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Explorer of Enceladus and Titan (E^2T): Investigating Ocean Worlds' Evolution and Habitability in the Solar System

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Abstract

Titan, with its organically rich and dynamic atmosphere and geology, and Enceladus, with its active plume, both harbouring subsurface oceans, are prime environments in which to investigate the habitability of ocean worlds and the conditions for the emergence of life. We present a space mission concept, Explorer of Enceladus and Titan (E^2T), dedicated to investigating the evolution and habitability of these Saturnian satellites proposed as a medium-class mission led by ESA in collaboration with NASA in response to ESA's M5 Cosmic Vision Call. E^2T proposes a focused payload that would provide in-situ composition investigations and high-resolution imaging during multiple flybys of Enceladus and Titan using a solar-electric powered spacecraft in orbit around Saturn. The E^2T mission would provide high-resolution mass spectrometry of the plumes currently emanating from Enceladus' south polar terrain and of Titan's changing upper atmosphere. In addition, high-resolution infrared (IR) imaging would detail Titan's geomorphology at 50-100 m resolution and the temperature of the fractures on Enceladus's south polar terrain at meter resolution. These combined measurements of both Titan and Enceladus would enable the E^2T mission scenario to achieve two major scientific goals: 1) Study the origin and evolution of volatile-rich ocean worlds; and 2) Explore the habitability and potential for life in ocean worlds. E^2T's two high-resolution time-of-flight mass spectrometers would enable to untangle the ambiguities left by the NASA/ESA/ASI Cassini-Huygens mission regarding the identification of low-mass organic species, detect high-mass organic species for the first time, further constrain trace species such as the noble gases, and clarify the evolution of solid and volatile species. The high-resolution IR camera would reveal the geology of Titan's surface and the energy dissipated by Enceladus fractured south polar terrain and plume in detail unattainable by the Cassini mission.

1. Introduction

The NASA/ESA/ASI Cassini-Huygens mission has revealed Titan and Enceladus to be two unique worlds in the Solar System during its thirteen years of observations in the Saturnian system (July 2004 - September 2017). Titan, with its organically rich and dynamic atmosphere and geology, and Enceladus, with its active plume composed of multiple jets (Waite et al., 2006; Spahn et al., 2006; Porco et al., 2006), both harbouring subsurface oceans (Iess et al., 2010, 2012, 2014), are ideal environments in which to investigate the conditions for the emergence of life and the habitability of ocean worlds as well as the origin and evolution of complex planetary systems. The prime criteria of habitability include energy sources, liquid water habitats, nutrients and a liquid transport cycle to move nutrients and waste (McKay et al., 2008, 2016; Lammer et al., 2009). The best-known candidates in the Solar System for habitability at present likely meeting these criteria are the ocean worlds in the outer Solar System, which include: Europa, Enceladus, Ganymede and Titan (Lunine, 2016). While the Jovian moons will be thoroughly investigated by the ESA Jupiter Icy moon Explorer (JUICE), Enceladus and Titan which provide environments that can be easily sampled from orbit in a single mission, are not currently targeted by any future exploration. The joint exploration of these two fascinating objects will allow us to better understand the origin of their organic-rich environment and will give access to planetary processes that have long been thought unique to the Earth.

Titan is an intriguing world similar to the Earth in many ways, with its dense nitrogen-methane atmosphere and familiar geological features, including dunes, mountains, seas, lakes and rivers (e.g., Stofan et al., 2007; Lorenz et al., 2009; Mitri et al., 2010). Titan undergoes seasonal changes similar to Earth, driven by its orbital inclination of 27° and Saturn's approximately 30 year orbit. Exploring Titan then offers the possibility to study physical processes analogous to those shaping the Earth's landscape, where methane takes on water's role of erosion and formation of a distinct geomorphological surface structure.

Enceladus is an enigma; it is a tiny moon (252 km radius) that harbours a subsurface liquid-water ocean (Iess et al., 2014; McKinnon et al., 2015; Thomas et al., 2016), which jets material into space. The eruption activity of Enceladus offers a unique possibility to sample fresh material ejected from subsurface liquid water and understand how exchanges with the interior controls surface activity as well as constrain the geochemistry and astrobiological potential of internal oceans on ocean worlds (e.g., Porco et al., 2006). Since the 1997 launch of the Cassini-Huygens mission, there has been great technological advancement in instrumentation that would enable answering key questions that still remain about the Saturnian ocean worlds.

We present a space mission concept, Explorer of Enceladus and Titan (E^2T), dedicated to investigating the evolution and habitability of Enceladus and Titan proposed as a medium-class mission led by ESA in collaboration with NASA in response to ESA's M5 Cosmic Vision Call. In Section 2 we present the science case for the future exploration of Enceladus and Titan as proposed by the E^2T mission, and Section 3 the science goals for the E^2T mission. In Sections 4 and 5 we discuss the proposed payload and mission and spacecraft configuration necessary to achieve E^2T mission goals.

2. Science Case for the Exploration of Enceladus and Titan

Titan, Saturn's largest satellite, is unique in the Solar System with its dense, extensive atmosphere composed primarily 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). As methane is close to its triple point on Titan, it gives rise to a methane 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).

FIGURE 1

Titan's atmosphere shows many similarities with our own planet, but the low temperature conditions and the absence of oxygen, render Titan a unique world to study on its own, probably bringing essential information on the conditions prevailing on the primitive Earth. The seasonal effects on Titan are essential to study. With an environment that changes on a 29.5 year cycle, it is crucial to study the satellite during an entire orbital period. Cassini has investigated Titan over only two seasons: from Northern winter solstice to summer solstice. And while ground-based observations, have observed Titan in other seasons, the data are not sufficient to address many of the outstanding questions. Current measurements with Cassini/CIRS show that the chemical content of Titan's atmosphere has significant seasonal and latitudinal variability (Coustenis et al., 2013; 2016); future extended exploration of Titan is necessary to get a full picture of the variations within this complex environment.

Titan is the only known planetary body, other than the Earth 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 crust (Hayes et al., 2008). 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 cryovolcanic activity or other exchange processes (Lopes et al., 2007, 2016; Solomonidou et al., 2014, 2016). The detection of a salty ocean at an estimated 50-80 km depth (Iess et al., 2012; Beghin et al., 2012; Mitri et al., 2014b) and the possible communication between this ocean and the organic-rich surface hint at exciting astrobiological possibilities. While Cassini has provided tantalizing views of the surface with its lakes and seas, dunes, equatorial mountains, impact craters and possible cryovolcanos, 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. Constraining the level of geological activity on Titan is crucial to understanding its evolution and determining if this ocean world could support abiotic/prebiotic activity.

Both Titan and Enceladus possess several, if not all, of the key ingredients necessary for life: an energy source, liquid habitats, nutrients (organic compounds) and a liquid transport cycle to move nutrients and waste (McKay et al., 2008, 2016). While sunlight is a minimal source of energy for solid bodies in the outer Solar System, interior heat sources derived from a rocky core or tidal forces produced by neighbouring satellites and planet can be quite significant. Most recently, the Cassini INMS has identified molecular hydrogen (0.4-1.4%) in Enceladus' plume (Waite et al., 2017)providing further evidence of water-rock interactions which suggests that methane formation from CO_2 in Enceladus' subsurface ocean could occur in a similar fashion as it occurs on Earth where extremophile microbes in hydrothermal sea vents produce methane as a metabolic by-product (McKay et al., 2008). Another compelling discovery is the complex large nitrogen-bearing organic molecules in Titan's upper atmosphere by Cassini (Waite et al., 2007; Coates et al., 2007). The low resolution of the in-situ mass spectrometers on Cassini, however, precludes the determination of the chemical composition of this complex organic matter. In situ exploration with more advanced instruments is required to investigate the prebiotic potential of Titan.

The discovery in 2005 of a plume emanating from multiple jets in Enceladus' south polar terrain 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). 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 vapour activity around Europa has been reported (Roth et al., 2014; Sparks et al., 2016,2017), Enceladus is the only satellite for which this activity is known to be endogenic in nature. The jets, of which approximately one hundred have been identified (Porco et al., 2014) form a huge plume of vapour and ice grains above Enceladus' south polar terrain and are associated with 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). Sampling of the plumeby Cassini's instruments revealed the presence of water vapour, ice grains rich in sodium and potassium salts (Postberg et al., 2011), organics, both in the gas (Waite et al., 2009) and in the ice grains (Postberg et al., 2008, 2015), and molecular H (Waite et al., 2017). The jet sources are connected to a subsurface salt-water reservoir that is likely alkaline in nature and undergoing hydrothermal water-rock interactions (Porco et al., 2006, 2014; Waite et al., 2006, 2009, 2017; Postberg et al., 2009, 2011; Hsu et al., 2011, 2014; Glein et al., 2015). The putative exothermic water-rock interactions on Enceladus could be further constrained by quantifying He and constraining the amount of H_2 in the plume. 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). The co-existence of organic compounds, salts, liquid water and energy sources on this small moon provides all 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.

Titan and Enceladus offer an opportunity to study analogous prebiotic processes that may have led to the emergence of life on Earth. Retracing the processes that allowed the emergence of life on Earth around 4 Ga is a difficult challenge since most traces of the environmental conditions at that time have been erased. It is, therefore, crucial for astrobiologists to find extraterrestrial planetary bodies with similarities to our planet, providing a way to study some of the processes that occurred on the primitive Earth, when prebiotic chemistry was active. 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.

