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Explorer of Enceladus and Titan (E²T): Investigating Ocean Worlds' Evolution and 1 Habitability in the Solar System 2

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46 Abstract

Titan, with its organically rich and dynamic atmosphere and geology, and Enceladus, with its 47 active plume, both harbouring subsurface oceans, are prime environments in which to 48 investigate the habitability of ocean worlds and the conditions for the emergence of life. We 49 present a space mission concept, Explorer of Enceladus and Titan (E²T), dedicated to 50 investigating the evolution and habitability of these Saturnian satellites proposed as a 51 52 medium-class mission led by ESA in collaboration with NASA in response to ESA's M5 Cosmic Vision Call. E²T proposes a focused payload that would provide in-situ composition 53 investigations and high-resolution imaging during multiple flybys of Enceladus and Titan 54 using a solar-electric powered spacecraft in orbit around Saturn. The E²T mission would 55 provide high-resolution mass spectrometry of the plumes currently emanating from 56 Enceladus' south polar terrain and of Titan's changing upper atmosphere. In addition, high-57 58 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. 59 These combined measurements of both Titan and Enceladus would enable the E²T mission 60 scenario to achieve two major scientific goals: 1) Study the origin and evolution of volatile-61 rich ocean worlds; and 2) Explore the habitability and potential for life in ocean worlds. $E^{2}T$'s 62 two high-resolution time-of-flight mass spectrometers would enable to untangle the 63 ambiguities left by the NASA/ESA/ASI Cassini-Huygens mission regarding the identification 64 of low-mass organic species, detect high-mass organic species for the first time, further 65 constrain trace species such as the noble gases, and clarify the evolution of solid and volatile 66 species. The high-resolution IR camera would reveal the geology of Titan's surface and the 67 energy dissipated by Enceladus fractured south polar terrain and plume in detail unattainable 68 by the Cassini mission. 69

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71 **1. Introduction**

The NASA/ESA/ASI Cassini-Huygens mission has revealed Titan and Enceladus to be two 72 unique worlds in the Solar System during its thirteen years of observations in the Saturnian 73 system (July 2004 - September 2017). Titan, with its organically rich and dynamic 74 atmosphere and geology, and Enceladus, with its active plume composed of multiple jets 75 (Waite et al., 2006; Spahn et al., 2006; Porco et al., 2006), both harbouring subsurface oceans 76 77 (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 78 79 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 80 waste (McKay et al., 2008, 2016; Lammer et al., 2009). The best-known candidates in the 81 Solar System for habitability at present likely meeting these criteria are the ocean worlds in 82 the outer Solar System, which include: Europa, Enceladus, Ganymede and Titan (Lunine, 83 2016). While the Jovian moons will be thoroughly investigated by the ESA Jupiter Icy moon 84 Explorer (JUICE), Enceladus and Titan which provide environments that can be easily 85 sampled from orbit in a single mission, are not currently targeted by any future exploration. 86 The joint exploration of these two fascinating objects will allow us to better understand the 87 origin of their organic-rich environment and will give access to planetary processes that have 88 long been thought unique to the Earth. 89

Titan is an intriguing world similar to the Earth in many ways, with its dense nitrogenmethane 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'srole of erosion and formation of a distinct geomorphological surface structure.

97 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 98 material into space. The eruption activity of Enceladus offers a unique possibility to sample 99 fresh material ejected from subsurface liquid water and understand how exchanges with the 100 101 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 102 103 of the Cassini-Huygens mission, there has been great technological advancement in instrumentation that would enable answering key questions that still remain about the 104 Saturnian ocean worlds. 105

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 mediumclass 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.

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114 **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).

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FIGURE 1

Titan's atmosphere shows many similarities with our own planet, but the low temperature 125 126 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. 127 128 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 129 investigated Titan over only two seasons: from Northern winter solstice to summer solstice. 130 And while ground-based observations, have observed Titan in other seasons, the data are not 131 sufficient to address many of the outstanding questions. Current measurements with 132 Cassini/CIRS show that the chemical content of Titan's atmosphere has significant seasonal 133 and latitudinal variability (Coustenis et al., 2013; 2016); future extended exploration of Titan 134 is necessary to get a full picture of the variations within this complex environment. 135

Titan is the only known planetary body, other than the Earth with long-standing liquid on 136 its surface, albeit hydrocarbons instead of water, likely fed by a combination of precipitation, 137 surface runoff and subsurface alkanofers (hydrocarbon equivalent of aquifers) in the icy crust 138 (Hayes et al., 2008). The presence of radiogenic noble gases in the atmosphere indicates some 139 communication between the surface and the subsurface and is suggestive of water-rock 140 interactions and methane outgassing processes (Tobie et al., 2012), possibly associated with 141 cryovolcanic activity or other exchange processes (Lopes et al., 2007, 2016; Solomonidou et 142 al., 2014, 2016). The detection of a salty ocean at an estimated 50-80 km depth (Iess et al., 143 2012; Beghin et al., 2012; Mitri et al., 2014b) and the possible communication between this 144

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 152 153 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 154 source of energy for solid bodies in the outer Solar System, interior heat sources derived from 155 156 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 157 Enceladus' plume (Waite et al., 2017)providing further evidence of water-rock interactions 158 which suggests that methane formation from CO₂ in Enceladus' subsurface ocean could occur 159 160 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 161 discovery is the complex large nitrogen-bearing organic molecules in Titan's upper 162 atmosphere by Cassini (Waite et al., 2007; Coates et al., 2007). The low resolution of the in-163 situ mass spectrometers on Cassini, however, precludes the determination of the chemical 164 composition of this complex organic matter. In situ exploration with more advanced 165 instruments is required to investigate the prebiotic potential of Titan. 166

167 The discovery in 2005 of a plume emanating from multiple jets in Enceladus' south polar 168 terrain is one of the major highlights of the Cassini–Huygens mission (Figure 2) (Dougherty 169 et al., 2006; Porco et al., 2006; Spahn et al., 2006). Despite its small size (10 times smaller

