetylene, propane and diacetylene) and nitriles, (e.g. hydrogen cyanide (HCN) cyanoacetylene (HC_3N)and cyanogen (C_2N_2)). Somewhat more complex molecules such as vinyl and ethylcyanide follow from these simpler units. In Titan's upper atmosphere, Cassini has detected large organic molecules with high molecular masses over 100 u. *In situ* measurements by the Cassini Plasma Spectrometer (CAPS) detected heavy positive ions (cations) up to 400 u (Crary et al. 2009) and heavy negative ions (anions) with masses up to 10,000 u (Coates et al. 2007) in Titan's ionosphere. Whereas Cassini INMS only had the ability to detect cations, current high-resolution mass spectrometer technology can detect both cations and anions with much better mass resolution than Cassini-INMS, and even better mass resolution than Cassini-CAPS. It is thought that these heavy negative ions, along with other heavy molecules found in the upper atmosphere, are likely the precursors of aerosols that make up Titan's signature orange haze, possibly even precipitating to the surface. While the identities of these molecules are still unknown, their presence suggest a complex atmosphere that could hold the precursors for biological molecules such as those found on Earth. The ability to detect prebiotic molecules in Titan's atmosphere is currently limited by the mass range of the Cassini INMS to the two smallest biological amino acids, glycine (75 u) and alanine (89 u), and the limited mass resolution precludes any firm identification. However, Cassini INMS detected mass spectra fragments for positive ions at masses of 76 u and 90 u, which may be consistent with protonated glycine and alanine, respectively (Vuitton et al. 2007; Hörst et al. 2012). Experimental results from a Titan atmosphere simulation experiment found 18 molecules that could correspond to amino acids and nucleotide bases (Hörst et al. 2012). The proposed baseline mission would use high-resolution mass spectrometry to measure heavy neutral and ionic constituents up to 1000 u, and the elemental chemistry of low-mass organic macromolecules and aerosols in Titan's upper atmosphere as well as monitor neutral-ionic chemical coupling processes.

The plume emanating from Enceladus' south pole probably contains the most accessible samples from an extra-terrestrial liquid water environment in the Solar System. The plume is mainly composed of water vapor and other gases: 0.91% H_2O, 0.04% N_2, 0.032% CO_2, 0.016% CH_4 (Waite et al. 2006). In addition, complex macromolecular organic species with masses exceeding 200 u, were detected in the plume emissions suggesting the presence of a thin organic-rich film on the upper layer of the ocean (Postberg et al., 2018). The presence of CO_2, CH_4 and N_2 can constrain the oxidation state of Enceladus' hydrothermal system during its evolution. The minor gas constituents in the plume are indicative of high-temperature oxidation-reduction (redox) reactions in Enceladus' interior possibly a result of decay of short-lived radionucleides (Schubert et al. 2007). In addition, H_2 production and escape may be a result of redox reactions. Further the high temperatures and H_2 escape may have led to the oxidation of NH_3 to N_2 (Glein et al. 2008). Enceladus' redox state may have or have had similarities with terrestrial submarine hydrothermal systems. Detection and inventory of reduced and oxidized species in the plume material (e.g., NH_3/N_2 ratio, H_2 abundance, reduced versus oxidized organic species) can constrain the redox state and evolution of Enceladus' hydrothermal system.

Cassini CDA measurements identified three types of grains in the plume and Saturn's E-ring. Type I and Type II grains are both salt-poor (Figure 9). Type I ice grains are nearly pure-water ice while Type II grains also possess silicates and organic compounds and Type III is salt-rich (0.5 – 2.0% by mass) (Postberg et al. 2009, 2011). The salinity of these particles suggests they originate in a place where likely water-rock interactions are taking place.

In addition, E-ring stream particles were identified as nanometer-sized SiO_2 (silica) dust particles that were initially embedded in plume ice grains (Hsu et al. 2015). These particles indicate an origin at locations where alkaline high temperature (>90°C) hydrothermal rock-water reactions are taking place (Hsu et al. 2015). Hsu et al. (2015) further suggests that a convective ocean is required to have silica nanoparticles transported from hydrothermal sites at the rocky core up to the surface of the ocean where they can be incorporated into icy plume grains. To confirm this hypothesis of current hydrothermal activity on Enceladus, a direct detection of silica and other minerals within ejected ice grains is required. SiO_2 nano-particles detected in Saturn's E-ring can now be much better investigated and quantified by high-resolution mass spectrometer with a higher dynamic range (10^6–10^8). In addition, with high resolution mass spectrometry in the proposed baseline mission it would also be possible to search for signatures of on-going hydrothermal activities from possible detection of native H_2 and He.