FIGURE 2

3. Scientific Objectives and Investigations

The scientific appeal of Titan and Enceladus have stimulated many previous mission studies (e.g. see reviews by Lorenz, 2000; 2009) which have articulated detailed scientific objectives for post-Cassini exploration (e.g. Tobie et al., 2014). At Titan, in particular, the diversity of scientific disciplines (Dougherty et al., 2009) has prompted a variety of observing platforms from orbiters ("Titan Explorer", Leary et al., 2007; Mitri et al., 2014), landers for the seas ("Titan-Saturn System Mission – TSSM", Strange et al., 2009; "Titan Mare Explorer - TiME", Stofan et al., 2013; Mitri et al., 2014), landers for land (Titan Explorer), fixed-wing aircraft ("AVIATR", Barnes et al., 2012), balloons (Titan Explorer, TSSM and others). Additionally, Enceladus' plume has attracted designs of spacecraft to sample it: "Titan and Enceladus Mission TANDEM" (Coustenis et al., 2009), "Journey to Enceladus and Titan – JET" and "Enceladus Life Finder – ELF" (Reh et al., 2016). Similar to TANDEM, TSSM and JET, E^2T would address science goals at both targets.

The proposed E^2T mission has two major goals and several science objectives (Table 1) that would be pursued through Enceladus and Titan investigations. These investigations would be conducted using the E^2T mission model payload which consists of three instruments: two time-of-flight mass spectrometers (TOF-MS), the Ion and Neutral Gas Mass Spectrometer (INMS) and the Enceladus Icy Jet Analyzer (ENIJA) dust instrument; and a high-resolution infrared (IR) camera, the Titan Imaging and Geology, Enceladus Reconnaissance (TIGER). With considerable improvements in mass range, resolution and sensitivity, as compared with Cassini, the INMS and the ENIJA time of flight mass spectrometers would provide the data needed to decipher the subtle details of the aqueous environment of Enceladus from plume sampling and of the varying complex pre-biotic chemistry occurring in Titan's atmosphere. The Titan Imaging and Geology, Enceladus Reconnaissance (TIGER) mid-wave infrared camera would map thermal emission from Enceladus' tiger stripes at meter scales and investigate Titan's geology and compositional variability at decameter scales, a resolution at least ten times better than Cassini. The scientific payload will be described in Section 4.

While Cassini-Huygens and its extended missions have revealed much about Enceladus and Titan, the spacecraft (S/C) was not equipped to search for life or constrain the evolution of these ocean worlds. In-situ mass spectroscopic measurements by Cassini-Huygens at Enceladus and Titan revealed a wealth of chemical complexity of neutral and positively charged molecules. Those analyses, however, are limited by the low sensitivity, mass range, and resolution of the Cassini-Huygens mass spectrometers limiting, for example, their ability to resolve low-mass isobaric molecular species. For example, in Enceladus' vapour plume an unidentified species with a mass-to-charge (m/z) ratio of 28, can be either CO, N_2, C_2H_4 or a combination thereof. Determining the relative abundances of these different species is essential to constraining the origin of volatiles on Enceladus and to assess whether they were reprocessed internally. E^2T mass spectrometers enable the separation of low-mass isobaric interferences, for example ^{13}C and ^{12}CH and CO and N_2. Further, Cassini mass spectrometers were limited to the study of only low-mass neutral and positive ions. The detection of heavy complex negative ions in Titan's upper atmosphere by the Cassini Plasma Spectrometer (CAPS), intended to detect electrons, was a surprising find that indicated complex coupling processes between neutral and ionic molecules that lead to the formation of aerosols and possibly to prebiotic activity. Negative water group ions were also detected in Enceladus' plume (Coates et al., 2010). The high mass range/resolution and ability to detect anions of E^2T's mass spectrometers would constrain the nature and dynamics of these heavy hydrocarbon and nitrile molecules.

The nature of the surfaces of Titan and Enceladus have been revealed by Cassini but only at low to moderate resolutions with the exception of the Descent Imager /Spectral Radiometer (DISR) onboard the Huygens probe that landed on Titan's surface on January 14, 2005, which had a resolution ranging from 10 m at 10 km from the surface down to centimeters at the surface giving an indication of the world waiting to be revealed by a new mission to the Saturn system. Huygens' DISR was able to obtain images of a 25 m^2 area (Tomasko et al., 2005). Data from Cassini Visual Infrared Mapping Spectrometer (VIMS) show that Titan is visible at several near-infrared atmospheric windows. Scattering by aerosols in the atmosphere, which limits the signal-to-noise ratio (SNR) and resolution of such data, decreases at longer wavelengths. At 5 μm there is virtually no scattering from Titan's atmospheric aerosols, allowing observations with spatial resolutions that are an order of magnitude better than Cassini observations (Clark et al., 2010; Soderblom et al., 2012; Barnes et al., 2014; Hayne et al., 2014; Sotin et al., 2016). Additionally, these data would be highly sensitive to organic composition (Clark et al., 2010; Barnes et al., 2012). A high-resolution map of Titan within the atmospheric windows at 1.3, 2 and 5 μm would enable E^2T to identify morphology not evident from Cassini data to quantify geological processes and relationships between different geological units and monitor changes due to geologic or atmospheric activity, such as erosion due to climatic changes or even transient features on the lakes and seas of Titan. In addition, high-resolution IR imaging of Enceladus' south polar terrain (both in reflected sunlight and in thermal emission) would provide new detail of the tectonically active surface and constrain characteristics of the hydrothermal system by determining the correlation between the spatial variations in plume composition (vapour and icy grains) measured by the mass spectrometers and source activity.

FIGURE 3

The first scientific goal of E^2T mission on Enceladus would focus on the origin and evolution of volatile compounds in the plume vapour and icy grains. On Titan, the focus would be on the origin and evolution of volatiles, the methane based cycle and evidence for climate change. In addition, on Titan, there would be a focus on determining the major processes controlling the distribution of atmospheric constituents, the impact the methane cycle has on Titan's surface evolution and the morphological signatures of the internal processes of Titan and surface-interior chemical communication. The second scientific goal on Enceladus would examine the nature of hydrothermal activity and search for evidence of abiotic/prebiotic processes. On Titan, the focus would be on discerning what level of complexity abiotic/prebiotic chemistry has evolved.

3.1 Origin and Evolution of Volatile-Rich Ocean Worlds in the Saturn System

The formation of satellites around the gas giant planets Jupiter and Saturn is commonly considered to be in many ways similar to the formation of a miniature version of the Solar System. Satellites are created as by-products of planet formation within a circumplanetary accretion disk of dust and gas (Estrada et al., 2009; Lunine et al., 2010). Their subsequent evolution can be constrained by current chemical and isotopic abundances, satellite activity whether it be endogenic or exogenic and present day internal structure and dynamics. The Saturn system may have followed a more complex evolution than the Jupiter system, with the disruption of lunar-size objects early during the system evolution and their re-accretion later during the system evolution (Canup, 2010; Charnoz et al., 2011). A late accretion scenario may explain the mass distribution and ice/rock ratio of the mid-sized moons and the existence of the planet's ring. Such a scenario is supported by recent estimation of the dissipation factor in Saturn, which is ten times smaller than initially anticipated (Lainey et al., 2012, 2016) and which implies a rapid tidal evolution of the system. In this context, Enceladus may have formed less than 1 billion years ago, while Titan may have accreted earlier. This may have resulted in significant differences in their initial volatile inventory and their subsequent evolution.

Whether the volatiles currently present on Titan and Enceladus are 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). Photochemical processes on Titan and aqueous alteration on Enceladus have affected the initial volatile inventory to an extent unknown. By combining in-situ chemical analysis of Titan's atmosphere and Enceladus' plume with observations of Enceladus' plume dynamics and Titan's surface geology, E^2T would provide clues on how the ocean worlds acquired their initial volatile inventory and how it was subsequently modified during their evolution, which would provide clues to an understanding of the nature of Saturn subnebula formation conditions and its subsequent evolution, 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.

3.1.1 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). To support a primordial methane source, xenon and krypton both would have to be sequestered from the atmosphere. While xenon is soluble in liquid hydrocarbon (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 measureable 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, the E^2T INMS has the mass range and the sensitivity to accurately measure xenon. E^2T would measure the abundance of noble gases in the upper atmosphere of Titan to 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 ~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, in a steady state where methane destruction and replenishment are in balance (Jennings et al., 2009), or 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; 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, favours 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. On Titan, both simple (methane, ethane and propane) and complex hydrocarbons precipitate out of the atmosphere onto the surface. Measuring the isotopic ratios ($^{14}N/^{15}N$; $^{12}C/^{13}C$; D/H; $^{16}O/^{18}O$; $^{17}O/^{16}O$) and abundances of the simple alkanes (e.g., methane, ethane and propane) would 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). Recent measurements by ground-based observatories including measurements of CO and its carbon and oxygen isotopologues accompanied by the first detection ^{17}O in Titan and indeed in the outer Solar System by Atacama Large Millimeter/submillimeter Array (ALMA) can be followed up on in more detail by in-situ spectroscopic measurements (Serigano et al., 2016). E^2T would measure the composition and isotopic ratios of Titan's upper atmosphere to determine the age of methane in the atmosphere and characterize outgassing history.

