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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 global 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, the Explorer of Enceladus and Titan (E^2T), which is dedicated to investigating the evolution and habitability of these Saturnian satellites. E^2T is 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 plume 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' 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

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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 resolution of the ambiguities in chemical analysis 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 system composed of multiple jets (Waite et al., 2006a; Spahn et al., 2006; Porco et al., 2006), both harbouring global subsurface oceans (Iess et al., 2010, 2012, 2014; see also discussion in Sotin et al., 2010), 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 meeting these criteria are the ocean worlds in the outer Solar System, which include: Enceladus, Titan, Europa, and Ganymede (Lunine, 2017; Nimmo and Pappalardo, 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 currently not 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 environments and will give access to planetary processes that have long been thought unique to the Earth.

Titan is an intriguing world that is 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., 2006; 2009; Lopes et al., 2007a; 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, 2015; Thomas et al., 2016; Čadek 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 to 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.

The scientific appeal of Titan and Enceladus has stimulated many previous mission studies (e.g. see reviews by Lorenz, 2000, 2009), which have articulated detailed scientific objectives for post-Cassini scientific exploration (e.g. Mitri et al., 2014a; Tobie et al., 2014). At Titan, in particular, the diversity of scientific disciplines (Dougherty et al., 2009) has prompted the study of a variety of observing platforms from orbiters ("Titan Explorer", Leary et al., 2007; Mitri et al., 2014a), landers for the seas ("Titan-Saturn System Mission – TSSM", Strange et al., 2009; "Titan Mare Explorer - TiME", Stofan et al., 2013; Mitri et al., 2014a), landers for land (Titan Explorer), fixed-wing aircraft ("AVIATR", Barnes et al., 2012), to 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., 2009a, b), "Journey to Enceladus and Titan – JET" and "Enceladus Life Finder – ELF" (Reh et al., 2016).

We present a space mission concept, the Explorer of Enceladus and Titan (E^2T), which is dedicated to investigating the evolution and habitability of these Saturnian satellites and is 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., Bèzard, 2014), and a long list of organic compounds resulting from multifaceted photochemistry that occurs in the upper atmosphere down to the surface (e.g., Israël et al., 2005; Waite et al., 2007; Gudipati et al., 2013; Bèzard, 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 (Fig. 1) (e.g., Tomasko et al., 2005; Stofan et al., 2007; Mitri et al., 2007; Lopes et al., 2007a; Hayes et al., 2008).

With an environment that changes on a 29.5 year cycle, it is crucial to study Titan during an entire orbital period. Cassini has investigated Titan over only two seasons: from Northern winter solstice to summer solstice. While ground-based observations, have observed Titan in other seasons, these 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

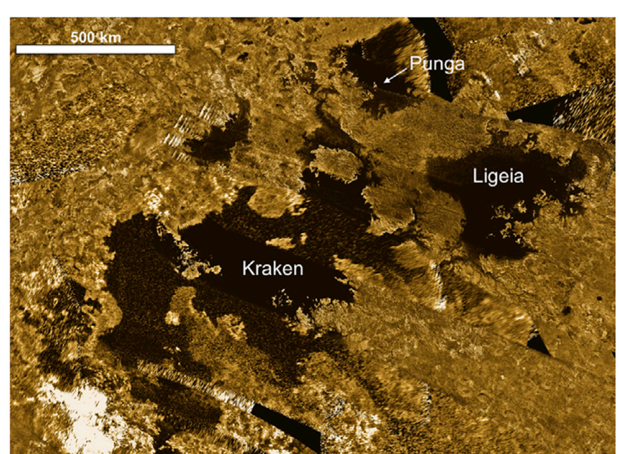

Fig. 1. Cassini SAR mosaic images of the north polar region showing Kraken, Ligeia and Punga Maria (from Mitri et al., 2014a).

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; these lakes and seas are 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., 2007b, 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, the low spatial, spectral, and mass resolution of the Cassini scientific instruments make it difficult to identify morphological features, to quantify geological processes and relationships between different geological units and to 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 at the level of 0.4–1.4% in Enceladus' plume (Waite et al., 2017) providing further evidence of water-rock interactions. This 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 (Fig. 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 geologically 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 plume by Cassini's instruments revealed the presence of water vapour, ice grains rich in sodium and potassium salts (Postberg et al., 2011). Organic materials were observed, both in the gas (Waite et al., 2009) and in the ice grains (Postberg et al., 2008, 2015), and molecular hydrogen (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., 2006b, 2009, 2017; Postberg et al., 2009a, b, 2011; Hsu et al., 2011, 2015; 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, 2015; Thomas et al., 2016; Čadek et al., 2016; Beuthe et al., 2016). The co-existence of organic compounds, salts, liquid water and energy sources on this small moon appear to provide all of the necessary ingredients for the emergence of life by chemoautotrophic pathways (McKay et al., 2008) – a generally held model for the origin of life on Earth in deep sea vents.

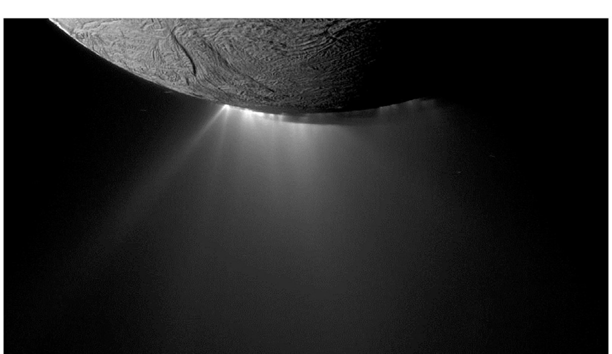

Fig. 2. Plume emanating from multiple jets in Enceladus' south polar terrain (NASA/JPL/Space Science Institute).

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 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 study phenomena in-situ that has been important in the past on Earth and throughout the outer Solar System.