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than Titan), Enceladus is the most active moon of the Saturnian system. Although geyser-like 170 plumes have been observed on Triton (Soderblom et al., 1990) and more recently transient 171 172 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 173 nature. The jets, of which approximately one hundred have been identified (Porco et al., 174 2014) form a huge plume of vapour and ice grains above Enceladus' south polar terrain and 175 are associated with elevated heat flow along tectonic ridges, called 'tiger stripes'. Enceladus' 176 endogenic activity and gravity measurements indicate that it is a differentiated body 177 178 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 179 potassium salts (Postberg et al., 2011), organics, both in the gas (Waite et al., 2009) and in the 180 ice grains (Postberg et al., 2008, 2015), and molecular H (Waite et al., 2017). The jet sources 181 are connected to a subsurface salt-water reservoir that is likely alkaline in nature and 182 undergoing hydrothermal water-rock interactions (Porco et al., 2006, 2014; Waite et al., 2006, 183 2009, 2017; Postberg et al., 2009, 2011; Hsu et al., 2011, 2014; Glein et al., 2015). The 184 putative exothermic water-rock interactions on Enceladus could be further constrained by 185 quantifying He and constraining the amount of H₂ in the plume. Gravity, topography and 186 libration measurements demonstrate the presence of a global subsurface ocean (Iess et al., 187 2014; McKinnon et al., 2015; Thomas et al., 2016). The co-existence of organic compounds, 188 salts, liquid water and energy sources on this small moon provides all necessary ingredients 189 for the emergence of life by chemoautotrophic pathways (McKay et al., 2008) – a generally 190 held model for the origin of life on Earth in deep sea vents. 191

192 Titan and Enceladus offer an opportunity to study analogous prebiotic processes that may 193 have led to the emergence of life on Earth. Retracing the processes that allowed the 194 emergence of life on Earth around 4 Ga is a difficult challenge since most traces of the

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environmental conditions at that time have been erased. It is, therefore, crucial for 195 astrobiologists to find extraterrestrial planetary bodies with similarities to our planet, 196 197 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 198 to sample fresh material emerging from subsurface liquid water and to understand how 199 exchange processes with the interior control surface activity. It provides us with an 200 201 opportunity to in-situ study phenomena that have been important in the past on Earth and throughout the outer Solar System. 202

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FIGURE 2

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205 3. Scientific Objectives and Investigations

The scientific appeal of Titan and Enceladus have stimulated many previous mission studies 206 (e.g. see reviews by Lorenz, 2000; 2009) which have articulated detailed scientific objectives 207 for post-Cassini exploration (e.g. Tobie et al., 2014). At Titan, in particular, the diversity of 208 scientific disciplines (Dougherty et al., 2009) has prompted a variety of observing platforms 209 210 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 -211 TiME", Stofan et al., 2013; Mitri et al., 2014), landers for land (Titan Explorer), fixed-wing 212 213 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 214 Enceladus Mission TANDEM" (Coustenis et al., 2009), "Journey to Enceladus and Titan -215 JET" and "Enceladus Life Finder - ELF" (Reh et al., 2016). Similar to TANDEM, TSSM 216 and JET, $E^{2}T$ would address science goals at both targets. 217

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 E²T mission model payload which consists of three 220 instruments: two time-of-flight mass spectrometers (TOF-MS), the Ion and Neutral Gas Mass 221 Spectrometer (INMS) and the Enceladus Icy Jet Analyzer (ENIJA) dust instrument; and a 222 high-resolution infrared (IR) camera, the Titan Imaging and Geology, Enceladus 223 Reconnaissance (TIGER). With considerable improvements in mass range, resolution and 224 225 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 226 environment of Enceladus from plume sampling and of the varying complex pre-biotic 227 chemistry occurring in Titan's atmosphere. The Titan Imaging and Geology, Enceladus 228 Reconnaissance (TIGER) mid-wave infrared camera would map thermal emission from 229 Enceladus' tiger stripes at meter scales and investigate Titan's geology and compositional 230 variability at decameter scales, a resolution at least ten times better than Cassini. The 231 scientific payload will be described in Section 4. 232

While Cassini-Huygens and its extended missions have revealed much about Enceladus 233 and Titan, the spacecraft (S/C) was not equipped to search for life or constrain the evolution 234 of these ocean worlds. In-situ mass spectroscopic measurements by Cassini-Huygens at 235 Enceladus and Titan revealed a wealth of chemical complexity of neutral and positively 236 charged molecules. Those analyses, however, are limited by the low sensitivity, mass range, 237 and resolution of the Cassini-Huygens mass spectrometers limiting, for example, their ability 238 to resolve low-mass isobaric molecular species. For example, in Enceladus' vapour plume an 239 unidentified species with a mass-to-charge (m/z) ratio of 28, can be either CO, N_2 , C_2H_4 or a 240 combination thereof. Determining the relative abundances of these different species is 241 essential to constraining the origin of volatiles on Enceladus and to assess whether they were 242 243 reprocessed internally. E²T mass spectrometers enable the separation of low-mass isobaric interferences, for example ¹³C and ¹²CH and CO and N₂. Further, Cassini mass spectrometers 244

were limited to the study of only low-mass neutral and positive ions. The detection of heavy 245 complex negative ions in Titan's upper atmosphere by the Cassini Plasma Spectrometer 246 247 (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 248 possibly to prebiotic activity. Negative water group ions were also detected in Enceladus' 249 plume (Coates et al., 2010). The high mass range/resolution and ability to detect anions of 250 251 $E^{2}T$'s mass spectrometers would constrain the nature and dynamics of these heavy hydrocarbon and nitrile molecules. 252

The nature of the surfaces of Titan and Enceladus have been revealed by Cassini but only 253 at low to moderate resolutions with the exception of the Descent Imager /Spectral Radiometer 254 (DISR) onboard the Huygens probe that landed on Titan's surface on January 14, 2005, 255 256 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 257 Saturn system. Huygens' DISR was able to obtain images of a 25 m² area (Tomasko et al., 258 2005). Data from Cassini Visual Infrared Mapping Spectrometer (VIMS) show that Titan is 259 visible at several near-infrared atmospheric windows. Scattering by aerosols in the 260 atmosphere, which limits the signal-to-noise ratio (SNR) and resolution of such data, 261 262 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 263 magnitude better than Cassini observations (Clark et al., 2010; Soderblom et al., 2012; Barnes 264 et al., 2014; Hayne et al., 2014; Sotin et al., 2016). Additionally, these data would be highly 265 sensitive to organic composition (Clark et al., 2010; Barnes et al., 2012). A high-resolution 266 map of Titan within the atmospheric windows at 1.3, 2 and 5 μ m would enable E²T to 267 identify morphology not evident from Cassini data to quantify geological processes and 268 relationships between different geological units and monitor changes due to geologic or 269

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.