On Enceladus, Cassini measurements by INMS (Waite et al., 2006, 2009, 2017) and UVIS (Hansen et al., 2006, 2008) showed that plume gas consists primarily of water vapour with a few percent other volatiles. In addition to H_2O, as the dominant species, INMS was able to identify CO_2 (0.3-0.8%), CH_4 (0.1-0.3%), NH_3 (0.4-1.3%) and H_2 (0.4-1.4%), in the vapour plume as well as an unidentified species with a mass-to-charge (m/z) ratio of 28, which is thought to be either N_2 or C_2H_4 or a combination of these compounds or CO. 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 if they were internally reprocessed. 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, the possible presence of trace quantities of C_2H_2,

C_3H_8, methanol, formaldehyde and hydrogen sulphide has been detected within the INMS data recorded during some Cassini flybys (Waite et al., 2009). 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 onboard 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 E^2T 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 would 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 would 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 if significant exchanges between the rock phase and water-ice phase occurred during Enceladus' evolution. The E^2T mission would be able to determine the abundance of ^{40}Ar, expected to be the most abundant isotope, as well as the primordial (non-radiogenic) argon isotopes, ^{36}Ar and ^{38}Ar. The detection and quantification of ^{36}Ar and ^{38}Ar would 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, E^2T 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 $^{20}N/^{21}Ne/^{22}Ne$ ratios would 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, would 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 planetesmals of Enceladus during their formation. Alternatively, methane may have been produced via hydrothermal reactions in Enceladus' interior; a possibility made more evident by the recent discovery of molecular hydrogen in Enceladus' plume (Waite et al., 2017). 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. The E^2T mission by performing in situ analysis with high-resolution mass spectrometry of both the vapour and solid phases would quantify the abundance ratios between the different volatile species present in the plume of Enceladus, the isotopic ratios in major species, and the noble gas abundance.

3.1.2 Sources and Compositional Variability of Enceladus' Plume

The detection of salty ice grains (Postberg et al., 2009, 2011), the high solid/vapour 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 (Figure 3). However, the abundance of the major gas species observed by Cassini suggests some contribution from the surrounding cold icy crust should also be considered. If plume gases exclusively originate from a liquid water reservoir, low-solubility species would be more abundant than high-solubility compounds, which is not apparent in the INMS data. 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 the recent detections of nanometer sized silica dust in E-ring particles, which are believed to come from Enceladus (Hsu et al., 2011, 2015), and molecular hydrogen in Enceladus' plume (Waite et al., 2017) all indicate their origin is a location where alkaline high temperature hydrothermal reactions and likely water-rock interactions are occurring.

FIGURE 3

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 E^2T ENIJA is capable of providing a spatial accuracy of less than 100 m, allowing for a precise determination of compositional profiles along the spacecraft trajectory (Srama et al., 2015). The Cassini INMS provided only plume integrated spectra and is not able to separate gas species with the same nominal mass. E^2T INMS' high mass resolution, which is 50 times larger than that of Cassini INMS, would allow for 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 crust. 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. The E^2T mission would allow for the determination of the compositional distribution between both solid and vapour phases of Enceladus' plume, thus providing crucial constraints on the nature and composition of the jet sources, and on the relative contributions of subsurface liquid reservoirs and the surrounding cold icy crust. Spatial variations in composition within the plume and possible correlations with the jet sources would permit for testing if the volatile compounds originate from a common reservoir and how the less volatile compounds are integrated in the solid particles during the eruption processes.

3.1.3 Geological Constraints on Titan's Methane Cycle and Surface Evolution

As discussed above, there is an open question 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). E^2T TIGER high-resolution colour images would provide the data needed to determine the genesis of these features. Stratigraphic relationships and crater counting would 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 if 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). Observations and models suggest Titan's methane distribution varies on seasonal timescales (e.g., Waite et al., 2007; Hayes et al., 2010; Turtle et al., 2011; Coustenis et al., 2013, 2016) 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 would allow us to determine if they once held seas. Identification of impact features or aeolian processes within these basins would 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 duneforms take longer to form than smaller duneforms. 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, E^2T TIGER's superior spatial resolution would resolve these potential smaller dunes on top of the known longitudinal dunes, and would therefore reveal if Titan's recent climate has been stable or if it has changed over the past few Ma. The E^2T mission would provide high-resolution colour imaging of Titan that can be used to characterize candidate cryovolcanic features that could be replenishing Titan's atmosphere and paleo-seas or dune patterns that evidence changes in Titan's climate.

Understanding climate change on Titan would provide insight that may be relevant to the future of our own planet, when surface conditions with warm tropospheric temperatures will preclude stable equatorial/mid-latitude oceans and the liquid water will be limited to the poles, while at the equator, occasional intense rainstorms might scour out fluvial features, but the principle sedimentary deposits will be sand dunes. The closest analogous in our solar system to such a future Earth is Titan (Coustenis et al., 2009). Indeed, the evolution of the solar luminosity makes it almost unavoidable that, in ~ 0.5-1 Ga from now, the tropopause temperature of the Earth will be elevated to the point that loss of the Earth's oceans by evaporation and then stratospheric photolysis of the water vapour will occur over a timescale of the order a hundred million years. From that point on, surface liquid water will be limited to the poles, will have a short photochemical lifetime, and if persistent would be resupplied by mantle/deep crustal water. At the equator, occasional intense rainstorms might scour out fluvial features, but the principle sedimentary deposits will be sand dunes.

Titan's geology is unique in that liquid and solid organics likely play key roles in many of the observed processes. These processes, in turn, play an important role in modifying these organics, both physically and chemically. Understanding these modification processes is crucial to investigating the complex chemistry occurring on this moon. Furthermore, study of

Titan's geology allows us to investigate processes that are 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., Tomasko et al., 2005; Soderblom et al., 2007; 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 would 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 also suspected to control the landscape of Titan's labyrinth terrains (Cornet et al., 2015) and may be responsible for the formation of the polar sharp edged depressions (Hayes et al., 2008): E^2T imaging would allow direct testing of these hypotheses.

Both fluvial and aeolian processes likely produce and transport sediments on Titan. Dunes are observed across Titan's equator (e.g., Radebaugh et al., 2008; Malaska et al., 2016) while a variety of fluvial sediment deposits have been identified across Titan (e.g., Burr et al., 2013; Birch et al., 2016). Detailed images of the margins of the dune fields would allow us to determine the source and fate of sands on Titan. E^2T images would 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). E^2T observation would provide insight into the primary erosion processes acting on crater rims, which likely comprise a mixture of organics and water ice (cf. Neish et al., 2015, 2016). Finally, E^2T imagining may 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 versus 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. E^2T imaging would also allow us to investigate the strength of the surface materials by constraining the maximum slopes supported by different geologic units. Detailed color and stereo imaging of the boundaries of units would also allow investigation of the morphology, topography, and spectral relationship across unit boundaries. E^2T would take high-resolution color images of Titan that would elucidate the nature of the geological evolution of Titan's organic-rich surface.

3.2 Habitability and Potential for Life in Ocean Worlds, Enceladus and Titan

Ocean worlds, such as Titan and Enceladus, are the subjects of great astrobiological interest as water is one of the key requirements for life as we know it (Lammer et al., 2009). 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 in ocean worlds in the outer Solar System is found beneath the surface of an insulating ice shell, that regulates heat and chemical transport.

The dissipation of energy from tidal flexing, combined with radiogenic energy from these moons' interiors provide the energy to sustain an ocean. 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 Steveson, 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's mission gravity, shape and libration data (Iess et al, 2010, 2012, 2014; Mitri et al, 2014b; McKinnon et al, 2015; Thomas et al, 2016), compositional in-situ measurements and thermal evolution models (Tobie et al., 2005, 2006; Mitri and Showman, 2008; Mitri et al., 2010). Enceladus is unique since water exchange is known to exist between the surface and 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 exist 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 deflection of the ice shell and thus enhanced tidal heating and stresses in the shell; therefore tectonic features are much more likely present 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 on Titan or lodged in the surface as a result of cometary impacts into subsurface oceans. Titan's hydrocarbon cycle and the associated meterology 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. 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 mission (Altwegg et al. 2016) and comet 81P/Wild-2 from samples returned by NASA's Stardust mission (Elsila et al. 2009). Transient liquid water environments, created by impact melts could be an incubator for the deposited aerosols to create prebiotic chemistry (Neish et al., 2010). 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-rock interactions (Mitri and Showman, 2005; Iess et al., 2014). As discussed above, detection of nanometer silica dust particles in Saturn's E-ring (Hsu et al., 2015) and molecular hydrogen in Enceladus' plume (Waite et al., 2017) strongly suggest water-rock interactions within Enceladus. The enormous heat output in the south polar terrain, associated with liquid water in contact with rocks, favours 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 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); molecular hydrogen in Enceladus' plume makes the occurrence of methanogenesis more likely (Waite et al., 2017). 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; although they 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, E^2T would determine what chemical processes control the formation and evolution of complex organics on Titan and would test if biotic processes are currently occurring inside Enceladus. The analysis of salts and minerals embedded in icy grains and their possible distribution throughout the plume would constrain 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 would determine if complex organics have been in contact with fresh water, either at the surface via cryovolcanism or impact melt, and/or if material is actively being exchanged between the surface and interior.