3. Scientific objectives and investigations

The proposed E^2T mission has two major goals and several science objectives that would be pursued through Enceladus and Titan investigations. The first scientific goal of the 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 first scientific goal includes two objectives; the first would focus on determining the history and extent of volatile exchange on Titan and the second objective would aim to understand how Titan's surface processes evolved. The second scientific goal on Enceladus would examine the nature of hydrothermal activity and search for evidence of abiotic/prebiotic processes. On Titan, the second scientific goal would aim to discern to what level of complexity abiotic/prebiotic chemistry has evolved. The scientific objectives and investigations of E^2T are discussed in detail in Sections 3.1 and 3.2; Table 1 details the scientific objectives, the scientific questions, and the measurements requirements (payload, instrument parameters) to address the scientific goals of the E^2T mission.

Enceladus and Titan' investigations would be conducted using the E^2T mission model payload, which consists of three instruments: two time-of-flight mass spectrometers, 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

Table 1
Scientific objectives and questions, and measurement requirements (payload, instrument parameters required and performance) of E^2T.. .

GOAL A: ORIGIN AND EVOLUTION OF VOLATILE-RICH OCEAN WORLDS, ENCELADUS AND TITAN						
Science Objectives	**Scientific Questions**	**Measurement Description**	**Measurement Requirements**			
			Payload	**Parameter**	**Requirement**	**Performance**
A.1: Are Enceladus' volatile compounds primordial or have they been re-processed and if so, to what extent?	Are major volatiles in the plume material primordial (as opposed to geochemical or biological) and, if so, how were they delivered?	Quantify the abundance of radiogenic and non-radiogenic noble gases (40/38/36 Ar, 4/3He, 20/22Ne, 128-136Xe) from mass spectra of plume vapour phases	INMS	Dynamic range Resolution Sensitivity	6/8 decades 5000 $m/\Delta m$ 10^1 #/cm^3	6/10 decades 5000 $m/\Delta m$ 10^0 #/cm^3
		Determine the extent of molecular complexity in the plume up to 1000 amu	INMS	Dynamic range Resolution Sensitivity	6/8 decades >300 $m/\Delta m$ 10^1 #/cm^3	6/10 decades 5000 $m/\Delta m$ 10^0 #/cm^3
		Measure isotopic ratios ($^{12}C/^{13}C$, D/H, $^{14}N/^{15}N$, $^{16}O/^{18}O$) in major species from mass spectra of plume vapour, including allowing the separation of species with isobaric interferences for example, ^{12}CH from ^{13}C	INMS	Dynamic range Resolution Sensitivity	6/8 decades >2500-3000 $m/\Delta m$ 10^3 #/cm^3	6/8 decades 5000 $m/\Delta m$ 10^0 #/cm^3
		Measure isotopic ratio $^{12}C/^{13}C$ from mass spectra of condensed organics in icy grains	ENIJA	Dynamic range Mass range Resolution Sensitivity	3 decades 12–100m/z 100 $m/\Delta m$ 1 ppm	6/8 decades 1–2000m/z 1000$m/\Delta m$ 0.1 ppm
		Determine the abundance ratio between major C-, N-, O-, S-bearing compounds from mass spectra of plume vapour and solid phases, including allowing the separation of vapour-phase species with isobaric interferences for example, CO from N_2	INMS	Dynamic range Resolution Sensitivity	6/8 decades 3000 $m/\Delta m$ 10^3 #/cm^3	6/10 decades 5000 $m/\Delta m$ 10^0 #/cm^3
			ENIJA	Dynamic range Mass range Resolution Sensitivity	5 decades 12–200 m/z 200 $m/\Delta m$ 1 ppm	6/8 decades 1–2000m/z 1000$m/\Delta m$ 0.1 ppm
	Do Enceladus' volatile compounds originate from a unique reservoir and, if so, how is their distribution between solid and vapour phases affected by eruption processes?	Determine the compositional profile of major species through the plume (both volatile and non-volatile) from mass spectra of plume vapour and condensed phases in icy grains	INMS	Dynamic range Resolution Sensitivity	6/8 decades 300 $m/\Delta m$ 10^3 #/cm^3	6/10 decades 5000 $m/\Delta m$ 10^0 #/cm^3
			ENIJA	Dynamic range Mass range Resolution Sensitivity Spatial resolution	5 decades 7–500 m/z 500 $m/\Delta m$ 1 ppm 1000 m	6/8 decades 1–2000m/z 1000$m/\Delta m$ 0.1 ppm 100 m
A.2: What is the history and extent of volatile exchange on Titan?	How were Titan's volatiles delivered, and were they internally processed?	Quantify the abundance of noble gases in the atmosphere	INMS	Dynamic range Resolution Sensitivity	6/8 decades 3000–5000 $m/\Delta m$ 10^3 #/cm^3	6/10 decades 5000 $m/\Delta m$ 10^0 #/cm^3
		Measure and compare isotopic ratios: $^{12}C/^{13}C$ and D/H in the atmospheric main constituents	INMS	Dynamic range Resolution Sensitivity	6 decades 3000 $m/\Delta m$ 10^5 #/cm^3	6 decades 5000 $m/\Delta m$ 10^0 #/cm^3
	What is the age of Titan's methane cycle, and is there evidence for renewal from internal outgassing?	Measure and compare isotopic ratios: ($^{14}N/^{15}N$; $^{12}C/^{13}C$; D/H; $^{16}O/^{18}O$) in the upper atmosphere	INMS	Dynamic range Resolution Sensitivity	6/8 decades 3000 $m/\Delta m$ 10^3 #/cm^3	6/10 decades 5000 $m/\Delta m$ 10^0 #/cm^3
		Constrain the genesis of candidate cryovolcanoes and cryovolcanic flows	TIGER	Coverage Scale Wavelength DTM vertical resol.	Sotra, Tui, & Hotei 50 m/pixel 3 colours 20 m	Sotra, Tui, & Hotei 30–50 m/pixel 3 colours 15–20 m
	How does Titan's surface reflect climate change?	Determine whether seas have existed in the tropics and/or south polar region	TIGER	Coverage Scale Wavelength DTM vertical resol.	Regions within Hotei, Tui, Xanadu & the putative south-polar basins 100m/pix 3 colour N/A	Regions within Hotei, Tui, Xanadu & the putative south-polar basins 100m/pix 3 colour N/A
		Investigate fine-scale dune patterns and how they reorient or breakup	TIGER	Coverage Scale Wavelength DTM vertical resol.	4 dune regions 50m/pix 3 colour N/A	4 dune regions 30–50m/pix 3 colour N/A

