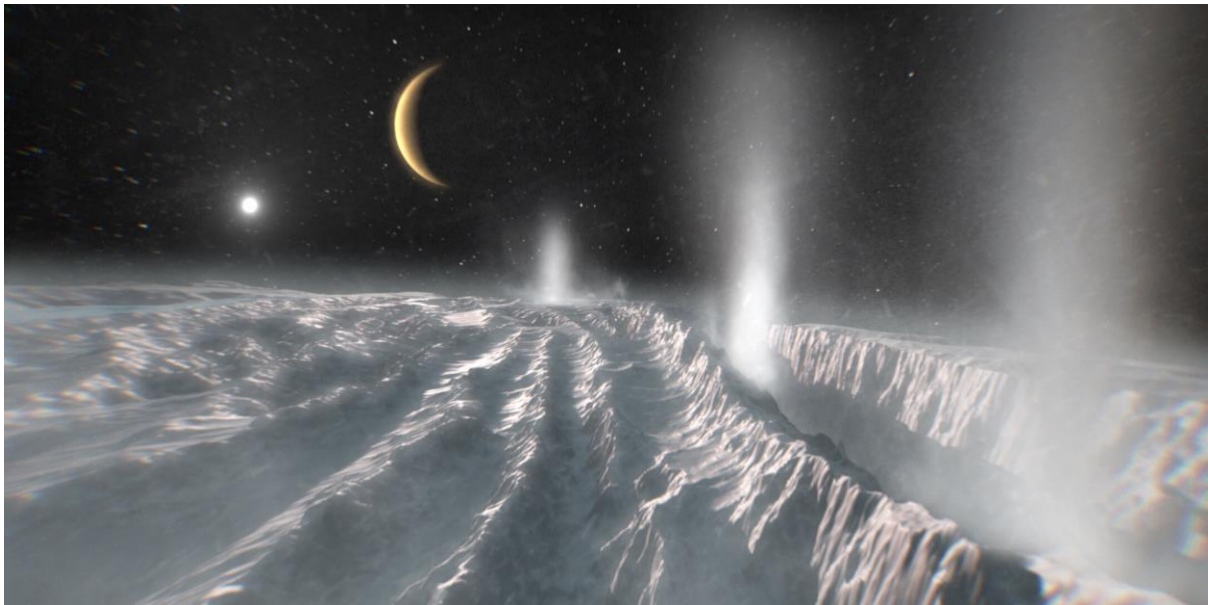*Report of the Expert Committee for the Large-class mission in ESA's Voyage 2050 plan covering the science theme "Moons of the Giant Planets"*

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Expert Committee for the Large mission covering the science theme "Moons of the Giant Planets"

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Executive Summary

Following the final recommendations from the Voyage 2050 Senior Committee Report, in December 2021, the European Space Agency (ESA) issued an open call for an Expert Committee for a Large-class (L4) mission covering the science theme "Moons of the Giant Planets". The Expert Committee has been tasked with: *i) analyzing the scientific merits of the various possible destinations for a space mission to a moon of one of the two giant planets, Jupiter or Saturn; and ii) supporting the Agency in the execution of initial feasibility studies aimed at defining technical solutions for possible space missions to these destinations.* The Expert Committee started working in February 2022, undertaking a series of discussions to identify the priority scientific targets at both the Jupiter and Saturn systems. The Expert Committee has considered how a new ESA L4 mission could address priority topics such as habitability, prebiotic chemistry, and biosignatures, providing new knowledge significantly beyond any previous space missions. The Expert Committee has considered planetary probe missions to one or more of the moons of Jupiter and Saturn, with a targeted launch date in the early 2040s and different possible mission scenarios that would ensure the L4 mission to deliver a transformational scientific return.

Several aspects of the habitability of ocean worlds need to be addressed by future large space science programmes, including *1) The issue of habitability of ocean worlds and the interaction between the surface and the interior; 2) The issue of habitability of oceans worlds and the interaction with the external environments; and 3) The identification of prebiotic chemistry and the search for biosignatures on ocean worlds.* Based on these three themes and considering the space missions to the moons of giant planets of the next decade, we identify Saturn's moon Enceladus as the most interesting target, followed by Titan in the same system, and Jupiter's moon Europa. In order for the mission to be really transformational, it should include an in-situ sample acquisition, either using a lander or by sampling ejecta during plume flythroughs to access fresh material from the subsurface.

An Enceladus south polar lander with an orbiter and plume sampling system would be the optimum candidate for the L4 mission. According to the analyses performed, this would be enabled by a dual launch configuration (A64+A64), with Near-Earth rendezvous prior to escape. For Titan the Expert Committee suggests the investigation of lake sediments, a very different type of landing location with respect to past or selected missions. In order to meet the goals for Titan, the mission should include a Titan orbiter, which seems currently challenging according to performed studies. Additionally, a reconnaissance phase and an autonomous hazard detection and avoidance system would be required to ensure targeted and safe landings on selected terrains. A lander on Europa at this time seems not feasible within the L-class framework. With the upcoming JUICE and NASA Europa Clipper missions, a lander on Europa would be a minimum requirement to substantially further our knowledge of this body.

For either an Enceladus or Titan mission, flybys of both of these moons should be carried out. Furthermore, an additional tour of other moons considered to potentially host a liquid subsurface should be performed, e.g., Mimas.

The availability of radioisotope power and heating options (RTGs and RHUs) would enable a dramatic scientific improvement to each of the mission profiles investigated, by allowing more resources, and a longer mission lifetime.

Overall, any of the L4 mission concepts considered in this study, with launch in the early 2040s, would dramatically improve our understanding of the habitability and the assessment of the presence of biosignatures on Saturn, a result never achieved before, and would guarantee ESA leadership in the science theme "Moons of the Giant Planets".

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Abbreviations

A64 (Ariane 6.4 launcher)

CDF (Concurrent Design Facility)

CHNOPS (Carbon, Hydrogen, Nitrogen, Oxygen, Phosphorus, Sulphur)

CLEO/P (CLipper ESA Orbiter or Penetrator)

DEM (Digital Elevation Models)

ETDS (Enceladus and Titan Definition Study)

GC-MS (Gas Chromatography-Mass Spectrometry)

IR (Infrared)

ISS (Imaging Science Subsystem)

JOI (Jupiter Orbit Insertion)

JUICE (Jupiter Icy Moons Explorer)

L4 (Large Class mission 4)

LDMS (Laser Desorption Mass Spectrometer)

P/L (Payload)

RHU (Radioisotope Heater Units)

RTG (Radioisotope Thermoelectric Generators)

SAR (Synthetic Aperture Radar)

S/C (Spacecraft)

SEP (Solar Electric Propulsion)

SPT (South Polar Terrain)

VILT (V-Infinity Leveraging Transfer)

1. Assumptions of the Expert Committee

The Final recommendations from the Voyage 2050 Senior Committee report (Tacconi et al., 2021) states:

"The Voyage 2050 Senior Committee recommends that ESA pursue efforts leading to exploration of the outer Solar System by considering a "Moons of the Giant Planets" theme that will continue and extend the characterisation era in Voyage 2050. An ESA mission to the moons of the giant planets will build on the agency's expertise for exploration of the outer Solar System after Cassini-Huygens and (the soon to fly) JUICE. One possible profile for an ESA-led Large mission would involve obtaining a global perspective on these moons via a spacecraft, or a possible dual-spacecraft mission in a mother-daughter configuration, performing multiple flybys and/or orbit insertions. Alternatively, a mission profile might include a significant in situ element to characterize the local surface and subsurface environments, for example via a lander, drones or sample return."

An ambitious ESA Large-class (L4) mission to one or more of the moons of the giant planets, in particular those at Jupiter and/or Saturn would provide an opportunity to fully explore the habitability of ocean worlds whose characteristics have been or will have been initially explored through other major solar system missions such as Galileo, Cassini-Huygens, JUICE, and Europa Clipper. In addition, the Voyage 2050 Senior Committee recommended that a future mission should address the following scientific challenges of the icy moons:

1) The issue of the <u>habitability of ocean worlds</u> through characterisation of the interior structure and the subsurface oceans with instrumentation capable of carrying out a full tomography of the moons' interiors.

2) The study of the <u>connection of interior and the near-surface environments</u>, and particularly how this connection may be driven by dynamical forcing, as well as the implications for the exchange of mass and energy in the overall moon-planet system (including the planet's magnetosphere).

3) The <u>search for biosignatures</u> and the identification of <u>prebiotic chemistry</u> at the surface, in the atmospheres, and within the plumes of ocean worlds (both with remote sensing and in situ instruments).

Following the final recommendations from the Voyage 2050 Senior Committee Report, in December 2021, ESA issued an open call for membership of an Expert Committee for the L4 mission covering the science theme "Moons of the Giant Planets". The intended remit of the committee, from here on referred to as the "Expert Committee" was to support the initial scientific and technical definition of space mission concepts to fulfill the goals set for the "Moons of the Giant Planets" science theme. The Expert Committee was tasked with *i) analyzing the scientific merits of the various possible destinations for a space mission to a moon of one of the two giant planets, Jupiter or Saturn; and ii) supporting the Agency in the execution of initial feasibility studies aimed at defining technical solutions for possible space missions to these destinations.*

The Expert Committee has worked since February 2022, undertaking a series of discussions covering the points outlined above, to identify the priority scientific targets at both the Jupiter and Saturn systems. The Uranus and Neptune systems were not to be considered within the scope of the study. This report investigates how a future ESA L4 mission could address priority topics such as habitability, biosignatures, and prebiotic chemistry, providing new knowledge significantly beyond any previous space missions. The Expert Committee has considered planetary probe missions to one or more of the moons of Jupiter (e.g., Europa and Ganymede) and Saturn (e.g., Enceladus and Titan) (Figure 1), and different possible mission scenarios that would ensure a Large-class mission science return.

Figure 1 - Key moons of Jupiter and Saturn, to scale. Individual images from NASA / JPL-Caltech.

It is important to note here that the Expert Committee were guided towards exploring technical solutions that could be enacted by ESA alone (i.e. without significant international contributions), that the power and heating solutions for the spacecraft and scientific payload should not include any radioisotope materials (i.e. not using radioisotope thermoelectric generators (RTGs) or radioisotope heater units (RHUs)), and that the budget constraints are those typical of an L-class missions. The Expert Committee assumed that the envisioned mission could launch around 2040-2045. Finally, it is recognised that there is significant appetite within the scientific community for a sample return mission to the outer solar system. However, it is beyond the scope of this report to consider such a mission. Nevertheless, we recommend that further dedicated studies on this option would be merited in the future.

What follows here is the final report of the Expert Committee for the science theme "Moons of the Giant Planets", intended to provide advice and recommendations to the Director of Science as initially requested.

2. Outstanding science questions

Following the lead from the Voyage 2050 Senior Committee, we define habitability as the fundamental characteristic that distinguishes targets of highest interest for habitability, prebiotic chemistry, and biosignatures. The definition of habitability is the ability of an environment to support the activity of an organism, considering the necessary conditions for maintaining life as we understand it, i.e., liquid water, bioessential chemical elements, and available energy for metabolism (Cockell et al., 2016) (see Figure 2). The Expert Committee is targeting liquid water as a priority interest since we are looking for signs of life as we know it. But there is also a secondary interest for the chemistry in other possible solvents (e.g., hydrocarbon liquids on Titan). Several aspects of the habitability of ocean worlds need to be addressed by future large space science programmes. These include:

1) The issue of habitability of ocean worlds and the interaction between the surface and the interior.