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3.2.1 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 hydrocarbons such as ethane, acetylene, and diacetylene, and nitriles, including hydrogen cyanide (HCN) and cyanogen (C_2N_2). Somewhat more complex molecules such as cyanoacetylene, 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, E^2T INMS can detect both cations and anions and can do so with much better mass resolution than Cassini-INMS (and a fortiori 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 compositions 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. While Cassini INMS has not detected 75 or 89 u molecules, it has detected positive ions at masses of 76 u and 90 u, which are 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 E^2T 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 vapour and trace amounts of other gases: 0.3-0.8% CO_2, 0.1-0.3% CH_4, 0.4-1.3% NH_3 and 0.4-1.4% H_2 (Waite et al., 2017). In addition, higher molecular weight compounds with masses exceeding 100 u, were detected in the plume emissions

(Waite et al., 2009; Postberg et al., 2015). The presence of CO_2, CH_4 and H_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 indicative of possible methanogenesis similar to the process occurring in terrestrial submarine hydrothermal vents (McKay et al., 2008; Waite et al., 2017). Further, the high temperatures and H_2 escape may have led to the oxidation of NH_3 to N_2 (Glein et al., 2008). 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 4). Type I ice grains are nearly pure-water ice while Type II grains also possess silicates and organic compounds and Type III grains are 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.

FIGURE 4

Hsu et al. (2015) suggest that the ocean should be convective in order 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 (Hsu et al. (2015). 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 could be much better investigated and quantified by E^2T ENIJA given its high dynamic range (10^6-10^8). By performing high-resolution mass spectrometry of ice grains in Enceladus' plume, the E^2T mission would characterize the composition and abundance of organics, salts and other minerals embedded in ice grains, as messengers of rock/water interactions. It would also search for signatures of on-going hydrothermal activities from possible detection of native He and further constrain recent measurements of native H_2 found in Enceladus' plume (Waite et al., 2017).

3.2.2 Physical Dynamics in Enceladus' Plume and Links to Subsurface Reservoirs

The total heat emission at Enceladus' 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 approximately 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). The ice to vapour ratio can constrain how Enceladus' plume material is formed and transported to the surface. For example, ice/vapour ratios > 0.1–0.2 would exclude plume generation mechanisms that require a large amount of ice grains to be condensed from vapour (Porco et al., 2006; Ingersoll and Pankine, 2011). 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). E^2T high-resolution IR images and ENIJA can 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 vapour 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). Most recently, Kite et al. (2016) has suggested that the tiger stripe fissures are interspersed with vertical pipelike 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. TIGER can provide high spatial resolution thermal emissions maps to constrain the amount of energy dissipated between the tiger stripes. The E^2T mission would use high resolution IR imaging of the south polar terrain and mass spectra of the grains to provide new details of its surface and constrain the links between plume activity, subsurface reservoirs and deep hydrothermal processes.

3.2.3 Geological Evidence for Interior-Surface Communication on Titan

Geological processes such as tectonism and cryovolcanism indicate communication between the surface and subsurface. While Titan's surface offers a wealth of geological processes, the Cassini data lack the resolution needed in which to constrain the detailed nature of these processes, and thus to understand the extent that Titan's surface may be chemically interacting with its water-rich interior. Also of great importance to habitability are the transient H_2O melt sheets and flows (e.g., Soderblom et al., 2010) associated with impacts. On Titan, several features with volcanic landforms, lengthy flows, tall mountains, large caldera-like depressions, have been identified as possible cryovolcanic sites but could also possibly be due to other endogenic processes (Lopes et al., 2016; Solomonidou et al., 2016). 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; Solomonidou et al., 2014, 2016). E^2T would provide high resolution mapping (30 m/pixel with DTM vertical resolution of 10 m) of regions that are candidates for cryovolcanic activity.

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 mountains suggest contractional tectonism (Mitri et al., 2010; Liu et al., 2016). This is somewhat surprising, however, since tectonic landforms observed on other ocean worlds and icy satellites in the outer solar system appear to be extensional in nature. Understanding Titan's tectonic regime would, thus not only provide insight into the transport of material between surface and the interior, but also into the evolution of the other ocean worlds. We would test the hypothesis that Titan's mountains are formed by contraction by mapping the faults driving mountain formation in topographic context. The shape of the fault outcrop draped against topography would allow us to measure the faults' dip, which would 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 melts 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. Titan offers numerous pathways for interaction between its organic-rich surface and liquid water. E^2T would provide high-resolution mapping (30 m/pixel with DTM vertical resolution of 10 m) that would offer the ability to distinguish cryovolcanic features and to investigate the morphology of Titan's mountains and impact craters.

4. Scientific Payload

The Explorer of Enceladus and Titan (E^2T) has a focused payload that would provide in-situ mass spectrometry and high-resolution imaging of Enceladus' south polar terrain and plume, and Titan's upper atmosphere and surface, from a solar-electric powered spacecraft in orbit around Saturn. The in-situ measurements of Titan's upper atmosphere would be acquired during 17 flybys with an altitude as low as 900 km. At Enceladus, in-situ measurements would be conducted during 6 flythroughs of the plume and flybys of the south polar terrain at altitudes between 50 and 150 km. At the closest approach the velocity of the S/C with respect to Enceladus surface is ~5 km/s and with respect to Titan surface is ~7 km/s. Imaging data will be collected during inbound and outbound segments of each flyby.

The E^2T mission model payload consists of three science instruments: two time-of-flight mass spectrometers (TOF-MS), the Ion and Neutral gas Mass Spectrometer (INMS) and the Enceladus Icy Jet Analyzer (ENIJA); and a high-resolution infrared camera, Titan Imaging and Geology, Enceladus Reconnaissance (TIGER). Two instruments in the E^2T payload were proposed to be provided by ESA member states, INMS, which would be provided by Swiss Space Office (SSO) and ENIJA, which would be provided by German Aerospace Center (DLR). NASA proposed to provide the third instrument, TIGER. The characteristics of the science payload are shown in Table 2. In addition, a Radio Science Experiment (RSE), not necessarily requiring specific hardware on-board the spacecraft – thus regarded as an "experiment of opportunity", was considered for further study. The RSE would improve the current determination of the gravity fields of Enceladus and Titan, by using the radio links between the E^2T spacecraft and Earth to better constrain their internal structure. The proposed main funding agency of the RSE is the Italian Space Agency (ASI).

TABLE 2

4.1 Ion and Neutral Mass Spectrometer (INMS)

The Ion and Neutral Mass Spectrometer (INMS) is a reflectron time-of-flight mass spectrometer (TOF-MS) that would record mass spectra of neutral and ionised gases during flybys and fly-throughs of Enceladus' plume and Titan's upper atmosphere. During flybys and flythroughs of Saturn's E-ring, Enceladus' plume and of Titan's upper atmosphere, INMS will record mass spectra of neutral and positive and negative ionized gases within the mass range 1 – 1000 u/e with a mass resolution at 5000 m/Δm (50%) with a sensitivity (detection threshold) of 1 cm^{-3} (~10^{-16} mbar) in a 5 s measurement cadence (Abplanalp et al., 2010; Wurz et al., 2012). The Cassini INMS (Ion and Neutral Mass Spectrometer) is limited to the detection of low mass species of 1–99 u and is therefore not able to measure the high-mass molecular species abundant in Enceladus' plume and in Titan's upper atmosphere. Further, E^2T INMS' high mass resolution (m/Δm = 5000), 50 times larger than Cassini INMS, allows for the separation of isobaric interference such as occur at 16, 20, 28, and 40 u/e which is possible based on heritage of RTOF/ROSINA from the Rosetta mission (Scherer et al., 2006; Wurz et al., 2015) as shown in Figure 5.

FIGURE 5

Cassini INMS only had the ability to measure positively charged ions. In-situ measurements by the Cassini Plasma Spectrometer (CAPS) detected heavy negative ions in Titan's ionosphere and negative water group ions in Enceladus' plume (Coates et al., 2010). E^2T INMS would record 10,000 mass spectra per second and accumulate these for a pre-set period, allowing for a time resolution of measurements in the range from 0.1 to 300 s. The maximum INMS resolution at Enceladus is 0.1 s (corresponding to a spatial resolution of ~0.5 km for a S/C velocity of 5 km/s) to resolve small-scale structure in the plume; the maximum used INMS resolution at Titan is 5 s (corresponding to a spatial resolution of ~35 km for a S/C velocity of 7 km/s).

The E^2T INMS has heritage based on P-BACE instrument, on the Rosetta ROSINA and on the gas-chromatograph-neutral gas mass spectrometer prototype which will be used in upcoming lunar exploration conducted by the Russian Space Agency in 2019 (Hofer et al., 2015;Wurz et al., 2015). Most recently, a similar instrument, the Neutral gas and Ion Mass spectrometer (NIM) instrument of the Particle Environment Package (PEP) consortium, is developed for the JUICE mission of ESA

4.2 Enceladus Icy Jet Analyzer (ENIJA)

Enceladus Icy Jet Analyzer (ENIJA) is optimized to search for prebiotic molecules and biogenic compounds in objects with high dust fluxes and number densities such as occur in Enceladus' plume or cometary comae. ENIJA consists of two time-of-flight mass spectrometer (TOF-MS) subsystems and a software-enabled high flux detector (HFD) that runs in parallel to the spectrometers. The HFD measurement mode will map the dynamical profile (number density and size distribution) of Enceladus' ice jets. Compared to the Cassini CDA (Cosmic Dust Analyzer), ENIJA has a 40 times better mass resolution, a 100 times better maximum flux and sensitivity, and a spatial resolution that is 50 times better (Srama et al., 2015). Moreover, the twin-detector instrument will acquire mass spectra of both cations and anions created upon ice particle impact, simultaneously, whereas CDA only measured cations. During flythroughs of Enceladus plume and in the E ring, ENIJA provides time-of-flight mass spectra for ice particles with a mass range of 1-2000 u with a mass resolution (m/Δm) of 970 between 23-2000 u. ENIJA acquires TOF mass spectra of individual ice grains by impact ionization and analyses the generated anions and cations with two separate time of flight spectrometer sub-units. In this way ENIJA is able to quantify organic compounds at <10 ppm; additionally some polar organic species, such as most amino acids, can be quantified well below 1 ppm (Figure 6). With a dynamic range up to 10^8, inorganic trace components with sub-ppm concentrations from Enceladus' ocean, can now be investigated simultaneously with the more abundant mineral species. ENIJA is not a newly developed instrument; rather it is an optimization and miniaturization of flight-proven hardware. ENIJA has heritage based on Giotto-Particle Impact Analyzer (PIA), Stardust Cometary Interstellar Dust Analyzer (CIDA), Cassini's' Cosmic Dust Analyzer (CDA), Rosetta-COSIMA and Europa-SUrface Dust mass Analyzer (SUDA).