FIGURE 9

4.7 Physical dynamics in Enceladus' plume and Titan's upper atmosphere

The total heat emission at the south polar "tiger stripes" is at least 5 GW (possibly up to 15 GW, Howett et al. 2011), and in some of the hot spots where jets emanate, the surface temperatures are as high as 200 K (Goguen et al. 2013). Cassini observations show that the plume is made up of ~100 discrete collimated jets as well as a diffuse distributed component (Hansen et al. 2008, 2011; Postberg et al. 2011; Porco et al. 2014). The majority of plume material can be found in the distributed diffuse portion of the plume, which likely originates from elongated fissures along Enceladus' tiger stripes while only a small portion of gas and grains are emitted from the jets (Hansen et al. 2011; Postberg et al. 2011). CDA measurements demonstrate that the majority of salt-poor grains tend to be ejected through the jets and at faster speeds while larger salt-rich grains tend to be ejected more slowly through the distributed portion of the plume (Postberg et al. 2011). Ice-to-vapor ratios can constrain how Enceladus' plume material is formed and transported to the surface. For example, ice-to-vapor ratios > 0.1–0.2 would exclude plume generation mechanisms which require a large amount of ice grains to be condensed from vapor (Ingersoll and Pankine 2011; Porco et al. 2006). However, this ratio is poorly constrained with estimates ranging from 0.05 (Schmidt et al. 2008) to 0.4 (Porco et al. 2006) to 0.35–0.7 (Ingersoll and Ewald 2011). Imaging and spectral mission from the proposed baseline mission could help constrain this important ratio. Cassini ISS images used to track plume brightness variation, which is proportional to the amount of grains in the plume, with the orbital position of Enceladus found more ice grains are emitted when Enceladus is near its farthest point from Saturn (apocenter). It is not understood if the plume vapor has such a variation. This temporal variation of the plume indicates that it is tidally driven but could also be due to possible physical libration (Hurford et al. 2009; Kite et al. 2016). Kite et al. (2016) has suggested that the tiger stripe fissures are interspersed with vertical pipe-like tubes with wide spacing that extend from the surface to the subsurface water. This mechanism allows tidal forces to turn water motion into heat, generating enough power to produce eruptions. in a sustained manner. High spatial resolution thermal emissions maps could be used to constrain the amount of energy dissipated between the tiger stripes

4.8 Geological evidence for interior-surface communication on Titan

Geological features such as tectonic and putative cryovolcanic are the reflection of interior processes and may indicate communication between atmosphere-surface and subsurface enabling prebiotic/abiotic processes. Titan's surface offers a wealth of geological processes with which to constrain the extent that Titan's surface chemically communicates with its water-rich interior, in particular possible cryovolcanism and tectonics. Also of great importance to habitability are the transient H_2O melt sheets and flows associated with impacts (e.g. Selk impact crater; Soderblom et al., 2010). On Titan, several features with volcanic landforms, lengthy flows, tall mountains, large caldera-like depressions, have been identified as possible cryovolcanic sites. At present, the Hotei Regio flows and the Sotra Patera region, which includes Sotra Patera, an elliptical deep depression on Titan, Mohini Fluctus, a lengthy flow feature, and Doom and Erebor Montes, two volcanic edifices, are considered to host the strongest candidates for cyrovolcanism on Titan (Lopes et al. 2013). High resolution mapping (at minimum, 30 m/pixel with DTM vertical resolution of 10 m) of regions that are candidates for cryovolcanic activity could improve the ability to distinguish cryovolcanic features.

A variety of mountainous topography has been observed on Titan (Radebaugh et al. 2007; Cook-Hallett et al. 2015). The observed morphologies of many of Titan's mountain suggest contractional tectonism (Mitri et al. 2010; Liu et al. 2016). This is somewhat surprising, however, in that most tectonic landforms observed on other ocean worlds and icy satellites in the outer solar system appear to be extensional in nature. Understanding the tectonic regime of Titan is fundamental in understanding the transport of material between the moon's organic-rich surface and subsurface ocean and will also provide insight into the evolution of the other ocean worlds. We will test the hypothesis that Titan's mountains are formed by contraction by mapping the faults driving mountain formation in topographic context. A future mission can test the hypothesis that Titan's mountains are formed by contraction by mapping the faults driving mountain formation in topographic context by using the shape of the fault outcrop draped against topography to measure the faults' dip, which will be ~30 degrees to the horizontal for compressive mountains and ~60 degrees for extensional mountains.

In addition to cryovolcanism and tectonism, which may transport water to Titan's surface, impact craters likely have created transient liquid-water environments on Titan's surface. Because of Titan's dense atmosphere, models suggest that melt sheets and flows associated with impact craters may remain liquid for 10^4–10^6 years (Thompson and Sagan 1992; Artemieva and Lunine 2005), though the stability of such lakes is questioned (Senft and Stewart 2011; Zahnle et al. 2014) and detailed imaging of the floors of young craters is needed to constrain these models.