2) The issue of habitability of ocean worlds and the interaction with the external environments.

3) The identification of prebiotic chemistry and the search for biosignatures on ocean worlds.
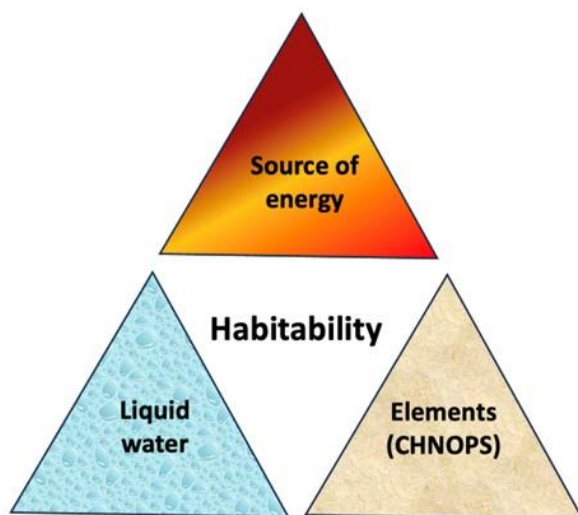

Figure 2 - The three requirements of habitability. Stability of the environment over time has been proposed as the fourth requirement (Cockell et al., 2016).

In the following sections, we will further elaborate on these three themes, and define specific scientific questions for each of them.

Future science missions should be able to determine if the aqueous environments within the icy moons have or have had the ability to support and sustain life (as we know it) at present or in the past.

Considering the current understanding of habitability, the main issues and objectives to address are:

a) What are the structure and dynamics of liquid (water) environments?

- Define the depth, dimensions and dynamics of aqueous reservoirs (e.g., global oceans, brine pockets);

- Define the degree of chemical and physical gradients;

- Define the moons' interior structure (including answering the question of whether the liquid environment is in contact with rocky layers to support water-rock interaction / chemistry and whether the liquid environment is in direct or indirect (e.g., volcanism and impact) contact with the surface to support material exchange);

- Define the mechanical and thermal state of the interior. Potential sources of energy may include, e.g., tides, geochemical processes, and isotopic decay;

- Investigate the presence and efficiency of ongoing ocean-circulation, including the question of whether there is a localized chemical environment on the ocean floor that is habitable, or if the circulation produces necessary chemical and physical gradients and disequilibria across the liquid reservoir;

- Define the stability of the orbit.

b) What is the physical-chemistry of the liquid environments (water and other solvents)?

- Characterize the chemical composition (identify potential nutrients, elements, and chemical energy sources) and physical-chemical boundary parameters (e.g., salinity, redox state, pH, temperature, pressure, etc.) of all liquid environments (water and other solvents);

- Identify forms of energy available for life.

c) How does surface geology and composition inform the evolution of the icy moons?

- Assess past habitability by characterising the planetary orbit and geological evolution;

- Study the stability of liquid layers to allow the formation and evolution of life, interactions with other layers, endogenous geochemical evolution, and geological and compositional evolution of the surfaces (tectonism, cryovolcanism, impact cratering, fluvial, lacustrine, and aeolian processes);

- Assess the "age" of liquid oceans, considering mechanisms that prevent freezing;

- Determine the ocean ages, considering how long the oceans have remained liquid and the sustainability of tidal heating.

All the above environment conditions are dependent on the planetary target - see section 3 below, in terms of, e.g., temperature, pH, salinity, and micronutrients.

In addition to the above points, some further considerations are important to specify primary methods for probing subsurface liquid environments.

The characteristics of the subsurface ocean can be constrained through global magnetic and gravity field measurements close to the moon, ideally performed from a proximal polar orbit.

For the magnetic field, at Jupiter, the asymmetry in the intrinsic planetary magnetic field produces a variable driving, inducing field at the synodic planetary period (and harmonics thereof) which allows the electromagnetic induction effect to be used to characterize a subsurface ocean (e.g., Kivelson et al., 2000). It is also possible to use the time frequencies associated with the moons' orbital periods and local time asymmetries in the magnetosphere, and possibly variations associated with the solar wind interaction. At Saturn, the intrinsic field is found to be almost perfectly axisymmetric (Dougherty et al., 2018), and as such the same technique cannot be easily used. Other, smaller amplitude, variable signatures may drive the induction effect, associated with, e.g., the planetary period oscillations (Provan et al., 2018), the moon's orbital location and local time asymmetries, the variability in the plasma-moon interactions, and/or the variability in the ionosphere (Neveu et al., 2017; Saur et al., 2010). However, the success of this method hinges on precise instrument calibration, and a good understanding of the individual (time-variable) magnetic field components outlined.

For gravity-based ocean detection and characterization, the moons' quadrupole gravity field will need to be measured both when the moon is near periapsis, and when it is near apoapsis, in order to yield the tidal variation of the potential. The variability of the quadrupole gravity field carries indications on the interior composition, usually represented in terms of fluid Love number $k2$ (Wahr et al., 2006).

Interior models based on gravity data only, however, are degenerate because of the similar density between ice and water (Iess et al., 2010, Durante et al., 2019, Gomez Casajus et al., 2021, Gomez Casajus et al., 2022). Also, the magnetic induction technique precludes unambiguous characterization of the hydrosphere properties. It is then advisable to combine the two datasets to improve the interior structure inversion. In particular, only the combination of

gravity and magnetic induction data enables a better characterization of the hydrosphere by separately constraining the ice shell thickness and the ocean depth (Petricca et al., 2023).

2.2. Habitability: Interactions with the external environments

A comprehensive understanding of the interplay between the local space environments of moons and their host planets is crucial. This understanding should encompass how this interaction impacts or dictates the conditions related to habitability, and in particular for potential biosignatures (for more detailed insights, please refer to section 2.3).

The main issues and objectives to achieve are:

a) What is the influence of dust impacts on the surface processes and chemistry?

- Characterise the dust environment;

- Characterise the effect of the bombardment by micrometeorites, including impact-generated ejecta.

b) What is the interaction of the charged particle environment (radiation, electromagnetic fields) with the target moon, including its atmosphere, if present?

- Characterise how the local radiation environment, dominated by energetic particles trapped in the parent planet's radiation belts, interact with surface materials, including potential biosignatures present there.

c) What is the influence of endogenous dynamics on the external environments?

- Define how the characteristics of a moon can influence its interaction with the external environment, e.g., plumes feeding the environment through fracture systems.

Further points that should be addressed within this topic are the origins of surface and atmospheric constituents, and the interaction between the moons' surfaces, atmospheres, and magnetic field with the parent planet's magnetosphere. This requires observations of the planetary magnetospheric fields and particle populations around the moons' orbits when the moons themselves are not present, to provide context for the near-moon measurements.

Concerning the origin of surficial or atmospheric constituents, one main goal is to assess whether they are of endogenic or exogenous origin, and how they have been processed over time (e.g., through space weathering or local geological activity). This variability is believed to reflect the complex interactions of solar irradiance and surrounding plasma with the surfaces and atmospheres (which is particularly relevant for Titan). The details on this interaction of the moons with their space environment (e.g., presence of intrinsic or induced magnetic fields) are crucial for the possible shielding against radiation and the protection of biosignatures. The local radiation environment, governed by the intrinsic magnetic field and plasma populations of the parent planet, plays a pivotal role in comprehending the radiation exposure encountered by potential biosignatures at the surface. This understanding extends beyond the influence of external cosmic rays, encompassing contributions from surface sputtering and space weathering, processes that can result in the presence of highly altered materials. It is noteworthy that the radiation environment on a planetary surface is intricately linked to the parent planet's characteristics. For instance, Jupiter's environment is notably more challenging to the unmodified survival of many surficial or atmospheric constituents than Saturn's, due to its stronger planetary magnetic field and the presence of more energetic plasma populations. A critical aspect of this investigation involves elucidating the specifics of exogenic bombardment on the surface, involving plasma elements such as energetic electrons and ions originating from the magnetosphere or solar wind. This deeper exploration is essential for a comprehensive understanding of the impact of these environmental factors on habitability and potential biosignatures.

One further point concerning the interactions with external environments is the planetary system as a whole. Indirect surface samples are ejected through mechanisms such as sputtering and bombardment by micrometeoroids, populating the moons' atmospheres and their enveloping dust clouds. At the same time, through neutral and ion loss, moons can exchange material with other moons, leading to a redistribution of material within a planetary system. This point is of particular relevance for the delivery of oxygen to the surfaces of the Galilean moons, where the volcanic moon Io is the main source of the oxygen in Jupiter's magnetospheric plasma. This oxidant can potentially diffuse through a moon's ice shell into its ocean, where it is available for redox reactions, and as such is a potential source of energy.

2.3. Prebiotic chemistry and biosignatures

Future science missions should search for evidence for life as we know it in the form of biosignatures (i.e., any object, substance, or pattern with a biological origin, serving as potential evidence for current or past life (Des Marais et al., 2003, 2008; National Academies of Sciences, Engineering, and Medicine, 2019)), taking into account the targets to measure. The pursuit of signs of life necessitates careful consideration of various factors, including their potentially subtle detectability (i.e., low concentration and potential for false negatives) and universality of their nature. In situ measurements are required due to the expected low concentration of any such signatures, which require sampling, e.g., from plume ejections or surface deposits. Multiple measurements are required to avoid false positives and to provide independent evidence. The priority is to search for chemical biosignatures under a detection strategy that considers different

levels of complexity, detectability, and universality (Neveu et al., 2018). Furthermore, the complexity of prebiotic molecules and the role of other solvents in organic (prebiotic) chemistry must be understood through laboratory work, including simulations and the analysis of extraterrestrial samples (e.g., meteorites, and samples returned to Earth), and future space missions.

The main issues and objectives related to prebiotic chemistry and biosignatures are:

a) What is the inventory of prebiotic molecules at the icy moons?

- Determine and characterize the organic molecules (i.e., molecular building blocks), including in the atmosphere.

b) Are there signatures of life (as we know it) at icy moons?

- Search for chemical biosignatures (e.g., from monomers to polymers or their fragments, enantiomeric excess, isotopic ratios);

- Search for any other detectable non-chemical biosignature such as biological textures and morphologies.

c) What are the local influences on the preservation state of biosignatures?

- Characterise the local context of biogenic material exposure: jet vents, materials fragmentation in the plumes, permeability of the crust, heat anomalies, solvents with exotic chemistry, interaction of the local environment.

A critical aspect of devising an effective search strategy involves pinpointing the locations and methods for detecting biosignatures - whether on the surface, within any atmosphere present, amidst plumes, or in Saturn's E-ring.

Whilst conducting a biosignature search on a moon's surface may seem more promising than a search in the atmosphere, if present, the technological challenges associated with this approach are considerable. On the other hand, conducting a search from orbit appears more feasible to carry out, but it raises questions about the detectability of biosignatures in such a setting, including enquiries into their concentration levels and the reliability of these detections. An intriguing compromise lies in plume-sampling, offering a convergence of technological feasibility and the availability of abundant endogenous material for sampling. However, plumes present their own set of challenges; presently, they are only reliably known to be consistently active on Saturn's moon Enceladus. Although there are suggestions that Jupiter's moon Europa might also possess erupting plumes, the observations of their occurrences prove elusive, implying that they lack the steadiness and repeatability observed in the plumes of Enceladus.