FIGURE 6

4.3 Titan Imaging and Geology, Enceladus Reconnaissance (TIGER)

Titan Imaging and Geology, Enceladus Reconnaissance (TIGER) is a near infrared (NIR) camera designed to acquire high resolution images of Titan and Enceladus. TIGER would observe Titan at 30–100 m/pixel in three wavelengths, 1.3, 2, and 5 μm and Enceladus emissions at 1 m/pixel at two wavelengths, 5 and 5.3 μm. Images acquired by TIGER would enable investigation of Titan's geology, hydrology, and compositional variability and study of the composition and kinematics of Enceladus' jets and plumes. The TIGER band passes are selected to match with Titan's atmospheric transmission windows (Lemmon et al., 1993; Sotin et al., 2005) to enable direct ground observations using reflected sunlight and to measure thermal emission from Enceladus. The 5 μm images are subject to virtually no scattering from Titan's atmospheric aerosols, allowing diffraction limited images achieving spatial resolutions an order of magnitude better than Cassini observations (Clark et al., 2010; Soderblom et al., 2012; Barnes et al., 2014) and would be highly sensitive to organic composition (Clark et al., 2010; Barnes et al., 2014). TIGER has the capability to image Titan at Huygens DISR resolution (Figure 7). At Enceladus, the 5 and 5.3 μm observations would measure thermal emission of surfaces as cold as 130 K and would provide temperature maps of the surface at Cassini-ISS image scales. A fine steering mirror (FSM) would be employed to select and track regions of interest during the flyby and compensate for spacecraft jitter allowing for longer exposures and better signal-to-noise ratio (SNR). Digital time-delay integration (TDI) would also be employed, as needed, during closest approach when the ground speed is highest.

FIGURE 7

While the TIGER instrument is a new design, it utilizes high-heritage subsystems (≥TRL 6). The TIGER Focal Plane Array (FPA) is from Teledyne Imaging Sensors and utilizes the same HgCdTe detector and H2RG qualified for James Webb Space Telescope (JWST) Near Infrared Camera (NIRCam) (Reike et al., 2005), Near Infrared Spectrometer (NIRSpec) (Rauscher et al., 2004), and Fine Guidance Sensor (FGS) (Doyon et al., 2012) instruments. TIGER also implements FPA readout electronics that have been qualified extensively for the JWST instruments (Loose et al., 2006) and are used by the Euclid Near Infrared Spectrometer and Photometer (NISP) (Maciaszek et al., 2014).

4.4 Radio Science Experiment

Gravity field measurements are powerful tools to constrain the interior structure of the planets and satellites and to assess mass anomalies, providing information on the internal dynamics and evolution. The observable quantities used by gravity science experiments are obtained by means of spacecraft tracking at microwave frequencies from a terrestrial ground antenna. The eight gravity flybys of Titan conducted by the Cassini mission (not including the T122 flyby, recently completed in August 2016) yielded sufficient information to obtain a robust estimation of the degree-3 static gravity field, plus the fluid Love number k_2 (Iess et al., 2010,2012); however, this was not the case for Enceladus (Rappaport et al., 2008; Iess et al., 2014), where only the degree-2 static gravity field and J_3 were observed, and the tidal response to Saturn's gravity was not detected.

In Enceladus' south polar terrain a larger time-variation of the gravity field with respect to the global solution of the time variation of the gravity field is expected because the ice shell thickness is anticipated to be locally thin in that area. A gravity science experiment, based on radio tracking and precise spacecraft multiarc orbit determination (see e.g. Tortora et al., 2016), would determine the local solution of the gravity field of Enceladus at the south polar terrain thus allowing the determination of the thickness variation at the south polar regions and constraining the mechanical properties (viscosity) of the ice overlying the outer ice shell. The expected tidal deformation is characterized by a pattern more complex than the standard degree-two pattern, with a strong amplification of the tidal fluctuation in the south polar terrain (Brzobohaty et al., 2016).

For Titan gravity science, a desirable objective would be the improve of Cassini's results in terms of reduction of the uncertainty in the fluid Love number k_2. In particular, the geophysics objectives relative to the subsurface liquid ocean extent, shell thickness and shell viscosity would be improved if the formal uncertainty of k_2 could be reduced down to values in the range 0.05-0.01. The feasibility of such result strongly depends on the actual geometry of Titan's flyby (in particular: altitude at pericenter and mean anomaly of Titan around Saturn at the time of closest approach with the E^2T spacecraft), in addition to the stability of the radio link (preferably at Ka-band, to reduce the detrimental effect of dispersive media).

The availability of a two-way (uplink and downlink) radio system would also allow expanding the long series of Titan's occultations carried out by Cassini's radio science subsystem to probe Titan's neutral and ionized atmosphere (Coustenis et al., 2016; Kliore et al., 2008, 2011; Schinder et al., 2012, 2015). The main objective would be the characterization of Titan's atmospheric structure (pressure, density, and total electron content profiles, versus altitude) at different latitude/longitudes.

5. Proposed Mission and Spacecraft Configuration

The baseline scenario for the E^2T mission is a solar electric powered spacecraft (S/C), in orbit around Saturn, performing multiple flybys of Titan and Enceladus. The baseline includes a shared launch on the Ariane 6.4 with a co-manifest of estimated launch mass of ~2636 kg to geosynchronous transfer orbit (GTO), with a forecasted shared launch opportunity in 2030. The Ariane 6.4 with four solid rocket boosters is scheduled to debut in 2020–2021. The upper stage reignition capability of the Ariane 6.4 will enable a GTO/escape dual launch. The mass estimate for the co-manifest places it in the lower end of the Intermediate Class (2,500-4,200 kg) of commercial satellites (FAA, 2015). After a transfer from GTO to a hyperbolic escape trajectory, E^2T S/C 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. The E^2T tour in the Saturn system would be 3.5 years long. The E^2T tour consists of 6 flybys of Enceladus above the south polar terrain with a flight altitude range between 50 to 150 km, and 17 flybys of Titan at a reference flight altitude ranging from 1500 down to 900 km.

5.1 Transfer Orbit to Saturn

The nominal transfer to Saturn uses a $1{:}1^+$ resonant Earth flyby trajectory, as shown in Table 3 and Figure 8. Electric propulsion is used to strongly increase the hyperbolic flyby speed at the Earth, and to provide a subsequent energy boost to reduce the total flight time to 6 years to Saturn orbit insertion (SOI). After separation from the co-manifested satellite and the SYLDA carrier, the upper stage will be re-ignited near perigee to impart approximately 1.2 km/s ΔV to the E^2T S/C, putting it on a hyperbolic escape trajectory with a C_3 of 9.6 km^2/s^2. Thanks to the use of electric propulsion and an Earth gravity assist, the declination of the asymptote can vary between ±5 degrees without significant propellant mass penalty. Similarly, as shown in Table 4, there is negligible performance variation over a 21-day launch period. The data in Table 3 is based on a proposed launch from January-May 2030 during which there is little variation in flight time or required propellant mass. Lunar flybys on the escape trajectory were not considered, but could be used to effectively lower the required escape ΔV which in turn would allow for a heavier co-manifested satellite.

FIGURE 8

TABLE 3

FIGURE 9

TABLE 4

5.2 Saturn Tour

The duration of the tour from SOI through to the end of the 17-flyby Titan phase is about 3.5 years. A sample tour is shown in Figure 9. Like Cassini, end-of-mission spacecraft disposal is Saturn impact, by means of three to four additional Titan flybys.

The tour 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 and at least 17 flybys of Titan. To prevent contamination from Titan's organics for Enceladus science, 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. After the main Enceladus phase, close flybys of Titan with atmospheric sampling will be performed (Titan science phase).

FIGURE 9

During Enceladus science phase, E^2T will provide in-situ sampling of the plume at a minimum altitude from Enceladus' surface ranging between 50 and 150 km using INMS and ENIJA. At the closest approach, the velocity of the S/C with respect to Enceladus' surface will be approximately 5 km/s. E^2T will provide high-resolution imaging of Enceladus surface with the TIGER camera. During Enceladus flybys the observations of INMS, ENIJA and TIGER will be performed simultaneously. During this phase observations of Titan's surface using TIGER are scheduled during distant flybys.

During the Titan science phase, E^2T will provide in-situ sampling of the upper atmosphere at a minimum altitude from Titan surface as low as 900 km using INMS. At the closest approach the velocity of the S/C with respect to Titan's surface will be approximately 7 km/s.

E^2T will provide high-resolution imaging of Titan's surface with TIGER camera. During Titan flybys the observations of INMS and TIGER can be performed simultaneously.