5. Science case for the option 1 and 2 mission scenarios

5.1 *In situ* Titan sea probe/lander

Titan presents approximately 600 standing bodies of liquid hydrocarbons at the polar regions forming seas and lakes (Stofan et al. 2007; Lopes et al. 2018) which are found poleward of 55° latitude and cover 1.2% of the surface that has been observed (~50%) by Cassini's instruments (Hayes et al. 2008, 2011). Seasonal asymmetry likely due to Saturn's current orbital configuration (Aharonson et al. 2009) has resulted in the majority of lakes, filled and empty, being located in the north pole while empty and paleo-lakes predominate in the south pole. In the north, 87% of the area of observed liquid deposits are contained within the three largest lakes, Ligeia, Kraken, and Punga Mare, which are similar in size to the Great Lakes (USA). This hemispheric asymmetry of lakes and seas yields a net transport of volatiles (methane/ethane) from the south to the north; however, as the orbital parameters shift the net flux of northward-bound volatiles is expected to slow and eventually reverse, resulting in a larger southern hemispheric liquid distribution in ~35 kyr. If this hypothesis is correct, the distribution of liquid deposits on Titan is expected to move between the poles with a period of ~50 kyr in a process analogous to Croll-Milankovich cycles on Earth. *In situ* measurement and comparison between the relative abundance of volatiles that are mobile over these timescales (e.g., methane, ethane) versus those that are involatile (e.g., propane, benzene), can be used to test this hypothesis and understand volatile transport on thousand years timescale. Volatile transport over shorter timescales (diurnal, tidal, and seasonal) can be investigated via *in situ* measurements of the methane evaporation rate and associated meteorological conditions (e.g., wind speed, temperature, humidity). These measurements can be used to ground-truth methane transport predictions from global climate models (e.g., Mitchell et al. 2008; Tokano et al. 2009; Schneider et al. 2012). Cassini RADAR altimetry results have been used to determine the depth and constrain the composition of the Ligeia Mare (Mastrogiuseppe et al. 2014) and Winnepeg Lacus (Mastrogiuseppe et al. 2019) at the north pole and Ontario Lacus at the south pole (Mastrogiuseppe et al. 2018). *In situ* sounding of one of the northern seas can be used to confirm the depth and composition of Ligeia Mare or else to determine the depth of the Kraken Mare, Titan's largest sea, thus improving our understanding of the total volume of liquid available for interaction with the atmosphere. The inventory of methane in Titan's Mare, which requires knowledge of both depth and composition, will provide a lower limit on the length of time that the lakes can sustain methane in Titan's atmosphere (Mitri et al. 2007) and help to quantify the required rate of methane resupply from the interior and/or crust. Similarly, the absolute abundance of methane photolysis products (e.g., ethane, propane) will determine a lower limit for the length of time that methane has been abundant enough to drive photolysis in the upper atmosphere and deposit its products onto the surface and, ultimately, into the lakes and seas.

Similar to the Earth's oceans, Titan's seas record a history of their parent body's origin and evolution. Specifically, the noble gas and isotopic composition of the sea can provide information regarding the origin of Titan's atmosphere, reveal the extent of communication with the interior, potentially constrain the conditions in the Saturn system during formation, and refine estimates of the methane outgassing history. Titan's lakes and seas collect organic material both directly, through atmospheric precipitation of photolysis products, and indirectly, through aeolian or fluvial transport of surface materials (e.g., river systems flowing into the Mare). As a result, the lakes and seas represent the most complete record of Titan's organic complexity and present a natural laboratory for studying prebiotic organic chemistry (Lunine et al. 2010). Titan's environment is similar to conditions on Earth four billion year ago and presents an opportunity to study active systems involving several key compounds of prebiotic chemistry (Schulze–Makuch and Grinspoon 2005; Raulin 2008; Coustenis and Raulin, 2015). Noble gas measurements and, isotopic ratios can also be used to decipher the history of Titan's atmosphere. For example, the $^{13}C/^{12}C$ ratio of methane was used by Niemann et al. (2010) to conclude that methane last outgassed from the interior ~10^7 years ago. However, this calculation assumes that the exposed methane reservoir has an isotopic composition that is in equilibrium with the atmosphere. If the carbon isotope ratio of hydrocarbons in Titan's lakes/seas were found to be different than in the atmosphere, it would imply chemical alteration of the isotopic composition and indicate a different timescale for the history of methane-outgassing.

In summary, *in situ* exploration of Titan's lakes and seas will address fundamental questions involving the origin, evolution, and history of both Titan and the broader Saturnian system. The study of Titan's organic chemistry has direct applicability to our understanding of early prebiotic chemistry on Earth, allowing the investigation of reactions and timescales inaccessible to terrestrial labs.

5.2 Ice penetrating radar (IPR)

The ice penetrating radar (IPR) would be capable of both shallow and deep sounding to characterize the subsurface with a depth of 9 km and ~30 m vertical resolution at minimum. An

IPR can characterize structural, compositional and thermal variations occurring in the subsurface providing data that can correlate surface and subsurface features and processes, deformation in the upper ice shell, as well as global and local surface age. On Titan, radar sounder observations with a penetration depth up to ~9 km with a vertical resolution of ~30 m, similar to JUICE RIME and Europa Clipper REASON, could directly determine the relict Brittle-Ductile transition of the ice shell revealing its thermal state, thus constraining its ice shell thickness and thermal evolution. Liu et al. (2016) suggests that subsurface liquid hydrocarbons could enable contractional structures to form on Titan without the necessity of large stresses. An IPR would be able to detect any near surface pockets of liquid. In addition, an IPR would also investigate the ice-ocean interface at Enceladus' SPT and its variability in the SPT.

An additional option for radar architecture could be a multi-mode radar design suitable for both sounding and imaging to be operated in two modes: a vertical sounder mode, with similar capabilities as described above but with different architecture, and a Synthetic Aperture Radar (SAR) imaging mode, similar to Cassini's, but with higher resolution at tens of meters. The additional SAR mode could be used for high-resolution imaging of the surface, complementing the IR imaging, as well as for creating three dimensional high resolution bathymetric maps of Titan seas and lakes and could permit investigation of any possible compositional variation in space and time of the hydrocarbon liquid and/or sea floor properties.

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TABLES

Table 1. Science goals of baseline mission

Science summary	
Science goals	**Science objectives**
Origin and evolution of volatile-rich ocean worlds, Enceladus and Titan	- Are Enceladus' volatile compounds primordial or have they been re-processed and if so, to what extent? - What is the history and extent of volatile exchange on Titan? - How has Titan's organic-rich surface evolved?
Habitability and potential for life of ocean worlds, Enceladus and Titan	- Is Enceladus' aqueous interior an environment favorable to the emergence of life? - To what level of complexity has prebiotic chemistry evolved in the Titan system?