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FIGURE 3

277 The first scientific goal of E²T mission on Enceladus would focus on the origin and evolution of volatile compounds in the plume vapour and icy grains. On Titan, the focus 278 would be on the origin and evolution of volatiles, the methane based cycle and evidence for 279 280 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 281 cycle has on Titan's surface evolution and the morphological signatures of the internal 282 processes of Titan and surface-interior chemical communication. The second scientific goal 283 on Enceladus would examine the nature of hydrothermal activity and search for evidence of 284 abiotic/prebiotic processes. On Titan, the focus would be on discerning what level of 285 complexity abiotic/prebiotic chemistry has evolved. 286

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288 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

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evolution can be constrained by current chemical and isotopic abundances, satellite activity 293 whether it be endogenic or exogenic and present day internal structure and dynamics. The 294 295 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 296 during the system evolution (Canup, 2010; Charnoz et al., 2011). A late accretion scenario 297 298 may explain the mass distribution and ice/rock ratio of the mid-sized moons and the existence 299 of the planet's ring. Such a scenario is supported by recent estimation of the dissipation factor 300 in Saturn, which is ten times smaller than initially anticipated (Lainey et al., 2012, 2016) and 301 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 302 resulted in significant differences in their initial volatile inventory and their subsequent 303 evolution. 304

Whether the volatiles currently present on Titan and Enceladus are primordial, originating 305 in the solar nebula or Saturnian subnebula possibly altered during the accretion process or 306 else were produced in some secondary manner is still being debated (e.g., Atreya et al., 307 2006). Photochemical processes on Titan and aqueous alteration on Enceladus have affected 308 the initial volatile inventory to an extent unknown. By combining in-situ chemical analysis of 309 Titan's atmosphere and Enceladus' plume with observations of Enceladus' plume dynamics 310 and Titan's surface geology, E²T would provide clues on how the ocean worlds acquired their 311 initial volatile inventory and how it was subsequently modified during their evolution, which 312 would provide clues to an understanding of the nature of Saturn subnebula formation 313 314 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 315 properties of terrestrial planets and exoplanets beyond the Solar System. 316

318 *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 319 methane is primordial likely through water-rock interactions in Titan's interior during its 320 321 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 322 Zahnle, 1995) is a key open question. On Titan, the Huygens probe detected small argon 323 abundance (³⁶Ar) and a tentative amount of neon (²²Ne) in its atmosphere (Niemann et al., 324 2005, 2010), but was unable to detect the corresponding abundance of xenon and krypton. 325 The presence of 22 Ne (36 Ar / 22 Ne~1) was unexpected as neon is not expected to be present in 326 any significant amounts in protosolar ices (Niemann et al., 2005, 2010) and may indicate 327 water-rock interactions and outgassing processes (Tobie et al., 2012). The non-detection of 328 xenon and krypton supports the idea that Titan's methane was generated by serpentinization 329 of primordial carbon monoxide and carbon dioxide delivered by volatile depleted 330 331 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 332 from the atmosphere. While xenon is soluble in liquid hydrocarbon (solubility of 10^{-3} at 95 K) 333 and could potentially be sequestered into liquid reservoirs, argon and krypton cannot (Cordier 334 et al., 2010). Therefore, the absence of measureable atmospheric krypton requires either 335 sequestration into non-liquid surface deposits, such as clathrates (Mousis et al., 2011), or 336 depletion in the noble gas concentration of the planetesimals (Owen and Niemann, 2009). 337 Unlike Cassini INMS, the $E^{2}T$ INMS has the mass range and the sensitivity to accurately 338 measure xenon. E²T would measure the abundance of noble gases in the upper atmosphere of 339 Titan to discriminate between crustal carbon sequestration and carbon delivery via depleted 340 planetesimals. 341

The longevity of methane in Titan's atmosphere is still a mystery. The value of ${}^{12}C/{}^{13}C$ in 342 Titan's atmosphere has been used to conclude that methane outgassed $\sim 10^7$ years ago (Yung 343 et al., 1984), and is being lost via photolysis and atmospheric escape (Yelle et al., 2008). It is 344 an open question whether the current methane rich atmosphere is a unique event, in a steady 345 state where methane destruction and replenishment are in balance (Jennings et al., 2009), or is 346 a unique transient event and is in a non-steady state where methane is being actively depleted 347 or replenished. Indeed, the possibility that Titan did not always possess a methane rich 348 atmosphere seems to be supported by the fact that the amount of ethane on Titan's surface 349 should be larger than the present inventory; though Wilson and Atreya (2009) contend that 350 missing surface deposits may simply be reburied into Titan's crust and Mousis and Schmitt 351 (2008) have shown that it is possible for liquid ethane to react with a water-ice and methane-352 clathrate crust to create ethane clathrates and release methane. Nixon et al. (2012), however, 353 favours a model in which methane is not being replenished and suggest atmospheric methane 354 duration is likely between 300 and 600 Ma given that Hörst et al. (2008) demonstrated that 355 300 Ma is necessary to create Titan's current CO inventory and recent surface age estimates 356 357 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 470 358 Ma or else up to 940 Ma if the presumed methane outgassing rate was large enough to 359 overcome ¹²C/¹³C isotope fractionation resulting from photochemistry and escape. Both the 360 results of Mandt et al. (2012) and Nixon et al. (2012) fall into the timeline suggested by 361 interior models (Tobie et al., 2006) which suggests that the methane atmosphere is the result 362 of an outgassing episode that occurred between 350 and 1350 Ma. On Titan, both simple 363 (methane, ethane and propane) and complex hydrocarbons precipitate out of the atmosphere 364 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 365 abundances of the simple alkanes (e.g., methane, ethane and propane) would constrain the 366

formation and evolution of the methane cycle on Titan. Further measurements of radiogenic 367 noble gases such as ⁴⁰Ar and ²²Ne, which are typically markers of volatile elements from 368 Titan's interior can constrain outgassing episodes. Detection of ⁴⁰Ar and tentatively ²²Ne in 369 the atmosphere has provided circumstantial evidence of water-rock interactions and methane 370 outgassing from the interior (Niemann et al., 2010; Tobie et al., 2012). Recent measurements 371 by ground-based observatories including measurements of CO and its carbon and oxygen 372 isotopologues accompanied by the first detection ¹⁷O in Titan and indeed in the outer Solar 373 System by Atacama Large Millimeter/submillimeter Array (ALMA) can be followed up on in 374 more detail by in-situ spectroscopic measurements (Serigano et al., 2016). E²T would 375 measure the composition and isotopic ratios of Titan's upper atmosphere to determine the age 376 377 of methane in the atmosphere and characterize outgassing history.