5.3 Spacecraft Design and Structure

The proposed E^2T spacecraft (S/C) design is the result of the harmonisation of several high-TRL key space technologies already developed on behalf of several ESA space exploration missions, such as: ExoMars 2016, JUICE, BepiColombo and Rosetta. The proposed E^2T spacecraft architecture would be derived from the ESA ExoMars Trace Gas Orbiter (TGO) developed for the 2016 mission. The proposed E^2T architecture is in compliance with the Ariane 6.4 launcher size constraints. Table 5 summarizes its main technical characteristics. The E^2T spacecraft baseline configuration is depicted in Figure 10.

TABLE 5

FIGURE 10

The Solar Arrays (SA) are the main S/C electrical power source, whereas the S/C main battery provides the emergency backup one. The E^2T four panel solar arrays are based on space-qualified Thales Alenia Space SolarBus W51 technologies and GaAs/Ge Low Intensity Low Temperature (LILT) solar cells technology used in the ESA JUICE mission. The Solar Electric Propulsion System (SEPS) is based on four (3+1 for redundancy) QinetiQ's T6 gridded ion thruster engines, whereas two chemical propulsion systems have been also implemented for S/C manoeuvres and Attitude and Orbital Control System (AOCS) purposes. The propulsion systems' designs have been directly derived from different mission heritages, such as the two ESA missions GOCE and BepiColombo, and the NASA/ESA/ASI Cassini mission. The heritage of systems and subsystems from previous ESA missions requiring limited technological development enables a relatively low cost for the industrial development. The E^2T S/C design was performed by Thales Alenia Space (TAS-I, Torino, Italy)

6. Summary

E^2T was proposed as mission led by ESA in collaboration with NASA and several ESA member states for the payload in response to ESA's M5 Cosmic Vision Call. The joint exploration of Enceladus and Titan with a flyby mission such as the E^2T mission can address fundamental scientific questions regarding extra-terrestrial habitability, abiotic/prebiotic chemistry, the emergence of life, and the origin and evolution of ocean worlds. In the Solar System, the best candidates for habitability at present are the ocean worlds in the outer Solar System: Europa, Enceladus and Titan. Of these, only Enceladus and Titan provide environments that can be easily sampled from orbit in a single mission. Titan, with its organically rich and dynamic atmosphere and geology, and Enceladus, with its active plume composed of multiple jets, both harbouring subsurface oceans, are ideal environments in which to investigate the conditions for the emergence of life and the habitability of ocean worlds as well as the origin and evolution of complex planetary systems. The joint exploration of these two fascinating objects will allow us to better understand the origin of their organic-rich environment and will give access to planetary processes that have long been thought unique to the Earth.

Given that the E^2T mission concept proposes the first solar-powered mission beyond Jupiter, a four-point strategy to minimize the cost and meet the M5 criteria was used:1) the reusing of systems and subsystems with a TRL ≥5 from previous ESA missions with a limited technological development necessary; 2) a science payload with a TRL ≥5 with low total mass (57.7kg), power (83.2 W) and data rate (115 Mbit/day) requirements; 3) a cruise phase with a duration of 6 years and a nominal mission operation duration of 3.5 years; and 4) a forecasted shared launch opportunity in 2030 with a commercial satellite to GTO by the Ariane 6.4 which will allow E^2T to pursue a cost-effective launch that will enable an efficient Earth escape trajectory to the Saturn system. The E^2T mission concept offers a cost-effective way to investigate the evolution and habitability of ocean worlds in the Saturn system and address key questions, which remain unanswered as the end of the Cassini-Huygens' mission draws near, regarding the origin, evolution and habitability of these ocean worlds. In combination with the results expected from the ESA JUICE mission on the ocean worlds around Jupiter, this mission would offer a unique opportunity to understand the habitable conditions in our own Solar System and beyond.

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TABLES AND FIGURES

Table 1 E.^{2}T Science Goals and Objectives.

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 favourable to the emergence of life? • To what level of complexity has prebiotic chemistry evolved in the Titan system?

Table 2. Summary of Instrument Characteristics.

Instrument/ Experiment (Proposed Agency)	Mass (kg)	Peak Power (W)	TRL	Science Contribution
INMS (SSO)	6.2	34	6	1) Analysis of elemental, molecular and isotopic composition of neutral and ionic gas phase constituents in a mass range of 1–1000 u/e in Saturn's E-ring, Enceladus' plume and Titan's upper atmosphere 2) Search for spatial variations in composition and correlate with jet sources.
ENIJA (DLR)	6.5	19.2	5–6	1) Analysis of elemental, molecular and isotopic composition of solid phase constituents in a mass range of 1–2000 u of Enceladus' plume / E-ring 2) Measure fluxes at high impact rates up to 108 s-1m-2 to map the dynamical profile (number density, ejection speeds and size distribution) of Enceladus' ice jets
TIGER (NASA)	45	30	5–6	1) Detailed analysis of the geology of Titan's surface at 30–100 m/pixel and of Enceladus' plume sources at 1 m/pixel 2) Measure of the thermal emission from Enceladus's south polar terrain, at 1 m/pixel
Total	57.7	83.2		

Table 3. Nominal interplanetary trajectory

Departure	
Launch date to GTO	April 2030
Hyperbolic Injection date	27 April 2030
Injection Δ V from upper stage (km/s)	1.20
Injected Mass (kg)	4056
C_3 (km^2/s^2)	9.58
Declination of escape asymptote (deg)	5
Cruise	
Earth flyby date	20 August 2031
Earth flyby altitude (km)	500
Earth flyby V-infinity (km/s)	9.28
S/C mass at Earth flyby	3637
Arrival	
Saturn arrival date	26 April 2036
Flight time (years)	6.0
Arrival V-infinity (km/s)	5.72
Arrival declination (deg)	19.0
SOI Δ V (m/s)	569
Range at SOI (R_S)	1.05
Orbital period (day)	150
Apoapsis range (R_S)	180
S/C mass after SOI (kg)	2753

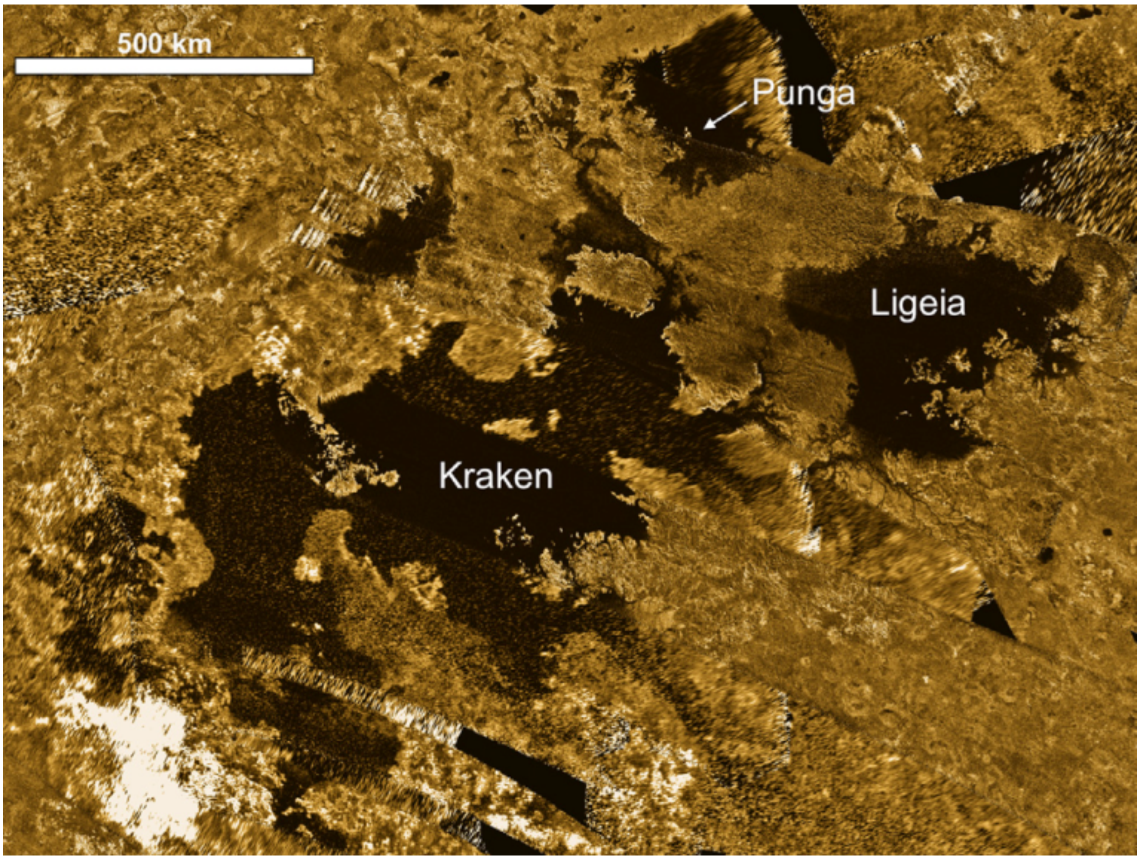
Table 4. Launch period performance, fixed arrival date.

Launch Date	Nominal –10 days	Nominal (27Apr2030)	Nominal+10days
C_3 (km^2/s^2)	9.58	9.58	9.58
Xe propellant (kg)	750	747	752
SOI ΔV (m/s)	563	569	571

Table 5. E^{2}T spacecraft technical characteristics.