A.3: How has Titan's organic-rich surface evolved?	How have liquid organics modified Titan's surface?	Investigate the morphology of river networks and channels	TIGER	Coverage Scale Wavelength DTM vertical resol.	3 drainages 30m/pix 3 colour 15 m	3 drainages 25–30m/pix 3 colour 10–15 m
		Determine whether the labyrinth terrains and sharp edged depressions are formed by dissolution	TIGER	Coverage Scale Wavelength DTM vertical resol.	2 regions 100m/pix 3 colour 40 m	2 regions 50–100m/pix 3 colour 20–40 m
	To what degree are sediments produced and transported by fluvial and eolian processes?	Investigate the margins of the dune fields to identify sources and sinks of sand	TIGER	Coverage Scale Wavelength DTM vertical resol.	4 dune regions 50m/pix 3 colour N/A	4 dune regions 30–50m/pix 3 colour N/A
		Determine the primary erosion processes that degrade impact crater rims	TIGER	Coverage Scale Wavelength DTM vertical resol.	4 impacts 100m/pix 3 colour N/A	4 impacts 50–100m/pix 3 colour N/A
		Investigate the fine-scale geologic processes that modify the plains	TIGER	Coverage Scale Wavelength DTM vertical resol.	3 regions 50m/pix 3 colour N/A	3 regions 30–50m/pix 3 colour N/A
	How do the mechanical and chemical properties (i.e., composition) vary between the observed geologic units on Titan?	Determine how fluvial erosion varies among geologic units	TIGER	Coverage Scale Wavelength DTM vertical resol.	5 regions 50m/pix 3 colour N/A	5 regions 30–50m/pix 3 colour N/A
		Constrain the maximum slopes and topography supported by different geologic units	TIGER	Coverage Scale Wavelength DTM vertical resol.	5 regions 100m/pix 3 colour 40m	5 regions 50–100m/pix 3 colour 20–40m
		Investigate the morphology, topography, and spectral relationships across unit boundaries	TIGER	Coverage Scale Wavelength DTM vertical resol.	5 boundaries 100m/pix 3 colour 40m	5 boundaries 50–100m/pix 3 colour 20–40m

GOAL B: HABITABILITY AND POTENTIAL FOR LIFE IN OCEAN WORLDS, ENCELADUS AND TITAN

Science Objectives	**Scientific Questions**	**Measurement Description**	**Instrument**	**Measurement Requirements**		
				Parameter	**Requirement**	**Performance**
B.1: Is Enceladus' aqueous interior an environment favourable to the emergence of life?	What is the nature of hydrothermal activity on Enceladus and how does it connect with the plume activity?	Detect and inventory reduced and oxidized species in the plume material (e.g., NH_3/N_2 ratio, H_2 abundance, reduced versus oxidized organic species)	INMS	Dynamic range Resolution Sensitivity	6/8 decades 3000m/Δm 10^3 #/cm^3	6/10 decades 5000m/Δm 10^0 #/cm^3
			ENIJA	Dynamic range Mass range Resolution Sensitivity	4 decades 7–200 m/z 200 m/Δm 1 ppm	6/8 decades 1–2000m/z 1000m/Δm 0.1 ppm
		Characterize composition and abundance of salts and other minerals as messengers of rock/water interaction from mass spectra of icy grains	ENIJA	Dynamic range Mass range Resolution Sensitivity	6 decades 7–200 m/z 200 m/Δm 1 ppm	6/8 decades 1–2000m/z 1000m/Δm 0.1 ppm
		Determine spatial variations in plume composition (vapour and icy grains) and correlate with source activity	ENIJA	Dynamic range Mass resolution Resolution Sensitivity Spatial Resolution	4 decades 7–500 m/z 500 m/Δm 1 ppm 1000 m	6/8 decades 1–2000m/z 1000m/Δm 0.1 ppm 100 m
			TIGER	Coverage Scale Wavelength DTM vertical res.	2 cross-stripe tracks 5m/pix 5 & 5.3 μm N/A	2 cross-stripe tracks 2.5–5m/pix 5 & 5.3 μm N/A
		Determine how much energy the jets dissipate	TIGER	Coverage Scale Wavelength DTM vertical res.	2 night-time cross-stripe tracks 5m/pix 5 & 5.3 μm N/A	2 cross-stripe tracks 2.5–5m/pix 5 & 5.3 μm N/A