The preservation of biosignatures is a critical aspect that warrants further attention. It is advantageous to explore biosignatures possessing attributes that fortify their resistance against radiation exposure. This consideration applies to the exposure of molecules and cells, which constitute biosignatures, within the moon's subsurface, when they are subjected to the moon's surface and atmosphere ("outside") through their eruption within plumes. The assessment of whether these altered forms can still be identified as biosignatures through in situ instrumentation is crucial for advancing our comprehension of extraterrestrial life indicators.

In the context of in situ measurements conducted during a flyby, the influence of impact or fragmentation on molecules, such as those in plumes, and these processes' influence on the detection of biosignatures is contingent on the sampling speed. Organic molecules remain intact even at speeds of up to 3 km/s when colliding with a metal plate (New et al., 2021). The fragmentation speed threshold is further increased when organic molecules are enveloped by ice. Up to approximately 5 km/s, no fragmentation occurs, but beyond this threshold, around 7 km/s, fragmentation transpires, leading to the synthesis of new species (Martins et al., 2013; Goldman et al., 2010; Jaramillo-Botero et al., 2021; Klenner et al., 2020a, 2020b; Postberg et al., 2018a). Even measurements beyond 7 km/s are useful, but then fragmentation patterns need to be well understood and taken into account.

The different chemistries of fluids (water and other solvents) present on the surface/subsurface, in the atmosphere, and within plumes, and how these variations may reflect different biosignatures need to be studied. To that effect, one needs to investigate how the chemistry of the ice shell differs from that of the ocean and, on celestial bodies lacking plumes, explore whether potential biosignatures from the subsurface ocean are manifested in the ice shell. Here one needs to consider factors such as the speed of freezing processes and the concentration at the water-ice interface, and to assess whether these conditions allow for the preservation of biosignatures in the solution.

3. Targets

3.1 Primary targets

According to the motivation expressed in the Voyage 2050 report, we focused on targets with astrobiological interest within the Saturn and Jupiter systems. The selected primary targets are the four moons that are almost certainly ocean worlds: Europa, Ganymede, Titan and Enceladus, with Europa and Enceladus being especially interesting due to the contact between their buried ocean and rocky core (Table 1). Furthermore, we also indicated several secondary targets, as described in Section 3.2.

The scientific relevance was determined after reviewing the key science questions. We summarise below the outcomes for each science theme:

Table 1 - Main characteristics of the four primary targets of this study.

	Europa	Ganymede	Enceladus	Titan
Diameter	3 122 km	5 268 km	504 km	5 150 km
Density	3.01 g/cm³	1.94 g/cm³	1.61 g/cm³	1.88 g/cm³
Distance to planet (in planet radius R$_P$)	9.4 R$_P$	15.0 R$_P$	3.9 R$_P$	20.3 R$_P$
Rotational period	3.5 days	7.2 days	33 hours	15.9 days
Intrinsic magnetic field	No	Yes	No	No
Induced magnetic field	Yes	Yes	Not detected	Not detected
Atmosphere	Tenuous	Tenuous	Tenuous	Dense
Thickness of the ice crust above the ocean	>10 km	>100 km	<40 km (<5 km at the SPT)	>50 km
Ocean contact to the core	Very likely	No	Yes	Likely no
Organic matter	Present	Likely present	Present	Abundant
Detected CHNOPS	C,H,O,S	C,H,N,O,(S)	C,H,N,O,P,(S)	C,H,N,O
Plumes/cryo-volcanic activity	Putative	Not detected	Yes	Putative
Thermal anomalies	Not confirmed	Not detected	Yes	Not detected

Habitability - Interactions between the surface and the interior. Enceladus and Europa are considered top priority given the very high relevance of the scientific objectives in this theme (see section 2.1.) for such targets, followed by Ganymede and Titan. Europa and Enceladus are especially interesting due to the highly probable contact between their ocean and rocky core with potential hydrothermal systems. Enceladus is of particular interest considering both the connection between the ocean and the surface, and the occurrence of plumes. Europa is likely to host shallow liquid water reservoirs, while Titan harbours hydrocarbon lakes and seas at its surface. The study of the surface geology and composition informs us about the geological and thermal evolution of the moon, which is pivotal for all targets. For instance, tectonic activity is occurring on Europa, Enceladus and Ganymede (though less recently active). Cryovolcanism is mainly of interest at Enceladus, possibly Europa, and potentially even Titan, while fluvial, lacustrine, and aeolian processes affect the Titan surface. Finally, the stability of the orbit is pivotal for Enceladus. The internal structure is crucial to understand the evolution of all targets.

Habitability - Interactions with external environments. The dust environment of Enceladus is of very high scientific relevance, as it informs us about internal processes. Micrometeorites' impacts and surface sputtering are of relevance on Enceladus, Europa and Ganymede. In addition, Titan's organic aerosols in the atmosphere may be involved in complex organic

chemistry at the surface, making the aerosols a target of high scientific relevance. Europa and Ganymede are top priority when considering the study of the radiation environment, magnetospheric interaction with other bodies, and their atmosphere/exosphere (see section 2.2.).

Prebiotic chemistry and biosignatures. Enceladus and Titan are considered top priority given the very high relevance of scientific objectives for such targets (see section 2.3.), followed by Europa (high) and Ganymede (moderate). This is due to the fact that Enceladus has hydrothermal vents that may provide a scenario for facilitating prebiotic chemistry (and easy access to it), while Titan is the target that most probably preserves a prebiotic chemistry environment, including in solvents other than water (e.g., liquid hydrocarbons). We do not have direct proof of the presence of hydrothermal vents on Europa and, in addition, its strong radiation environment may prevent the preservation of biosignatures. Considering the depth beneath the surface of the expected ocean at Ganymede, this moon is considered the lowest priority.

The Expert Committee discussed the questions outlined in the Voyage 2050 report and scientific objectives for each selected target, giving a different priority rank. The Expert Committee also reports on whether a given science case will be addressed by upcoming planned space missions. Specifically, the upcoming ESA/JUICE and NASA/Europa Clipper missions have been considered for the exploration of Europa and Ganymede, while the NASA/Dragonfly mission has been considered for Titan. Currently, there is no future approved mission to Enceladus. The Expert Committee determined whether such scientific objectives will be addressed by the upcoming missions, examining their publicly available science traceability matrices (for JUICE[1], Clipper[2], and Dragonfly), and considering the onboard instrument capabilities. Table 2 reflects all the above points.
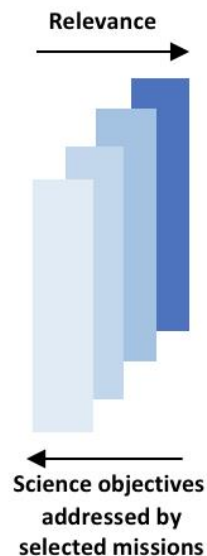
Based on Table 2, the Expert Committee considers Enceladus to be the best candidate for a future mission. Enceladus is considered to have a habitable environment, since all the requisites have been observed, including a liquid water ocean, all the bio-essential elements carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur (CHNOPS), and a chemical energy source. Also, based on the combination of scientific relevance and (lack of) coverage by upcoming missions of the themes, Enceladus is considered the most compelling target. Titan is considered as target number 2 for similar reasons. Based on the science objectives, Europa was also on a similar level as Titan, but was not considered a preferential target as many science objectives will be addressed by the NASA Europa Clipper mission.

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[1]https://sci.esa.int/science-e/www/object/doc.cfm?fobjectid=50319

[2]https://www.lpi.usra.edu/opag/jul2013/presentations/Clipper_Summary.pdf

Table 2 - Summary of the Scientific objectives versus their relevance and whether they will be addressed by planned missions (JUICE, Europa Clipper, and Dragonfly) for each target (Europa, Ganymede, Enceladus, and Titan). Dark blue marked areas indicate most relevant objectives that will not be addressed by other coming missions and are thus of highest interest for the L4 mission.

3.2 Secondary targets: Moon tour

The Cassini-Huygens mission revealed that the mid-sized Saturnian moons other than Enceladus in the Saturn system are also most certainly deserving of further study. Encounters with these bodies with a suitably instrumented spacecraft, ideally below altitudes of 500 km, could address several scientific areas that were not satisfactorily addressed by the Cassini-Huygens mission, either due to instrument limitations or the geometries and distances of the flybys performed at these bodies. Such encounters could be considered similar to flybys that are to be performed by JUICE in the Jovian system.

Of highest importance is one or more close encounters with Mimas. This 198 km-radius body orbits interior to Enceladus, and its heavily cratered surface is dominated by the large impact basin Herschel. Only one targeted encounter with the moon was performed by the Cassini probe, approaching to within ~9500 km. Studies based on the Cassini libration measurements are highly suggestive of Mimas possessing its own subsurface ocean, with the morphology of Herschel and the lack of tectonic activity on the moon being compatible with a thin crust and relatively young ocean (Denton & Rhoden, 2022; Lainey et al., 2024).

Tethys has relatively young terrain, is submitted to larger tides, and may have been active before Enceladus; like Mimas, it may have become active after Enceladus. Dione also has parameters that may be compatible with a subsurface ocean (Kamata 2018). Rhea has a tenuous atmosphere (Teolis et al. 2010) and a possible ring system (Jones et al. 2008; Tiscareno et al. 2010). Hyperion and Iapetus are also very valuable targets. The panel members recognize that targeting the outer moons Hyperion and Iapetus in particular could be challenging due to orbital dynamics, but note that the both of them, like Mimas, were only encountered at close range once each by the Cassini orbiter.

In summary, a mission to the Saturn system could not address one or more of the very scientifically-valuable topics summarised above, without encounters with these moons also being a primary driver for the mission.

3.3. Initial mission profile priority

The Expert Committee identifies the desire for landing elements as part of the L4 mission, in order to ensure major advancements in addressing the science questions generally (Section 2) and compared to previous missions that captured data on the targets considered here. Based on the target selection rationale presented here in Section 3, two main targets of interest for a feasible mission including a landing element were considered: Enceladus and Titan. As mentioned at the end of section 3.1, in order to further address more information on Europa besides the ones obtained by the NASA Europa Clipper mission, it would be necessary to have a lander element, which is presently considered technically challenging for an ESA L4 space mission.