On Enceladus, Cassini measurements by INMS (Waite et al., 2006, 2009, 2017) and UVIS 378 (Hansen et al., 2006, 2008) showed that plume gas consists primarily of water vapour with a 379 380 few percent other volatiles. In addition to H₂O, as the dominant species, INMS was able to identify CO₂ (0.3-0.8%), CH₄ (0.1-0.3%), NH₃ (0.4-1.3%) and H₂ (0.4-1.4%), in the vapour 381 plume as well as an unidentified species with a mass-to-charge (m/z) ratio of 28, which is 382 thought to be either $N^{}_{_2}$ or $C^{}_2H^{}_4$ or a combination of these compounds or CO. The low mass 383 resolution of Cassini INMS is insufficient to separate these species, and the UVIS 384 measurements can only provide upper limits on N₂ and CO abundance. Determining the 385 abundance ratio between these different species is, however, essential to constrain the origin 386 of volatiles on Enceladus and to assess if they were internally reprocessed. A high CO/N₂ 387 ratio, for instance, would suggest a cometary-like source with only a moderate modification 388 of the volatile inventory, whereas a low CO/N₂ ratio would indicate a significant internal 389 reprocessing. 390

In addition to these main volatile species, the possible presence of trace quantities of C_2H_2 ,

 $C_{3}H_{8}$, 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 H₂O on Enceladus (which has large uncertainty, 397 Waite et al., 2009), no information is yet available for the isotopic ratio in Enceladus' plume 398 gas. The E²T mission would determine the isotopic ratios (D/H, ¹²C/¹³C, ¹⁶O/¹⁸O, ¹⁴N/¹⁵N) in 399 major gas compounds of Enceladus' plume as well as ¹²C/¹³C in organics contained in icy 400 grains. Comparison of gas isotopic ratios (e.g., D/H in H₂O and CH₄, ¹²C/¹³C in CH₄, CO₂, and 401 CO; ¹⁶O/¹⁸O in H₂O, CO₂, CO; ¹⁴N/¹⁵N in NH₃ and N₂) and with Solar System standards would 402 403 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 404 species in Enceladus' plume and Titan's atmosphere would permit a better determination of 405 the initial reference values and a quantification of the fractionation due to internal and 406 atmospheric processes on both moons. 407

Noble gases also provide essential information on how volatiles were delivered to 408 409 Enceladus and if significant exchanges between the rock phase and water-ice phase occurred during Enceladus' evolution. The E²T mission would be able to determine the abundance of 410 ⁴⁰Ar, expected to be the most abundant isotope, as well as the primordial (non-radiogenic) 411 argon isotopes, ³⁶Ar and ³⁸Ar. The detection and quantification of ³⁶Ar and ³⁸Ar would place 412 fundamental constraints on the volatile delivery in the Saturn system. A low ³⁶Ar/N₂ ratio, for 413 instance, would indicate that N₂ on Enceladus is not primordial, like on Titan (Niemann et al., 414 2010), and that the fraction of argon brought by cometary materials on Enceladus is rather 415

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 ⁴⁰Ar/³⁸Ar/³⁶Ar as well as ²⁰N/²¹Ne/²²Ne 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 423 in the interstellar medium was most likely embedded in the protosolar nebula gas. The inflow 424 of protosolar nebular gas into the Saturn subnebula may have trapped methane in clathrates 425 that were embedded in the planetesmals of Enceladus during their formation. Alternatively, 426 427 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' 428 plume (Waite et al., 2017). Mousis et al. (2009) suggests that if the methane of Enceladus 429 originates from the solar nebula, then Xe/H₂O and Kr/H₂O ratios are predicted to be equal to 430 $\sim 7 \times 10^{-7}$ and 7×10^{-6} in the satellite's interior, respectively. On the other hand, if the methane 431 of Enceladus results from hydrothermal reactions, then Kr/H₂O should not exceed $\sim 10^{-10}$ and 432 Xe/H₂O should range between $\sim 1 \times 10^{-7}$ and 7×10^{-7} in the satellite's interior. The E²T mission 433 by performing in situ analysis with high-resolution mass spectrometry of both the vapour and 434 solid phases would quantify the abundance ratios between the different volatile species 435 present in the plume of Enceladus, the isotopic ratios in major species, and the noble gas 436 abundance. 437

438

439 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 440 (Porco et al., 2006; Ingersoll and Ewald, 2011), and the observations of large particles in the 441 lower part of the plume (Hedman et al., 2009) all indicate that the plume of Enceladus 442 originates from a liquid source likely from the subsurface ocean rather than from active 443 melting within the outer ice shell (Figure 3). However, the abundance of the major gas 444 species observed by Cassini suggests some contribution from the surrounding cold icy crust 445 should also be considered. If plume gases exclusively originate from a liquid water reservoir, 446 447 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 ~100 448 discrete collimated jets as well as a broad, diffuse component (Hansen et al., 2008, 2011; 449 Postberg et al., 2011; Porco et al., 2014). The majority of plume material is found in the 450 distributed diffuse portion of the plume while only a small portion of gas and grains are 451 emitted from the jets (Hansen et al., 2011; Postberg et al., 2011). The saltiness of the ice 452 grains and the recent detections of nanometer sized silica dust in E-ring particles, which are 453 believed to come from Enceladus (Hsu et al., 2011, 2015), and molecular hydrogen in 454 455 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. 456

457

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 E²T 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 464 nominal mass. E²T INMS' high mass resolution, which is 50 times larger than that of Cassini 465 INMS, would allow for separation of isobaric interferences, for example separating ¹³C and 466 ¹²CH and CO and N₂. Determining high-resolution spatial variations in composition is crucial 467 to establish whether the jets are fed by a common liquid reservoir or if jet sources are 468 disconnected, and if the local liquid sources interact with a heterogeneous in the icy crust. 469 Variations in composition between the solid and gas phases as a function of distance from jet 470 sources can also provide information about how the less volatile species condense on the 471 grains, thus constraining the eruption mechanisms. The E²T mission would allow for the 472 determination of the compositional distribution between both solid and vapour phases of 473 Enceladus' plume, thus providing crucial constraints on the nature and composition of the jet 474 sources, and on the relative contributions of subsurface liquid reservoirs and the surrounding 475 cold icy crust. Spatial variations in composition within the plume and possible correlations 476 with the jet sources would permit for testing if the volatile compounds originate from a 477 common reservoir and how the less volatile compounds are integrated in the solid particles 478 479 during the eruption processes.

480

481 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 488 shell during its evolution could have produced thermal destabilization of methane clathrates 489 490 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 491 Cassini observations (Lopes et al., 2013). E²T TIGER high-resolution colour images would 492 493 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 494 be constrained. 495

496 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 497 et al., 2009). There have been suggestions, however, that organic seas may have existed in 498 499 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 500 models suggest Titan's methane distribution varies on seasonal timescales (e.g., Waite et al., 501 2007; Hayes et al., 2010; Turtle et al., 2011; Coustenis et al., 2013, 2016) or Milankovitch 502 timescales (Aharonson et al., 2009). Alternative models suggest that methane is being 503 depleted and Titan's atmosphere is drying out (Moore and Howard, 2010). High-resolution 504 images of the margins and interiors of these basins would allow us to determine if they once 505 held seas. Identification of impact features or aeolian processes within these basins would 506 help to constrain the timing of their desiccation. 507

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 512 dunes (sometimes called rake dunes, or flanking dunes) have responded to the winds during our current interglacial and orient ages accordingly. On Titan, E²T TIGER's superior spatial 513 resolution would resolve these potential smaller dunes on top of the known longitudinal 514 dunes, and would therefore reveal if Titan's recent climate has been stable or if it has changed 515 over the past few Ma. The E²T mission would provide high-resolution colour imaging of 516 Titan that can be used to characterize candidate cryovolcanic features that could be 517 replenishing Titan's atmosphere and paleo-seas or dune patterns that evidence changes in 518 519 Titan's climate.