			Compare mass distribution of organic molecules to that expected from abiotic synthesis (e.g., Poisson versus non-Poisson) in the mass distribution of organic molecules	INMS	Dynamic range Resolution Sensitivity	6/8 decades 3000m/Δm 10^3 #/cm^3	6/10 decades 5000m/Δm 10^0 #/cm^3
				ENIJA	Dynamic range Mass range Resolution Sensitivity	6 decades 26-1000 m/z 500 m/Δm 1 ppm	6/8 decades 1-2000m/z 1000m/Δm 0.1 ppm
		Is there evidence that biotic/prebiotic processes are operating in Enceladus' interior?	Search for abnormal isotopic ratio in organics in plume vapour, including allowing the separation of species with isobaric interferences for example, ^{12}CH from ^{13}C	INMS	Dynamic range Resolution Sensitivity	6/8 decades 2500-3000 m/Δm 10^3 #/cm^3	6/10 decades 5000 m/Δm 10^0 #/cm^3
			Search for amino acids and abnormal ^{12}C/^{13}C ratio in organics that may have been captured in the ice matrix of solid plume material	ENIJA	Dynamic range Mass range Resolution Sensitivity	5 decades 12–500m/z 500 m/Δm 1 ppm	6/8 decades 1–2000m/z 1000m/Δm 0.1 ppm
	B.2: To what level of complexity has prebiotic chemistry evolved in the Titan system?	What chemical processes control the formation and evolution of complex organics in Titan's atmosphere?	Measure the elemental chemistry of low mass organic molecules in Titan's atmosphere	INMS	Dynamic range Resolution Sensitivity	6/8 decades 3000m/Δm 10^1 #/cm^3	6/10 decades 5000m/Δm 10^0 #/cm^3
			Measure organic macromolecules and ioni species (cations and anions) in order to monitor chemical coupling processes between ions and neutral species	INMS	Dynamic range Resolution Sensitivity	6/8 decades 3000m/Δm 10^1 #/cm^3	6/10 decades 5000m/Δm 10^0 #/cm^3
			Characterize the structure of haze layers, along with their spatial and temporal variations	TIGER	Coverage Scale	10 temporally spaced full-disk images 1km/pix	10 temporally spaced full-disk images 500m–1km/pix
					Wavelength DTM vertical resol.	3 colours N/A	3 colours N/A
			Determine the cloud distribution and morphology, including estimates of their top altitudes and vertical extent	TIGER	Coverage Scale Wavelength DTM vertical resol.	10 temporally spaced full-disk images 1km/pix 3 colours N/A	10 temporally spaced full-disk images 500m–1km/pix 3 colours N/A
		To what extent does Titan's organic-rich surface chemically communicate with its water-rich interior?	Investigate the morphology and compositional variability of candidate cryovolcanoes	TIGER	Coverage Scale Wavelength DTM vertical resol.	Sotra, Tui & Hotei 50m/pix 3 colours 20m	Sotra, Tui & Hotei 30–50m/pix 3 colours 15–20m
			Investigate the morphology of Titan's mountains to look for evidence of compressional vs extensional tectonics	TIGER	Coverage Scale Wavelength DTM vertical resol.	3 mountains 100 m/pix 3 colours 40 m	3 mountains 50–100 m/pix 3 colours 20–40 m
			Investigate melt sheets and flows associated with impact craters	TIGER	Coverage Scale Wavelength DTM vertical resol.	2 larger fresh craters 50 m/pix 3 colours N/A	2 larger fresh craters 30–50 m/pix 3 colours N/A
			Measure the abundance of radiogenically derived noble gases (e.g., ^{40}Ar, ^{21}Ne) and helium	INMS	Dynamic range Resolution Sensitivity	6/8 decades 3000m/Δm 10^1 #/cm^3	6/10 decades 5000m/Δm 10^0 #/cm^3

and Geology, Enceladus Reconnaissance (TIGER). The scientific payload will be described in Section 4.

3.1. Origin and evolution of volatile-rich ocean worlds in the saturn 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. It is a key open question whether Titan's methane is primordial likely due to water-rock interactions in Titan's interior during its accretionary phase (Atreya et al., 2006) or else is delivered to Titan during its formation processes (Mousis et al., 2009) or by cometary impacts (Zahnle et al., 1992; Griffith and Zahnle, 1995). On Titan, the Huygens probe detected a 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 be sequestered as soluble materials (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^{2}T INMS has the mass range and the sensitivity to accurately measure xenon. E^{2}T 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 $\sim 10^7$ years ago (Yung et al., 1984), and is being lost via photolysis and atmospheric escape (Yelle et al., 2008). It is an open question whether the current methane rich atmosphere is a unique event, in a steady state where methane destruction and replenishment are in balance (Jennings et al., 2009), or is a 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 1 350 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 of ^{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^{2}T 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., 2006a, b, 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, 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 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 ratios in Enceladus' plume gas. The E^{2}T mission would determine the isotopic ratios (D/H, $^{12}C/^{13}C$, $^{16}O/^{18}O$, $^{14}N/^{15}N$) in major gases 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^{2}T 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 limits, would offer an opportunity to test the influence of clathrate storage and decomposition in volatile exchanges through Enceladus's ice shell.

The origin of methane detected in Enceladus' plume is still uncertain. Methane, ubiquitous in the interstellar medium, was most likely embedded in the protosolar nebula gas. The inflow of protosolar nebular gas into the Saturn subnebula may have trapped methane in clathrates that were embedded in the planetesimals of Enceladus during their formation. Alternatively, methane may have been produced via hydrothermal reactions in Enceladus' interior; 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 $\sim 7 \times 10^{-7}$ 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 $\sim 1 \times 10^{-7}$ 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., 2009a,b, 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 (Fig. 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. 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.