All the considerations outlined earlier have been synthesised into an initial mission profile priority chart, as illustrated in Figure 3. The chart includes both different targets and different options for mission profiles. It includes (i) a mission to Enceladus, (ii) a mission visiting both Enceladus and

Titan, and (iii) a mission visiting Titan only. For each target, a number of possible mission scenarios were suggested. These scenarios underwent evaluation based on three key criteria: the ability to fully address the open questions posed in Section 2 concerning (i) the character of the moon's surface and the interior, (ii) interactions with the external environment, and (iii) the exploration of prebiotic chemistry and biosignatures. A green mark corresponds to 'can be fully addressed', a yellow mark corresponds to 'can be partially addressed', and a red mark corresponds to 'cannot or cannot be addressed well' by the given mission profile.
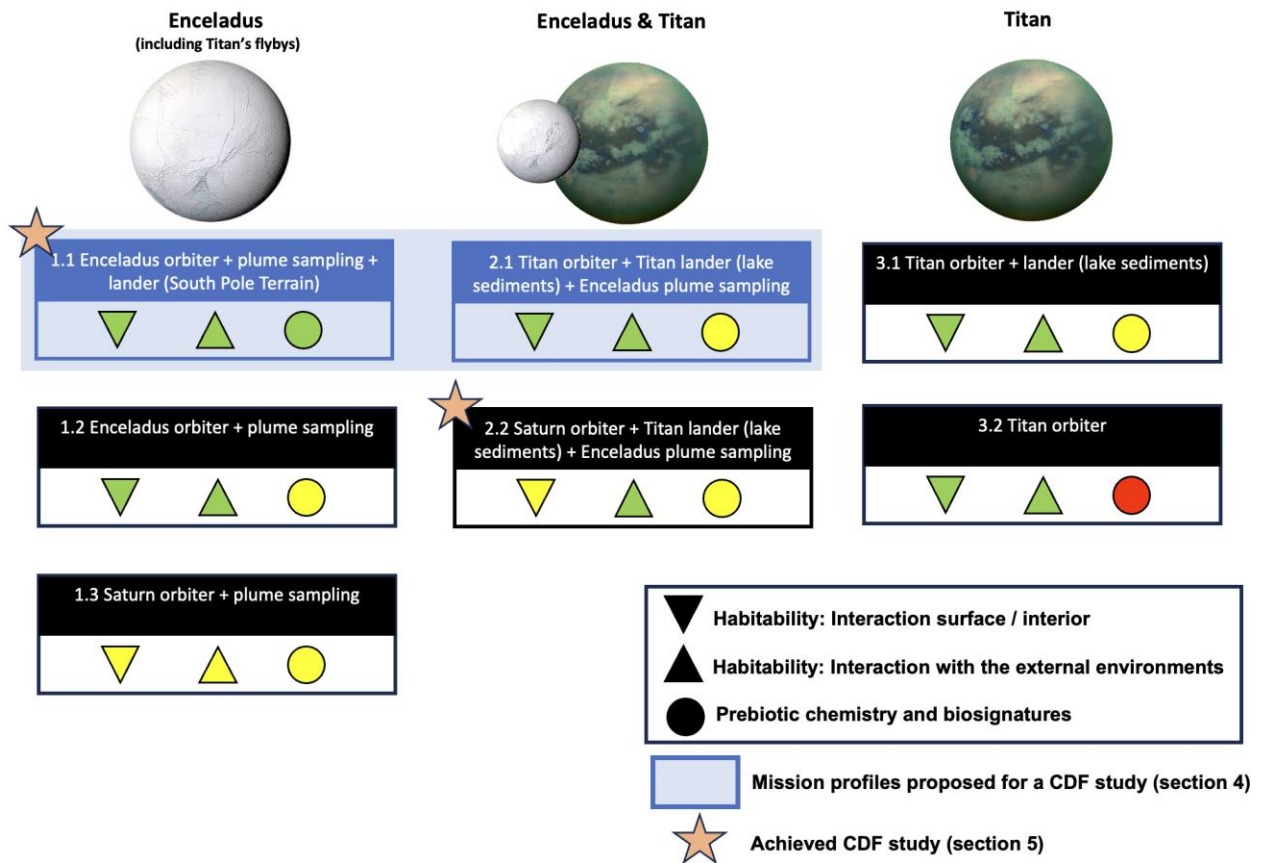
Figure 3 - Possible mission profiles for Enceladus and Titan. A green mark corresponds to 'can be fully addressed', a yellow mark corresponds to 'can be partially addressed', and a red mark corresponds to 'cannot or cannot be addressed well' by the given mission profile.

For Enceladus (option 1), the three scenarios are logically ranked from top to bottom, since each option is a degraded version of the upper one. In the case of Enceladus and Titan (option 2), the first box (2.1) corresponds to the ideal case, while the second box (2.2) is a trade-off in case it is not possible to get an orbiter of Titan within the constraints of the studies presented here. As for Titan only (option 3), the Expert Committee considered two scenarios only, the case (3.2) being a trade-off of 3.1. The Expert Committee considers that a priority should be given to the case 1.1 (the only one that is all green). If not feasible, then the priority should be moved to either 1.2. or 2.1. The Expert Committee prefers scenario 2.1 over 3.1 because in comparison to a Titan only

mission (3.1), scenario 2.1 adds Enceladus plume sampling without losing any of the Titan science goals.

4. Scientific assessment of mission profiles

4.1 General considerations of mission profiles by the Expert Committee

Possible mission profiles were developed by the Expert Committee based on our current knowledge of Enceladus and Titan (mainly owing to the Cassini-Huygens mission), heritage from, and studies for, future missions and concepts to outer planet moons (e.g., Europa Clipper, Europa lander, JUICE, Dragonfly, and Enceladus Orbilander), under some assumptions, and discussions of potential scenarios with the ESA study team.

Before the deployment of any kind of landing element (or descent of a landing spacecraft), there will be a significant orbital phase during which the spacecraft orbits either the host planet and/or the targeted moon. Host planet orbit phases provide opportunities to visit and explore other targets, in particular secondary targets of interest as discussed in Section 3.2, as well as the host planet's general space environment.

The following mission profiles were proposed by the Expert Committee to be considered for Concurrent Design Facility (CDF) studies by ESA:

1) **Enceladus as the main target:** *Orbiter of Enceladus, plume sampling (from flyby and/or orbiter), and a soft-lander at the surface in the South Polar Terrain (SPT).*

The operational phase in the Saturn system would start with an Enceladus plume sampling phase with at least 10 targeted flybys while in Saturn orbit. The Saturn tour should include several flybys of Mimas, Titan, Rhea, Dione, and Tethys.

For the Enceladus orbiter, one of the main requirements is to find a sufficiently stable, high inclination orbit (for gravity and magnetometry science, surface topography, and to release the lander to land in the SPT), given the large third-body perturbation by Saturn. Indeed, an unstable orbit would lead to a very short S/C orbital lifetime or the requirement of a very large ΔV to continuously compensate for the gravitational perturbations.

The mission should also include a lander/probe element to be deployed to the surface of Enceladus at the SPT. The minimum operational lifetime of its science instruments should be about two weeks, and the following payload requirements were considered: (a) at least 20 kg (incl. 20% margin, excluding sample acquisition system), (b) around 650 Wh per Earth-day (incl. 30% margin, excluding sample acquisition system power), and (c) at least 500 Mb of data volume for each sample analysis cycle (assumed 3 cycles in total).

2) **Titan as the main target for the lander (in the Enceladus & Titan mission):** *Orbiter of Titan, and/or a probe to Titan lake sediments, excluding the lakes themselves.*

The operational phase in the Saturn system would include a moon tour (see section 3.2) and several samplings of Enceladus's plumes performed as early as possible (to avoid instrument contamination). Subsequently the orbiter would release a lander to Titan's high latitudes. If possible, the conditions of the landing site should be checked prior to releasing the surface probe, i.e., during a reconnaissance phase. The lander shall softly land in the northern hemisphere, not in a lake but as close as possible to liquid expanses in areas identified as "evaporite terrains" (more detail in Section 4.3.2.3), based on Cassini observations. It should operate at the surface for at least two weeks (goal: one month). The orbiter would act as a data relay for the probe, as well as performing remote sensing measurements. It should also be able to sample Titan's atmosphere from the lowest safest possible altitude at several instances, as was carried out by the Cassini orbiter.

The following payload requirements for the lander were considered: (a) at least 20 kg (incl. 20% margin, excluding sample acquisition system), (b) around 650 Wh per Earth day (incl. 30% margin, excluding sample acquisition system power), (c) at least 500 Mb of data volume for each sample analysis cycle (assumed 3 cycles in total).

4.2. Mission timeline and characteristics as indicated by the Expert Committee

The following desired mission timeline and characteristics were defined by the Expert Committee. The mission should be launched within the 2040-2045 timeframe. The launch date shall be compatible with a landing near the Enceladus SPT starting ideally **from** equinox in mid-2054, or landing in Titan's northern hemisphere ideally **by** mid-2054 at the latest (Figure 4 and Figure 5, respectively). In addition, the trajectory design for the transfer to the Saturn system should be such that a backup launch date within 1-2 years from the baselined launch date exists and is still compatible with the available ΔV budget. The mission shall be compliant with a transfer time from launch to arrival at the Saturn system not longer than 11 years, and shall be launched with a European launcher, i.e., Ariane 6.4 or its evolutions. The mission shall be within the ESA Science L-class mission boundaries. Lastly, from a technical point of view, one of the most important requirements indicated by ESA is that the mission shall not rely on any nuclear power source. This yields important consequences: the limited solar power available in the outer Solar System imposes a very large solar array design, able to power a solar electric propulsion transfer, but generating limited power during orbiter and probe science phases. Moreover, a lander powered by batteries severely restricts both its lifetime and its science payload compared to a nuclear-powered one. Very large solar arrays can also limit the pointing accuracy of remote-sensing platforms and could constrain possible altitudes for safe in situ plume and/or atmospheric sampling measurements.
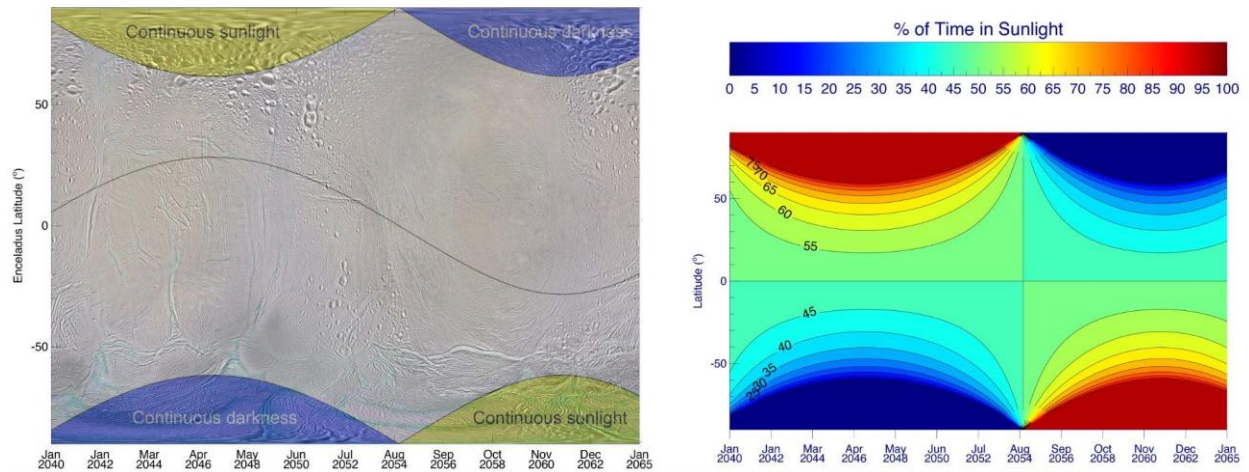
Figure 4 - **Left:** Illuminated latitude ranges at Enceladus during 2040-2065. Dark line indicates sub-solar latitude. When the Sun is north of the equator, northern high latitudes are continuously illuminated, and southern high latitudes are in continuous darkness. The situation reverses following the equinox in 2054. Background image shows surface imaged by the Cassini ISS camera for reference, including active regions at high southern latitudes. Note that illumination latitude ranges apply to all longitudes. **Right**: Percentage of time in daylight against all latitudes at Enceladus over 25 years (2040-2065). The results for Titan are very similar.
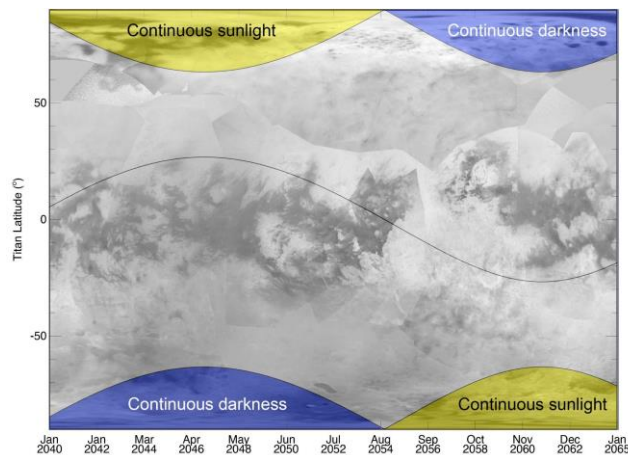
Figure 5 - Illuminated latitude ranges at Titan during 2040-2065. Dark line indicates sub-solar latitude. When north of the equator, northern high latitudes are continuously illuminated, and southern high latitudes are in continuous darkness. The situation reverses following the equinox in 2054. Background image shows major albedo features imaged by Cassini ISS for reference, including northern lakes/seas, primarily at upper left of this projection. Note that illumination latitude ranges apply to all longitudes.