Table 2. *Science goals of optional sea probe (lander) element*

Science summary	
Science goals	**Science objectives**
Origin and evolution of Titan's lakes and seas	- How does the hydrological cycle work, and what is the role of the lakes and seas? How have the seas and lakes evolved over time (e.g., shorelines)? - Constrain the depth of a Titan sea - What is the lower atmosphere over the sea? - Constrain sea-atmosphere interactions
Habitability and potential for life of Titan's lakes and seas	- What is the composition of the seas and lakes? - Are there any prebiotic or biotic signature compositions? - What is the composition of evaporites and what is their relation to the lakes and seas?

Table 3. Science goals of optional Ice Penetrating Radar (IPR) element

Science summary	
Science goals	**Science objectives**
Interior structure and processes of Enceladus and Titan	- What is the thickness of the surface organic material layer on Titan? - How does ice thickness vary in Enceladus' south polar terrain? - Constrain brittle-ductile transition within Titan's ice shell - How do the surface and subsurface features correlate on Titan and Enceladus? - Constrain the extent of Enceladus' ocean at SPT - Constrain anomalous thermal emission beneath SPT - What is the extent of surface and subsurface communication especially in the polar regions of both Titan and Enceladus?

Table 4. Science objectives, measurements and proposed techniques for option 1, the sea probe/lander (Mitri et al. 2014)

Science objectives		Measurements	Approaches and requirements
Lakes/seas	Characterize one of Titan's northern seas and its chemical composition (astrobiological potential)	Sea composition, including low and high mass hydrocarbons, noble gases, and carbon isotopes	Mass spectrometry
			Low atmosphere physical properties package (temperature sensor, barometer, anemometer)
		Exchange processes at the sea-air interface to help constrain the methane cycle	Low-atmosphere physical properties package (temperature sensor, barometer, anemometer)
		Presence and nature of waves and currents	Physical properties package
			Surface Imaging (~250 μrad/pixel)
		Properties of sea liquids including turbidity and dielectric constant	Sea physical properties package (turbidity and dielectric constant measurements)
		Sea depths to constrain basin shape and sea volume	Sonar
		Shoreline characteristics, including evidence for past changes in sea level	Surface Imaging (~250 μrad/pixel)
			Surface Imaging (~250 μrad/pixel)
Atmosphere	Determine T, P, composition, evaporation rate and physical properties that characterize lake and atmosphere interactions	Determine T, P, composition, evaporation rate and physical properties that characterize lake and atmosphere interactions	Mass spectrometry Physical properties package
	Characterize the atmospheric composition during probe decent	Determine the composition	Mass spectrometry

FIGURES

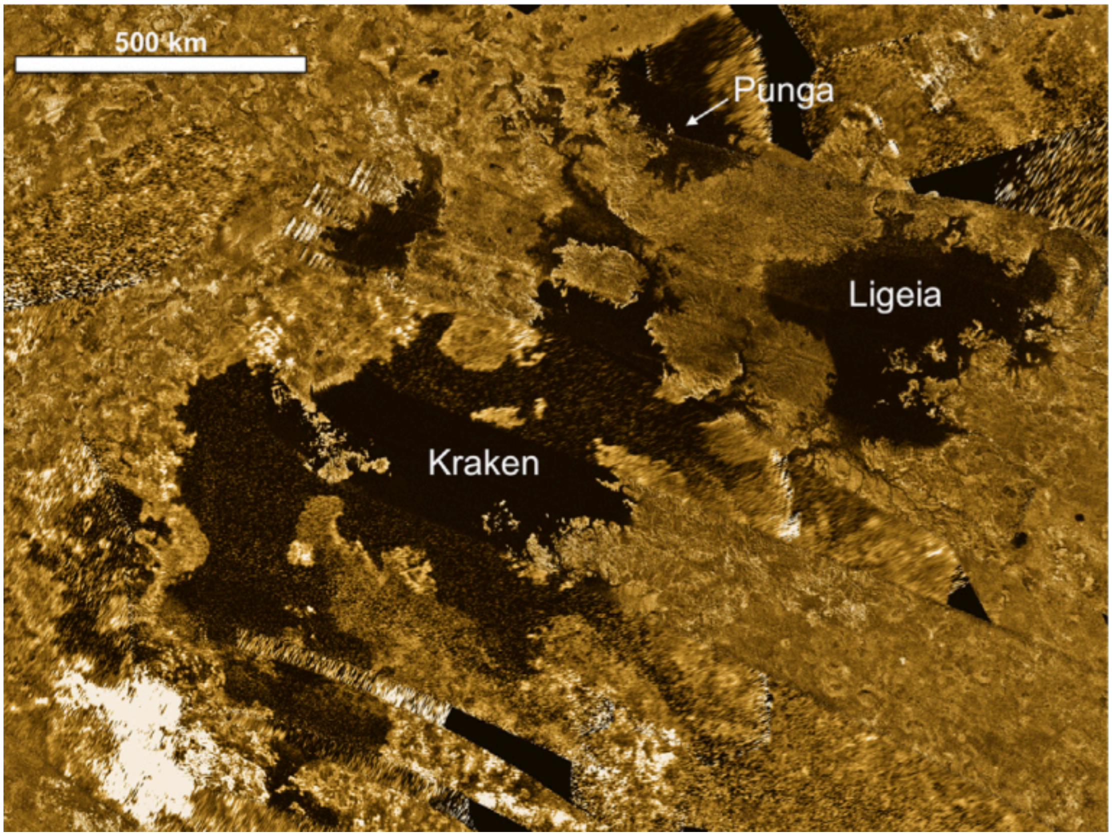

Figure 1. Cassini SAR mosaic images of the north polar region showing Kraken, Ligeia and Punga Maria. Black–yellow color map was applied to the single band data (from Mitri et al. 2014a).