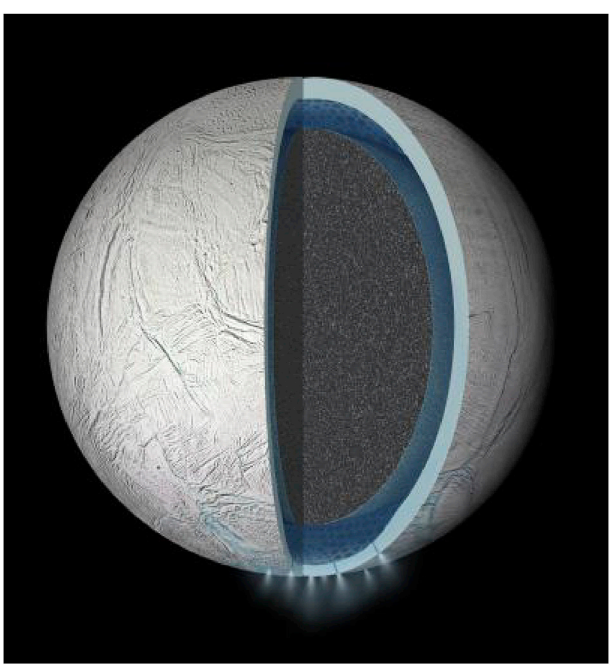

Fig. 3. Enceladus' internal structure inferred from gravity, topography and libration measurement provided by Cassini mission. A global subsurface ocean is present under the outer ice shell. The ice shell is believed to be a few kilometers thin at the south polar region where the center of the geological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

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 better 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 region 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

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 color 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 serve as sensitive indicators of climatic evolution (Lorenz, 2006; Radebaugh et al., 2008). Larger dune forms take longer to form than smaller dune forms. In Earth's Namib desert, these differing timescales result in large, longitudinal dunes that adhere to the overall wind conditions from the Pleistocene 20,000 years ago, while smaller superposing dunes (sometimes called rake dunes, or flanking dunes) have responded to the winds during our current interglacial and orient ages accordingly (Lancaster, 1989). 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 color 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.

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., 2017). 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 images 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

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 1 000 u, and the elemental chemistry of low-mass organic macromolecules and aerosols in Titan's upper atmosphere, and would 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 (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

(Fig. 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., 2009a,b, 2011). The salinity of these particles, the high solid/vapour ratio (Porco et al., 2006; Ingersoll and Ewald, 2011) of the plume and observations of large particles in the lower part of the plume (Hedman et al., 2009) indicate that the plume originates from a subsurface liquid source. The Cassini CDA later detected nanometer sized silica dust particles in E-ring stream particles (Hsu et al., 2011, 2015) which indicate that water-rock interactions are likely taking place within this liquid reservoir. Gravity and libration data demonstrated that this liquid reservoir was a subsurface global ocean (Iess et al., 2014).

Hsu et al. (2011) 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., 2011). 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^{2}T ENIJA given its high dynamic range (10^6–10^8). By performing high-resolution mass spectrometry of ice grains in Enceladus' plume, the E^{2}T 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, 2010). 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^{2}T 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 and Rubin, 2016). Most recently, Kite and Rubin (2016) has suggested that the tiger stripe fissures are interspersed with vertical pipe-like tubes with wide spacing that extend from the surface to the subsurface water. This mechanism allows tidal forces to turn water motion into heat, generating enough power to produce eruptions in a sustained manner. TIGER can provide high spatial resolution thermal emissions maps to constrain the amount of energy dissipated between the tiger stripes. The E^{2}T 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.

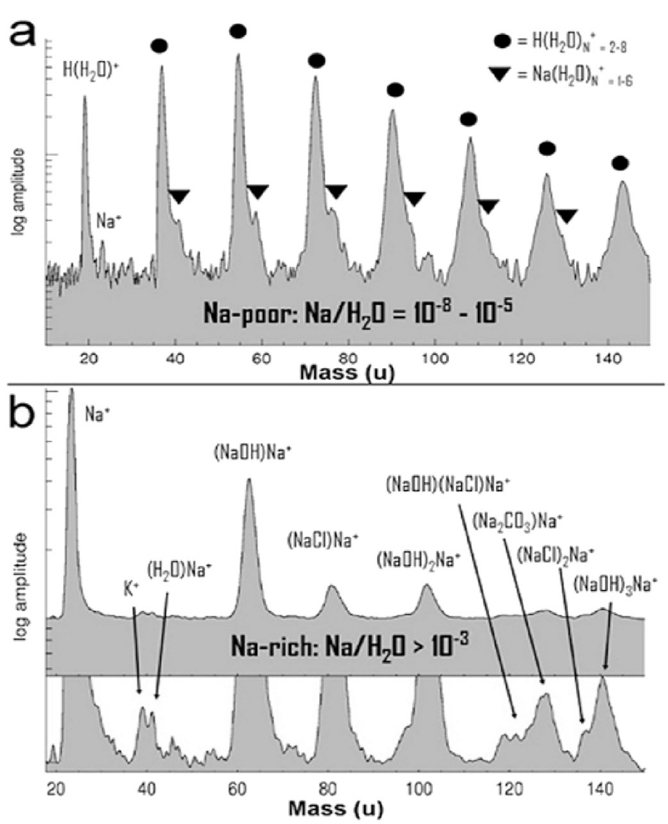

Fig. 4. Composition of salt-poor (Type I and II) and salt-rich (Type III) particles in Saturn's E-ring and Enceladus' plume as measured by Cassini CDA instrument (Postberg et al., 2009a,b).

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).