E^{2}T Spacecraft main technical characteristics		**Heritage**
Spacecraft Dimensions	• Main S/C body: 2974mm × 2860mm × 2589mm with 4 Solar Array wings of an overall area of 160 m^2. • SEPS cylindrical section: 600mm radius × 970mm height with 3+1 QinetiQ T6-Ion Thruster Engine of 7.5 kW each one.	ExoMars BepiColombo
Overall Launch mass	• 4056 kg (including 58 kg of science payload), dry mass 1876 kg	
Propulsion Architecture	The E^{2}T S/C propulsion architecture is based on the integration of three different propulsion systems: • Solar Electrical Propulsion System (SEPS) based on 3+1 QinetiQ T6 gridded Ion-Thruster engines (1 for redundancy) • Main Bi-propellant propulsion system for S/C manoeuvres purposes • Hydrazine Mono-propellant propulsion system of 16 RCS Thruster (8+8 in hot redundancy) for Attitude and Orbital Control System (AOCS) purposes.	ExoMars BepiColombo
Power Architecture	The E^{2}T Electrical Propulsion System (EPS) architecture proposed is based on: • 4 Solar Array Wings able to sustain an End of Life (EOL) power demand of 620 W (including margins) with a reference solar constant of 15 W/m^2 at 9.14 AU, with a Sun-Aspect-Angle of 0°. • One 31 kg Li-Ion battery of 3691 Wh total capacity and able to sustain a peak power load of demand of 700 W during the forecast eclipses. • One secondary battery installed on SEPS module for 100 V High-Voltage Sun-regulated power bus stability purposes.	JUICE Rosetta BepiColombo
Baseline payload	• Ion and Neutral Mass Spectrometer (INMS) • Enceladus Icy Jet Analyser (ENIJA) • Titan Imaging and Geology, Enceladus Reconnaissance (TIGER) high-resolution infrared camera	

1558



1559 **Figure 1.** Cassini SAR mosaic images of the north polar region showing Kraken, Ligeia and Punga

1560 Maria (from Mitri et al., 2014a).

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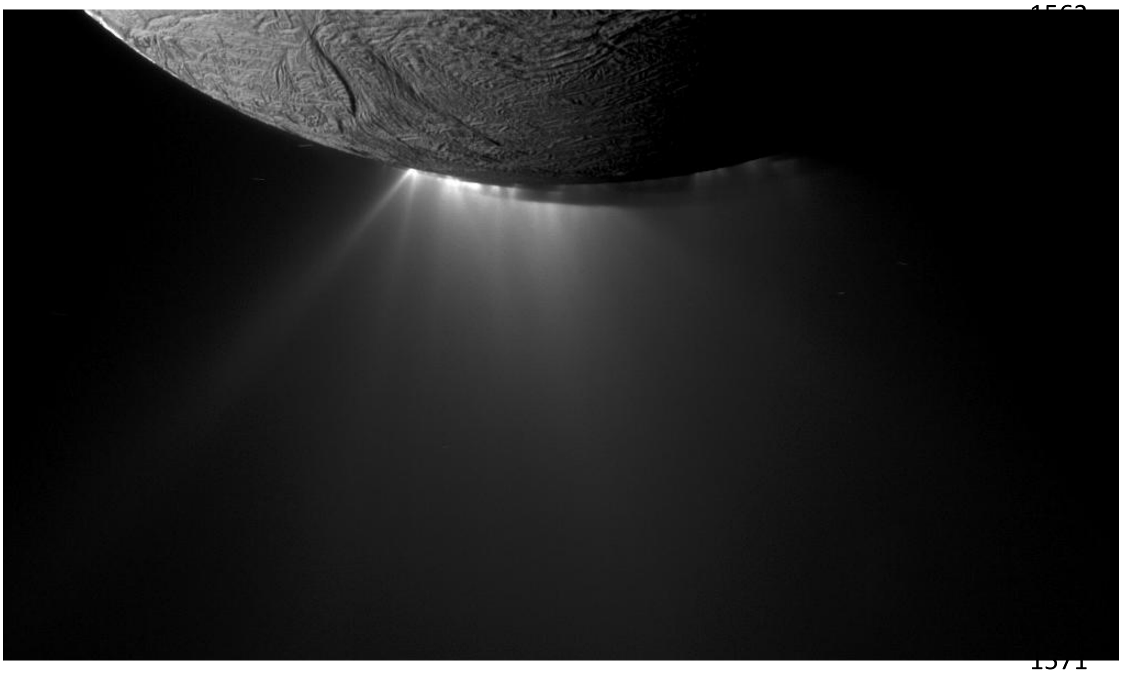


Figure 2. Plume emanating from multiple jets in Enceladus' south polar terrain (NASA/JPL/Space Science Institute).

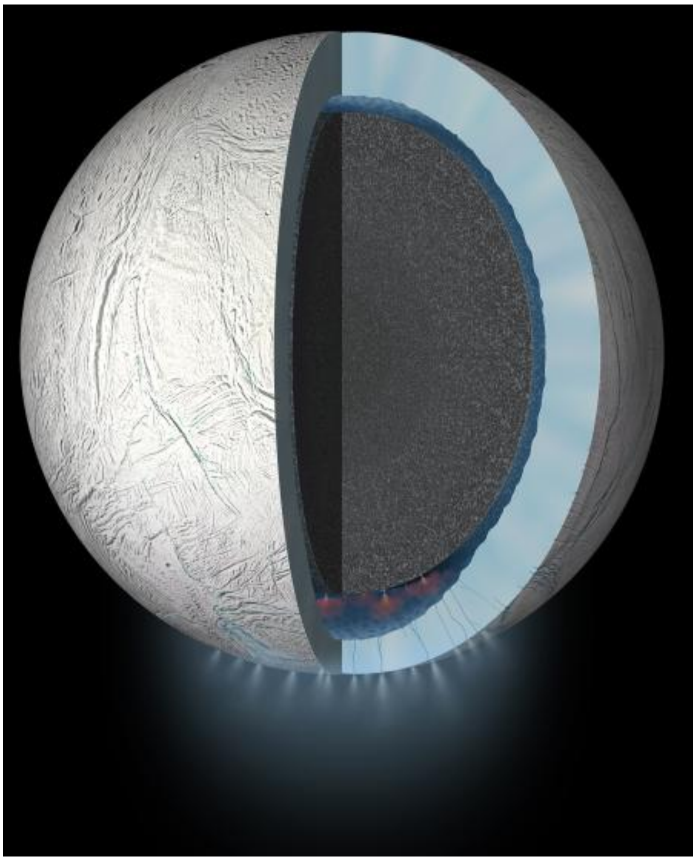


Figure 3. Enceladus' internal structure inferred from gravity, topography and libration measurement provided by Cassini mission. A global subsurface ocean is present under the outer ice shell. The ice shell is believed to be a few kilometers thin at the south polar region where the center of the geological activity is with the formation of the plume formed by multi-jets (NASA/JPL-Caltech).

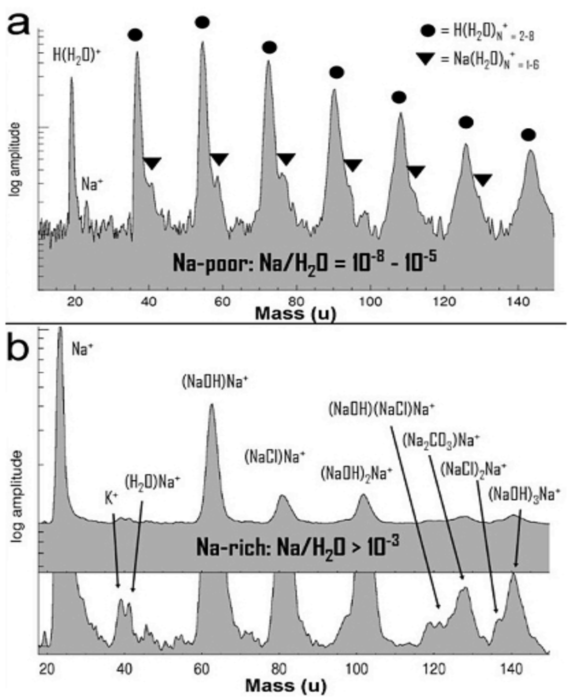
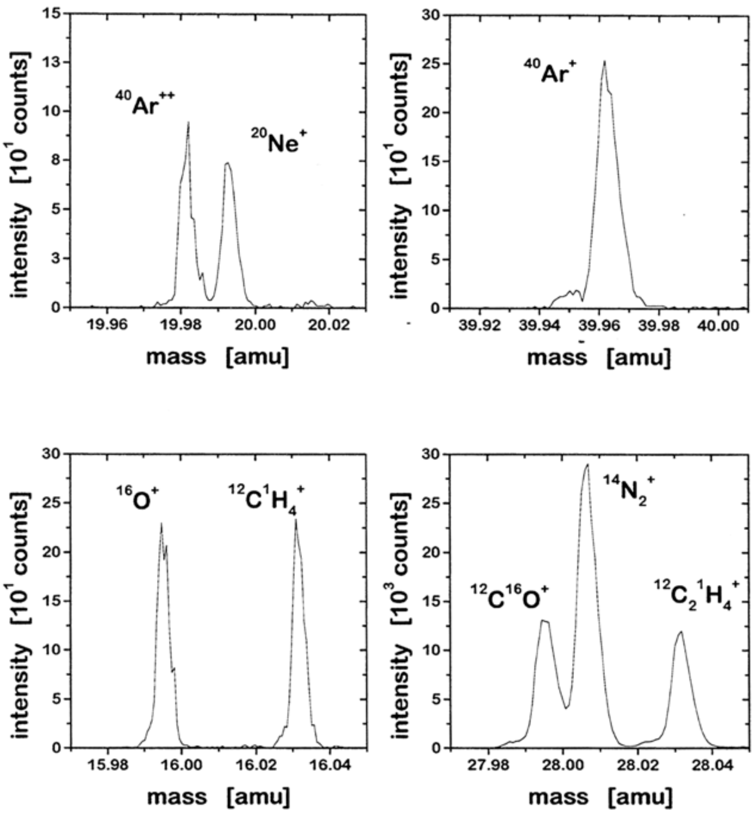


Figure 4. Composition of salt-poor (Type I and II) and salt-rich (Type III) particles in Saturn's E-ring and Enceladus' plume as measured by Cassini CDA instrument (Postberg et al., 2009).