Understanding climate change on Titan would provide insight that may be relevant to the 520 future of our own planet, when surface conditions with warm tropospheric temperatures will 521 preclude stable equatorial/mid-latitude oceans and the liquid water will be limited to the 522 523 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 524 system to such a future Earth is Titan (Coustenis et al., 2009). Indeed, the evolution of the solar 525 526 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 527 528 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 529 530 photochemical lifetime, and if persistent would be resupplied by mantle/deep crustal water. At the 531 equator, occasional intense rainstorms might scour out fluvial features, but the principle sedimentary 532 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 540 (e.g., Tomasko et al., 2005; Soderblom et al., 2007; Burr et al., 2013). Fluvial erosion is 541 observed at all latitudes, with a variety of morphologies suggesting a range of controls and 542 fluvial processes (Burr et al., 2013). High-resolution color imaging would provide insight into 543 the nature of this erosion: whether it is predominantly pluvial or sapping in nature and 544 545 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 546 be responsible for the formation of the polar sharp edged depressions (Hayes et al., 2008): 547 548 $E^{2}T$ imaging would allow direct testing of these hypotheses.

Both fluvial and aeolian processes likely produce and transport sediments on Titan. Dunes 549 are observed across Titan's equator (e.g., Radebaugh et al., 2008; Malaska et al., 2016) while 550 a variety of fluvial sediment deposits have been identified across Titan (e.g., Burr et al., 2013; 551 Birch et al., 2016). Detailed images of the margins of the dune fields would allow us to 552 determine the source and fate of sands on Titan. E²T images would also help determine 553 whether the observed fluvial features are river valleys or channels (cf. Burr et al., 2013) 554 providing key information in obtaining accurate discharge estimates needed to model 555 sediment transport (Burr et al., 2006). E²T observation would provide insight into the primary 556 erosion processes acting on crater rims, which likely comprise a mixture of organics and 557 water ice (cf. Neish et al., 2015, 2016). Finally, E²T imagining may provide insight into the 558 559 nature of erosion that exists in Titan's mid-latitudes, a region that shows little variability in Cassini observations. 560

561 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 562 processes, the degree to which mechanical versus dissolution dominates and the existence of 563 sapping, reflect the material properties of the surface and therefore can be used as a powerful 564 tool to investigate the properties of the surface. E²T imaging would also allow us to 565 investigate the strength of the surface materials by constraining the maximum slopes 566 supported by different geologic units. Detailed color and stereo imaging of the boundaries of 567 units would also allow investigation of the morphology, topography, and spectral relationship 568 across unit boundaries. E²T would take high-resolution color images of Titan that would 569 elucidate the nature of the geological evolution of Titan's organic-rich surface. 570

571

572 **3.2** Habitability and Potential for Life in Ocean Worlds, Enceladus and Titan

573 Ocean worlds, such as Titan and Enceladus, are the subjects of great astrobiological interest 574 as water is one of the key requirements for life as we know it (Lammer et al., 2009). 575 Additionally, the organic surface environment of Titan provides an ideal, and in many ways 576 unique setting to investigate the prebiotic chemistry that may have led to the emergence of 577 life on the Earth. Water in ocean worlds in the outer Solar System is found beneath the 578 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 585 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 586 and thermal evolution models (Tobie et al., 2005, 2006; Mitri and Showman, 2008; Mitri et 587 al., 2010). Enceladus is unique since water exchange is known to exist between the surface 588 and subsurface and, quite conveniently, this water is ejected into space for easy in situ 589 sampling. Titan provides its own unique environment in which a rich array of complex 590 organics exist on the surface and may interact with the subsurface ocean via cryovolcanic 591 activity or, alternatively, with transient liquid water at the surface following impact events. 592

593 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 594 595 in the shell; therefore tectonic features are much more likely present on ocean worlds (Mitri 596 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 597 via precipitation from the atmosphere on Titan or lodged in the surface as a result of cometary 598 impacts into subsurface oceans. Titan's hydrocarbon cycle and the associated meterology 599 creates a global distribution of trace species, evident in the formation and dynamics of clouds 600 and an extensive photochemical haze in Titan's atmosphere, which affects the dynamics of 601 how, when and where organic material settles on the surface and possibly interacts with the 602 subsurface. In addition, cometary impacts could deliver key organics such as glycine, the 603 simplest amino acid which has been detected on both comet 67P/Churyumov-Gerasimenko 604 from in-situ sampling by ESA's Rosetta mission (Altwegg et al. 2016) and comet 81P/Wild-2 605 606 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 607 to create prebiotic chemistry (Neish et al., 2010). Further it is likely that such impact melt 608 pools could be stable for 10^2 - 10^4 years (O'Brien et al., 2005). This process could be circular; 609

610 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 611 612 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, 613 detection of nanometer silica dust particles in Saturn's E-ring (Hsu et al., 2015) and 614 615 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 616 with liquid water in contact with rocks, favours prebiotic processes, providing both an energy 617 source and mineral surfaces for catalyzing chemical reactions. 618

Titan and Enceladus, have already demonstrated remarkable astrobiological potential as 619 evidenced by Titan's complex atmosphere and methane cycle, analogous to Earth's water 620 621 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. 622 For instance, part of the CH₄ detected in the plume of Enceladus may result from 623 methanogens analogous to those occurring in anaerobic chemosynthetic ecosystems on Earth 624 (Stevens and McKinley, 1995; McKay et al., 2008); molecular hydrogen in Enceladus' plume 625 makes the occurrence of methanogenesis more likely (Waite et al., 2017). A powerful method 626 to distinguish between biogenic and abiogenic CH₄ is to analyze the difference in carbon 627 isotope, ${}^{12}C/{}^{13}C$, between CH₄ and a potential source of C, most likely CO₂ on Enceladus and 628 Titan, and to analyze the pattern of carbon isotopes in other hydrocarbons, such as C_2H_6 , 629 C₂H₄, C₂H₂, C₃H₈ etc. (Sherwood et al., 2002; McKay et al., 2008). The abundances of other 630 631 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 632 acids could provide additional evidence for active biogenic processes; although they can be 633 produced, both biologically and via aqueous alteration of refractory organics, their 634