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 dips of faults, which would be ~30° to the horizontal for compressive mountains and ~60° 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, 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 would be provided by the Swiss Space Office (SSO) and ENIJA would be provided by the 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
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-to-charge range of 1–1 000 u 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-to-charge range of 1–2000 u of Enceladus' plume/E-ring 2) Measure fluxes at high impact rates up to 108 $s^{-1}m^{-2}$ 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		

4.1. Ion and Neutral Mass Spectrometer (INMS)

The Ion and Neutral Mass Spectrometer (INMS) is a reflectron time-of-flight mass spectrometer that would record mass spectra of neutral and ionized 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 would record mass spectra of neutral, positive and negative ionized gases within the mass range 1–1 000 u/e with a mass resolution at 5 000 m/Δm (50%) and 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 = 5 000), 50 times larger than Cassini INMS, allows for the separation of isobaric interference such as occur at masses 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 Fig. 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 time resolution at Enceladus is 0.1 s for recording a mass spectrum (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 (Abplanalp et al., 2009.), RTOF instrument of ROSINA (Scherer et al., 2006) on Rosetta 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 subsystems and a software-enabled high flux detector (HFD) that runs in parallel to the spectrometers. The high flux detector 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

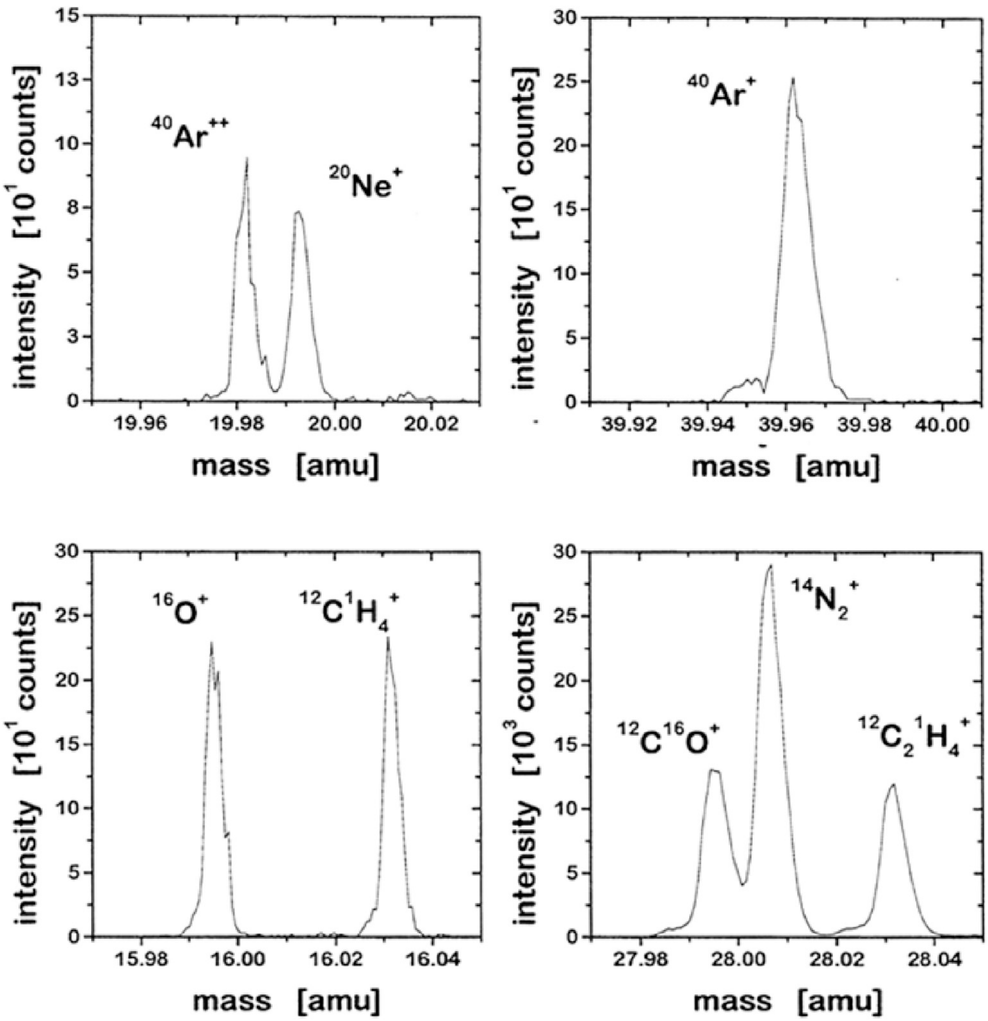

Fig. 5. Separation of isobaric interference such as occur at 16, 20, 28, and 40 u/e for the indicated species is possible based on heritage of RTOF/ROSINA from the Rosetta mission (Scherer et al., 2006; Wurz et al., 2015).

flux and sensitivity, and a spatial resolution that is 50 times better (Srama et al., 2004, 2015; Postberg et al., 2009a,b). 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 and 2000 u. ENIJA acquires time-of-flight 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 (Fig. 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 COmetary Secondary Ion Mass Analyzer (COSIMA) and Europa-SUrface Dust mass Analyzer (SUDA).

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 (Fig. 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.

While the TIGER instrument is a new design, it utilizes high-heritage

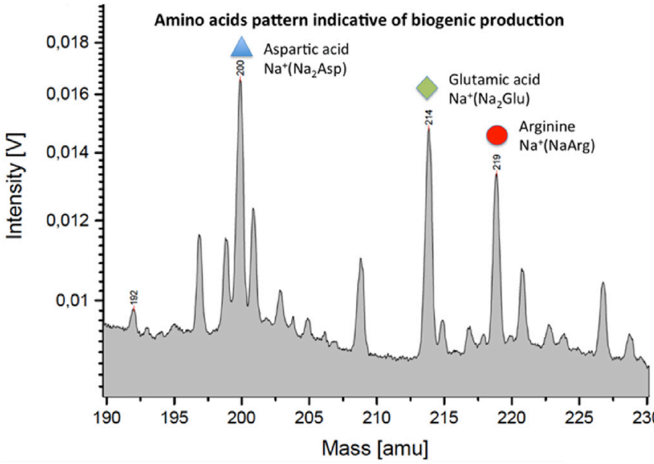

Fig. 6. Laser dispersion mass spectrum of aspartic acid (12 ppm), glutamic acid (12 ppm), and arginine (8 ppm) dissolved in a salt-water matrix simulating Enceladus' ocean composition. The complex amino acids are detectable in comparable quantities to glycine (15 ppm, not shown), even though the spectrum 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.

subsystems with a Technology Readiness Level (TRL) larger of 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) (Rieke 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).