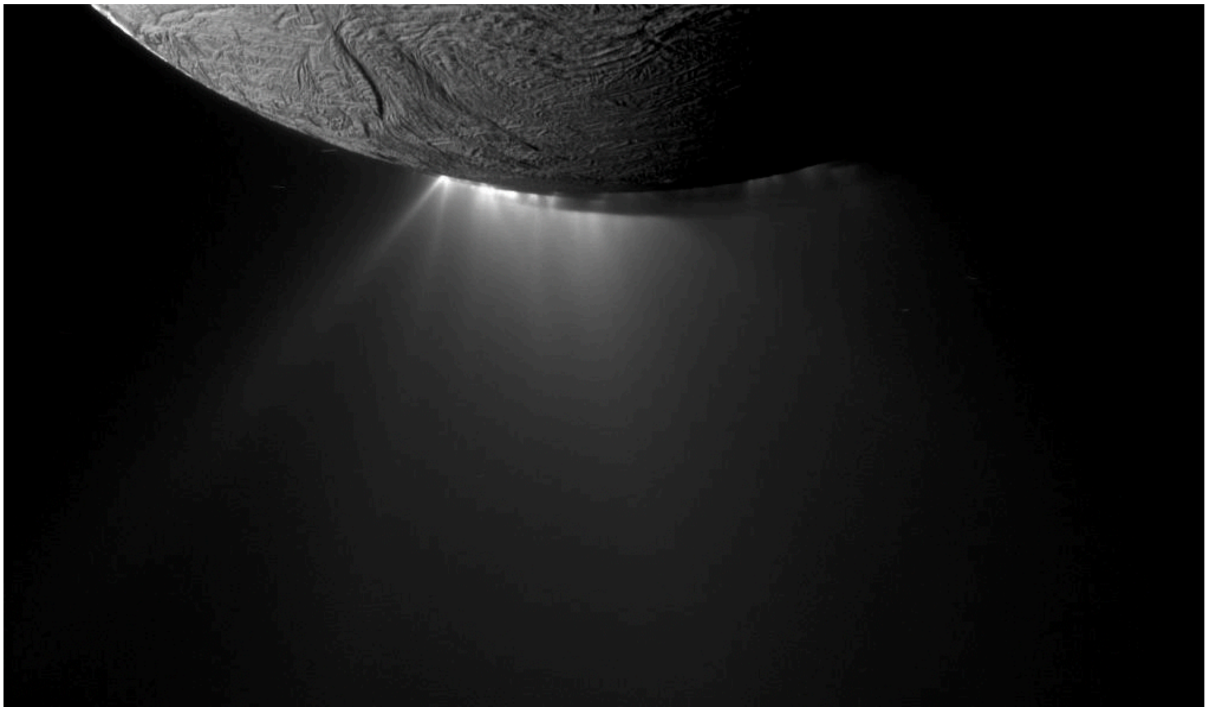

Figure 2. Plume emanating from multiple jets in Enceladus' south polar terrain.

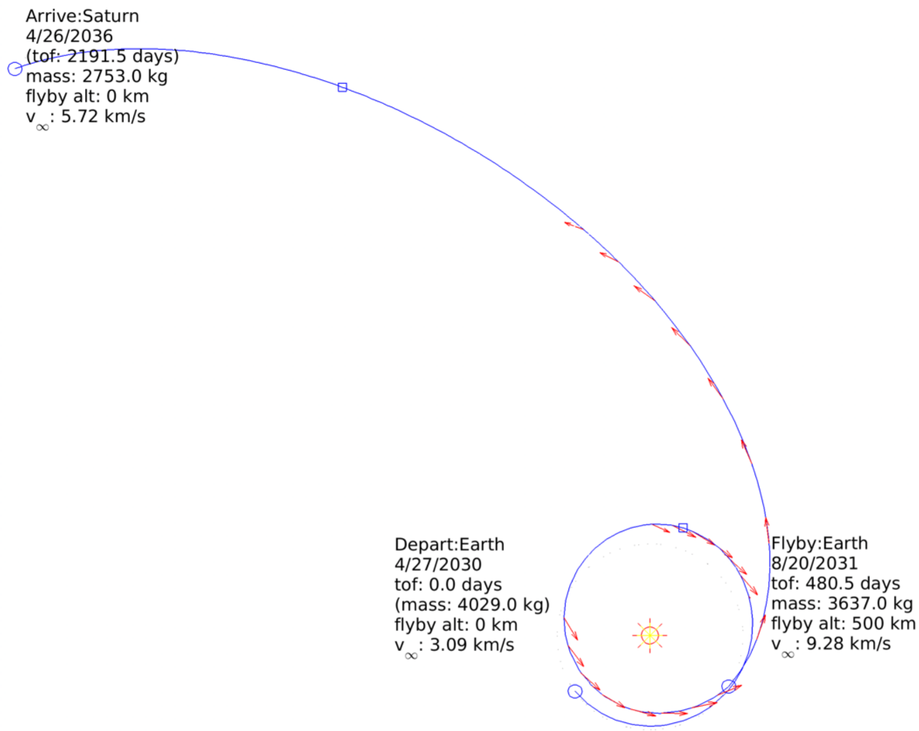

Figure 3. Example interplanetary transfer to Saturn studied for E^2T proposal based on a proposed launch in 2029–2030 (Mitri et al. 2018). Red arrows indicate electric propulsion thrust. Such a scenario could be used to design a future transfer trajectory.