4.3 (Minimum) requirements by the Expert Committee on spacecraft design and mission profiles

In order to address the search for biosignatures (Section 2, theme 3), it is crucial to have sample acquisition in-situ, either from a lander and/or by plume sampling. Below we describe the minimum requirements for an Enceladus or a Titan lander before presenting the constraints on the mothership platform (which could be an Enceladus, Titan, or Saturn orbiter).

4.3.1. Mothership

In order to keep the study as general as possible, we kept the orbiter requirements rather generic, to be compatible with targeting Enceladus or Titan, or both. In this respect, this mission element could be an orbiter of Enceladus, Titan and/or Saturn. In the case of an Enceladus orbiter, the most stringent requirement would be to carry out in situ plume sampling before entering a sufficiently low and stable orbit about the moon. In the case of a mission with Titan as the main target, ideally the orbiter should first be able to perform Enceladus plume sampling before getting closer and closer to Titan, sample the latter's atmosphere, and then entering a low and stable orbit (but keeping into account Titan's dense atmosphere to avoid excessive atmospheric drag). The minimum payload is described in the next subsections.

4.3.1.1. Enceladus as main target: orbit, plume sampling and minimum payload

We require the spacecraft to execute some high velocity flybys through the plume while still being in a Saturn resonant orbit (Figure 6). At least 10 such flybys should be executed, targeting plume sampling with the spacecraft's in situ instrumentation at altitudes ideally below 50 km. The flyby speed should be in the range of 3 - 5 km/s to allow on one hand compositional characterization of individual ice grains by impact ionization mass spectrometry, and on the other hand be slow enough to allow sampling of the plumes' gas phase by a neutral gas spectrometer without molecular breakup. A few faster flybys at 5 - 9 km/s preceding this phase would allow the study of molecular fragments that can then be compared with the intact molecules sampled at 3 - 5 km/s, thereby enhancing the diagnostic capability. Plume sampling during these flybys allows the assessment of the compositional diversity of the plume (e.g., Postberg et al., 2018b), while samples taken from the surface will always be a mixture, erasing compositional diversity in both time and space. Since Saturn's E-ring is made from ice and gas emitted by Enceladus's plume at sufficient velocities to leave the Hill sphere of the small moon, sampling of E-ring material would ideally complement the plume sampling during this phase. This phase would also include a moon tour with flybys targeting Titan, Rhea, Dione, Tethys and Mimas (Figure 7; Campagnola et al., 2010). After this moon tour phase, the mothership would be injected into an Enceladus orbit with an altitude of 100 km or less for gravity field measurements. The orbiter, which should have an operational lifetime of at least 4 years, will conduct a reconnaissance survey to identify the safest landing site, serve as a relay during the surface element landing phase and then remotely investigate Enceladus from orbit.

The minimum strawman payload for the mothership includes a remote sensing package with a camera (visible/near-IR up to 1100 nm) and a thermal imager; an in-situ package with a magnetometer, a dust analyser and a gas analyser; a geophysical package including an ice-penetrating radar (with the potential to characterize the boundary between the icy crust and the

liquid layer below); and gravity and radio science experiments to be performed using the onboard telecommunication system working both at X- and Ka-bands.
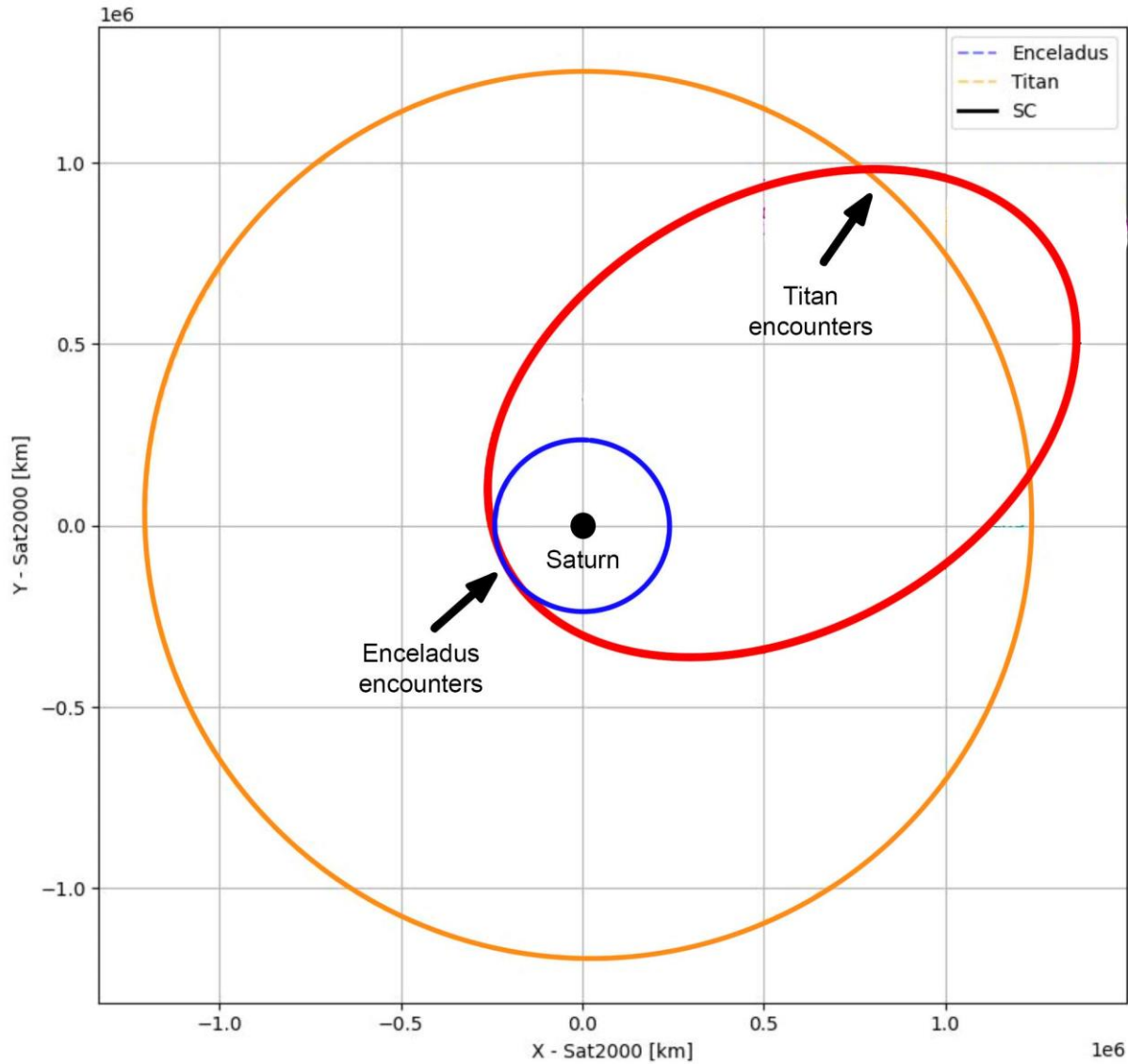

Figure 6 - An example Enceladus resonant orbit that would allow regular encounters with Enceladus, perturbed by distant Titan encounters. The orbital period would be 9.6 Earth days, with Enceladus encounter velocities of around 4 km/s. All plume crossings would be parallel to the same Enceladus meridian.
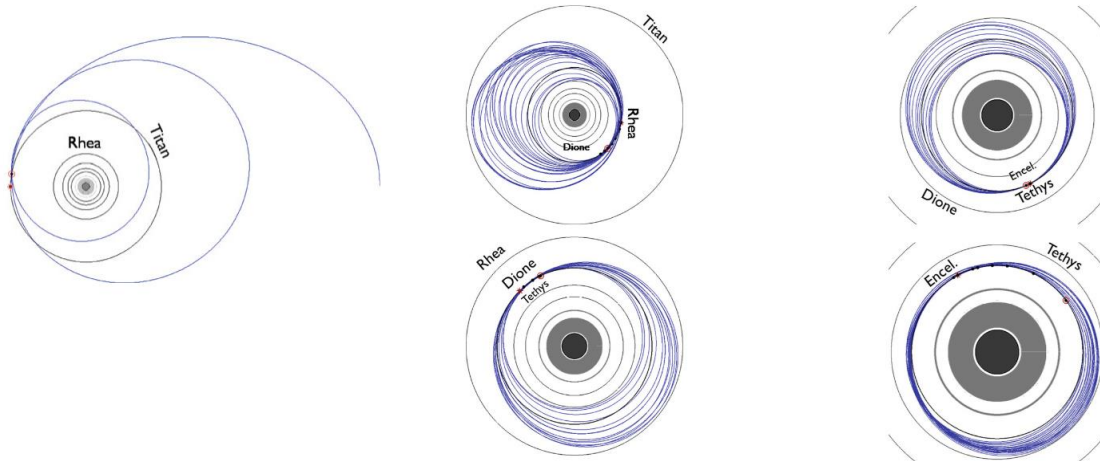
Figure 7 - Fast tour design method of the moons of Saturn using non-tangent v-infinity leveraging transfer (VILT) (from Campagnola et al., 2010).

4.3.1.2. Titan as main target for the lander: orbit, atmosphere sampling and minimum payload

Once inserted in the Saturn's system, the mothership will perform a tour of the moons with at least one flyby of Mimas, and a minimum of five flybys of Enceladus. During the Enceladus flybys, the mothership will conduct plume sampling at an altitude of around ideally 50 km or lower, with different velocities ranging from 3 km/s to 7 km/s (see rationale in section 4.3.1.1.).

After this phase, the mothership will be ideally transferred into a final orbit around Titan, at an altitude of >1500 km (to avoid atmospheric drag) and with a high inclination (polar or near-polar to better image the poles and later release the lander). If power and data volume allow, the landing zone will be selected after a reconnaissance phase from orbit, including high resolution radar (SAR) and infrared (IR) mapping, and the production of Digital Elevation Models (DEM). If there is an elliptical phase prior to the stable orbit, periapsis passes over the north polar regions could be beneficial for maximum SAR and IR mapping resolution in the key region of interest. An elliptical phase would also allow the analysis of the atmosphere at different altitudes with a gas analyser.

The Titan (or Saturn) orbiter will serve as a relay during the surface landing phase, and then remotely investigate Titan's atmosphere and surface using a dedicated payload. It will also perform several deep dives into Titan's atmosphere at the lowest possible altitude (typically around 750 km). This will allow in situ measurements of the composition of the upper atmosphere with the same suite of instruments used for Enceladus plume sampling.