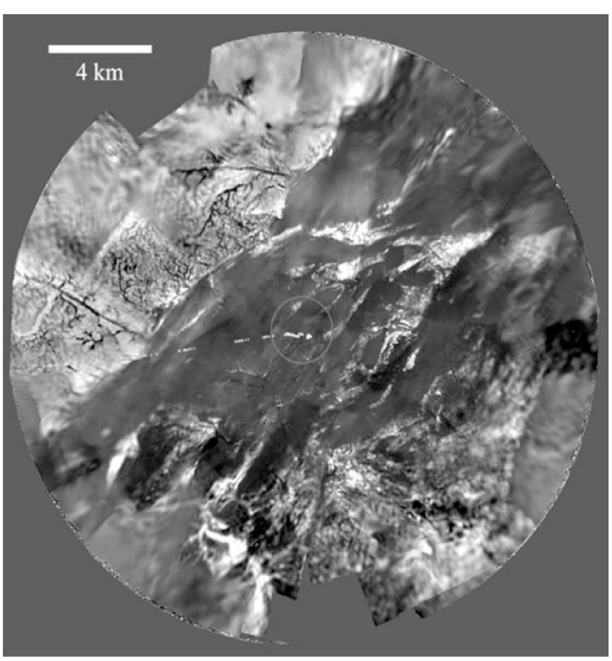

Fig. 7. The surface of Titan imaged by DISR camera during the Huygens probe descend. TIGER has the capability to image Titan at Huygens DISR resolution (ESA/NASA/JPL/University of Arizona).

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 (Behounkova et al., 2017).

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 ~2 636 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 (2500–4200 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 and 150 km, and 17 flybys of Titan at a reference flight altitude ranging from 1 500 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 Fig. 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 SYstème de Lancement Double Ariane (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 characteristic energy (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° 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 Jennings et al., 2009 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.

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 Fig. 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 would be performed during the initial tour phase. After the main Enceladus phase, close flybys of Titan with atmospheric sampling would be performed (Titan science phase).

During Enceladus science phase, E^2T would 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 would provide high-resolution imaging of Enceladus surface with the TIGER camera. During Enceladus flybys the observations of INMS, ENIJA and TIGER would 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 would 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.

Table 3
Nominal interplanetary trajectory.

Departure	
Launch date to GTO	April 2030
Hyperbolic Injection date	27 April 2030
Injection ΔV from upper stage (km/s)	1.20
Injected Mass (kg)	4 056
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	3 637
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 ΔV (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)	2 753

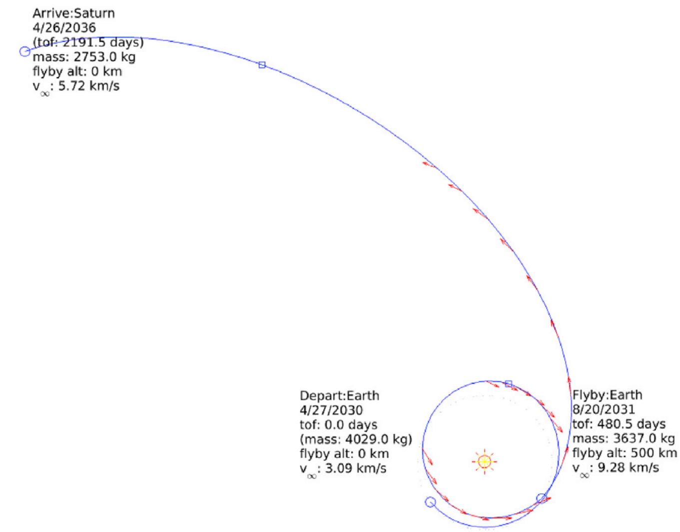

Fig. 8. Interplanetary transfer to Saturn. Red arrows indicate electric propulsion thrust. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 4
Launch period performance, fixed arrival date.

Launch Date	Nominal −10 days	Nominal (27Apr 2030)	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

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 Fig. 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

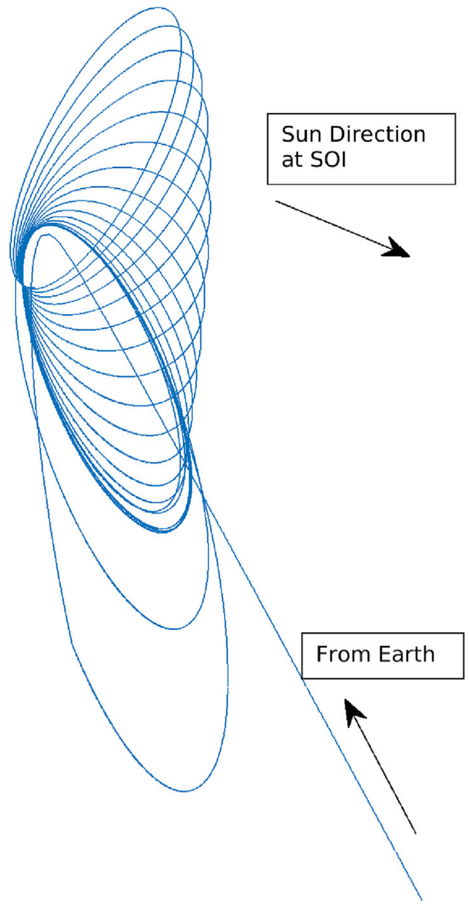

Fig. 9. Sample tour with two period- and inclination-management Titan flybys followed by a science phase with 6 Enceladus flybys and 17 Titan flybys (Inertial representation).