1621 **Figure 5.** Separation of isobaric interference such as occur at 16, 20, 28, and 40 u/e for the
1622 indicated species is possible based on heritage of RTOF/ROSINA from the Rosetta mission
1623 (Scherer et al., 2006; Wurz et al., 2015).

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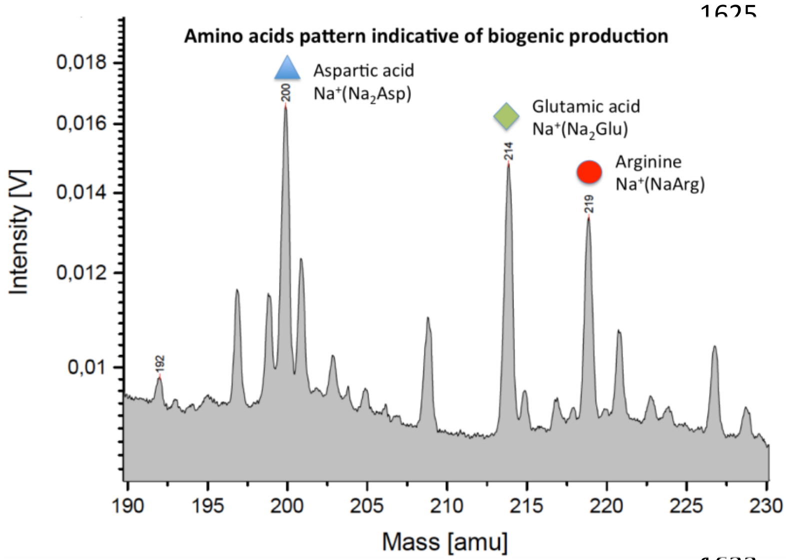

Figure 6. Laser dispersion mass spectrum of aspartic acid (12 ppm), glutamic acid (12 ppm), and arginine (8 ppm) dissolved in a salt-water matrix simulating Enceladus' ocean composition. The complex amino acids are detectable in comparable quantities to glycine (15 ppm, not shown), even though the spectrum has a mass resolution 3 times less than ENIJA's. S/N ratio of this laser dispersion spectrum is comparable to a much lower analysed concentration in ENIJA spectra (≤1 ppm). Most un-annotated mass lines are due to salt-water cluster ions. By co-adding multiple ice grain spectra the S/N ratio can be further improved leading to an ENIJA detection limit of 10–100 ppb for most amino acids in ice grains formed from Enceladus' ocean water.

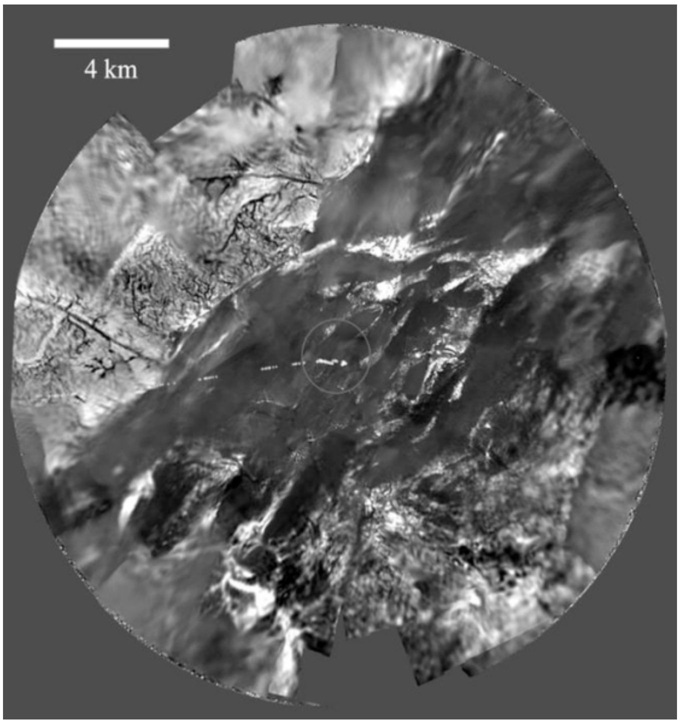

Figure 7. The surface of Titan imaged by DISR camera during the Huygens probe descend. TIGER has the capability to image Titan at Huygens DISR resolution (ESA/NASA/JPL/University of Arizona).

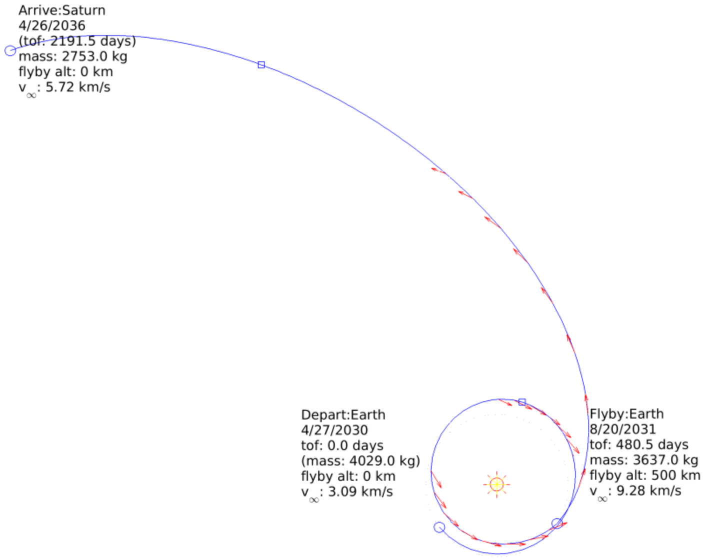

Figure 8. Interplanetary transfer to Saturn. Red arrows indicate electric propulsion thrust.

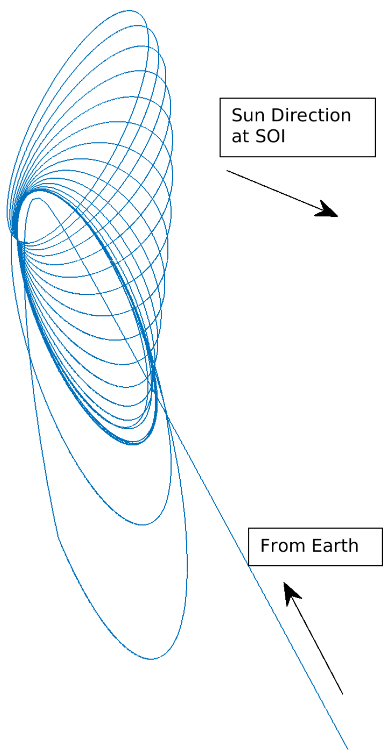

Figure 9. Sample tour with two period- and inclination-management Titan flybys followed by a science phase with 6 Enceladus flybys and 17 Titan flybys (Inertial representation).

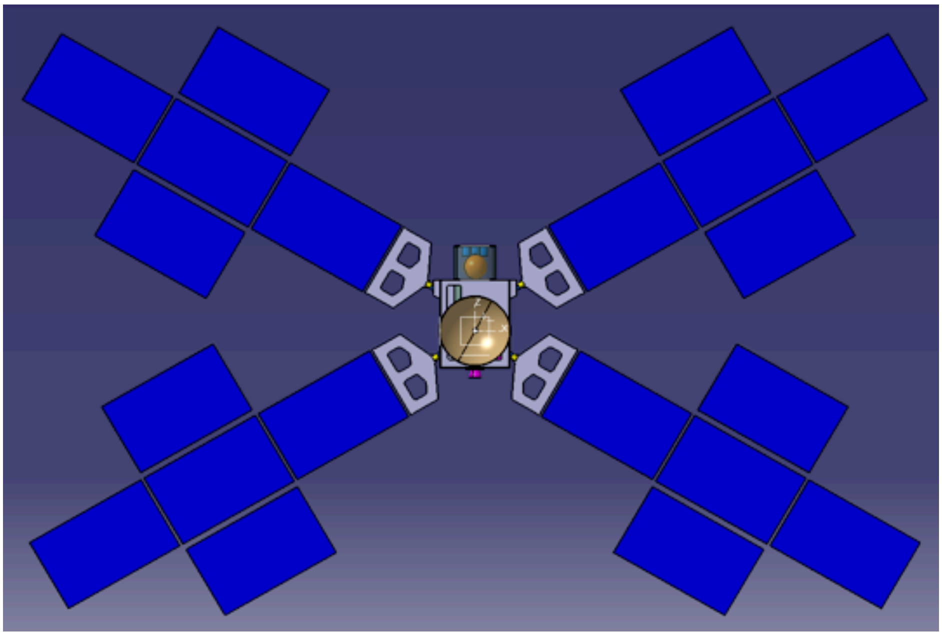

Figure 10. E^{2}T baseline proposed configuration of the S/C.