An example strawman payload for the mothership includes an imaging radar (with a resolution better than 100 m), an ice-penetrating radar, high-resolution IR cameras (including Titan's atmospheric transparency windows), a thermal mapper, a gas analyser (high resolution mass spectrometer), a dust analyser, and an in situ package for magnetic and plasma observations, including heavy ions (both positive and negative). Gravity and radio science experiments will also be performed using the onboard tele-communications system working both at X- and Ka-bands.

4.3.2. Lander

4.3.2.1. Minimum strawman payload

The minimum requirements for the landed strawman payload are identical whether Enceladus or Titan is the main target. The lander will carry a sample acquisition system to collect material from the surface/near-surface and/or take them from the plume fall-out in case of Enceladus ("snow" from above). The payload should be essentially astrobiology-dedicated instrumentation, including microfluidics, a system to minimize sampling activities while optimizing measurement of low concentration relevant compounds, analytical instruments for the identification of bio- and organic targets (e.g., GC-MS, lab-chip, high resolution mass spectrometry), micro-camera, and physical-chemical sensors to characterize the geological context.

For scientific robustness a minimum of 3 samples need to be analyzed, and ideally these samples should be collected at different locations around the lander (e.g., with a robotic arm), and/or plume fall-out at Enceladus. For Titan, the lander could include a meteorological and geophysical package (measuring e.g., temperature, pressure, moisture, wind, and could also include a seismometer, permittivity probe, and electric field probe).

The lander could also be equipped with thrusters or a steerable parachute (in the case of Titan) and an autonomous hazard detection and avoidance system to be used at the end of the descent phase. However, the final phase of the landing should be made in free fall to avoid heating and contamination of the surface material to be sampled.

4.3.2.2. Enceladus as main target: landing location and timing

The landing site should be close to the south pole fractures. Illumination of the SPT becomes optimal starting in 2054 (Figure 4) depending on the exact latitude of the landing site.

The lander shall land within a few kilometers of an active fracture (i.e., a Tiger Stripe). Data from Cassini's Cosmic Dust Analyser has shown that ice grains larger than about 0.1 μm emitted by the plume consist of at least three different compositional types: almost pure water ice, organic-enriched, and salt-rich (Postberg et al. 2009, 2011, 2018a). Pure water ice grains are the smallest population that possibly extend down to the nm regime (e.g., Jones et al., 2009) and are the least interesting for habiltability, while the other two larger populations will allow us to constrain Enceladus habitability (e.g., Glein et al., 2018, Postberg et al., 2018b). Such larger grains will be enriched at the surface closer to the tiger stripes. Additionally, landing close to an active source will ensure that the surface will consist of relatively fresh material, that has only been ejected into the plume and redeposited onto the ground at rates in the order of 0.1 mm/yr or higher (Southworth et al., 2019) and that has not been altered by space weathering. On the other hand,

such areas may be unsafe if unsintered particles make the landing site unstable (e.g., Harmon et al., 2023). Since this is impossible to infer from the low-resolution Cassini images (at least 6 m resolution), the landing site should only be selected after a reconnaissance by the Mothership during the first mission phases.

At least three different surface samples should be analyzed, which require a minimum of about two weeks of surface operations. In addition to surface samples, almost pristine samples that have been ejected less than an hour earlier could be acquired by the sampling of plume fallout ("fresh snow") from above.

The lander descent should occur on the day side of Enceladus, and the landing site should be ideally in sunlight at least 50% of the time during the lander mission duration. This places constraints on the landing period: from mid-2054 onwards for mid- to high-southern latitudes (Figure 4).

4.3.2.3. Titan as main target for the lander: landing location and timing

The Titan lander will investigate lake shore sediments or/and study organic evaporite-rich deposits precipitated by wet-dry conditions (Barnes et al., 2011; MacKenzie et al., 2014). Both sediment types might contain complex organics that can inform us about how far organic reactions can progress in exotic solvents. On Titan, the surface liquid is a predominantly methane–ethane mixture, which is non-polar. Soluble compound candidates in this liquid are organics that can precipitate as solids when the solute evaporates. Identification of the chemistry of these deposits has not yet been achieved. Cycles of dissolution and crystallization are interesting mechanisms that selectively transport and purify such compounds, forming exotic co-crystals and supporting reactions to a more complex organic chemistry (Cable et al. 2021). The organic molecules may be deposited at the bottom of the lake but at low concentration in the liquid volume, and therefore the missions should not target liquid bodies.

The landing ellipse should therefore include mainly solid ground and be centered on terrains interpreted as evaporite-rich based on Cassini measurements (Barnes et al. 2011; MacKenzie et al., 2014). Such terrains exist at all latitudes (Figure 8) but are more abundant in the northern polar region where the lander should land, ideally close to lakes, but far away from Kraken, Ligeia and Punga seas in order to minimize the risk of landing in a liquid expanse. Woytchugga and Nakuru are good examples of the targeted terrains (Figure 8). The lander should survive at least two weeks (one Titan day-night cycle), preferentially for at least one month. A minimum of three samples should be analyzed. Since evaporites precipitate by fractional crystallization, sampling not only the surface but also the near-subsurface (e.g., using a scoop in the same place many times) should be considered.

The lander descent should occur on the day side of Titan, and the landing site ideally should be in sunlight at least 50% of the time during the lander mission duration. This places constraints on the landing period: between early 2040 and mid-2054 for the mid-to high northern latitudes (Figure 5).
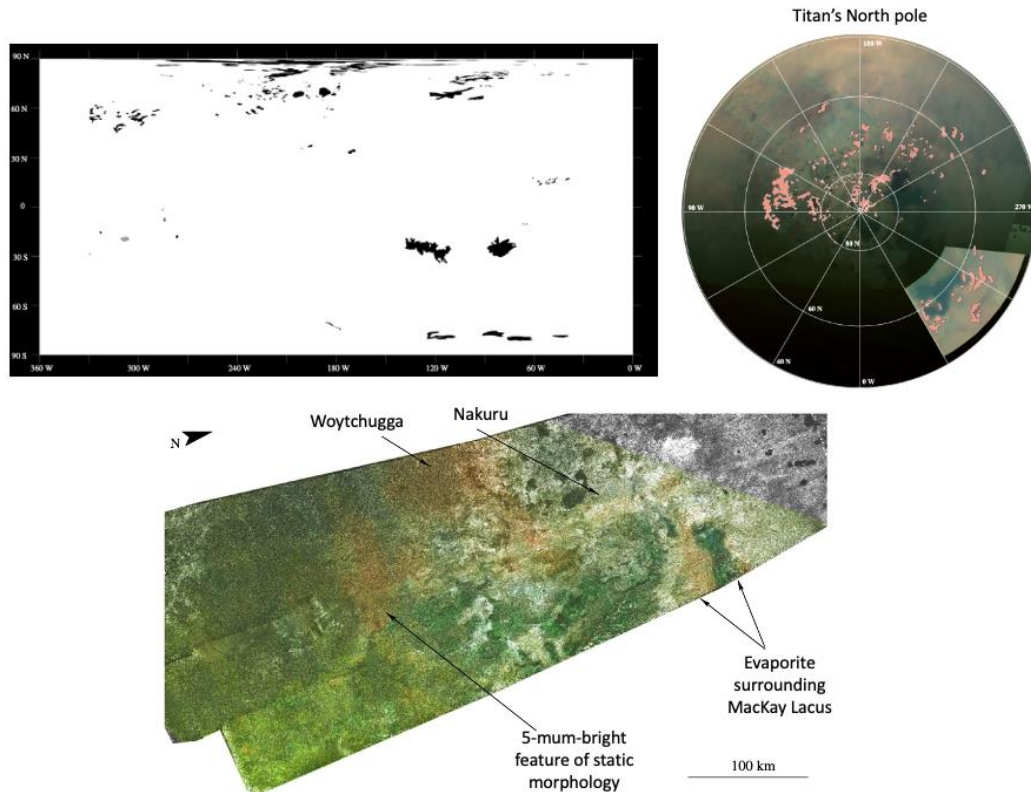
Figure 8 - **Top left**: Global distribution of evaporitic deposits, shown in black, as well as in grey several 5μm-bright areas that did not meet sufficient criteria (e.g., not observed twice, no data of high enough resolution) to be considered evaporite candidates. **Top right:** Cassini IR spectrometer map of Titan's North pole, to 40°N latitude, showing the evaporite candidates in pink. **Bottom**: IR images of the eastern north pole evaporites overlaid atop Cassini RADAR image showing some possible landing sites for the Titan probe. Woythchugga is located at 69°N, 110°W (66,700 km^2); Nakuru is at 65.5°N, 92.38°W (2,580 km^2). To date, the best resolution images of Woytchugga and Nakuru are from T97. Resolution: 13 km. Images adapted from MacKenzie et al. (2014).

5. Results of the CDF studies

The ESA study team has carried out four studies based on the requirements and constraints from the Expert Team Committee. The first two studies focused on a Saturn orbiter only mission and a potential mission to Jupiter respectively. After the conclusion of the first two CDF studies, it was decided to focus on a lander/probe for Enceladus and Titan. The third study was on the primary target Enceladus (section 5.1). The fourth study considered landing elements for Titan, (section 5.2) and was also motivated by the results from the third study, namely that an Enceladus lander is not considered feasible with a single ESA launcher.

The Expert Committee recognises that in all scenarios studied, a stand-alone mission using solar panels will be constrained in terms of the following resources:

● Power: the spacecraft should be in charging mode for 9 out of 10 days, during which only ~15 W is available. A maximum of ~1340 Wh (e.g., ~75W for 15h + ~154W for 1 h + ~21W for 3h during fly-bys) could be made available in science mode.

● Downlink capabilities: ~ 22 kbps on average. Linked to the power issues above, it means that, assuming a 1:8 compression ratio, ~4 Gb could be made available during a science observation (followed by 9 days of recharging).

5.1. Enceladus

5.1.1. Study flow

The Enceladus study, referred to as Enceladus and Titan Definition Study 1 (ETDS-1), was set up to analyze the feasibility of a "stand-alone" mission to Enceladus compliant with the science requirements described in section 4. The study was carried out by an interdisciplinary team of experts from across ESA sites, with the active participation of members of the Expert Committee. The study was conducted from November to December 2022. The study considered the following, assuming one A64 launch (see below):

·   An individual spacecraft (orbiter) to Enceladus;
·   The feasibility and the design of a surface package to the SPT;
·   Targeted Enceladus flybys for plume sampling;
·   Mimas flybys[3].

5.1.2. Mission design

During the CDF studies, the scenario considered was a single A64 launcher. Only after the conclusion of the CDF studies was a double launch scenario introduced for the Enceladus mission, (see paragraph below). All the mission concepts consider a Hybrid Propulsion system (Chemical + Solar electric propulsions-SEP). Assuming a typical Saturn moon tour before entering into Enceladus orbit, it has been demonstrated that all of the scientific requirements regarding the mission profile could be achieved, except for the lander. First of all, several flybys of different moons are possible during the tour (Titan: 5; Rhea: 15; Dione: ~10; Tethys: >10), as well as at least one low-velocity flyby of Mimas. One key component of the mission, i.e., the ability to sample the plumes above the SPT, is also feasible if inserted in the early part of the Moons Tour. The strategy should be to use a 7:1 Enceladus Resonant Orbit allowing a fly-by every ~9.6 days (up to 10 flybys considered) at 4 km/s. The total duration of the tour has been estimated to be 2.7 years, with roughly 50 Saturn moon flybys. During the first month after Enceladus orbit insertion (Figure 9), the orbiter would first provide reconnaissance to find the optimal landing site, and then operate as a data relay for the lander. After the end of the lander lifetime, the orbiter will stay in NRHO orbit for a time duration that will depend on the remaining amount of propellant. The orbiter will then be inserted into a stable, low inclination Enceladus orbit (~200km, <48 degrees) where it can continue to perform science until the end of the mission.