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

The previous decades have seen a revolution in our understanding of ocean worlds thanks in part to the Cassini-Huygens mission. Recent space missions to the outer Solar System have shown that liquid water once thought to be confined to Earth is quite common in the Solar System. The finding of subsurface oceans on Titan and Enceladus increases the possibility of extra-terrestrial habitability since life as we know it requires water, energy and nutrients (McKay et al., 2008, 2016). The geological activity represented by the eruptions forming Enceladus' plume at its south polar terrain and the organic-rich atmosphere and geological landscape, including lakes and seas, on Titan provide an ideal laboratory to investigate processes that may have been operational in Earth's early history.

Scientific investigations at both Titan and Enceladus as well as terrestrial experiments replicating conditions found on the icy moons have hinted at the real possibility of prebiotic activity on these icy ocean worlds. The ability to detect prebiotic molecules in Titan's atmosphere is currently limited by the mass range of the Cassini INMS to the two smallest biological amino acids, glycine (75 u) and alanine (89 u), and the limited mass resolution precludes any firm identification. However, the recent detection of prebiotic chemicals (glycine and phosphorus) in comet Churyumov/Gerasimenko (Altwegg et al., 2016) makes it likely that prebiotic molecules could be also present in Enceladus' plumes. 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 1 000 u, and the basic chemistry of low-mass organic macromolecules and aerosols in Titan's upper atmosphere, and would monitor neutral-ionic chemical coupling processes.

Investigations of Enceladus' plume emissions has yielded tantalizing information which are suggestive of prebiotic/biotic activity, including the detection of higher molecular weight compounds with masses exceeding 100 u (Waite et al., 2009; Postberg et al., 2015), and minor gas constituents in the plume that are indicative of high-temperature oxidation-reduction (redox) reactions in Enceladus' interior. Recent detection of molecular hydrogen in Enceladus' plume by Cassini could indicate processes that are similar in nature to processes that occur in terrestrial submarine hydrothermal vents which emit large quantities of molecular hydrogen due to water-rock interactions. In these hydrothermal vents, molecular hydrogen serves as a fuel that supports both abiotic and biotic production of organic molecules that have been detected in Enceladus' plume (McKay et al., 2008; 2017). 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) such as proposed by the E^2T mission could constrain the redox state and evolution of Enceladus' hydrothermal system.

Another key question still to be resolved is to understand how the plume is generated. E^2T's imaging system could provide high spatial resolution thermal emissions maps to constrain the amount of energy

Table 5
E^2T spacecraft technical characteristics.

E^2T Spacecraft main technical characteristics		Heritage
Spacecraft Dimensions	• Main S/C body: 2974 mm × 2860 mm × 2589 mm with 4 Solar Array wings of an overall area of 160 m2. • SEPS cylindrical section: 600 mm radius × 970 mm height with 3 + 1 QinetiQ T6-Ion Thruster Engine of 7.5 kW each one.	ExoMars BepiColombo
Overall Launch mass	• 4 056 kg (including 58 kg of science payload), dry mass 1876 kg	
Propulsion Architecture	The E2T 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 E2T 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/m2 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 Analyzer (ENIJA) • Titan Imaging and Geology, Enceladus Reconnaissance (TIGER) high-resolution infrared camera	

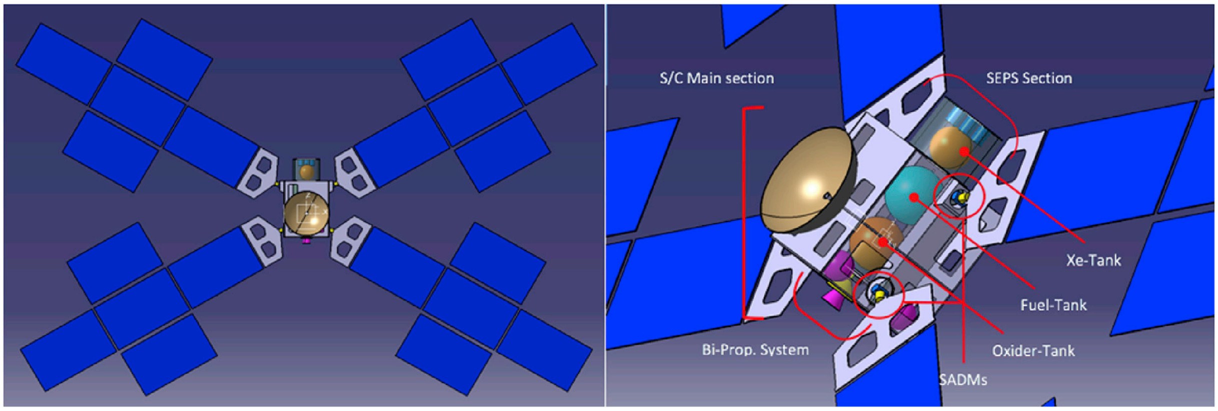

Fig. 10. E²T baseline proposed configuration of the spacecraft. Left panel shows an enlarged view of the S/C and right panel shows a close-up view of the spacecraft.

dissipated between the tiger stripes. The E²T mission would use high resolution infrared imaging of the south polar terrain and mass spectra of the grains to provide new data of its surface to constrain the links between plume activity, subsurface reservoirs and deep hydrothermal processes.

While Titan's surface offers a wealth of geological processes, the Cassini data lack the resolution necessary to constrain the detailed nature of these processes. E²T would provide high-resolution mapping (30 m/pixel with DTM vertical resolution of 10 m) that would offer the ability to distinguish geological features and morphology. Further, the high-resolution imaging of Titan's surface could improve understanding of the extent that Titan's organic-rich surface may be chemically interacting with its water-rich interior. By combining in-situ chemical analysis of Titan's atmosphere and Enceladus' plume with observations of Enceladus' plume dynamics and Titan's surface geology, E²T will be able to address fundamental science questions that would relate to content, origin and evolution of ocean worlds. The science that a mission such as E²T can provide can also answer questions about Earth's early history as well as help to predict the physical and chemical properties of exoplanets beyond the Solar System.

Acknowledgments

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