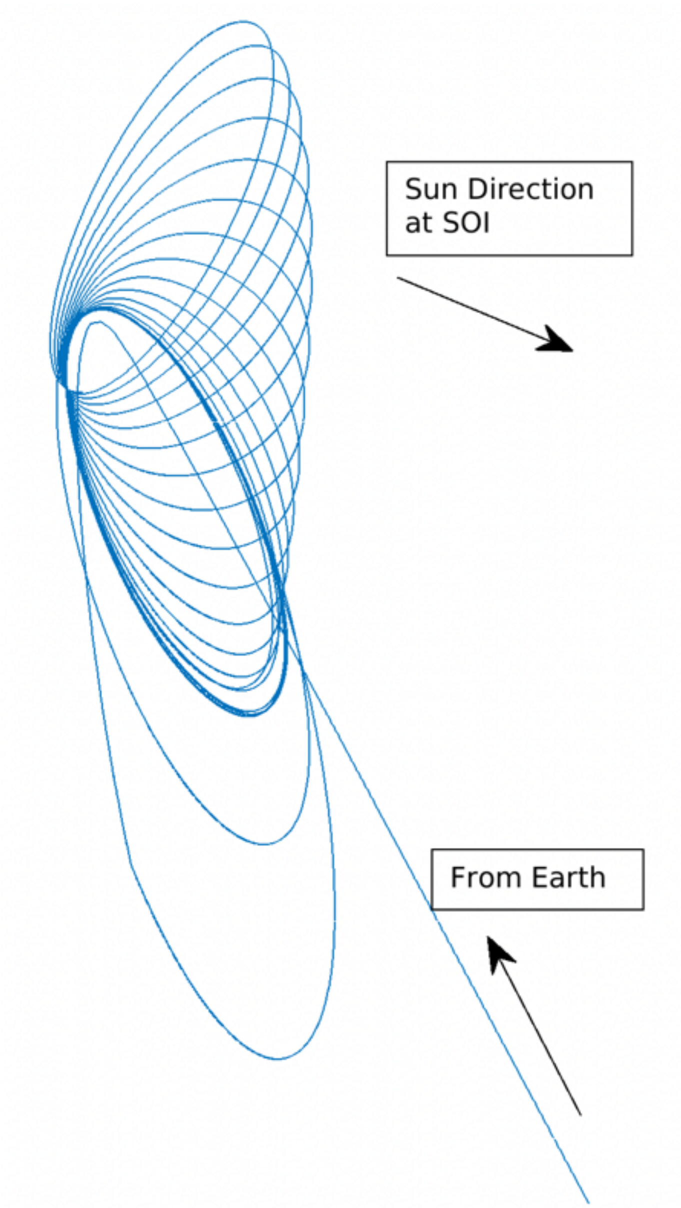

Figure 4. Inertial representation of a sample tour based on a proposed 2029–2030 launch with two period- and inclination-management Titan flybys followed by a science phase with 6 Enceladus flybys and 17 Titan flybys (Mitri et al. 2018).

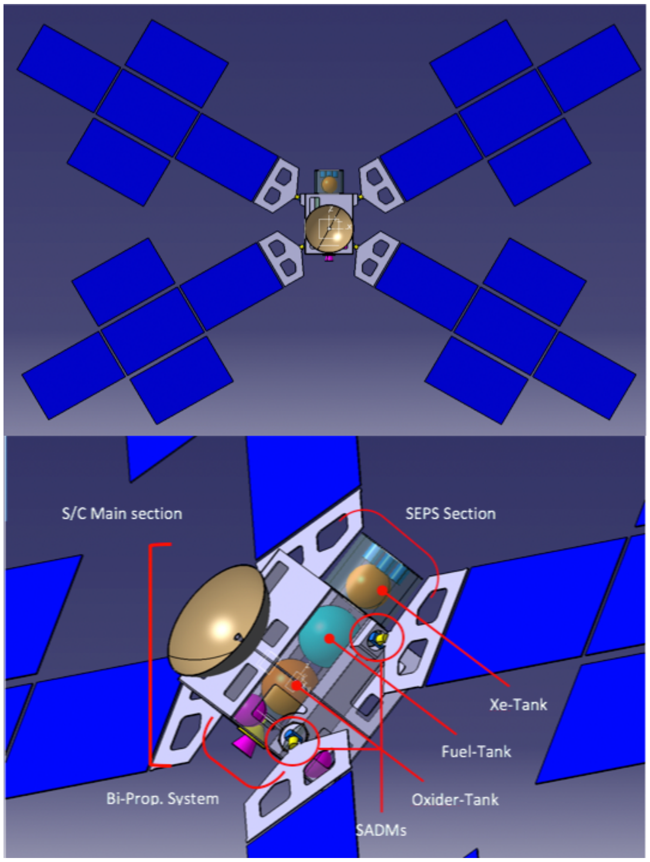

Figure 5. Proposed configuration of the S/C for the E^2T project. Top panel shows an enlarged view of the S/C and below panel shows a close-up view of the S/C (Mitri et al. 2018).