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, 640 including amino acids, E²T would determine what chemical processes control the formation 641 and evolution of complex organics on Titan and would test if biotic processes are currently 642 occurring inside Enceladus. The analysis of salts and minerals embedded in icy grains and 643 their possible distribution throughout the plume would constrain the nature of hydrothermal 644 activity occurring in Enceladus' deep interior and on how it connects with the plume activity. 645 646 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 647 material is actively being exchanged between the surface and interior. 648

649

650

651 **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 659 masses up to 10,000 u (Coates et al., 2007) in Titan's ionosphere. Whereas Cassini INMS 660 only had the ability to detect cations, E²T INMS can detect both cations and anions and can 661 do so with much better mass resolution than Cassini-INMS (and a fortiori than Cassini-662 CAPS). It is thought that these heavy negative ions, along with other heavy molecules found 663 664 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 665 molecules are still unknown, their presence suggest a complex atmosphere that could hold the 666 precursors for biological molecules such as those found on Earth. The ability to detect 667 prebiotic molecules in Titan's atmosphere is currently limited by the mass range of the 668 Cassini INMS to the two smallest biological amino acids, glycine (75 u) and alanine (89 u), 669 and the limited mass resolution precludes any firm identification. While Cassini INMS has 670 not detected 75 or 89 u molecules, it has detected positive ions at masses of 76 u and 90 u, 671 which are consistent with protonated glycine and alanine, respectively (Vuitton et al., 2007; 672 Hörst et al., 2012). Experimental results from a Titan atmosphere simulation experiment 673 674 found 18 molecules that could correspond to amino acids and nucleotide bases (Hörst et al., 2012). The E²T mission would use high-resolution mass spectrometry to measure heavy 675 neutral and ionic constituents up to 1000 u, and the elemental chemistry of low-mass organic 676 macromolecules and aerosols in Titan's upper atmosphere as well as monitor neutral-ionic 677 chemical coupling processes. 678

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% CO₂, 0.1-0.3%CH₄, 0.4-1.3% NH₃ and 0.4-1.4% H₂ (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 CO₂, CH₄ and H₂ can constrain the 684 oxidation state of Enceladus' hydrothermal system during its evolution. The minor gas 685 686 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 687 688 (Schubert et al., 2007). In addition, H₂ production and escape may be a result of redox 689 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 690 temperatures and H_2 escape may have led to the oxidation of NH_3 to N_2 (Glein et al., 2008). 691 Detection and inventory of reduced and oxidized species in the plume material (e.g., NH_3/N_2) 692 ratio, H₂ abundance, reduced versus oxidized organic species) can constrain the redox state 693 694 and evolution of Enceladus' hydrothermal system.

695 Cassini CDA measurements identified three types of grains in the plume and Saturn's E-696 ring. Type I and Type II grains are both salt-poor (Figure 4). Type I ice grains are nearly 697 pure-water ice while Type II grains also possess silicates and organic compounds and Type 698 III grains are salt-rich (0.5–2.0% by mass) (Postberg et al., 2009, 2011). The salinity of these 699 particles suggests they originate in a place where likely water-rock interactions are taking 700 place.

701

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. SiO₂ 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 E²T 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 H₂ found in Enceladus' plume (Waite et al., 2017).

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715 **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, 716 (Howett et al., 2011), and in some of the hot spots where jets emanate, the surface 717 temperatures are as high as 200 K (Goguen et al., 2013). Cassini observations show that the 718 plume is made up of approximately 100 discrete collimated jets as well as a diffuse 719 distributed component (Hansen et al., 2008, 2011; Postberg et al., 2011; Porco et al., 2014). 720 721 The majority of plume material can be found in the distributed diffuse portion of the plume, 722 which likely originates from elongated fissures along Enceladus' tiger stripes while only a 723 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 724 ejected through the jets and at faster speeds while larger salt-rich grains tend to be ejected 725 726 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 727 surface. For example, ice/vapour ratios > 0.1-0.2 would exclude plume generation 728 mechanisms that require a large amount of ice grains to be condensed from vapour (Porco et 729 al., 2006; Ingersoll and Pankine, 2011). However, this ratio is poorly constrained with 730 estimates ranging from 0.05 (Schmidt et al., 2008) to 0.4 (Porco et al., 2006) to 0.35-0.7 731

(Ingersoll and Ewald, 2011). E²T high-resolution IR images and ENIJA can help constrain 732 this important ratio. Cassini ISS images used to track plume brightness variation, which is 733 proportional to the amount of grains in the plume, with the orbital position of Enceladus 734 found more ice grains are emitted when Enceladus is near its farthest point from Saturn 735 (apocenter). It is not understood if the plume vapour has such a variation. This temporal 736 variation of the plume indicates that it is tidally driven but could also be due to possible 737 physical libration (Hurford et al., 2009; Kite et al., 2016). Most recently, Kite et al. (2016) 738 has suggested that the tiger stripe fissures are interspersed with vertical pipelike tubes with 739 740 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 741 sustained manner. TIGER can provide high spatial resolution thermal emissions maps to 742 constrain the amount of energy dissipated between the tiger stripes. The E²T mission would 743 use high resolution IR imaging of the south polar terrain and mass spectra of the grains to 744 provide new details of its surface and constrain the links between plume activity, subsurface 745 reservoirs and deep hydrothermal processes. 746

747

748 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 756 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). 757 At present, the Hotei Regio flows and the Sotra Patera region, which includes Sotra Patera, an 758 elliptical deep depression on Titan, Mohini Fluctus, a lengthy flow feature, and Doom and 759 Erebor Montes, two volcanic edifices, are considered to host the strongest candidates for 760 cyrovolcanism on Titan (Lopes et al., 2013; Solomonidou et al., 2014, 2016). E²T would 761 provide high resolution mapping (30 m/pixel with DTM vertical resolution of 10 m) of 762 regions that are candidates for cryovolcanic activity. 763

A variety of mountainous topography has been observed on Titan (Radebaugh et al., 2007; 764 Cook-Hallett et al., 2015). The observed morphologies of many of Titan's mountains suggest 765 766 contractional tectonism (Mitri et al., 2010; Liu et al., 2016). This is somewhat surprising, 767 however, since tectonic landforms observed on other ocean worlds and icy satellites in the 768 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 769 770 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 771 formation in topographic context. The shape of the fault outcrop draped against topography 772 would allow us to measure the faults' dip, which would be ~30 degrees to the horizontal for 773 compressive mountains and ~60 degrees for extensional mountains. 774

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. E²T 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.