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[3]In the view of the recent published results (Lainey et al., 2024), more flybys of Mimas should be performed. According to the CDF study, this could be achieved every four months at a low delta-V cost (or at a higher cadence at a higher delta-V cost).

A second scenario has also been considered after the conclusion of the CDF studies (Figure 10), assuming the possibility of launching the orbiter and the lander on <u>two separate A64 rockets</u>, requiring a rendez-vous for the docking of the two elements before transfer to the Saturn system. This option provides the same characteristics for the tour but is much more favourable because it permits a lander on Enceladus of ~800 kg, operating for more than 20 days.

The main outcomes of this CDF study are summarised in Table 3.
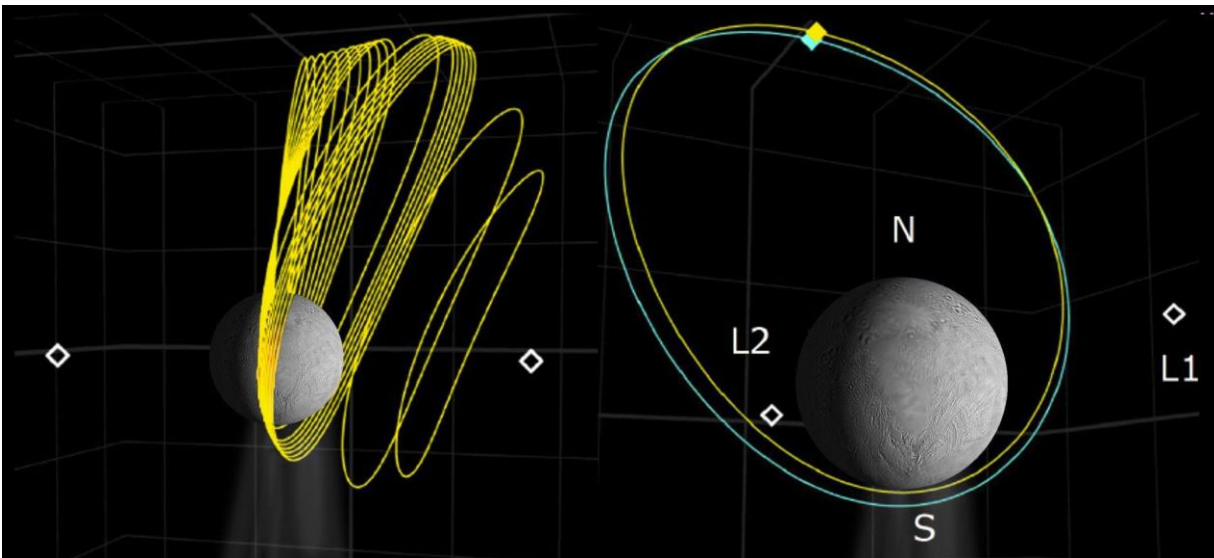

Figure 9 - Two views of variations of the Near-Rectilinear Halo Orbit (NRHO) of the orbiter around Enceladus. Many different NRHO orbits are possible and the one selected will depend on the selected landing location, the communications window needed with the lander, and whether the orbiter shall pass through the plumes for additional sampling. L1 and L2 are Saturn-Enceladus Lagrange points 1 and 2.

5.2. Titan

5.2.1. Study flow

Similar to the case of Enceladus, the Titan CDF study was set up to analyse the feasibility of a "stand-alone" mission to Titan. The study was carried out by an interdisciplinary team of experts from across ESA sites with the active participation of members of the Expert Committee. The study was conducted from October to December 2023.

The study considered the mission profile described in section 4 including:
- An individual spacecraft (possibly an orbiter) to Titan for addressing the identified Titan science objectives, both remotely and with aerosamplings in Titan's atmosphere, and serving as a communications relay with the surface element;
- The feasibility and the design of a lander to Titan's northern polar region;
- Targeted Enceladus flybys for plume sampling and at least one flyby of Mimas[3].

The mission baselines both the Enceladus and Mimas flybys, as done in the Enceladus focused study. However, to maximize the available mass for the probe the moon tour was not considered, and the 1:1 resonant orbit with Titan is reached after a section of Titan gravity assists and impulsive maneuvers directly after the Enceladus fly-bys. The study of a Titan orbiter has not been investigated any further. At the end of the mission, a series of atmospheric passes enabling aerosampling can be envisaged. Depending on the amount of propellant remaining, an extended remote sensing phase with several TGAs before disposal or a tour after the atmospheric sampling could potentially be studied for feasibility. The mission then ends with disposal of the orbiter via a targeted crash on Titan. The main design drivers of the mission are the limited power available for communication, heating, and science measurements, and the limited data rate.
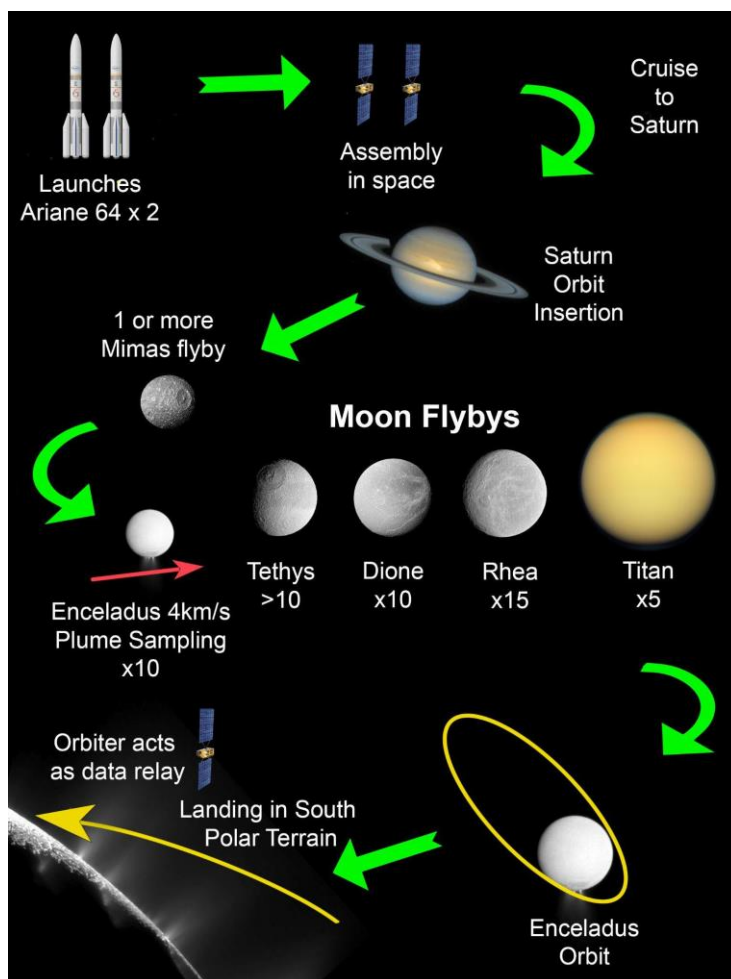

Figure 10 - A scenario assuming the possibility of launching an orbiter and a lander on two separate A64 rockets, requiring a rendez-vous for the docking of the two elements before transfer to the Saturn system. The moon tour is summarized in increasing order of each satellite's distance from Saturn, not necessarily in the order in which encounters will take place.

Table 3 - Mission scenario overview of ETDS-1 and ETDS-2.

	ETDS-1	System-level assessment	ETDS-2
Destination	Enceladus	Enceladus	Titan (& Enceladus fly-bys)
Launcher	A64	A64+ A64	A64
Spacecraft elements	SEP Cruise Stage; CP Orbiter; Strawman Payload; Impactor	**CP kick-stage**; SEP Cruise Stage; CP Orbiter; Strawman Payload; Lander	SEP Cruise Stage; CP Orbiter; Strawman Payload; Titan Probe
Mimas fly-by	at 4.5 km/s after split PRM-2 or at 5.7km/s after split PRM-1	at 4.5 km/s after split PRM-2 or at 5.7km/s after split PRM-1	at 4.5 km/s after split PRM-2 or at 5.7km/s after split PRM-1
Enceladus plume sampling	10 fly-bys (every 9.6 days) from 7:1 resonant orbit at **4km/s**	10 fly-bys (every 9.6 days) from 7:1 resonant orbit at **4km/s**	10 fly-bys (every 9.6 days) from 7:1 resonant orbit at **4km/s**
Saturn tour (typical)	Titan: 5; Rhea: 15; Dione: ~10; Tethys: >10	Titan: 5; Rhea: 15; Dione: ~10; Tethys: >10	>10 Titan gravity assists + Titan atmospheric sampling at end of the mission
Enceladus orbiter	few weeks to years in NRHO, depending on fuel reserves	few weeks to years	x
Enceladus lander	impactor only	~800kg >20 days survival	x
Titan probes	x	x	~1100kg >16 days survival
Titan orbiter	x	x	x

5.2.2. Mission design

The proposed scenario considers a single A64 launcher (for a launch mass of 8.5 tonnes) and a Hybrid Propulsion system (Chemical + SEP) (Figure 11). The possibility of using two launchers as in the Enceladus case has been explored but not considered in detail, because it significantly increases the cost and risk (associated with rendezvous and docking) of the mission without solving the issues of the energy/power and low data rates. In addition, a compelling single-launch scenario was found to be feasible. However, further investigations could be conducted to better assess the benefits of a double launch to a mission to Titan.

The CDF study assumed that aerocapture, aero-gravity assist, or atmospheric sampling should not be compatible with solar-powered spacecraft (the total wing area being 183 m^2). In addition, the delta-V required to reach a low Titan orbit (thus allowing sampling of the upper atmosphere) is considered highly challenging and has not been studied in further detail. It was then suggested to use a pseudo-orbiter in a final orbit around Saturn with 1:1 resonance with Titan, not only for performing more distant science measurements but also for serving as a communications relay with the lander during surface operations. This makes the mission profile very constrained for addressing the science objectives compared to a full orbiter, but it is still considered acceptable by the Expert Committee. For a total wet mass of 8.4 tonnes (Orbiter: 5.6 tonnes; SEP: 1.65 tonnes; Titan probe: 1.15 tonnes), the orbiter could embark up to ~80 kg of payload (P/L) which is constrained but compatible with the science requirements addressed in section 4. The solar arrays should provide ~650 W at 9.54 AU and a secondary battery is used for storing up to ~3.6 kWh, which seems fully compatible with the science requirements for both daily measurements and flyby science operations. Although this is very constrained with respect to the needs for the strawman P/L proposed above, it seems to be compatible with science requirements.