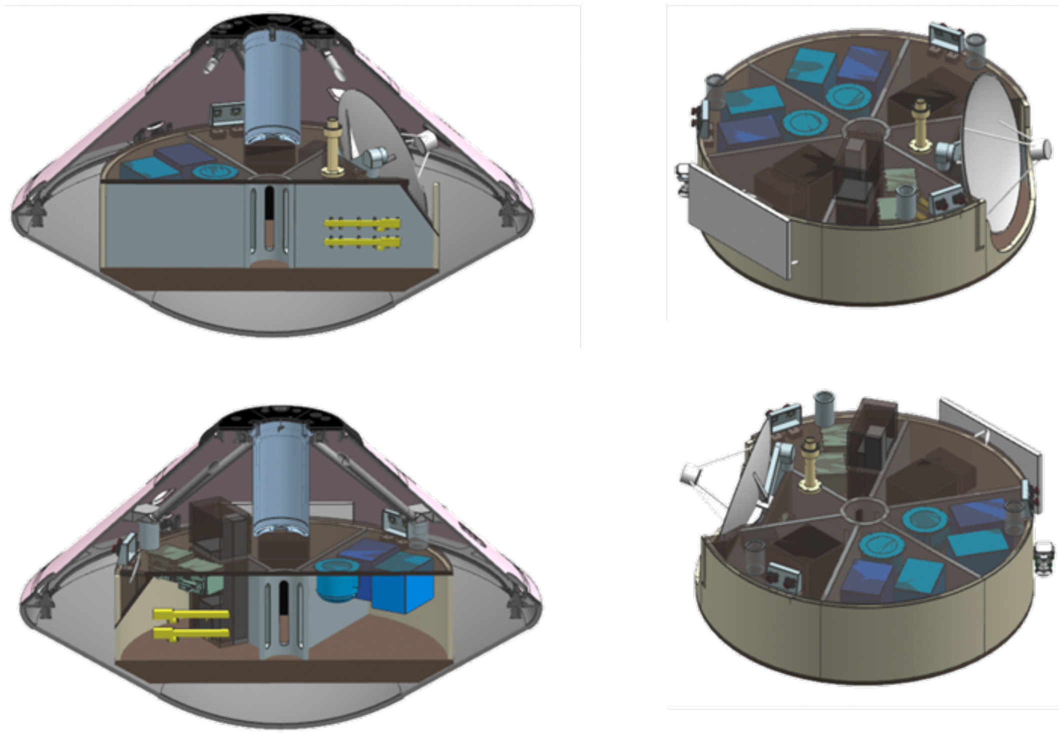

Figure 6. Examples of a sea lander and entry vehicle. The right-hand panel shows front and back views of the sea lander inside the entry vehicle while the left-hand panel shows the sea lander only. Credit: JPL.

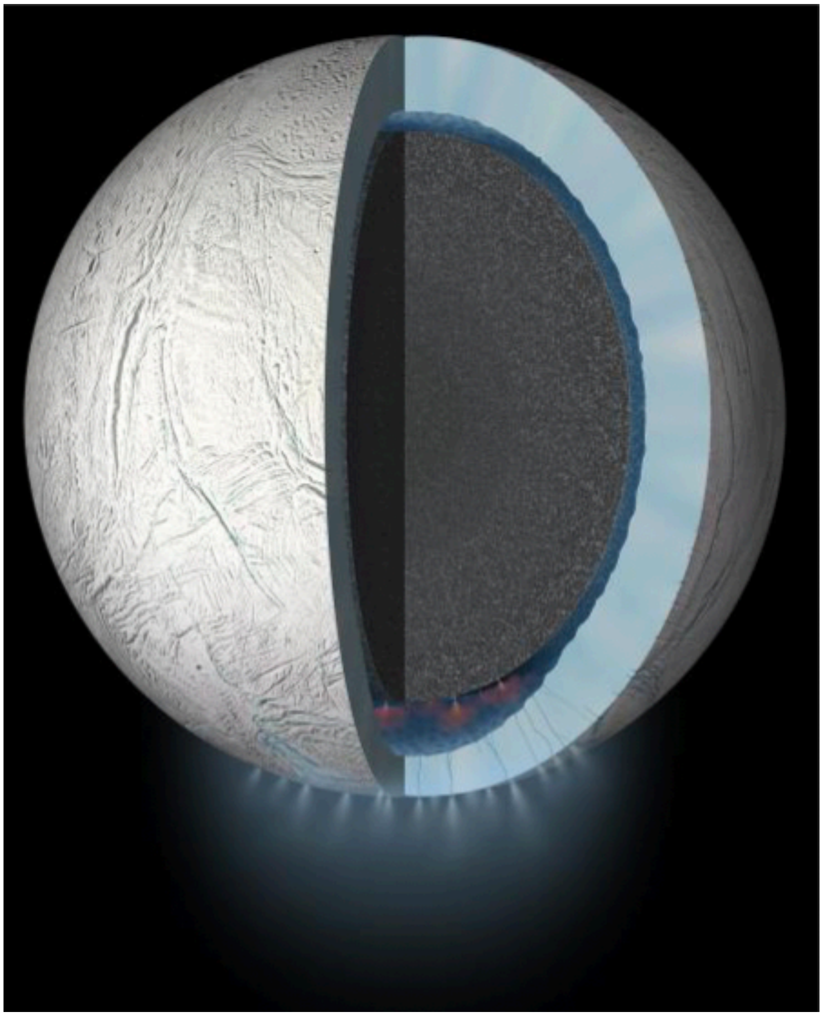

Figure 7. Enceladus' internal structure inferred from gravity, topography and libration measurement provided by Cassini mission. A global subsurface ocean is present under the outer ice shell. The ice shell is believed to be a few kilometers thin at the south polar region where the center of the geological activity is with the formation of the plume formed by multi-jets.