786

787 4. Scientific Payload

The Explorer of Enceladus and Titan (E²T) has a focused payload that would provide in-situ 788 mass spectrometry and high-resolution imaging of Enceladus' south polar terrain and plume, 789 and Titan's upper atmosphere and surface, from a solar-electric powered spacecraft in orbit 790 around Saturn. The in-situ measurements of Titan's upper atmosphere would be acquired 791 during 17 flybys with an altitude as low as 900 km. At Enceladus, in-situ measurements 792 would be conducted during 6 flythroughs of the plume and flybys of the south polar terrain at 793 794 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 795 will be collected during inbound and outbound segments of each flyby. 796

The E²T 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 E²T 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).

810

TABLE 2

811 4.1 Ion and Neutral Mass Spectrometer (INMS)

The Ion and Neutral Mass Spectrometer (INMS) is a reflectron time-of-flight mass 812 spectrometer (TOF-MS) that would record mass spectra of neutral and ionised gases during 813 flybys and fly-throughs of Enceladus' plume and Titan's upper atmosphere. During flybys 814 and flythroughs of Saturn's E-ring, Enceladus' plume and of Titan's upper atmosphere, 815 INMS will record mass spectra of neutral and positive and negative ionized gases within the 816 817 mass range 1 – 1000 u/e with a mass resolution at 5000 m/ Δ m (50%) with a sensitivity (detection threshold) of 1 cm^{-3} (~ 10^{-16} mbar) in a 5 s measurement cadence (Abplanalp et al., 818 819 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-820 mass molecular species abundant in Enceladus' plume and in Titan's upper atmosphere. 821 Further, E²T INMS' high mass resolution (m/ $\Delta m = 5000$), 50 times larger than Cassini 822 INMS, allows for the separation of isobaric interference such as occur at 16, 20, 28, and 40 823 u/e which is possible based on heritage of RTOF/ROSINA from the Rosetta mission (Scherer 824 et al., 2006; Wurz et al., 2015) as shown in Figure 5. 825

826

FIGURE 5

34

Cassini INMS only had the ability to measure positively charged ions. In-situ 827 measurements by the Cassini Plasma Spectrometer (CAPS) detected heavy negative ions in 828 Titan's ionosphere and negative water group ions in Enceladus' plume (Coates et al., 2010). 829 $E^{2}T$ INMS would record 10,000 mass spectra per second and accumulate these for a pre-set 830 period, allowing for a time resolution of measurements in the range from 0.1 to 300 s. The 831 maximum INMS resolution at Enceladus is 0.1 s (corresponding to a spatial resolution of 832 ~0.5 km for a S/C velocity of 5 km/s) to resolve small-scale structure in the plume; the 833 maximum used INMS resolution at Titan is 5 s (corresponding to a spatial resolution of ~35 834 km for a S/C velocity of 7 km/s). 835

The E²T 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

842

843 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
851 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 852 and anions created upon ice particle impact, simultaneously, whereas CDA only measured 853 cations. During flythroughs of Enceladus plume and in the E ring, ENIJA provides time-of-854 flight mass spectra for ice particles with a mass range of 1-2000 u with a mass resolution 855 $(m/\Delta m)$ of 970 between 23-2000 u. ENIJA acquires TOF mass spectra of individual ice 856 grains by impact ionization and analyses the generated anions and cations with two separate 857 time of flight spectrometer sub-units. In this way ENIJA is able to quantify organic 858 859 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 860 trace components with sub-ppm concentrations from Enceladus' ocean, can now be 861 investigated simultaneously with the more abundant mineral species. ENIJA is not a newly 862 developed instrument; rather it is an optimization and miniaturization of flight-proven 863 hardware. ENIJA has heritage based on Giotto-Particle Impact Analyzer (PIA), Stardust 864 Cometary Interstellar Dust Analyzer (CIDA), Cassini's' Cosmic Dust Analyzer (CDA), 865 866 Rosetta-COSIMA and Europa-SUrface Dust mass Analyzer (SUDA).

867

FIGURE 6

868

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 μ m and Enceladus emissions at 1 m/pixel at two wavelengths, 5 and 5.3 μ m. Images acquired by TIGER would enable investigation of Titan's geology, hydrology, and compositional variability and study 875 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; 876 Sotin et al., 2005) to enable direct ground observations using reflected sunlight and to 877 measure thermal emission from Enceladus. The 5 μ m images are subject to virtually no 878 scattering from Titan's atmospheric aerosols, allowing diffraction limited images achieving 879 880 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 881 composition (Clark et al., 2010; Barnes et al., 2014). TIGER has the capability to image Titan 882 at Huygens DISR resolution (Figure 7). At Enceladus, the 5 and 5.3 μ m observations would 883 measure thermal emission of surfaces as cold as 130 K and would provide temperature maps 884 of the surface at Cassini-ISS image scales. A fine steering mirror (FSM) would be employed 885 to select and track regions of interest during the flyby and compensate for spacecraft jitter 886 allowing for longer exposures and better signal-to-noise ratio (SNR). Digital time-delay 887 integration (TDI) would also be employed, as needed, during closest approach when the 888 ground speed is highest. 889

890

FIGURE 7

While the TIGER instrument is a new design, it utilizes high-heritage subsystems (≥TRL 891 892 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 893 Infrared Camera (NIRCam) (Reike et al., 2005), Near Infrared Spectrometer (NIRSpec) 894 (Rauscher et al., 2004), and Fine Guidance Sensor (FGS) (Doyon et al., 2012) instruments. 895 TIGER also implements FPA readout electronics that have been qualified extensively for the 896 897 JWST instruments (Loose et al., 2006) and are used by the Euclid Near Infrared Spectrometer and Photometer (NISP) (Maciaszek et al., 2014). 898

900 4.4 Radio Science Experiment

Gravity field measurements are powerful tools to constrain the interior structure of the planets 901 and satellites and to assess mass anomalies, providing information on the internal dynamics 902 and evolution. The observable quantities used by gravity science experiments are obtained by 903 means of spacecraft tracking at microwave frequencies from a terrestrial ground antenna. The 904 eight gravity flybys of Titan conducted by the Cassini mission (not including the T122 flyby, 905 recently completed in August 2016) yielded sufficient information to obtain a robust 906 estimation of the degree-3 static gravity field, plus the fluid Love number k₂ (Iess et al., 907 908 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 909 response to Saturn's gravity was not detected. 910

In Enceladus' south polar terrain a larger time-variation of the gravity field with respect to 911 the global solution of the time variation of the gravity field is expected because the ice shell 912 913 thickness is anticipated to be locally thin in that area. A gravity science experiment, based on 914 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 915 terrain thus allowing the determination of the thickness variation at the south polar regions 916 and constraining the mechanical properties (viscosity) of the ice overlying the outer ice shell. 917 The expected tidal deformation is characterized by a pattern more complex than the standard 918 919 degree-two pattern, with a strong amplification of the tidal fluctuation in the south polar terrain (Brzobohaty et al., 2016). 920

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 E²T 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.

935

936 5. Proposed Mission and Spacecraft Configuration

The baseline scenario for the E^2T mission is a solar electric powered spacecraft (S/C), in orbit 937 around Saturn, performing multiple flybys of Titan and Enceladus. The baseline includes a 938 shared launch on the Ariane 6.4 with a co-manifest of estimated launch mass of ~2636 kg to 939 geosynchronous transfer orbit (GTO), with a forecasted shared launch opportunity in 2030. 940 The Ariane 6.4 with four solid rocket boosters is scheduled to debut in 2020–2021. The upper 941 stage reignition capability of the Ariane 6.4 will enable a GTO/escape dual launch. The mass 942 943 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 944 trajectory, E²T S/C would pursue a gravity assist flyby of the Earth to help propel itself to the 945 Saturn system. The cruise phase from Earth to Saturn would be 6 years long. The E²T tour in 946

the Saturn system would be 3.5 years long. The E²T 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.

950

951 5.1 Transfer Orbit to Saturn

The nominal transfer to Saturn uses a 1:1⁺ resonant Earth flyby trajectory, as shown in Table 952 3 and Figure 8. Electric propulsion is used to strongly increase the hyperbolic flyby speed at 953 the Earth, and to provide a subsequent energy boost to reduce the total flight time to 6 years 954 to Saturn orbit insertion (SOI). After separation from the co-manifested satellite and the 955 SYLDA carrier, the upper stage will be re-ignited near perigee to impart approximately 1.2 956 km/s ΔV to the E²T S/C, putting it on a hyperbolic escape trajectory with a C₃ of 9.6 km²/s². 957 958 Thanks to the use of electric propulsion and an Earth gravity assist, the declination of the 959 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 960 period. The data in Table 3 is based on a proposed launch from January-May 2030 during 961 which there is little variation in flight time or required propellant mass. Lunar flybys on the 962 escape trajectory were not considered, but could be used to effectively lower the required 963 escape ΔV which in turn would allow for a heavier co-manifested satellite. 964

- 965FIGURE 8966TABLE 3967FIGURE 9968TABLE 4
- 969

970 **5.2 Saturn Tour**

971 The duration of the tour from SOI through to the end of the 17-flyby Titan phase is about 3.5
972 years. A sample tour is shown in Figure 9. Like Cassini, end-of-mission spacecraft disposal is
973 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, E²T 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).

981

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. 992 E^2T will provide high-resolution imaging of Titan's surface with TIGER camera. During 993 Titan flybys the observations of INMS and TIGER can be performed simultaneously.

994

995 **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.

1003

TABLE 5

1004

FIGURE 10

1005 The Solar Arrays (SA) are the main S/C electrical power source, whereas the S/C main battery provides the emergency backup one. The E²T four panel solar arrays are based on 1006 space-qualified Thales Alenia Space SolarBus W51 technologies and GaAs/Ge Low Intensity 1007 Low Temperature (LILT) solar cells technology used in the ESA JUICE mission. The Solar 1008 Electric Propulsion System (SEPS) is based on four (3+1 for redundancy) QinetiQ's T6 1009 1010 gridded ion thruster engines, whereas two chemical propulsion systems have been also 1011 implemented for S/C manoeuvres and Attitude and Orbital Control System (AOCS) purposes. 1012 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 1013 mission. The heritage of systems and subsystems from previous ESA missions requiring 1014

1015 limited technological development enables a relatively low cost for the industrial
1016 development. The E²T S/C design was performed by Thales Alenia Space (TAS-I, Torino,
1017 Italy)

1018

1019 **6.** Summary

 $E^{2}T$ was proposed as mission led by ESA in collaboration with NASA and several ESA 1020 member states for the payload in response to ESA's M5 Cosmic Vision Call. The joint 1021 exploration of Enceladus and Titan with a flyby mission such as the E²T mission can address 1022 fundamental scientific questions regarding extra-terrestrial habitability, abiotic/prebiotic 1023 chemistry, the emergence of life, and the origin and evolution of ocean worlds. In the Solar 1024 1025 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 1026 environments that can be easily sampled from orbit in a single mission. Titan, with its 1027 1028 organically rich and dynamic atmosphere and geology, and Enceladus, with its active plume 1029 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 1030 worlds as well as the origin and evolution of complex planetary systems. The joint 1031 exploration of these two fascinating objects will allow us to better understand the origin of 1032 1033 their organic-rich environment and will give access to planetary processes that have long 1034 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 \geq 5 from previous ESA missions with a limited technological development necessary; 2) a science payload with a TRL \geq 5 with low 1039 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) 1040 a forecasted shared launch opportunity in 2030 with a commercial satellite to GTO by the 1041 Ariane 6.4 which will allow E²T to pursue a cost-effective launch that will enable an efficient 1042 Earth escape trajectory to the Saturn system. The E²T mission concept offers a cost-effective 1043 way to investigate the evolution and habitability of ocean worlds in the Saturn system and 1044 1045 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 1046 1047 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 1048 conditions in our own Solar System and beyond. 1049

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1540 TABLES AND FIGURES

Table 1 E.²T 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	 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 Search for spatial variations in composition and correlate with jet sources.
ENIJA (DLR)	6.5	19.2	5–6	 Analysis of elemental, molecular and isotopic composition of solid phase constituents in a mass range of 1–2000 u of Enceladus' plume / E-ring 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	 Detailed analysis of the geology of Titan's surface at 30– 100 m/pixel and of Enceladus' plume sources at 1 m/pixel Measure of the thermal emission from Enceladus's south polar terrain, at 1 m/pixel
Total	57.7	83.2		

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)	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 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)	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 ma	Heritage	
Spacecraft Dimensions	 Main S/C body: 2974mm × 2860mm × 2589mm with 4 Solar Array wings of an overall area of 160 m². 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 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 Analyser (ENIJA) Titan Imaging and Geology, Enceladus Reconnaissance (TIGER) high-resolution infrared camera 	



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

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



- **Figure 2.** Plume emanating from multiple jets in Enceladus' south polar terrain
- 1573 (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).



Figure 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).



1634 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 1635 composition. The complex amino acids are detectable in comparable quantities to glycine (15 1636 ppm, not shown), even though the spectrum has a mass resolution 3 times less than ENIJA's. 1637 S/N ratio of this laser dispersion spectrum is comparable to a much lower analysed 1638 concentration in ENIJA spectra (≤ 1 ppm). Most un-annotated mass lines are due to salt-water 1639 cluster ions. By co-adding multiple ice grain spectra the S/N ratio can be further improved 1640 leading to an ENIJA detection limit of 10–100 ppb for most amino acids in ice grains formed 1641 from Enceladus' ocean water. 1642



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).


1658 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).

1675



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