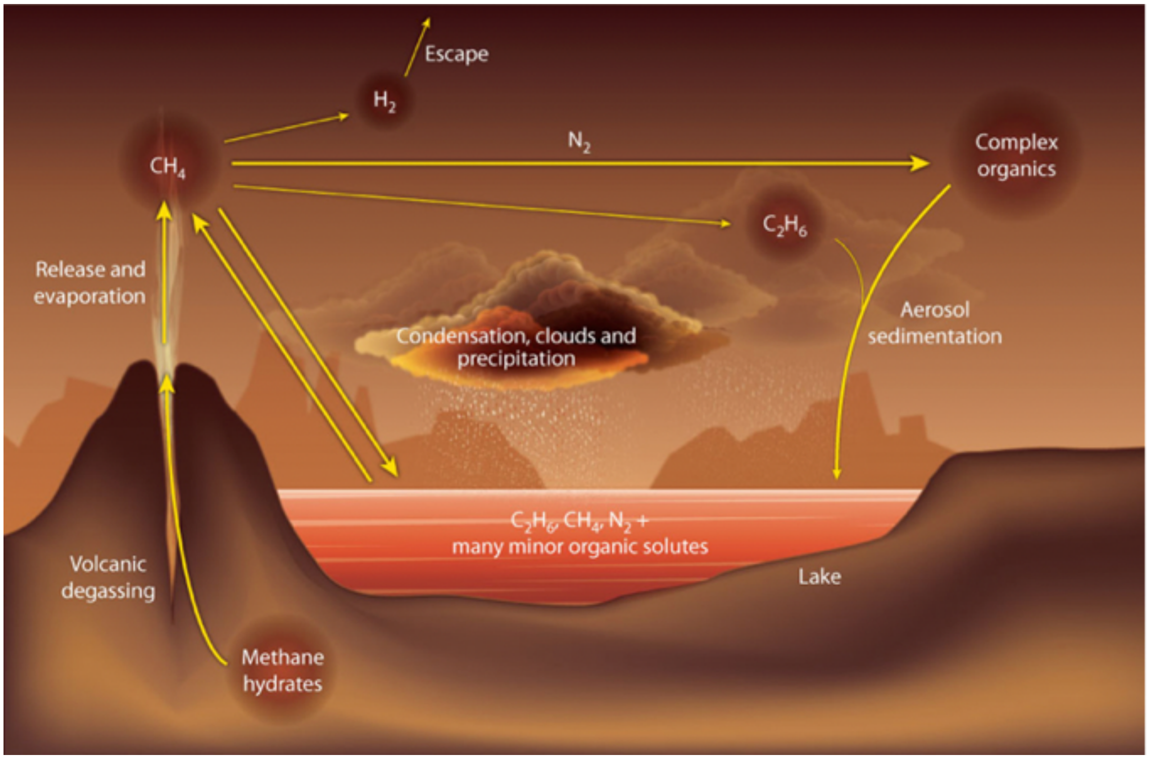

Figure 8. Titan's methanological cycle (Raulin, 2008).

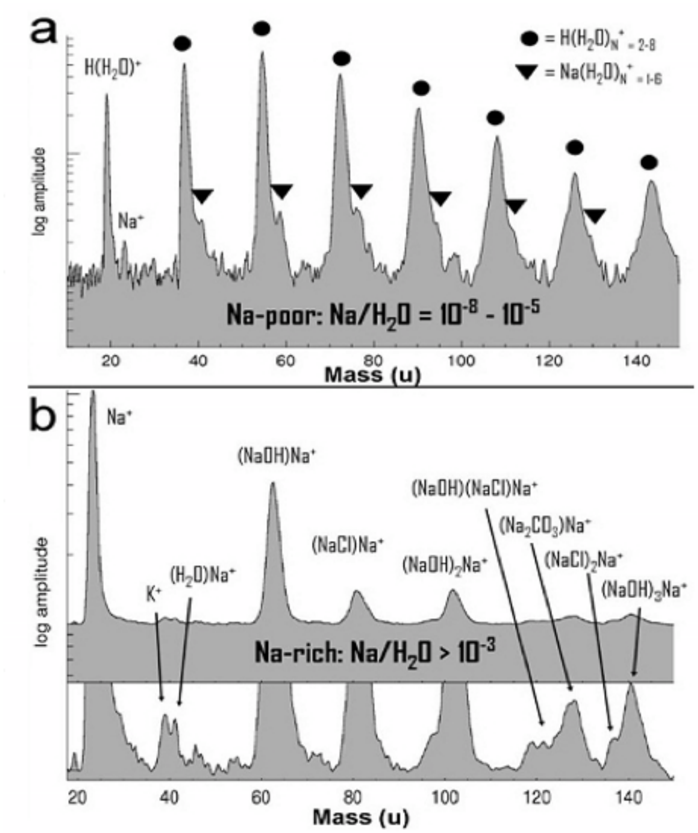

Figure 9. Composition of salt-poor (Type I and II) and salt-rich (Type III) particles in Saturn's E-ring and Enceladus' plume (Postberg et al. 2011).