Landing a probe on the surface with sufficient mass and energy to operate for 16 days (one Titan day) with the orbiter available as a relay was found to be technically feasible assuming a passive entry with heat shield and (non-steered) parachute, but only if the entry occurs when the orbiter has been placed in its resonant orbit (i.e. not during the tour). The communication strategy requires the use of the orbiter as a relay for ensuring a high data rate compatible with the science expectations. Though very constraining, these characteristics are regarded as sufficient for addressing the science objectives listed above, the main issue being the ability to reach a region of interest between 65°N and 90°N with a landing ellipse better than 150 km x 70 km (Dragonfly-like performance). The dispersion of the landing ellipse is mainly due to the large uncertainty on the wind speeds at these latitudes (Lorenz and Newman, 2015), meaning that the landing ellipse at Woytchugga Lacuna is estimated to be ~300 km x 100 km. A landing site reconnaissance phase for risk reduction by precision landing was not considered reasonable but could be compensated for by autonomous hazard detection and avoidance. The launch could occur in October 2042 (with a back-up 2 years later) for arrival at the Saturn system in October 2051, after two Earth swing-bys. The mass of the Titan lander payload can be up to 33 kg (assuming 331 kg of battery, no fuel cell or RHUs allowed).

The main outcomes of this CDF study for Titan are also summarized in Table 3.
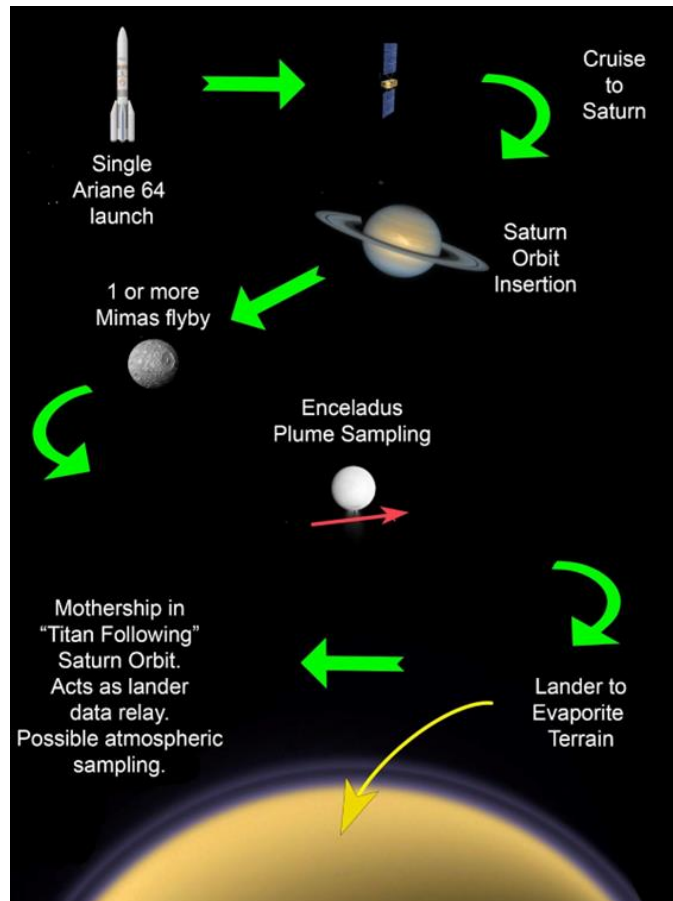
Figure 11 - A scenario assuming the possibility of launching an orbiter and a lander on two separate A64 rockets, requiring a rendez-vous for the docking of the two elements before transfer to the Saturn system.

5.3. Europa

Mission analysis of possible mission concepts to Europa started in 2008 with the Laplace project where the first CDF study demonstrated the extremely challenging issues related to a stand-alone mission. More recently in 2015, another study was dedicated to the possible ESA contribution to the NASA Europa Clipper mission. In this study (CLEO/P) the ESA contribution was a 250 kg class small satellite, attached to Clipper during launch and interplanetary transfer and released by Clipper after Jupiter Orbit Insertion (JOI) for close inspection and fly-bys of the Jupiter moon Io or possibly Europa[4]. An alternative mission scenario, as part of the same study, considered an instrumented high-speed penetrator delivered to the surface of Europa[5]. At that time, the analysis demonstrated that the harsh environment at Europa did not allow for more than 10 days of science operations at the surface, but an insulated design of a penetrator that could operate at Europa for that period was developed. Since then, the thorough analysis provided by the preparation of

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[4]https://sci.esa.int/documents/34923/36148/1567260232629-CLEOP_Orbiter_CDF_study_report.pdf

[5]https://sci.esa.int/documents/34923/36148/1567260234568-CLEOP_Penetrator_CDF_study_report.pdf

NASA Europa Clipper, and also the building of the JUICE S/C have confirmed that any future mission to Europa that included a surface element together with a full orbiter (as described in section 4 for addressing the science objectives of the next L4) will be extremely challenging with respect to both technical and cost issues.

In 2022, a new CDF study was completed to assess the technical and programmatic feasibility of a "hybrid power" system for planetary missions with focus on Jupiter (Hybrid Power Systems Study-2 - HPSS-2), thus providing a way to increase the science return at Europa. Finally, in the timeframe of this study, a very preliminary update of HPSS2 assuming a double launcher option with A64 has been proposed. Compared to HPPS2, a net gain of ~1 tonne dry mass for the final orbit around Europa can be envisaged but the actual gain would need to be confirmed through a full CDF study. This additional dry mass could be used in two ways (or a combination thereof):

- Increase of radiation shielding of the orbiter (HPSS2 required 230 kg of aluminum to survive 1 month at Europa) - allocating the full 1 tonne to radiation shielding could potentially extend the lifetime of the orbiter to around a year;
- Increase of landed probe dry mass from 300 kg to ~580 kg. This might allow a lander such as the one described for Enceladus but that includes heavy shielding and a larger propulsion subsystem. Only a full CDF study could estimate whether operation on Europa's surface is possible for a sufficiently long time to allow the key science measurements.

5.4. Expert Committee assessment of the options for Enceladus, Titan, and Europa

A mission to Enceladus is considered feasible and in good compliance with the science requirements only if the dual-launch option is considered. It is crucial to land near the south pole with a significant payload and therefore a dual launcher solution is needed, because many of the biosignatures and prebiotic chemistry objectives identified in section 2 will then be fully achieved.

For Titan, the CDF study showed that different mission profiles were feasible, but none that completely satisfied the science goals outlined in section 3. The Expert Committee encourages further studies into this, as a mission to Titan would require a Titan orbiter to meet the science requirements effectively. Additionally, it would necessitate a reconnaissance phase and an autonomous hazard detection and avoidance system to ensure targeted and safe landings on selected terrains. Finally, the power of the mothership needs to be increased to allow a diverse range of measurements.

Europa should not be considered as a priority since most of the objectives will be addressed at least partially by JUICE and the NASA Europa Clipper. Building on the results of these two space missions it could be possible to consolidate the scientific questions related to habitability, prebiotic chemistry and biosignatures. However, based on the input from the ESA study team (Section 6.3), a mission to Europa that fully addresses the science requirements seems not feasible within the framework of L4.

6. International landscape

Our target selection rationale (Section 3) considers how the current important scientific questions are addressed by ongoing and planned future missions, also taking into account the roadmaps of other space agencies. Figure 3 gives a flexible initial mission profile priority chart that could allow ESA to maintain its leadership for the next Large-class mission, complementary to the evolution of the international landscape.

For the target assessment in Section 3, we considered the planned science from three upcoming missions: the ESA JUICE mission, the NASA Europa Clipper and Dragonfly missions. These missions should significantly address outstanding scientific questions for the Galilean moons and Titan. With no upcoming Enceladus mission adopted through any international agency, this means that an L4 ESA mission to Enceladus has the highest potential for a spectacular scientific return.

In the upcoming years, NASA missions to the outer Solar System could be adopted as a large strategic science mission, also called "Flagship" class, or for the New Frontiers programme as a smaller mission. In the spring of 2022, the Planetary Science and Astrobiology Decadal Survey 2023–2032 was released to the public (National Academies of Sciences, Engineering, and Medicine, 2023). Among the various recommendations, the committee identified Uranus as the primary target for a large Flagship-class science mission via a concept named "Uranus Orbiter and Probe" (UOP) (Simon et al., 2021). This mission would carry out a multi-year orbital tour to explore the ice giant and its system as a whole, studying Uranus's interior, atmosphere, magnetosphere, moons, and rings. At the time of writing this report, the timeline for a large Uranus Orbiter and Probe mission is unknown and projected launch dates are not before the early 2040s.

The second-highest priority for a large mission was identified as an Enceladus "Orbilander" (MacKenzie et al., 2021). The "Orbilander" concept foresees a multi-phase element. It would first orbit Enceladus, carrying out a landing site reconnaissance, remote sensing investigations and plume sampling. It would then land on the surface, and then spend 2 years on the surface carrying out the analysis of plume material and seismic activity. This mission would be implemented after the Uranus Orbiter and Probe.

A mission with a lander element to Jupiter moon Europa, which was given high priority in previous surveys, was not considered in the 2023-2032 Decadal Survey and is thus unlikely to happen in the next two decades. Similarly, after the Dragonfly mission there are no further planned missions to Titan.

The Announcement of Opportunity (AO) for the fifth mission of the New Frontiers programme (NF5), which was originally expected to be issued at the end of 2023, has been delayed until "not earlier than 2026"[6]. Enceladus missions could be among the proposed concepts but would be limited by the NF5 constraints.

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[6]https://newfrontiers.larc.nasa.gov/NF5/

The China National Space Administration (CNSA) have announced plans for a mission to the Jupiter system[7]. The Indian Space Research Organisation (ISRO) and the United Arab Emirates Space Agency (UAESA) are also expanding their planetary science programmes, but their focus is on the terrestrial planets and the inner Solar System so far.

7. Main conclusions and suggestions for the future

Following the outcome of the Voyage 2050 Senior Committee, the next ESA-Science Large mission, L4 is planned to focus on the "Moons of the Giant Planets" to investigate the habitability of these ocean worlds, the detection of biosignatures, the identification of prebiotic chemistry, and understanding the interconnection between the subsurface and the surface, and near-space environment.

The main conclusions for the Expert Committee are as follows:

- Any future mission to these icy moons will require expertise from a wide range of scientists from the planetary community to complete the primary goals that have been identified. Further, whilst the primary focus of this mission will be based on the habitability of icy moons, it is critical that an ambitious ESA L4 mission drives forward our knowledge of these icy moons from all perspectives and should aim to engage and inform the wider planetary research community.
- In order to make transformative advancements following previous missions, particularly with the search for biosignatures and identifying prebiotic chemistry, the mission must involve in-situ sample acquisition. A lander on an icy moon is the primary aim to acquire pristine samples, however plume sampling is also considered for accessing fresh material from the subsurface.
- Enceladus is the optimum candidate for the L4 mission. Enceladus is considered a habitable environment, meeting the key requirements for supporting and sustaining life. A future mission to Enceladus would substantially further our knowledge and make considerable advancements upon the last mission to visit Enceladus (Cassini-Huygens). Considering the combination of the scientific relevance and that there are no selected future missions to Enceladus by any space agency, this moon is therefore considered the most compelling target for a future ESA Large mission. The ESA study shows that a dual launch configuration (A64+A64), with Near-Earth rendezvous prior to escape, in addition to an Enceladus orbiter, would allow an ~800 kg lander to be delivered to the surface of Enceladus. This could accommodate for example 23 kg of scientific payload and ~250 kg battery mass that ensure at least 30 days of operation or else a larger scientific payload with reduced lifetime.
- Titan follows Enceladus in terms of priority. It is clear that great improvements in our current knowledge would be made with a lander to, and/or orbiter around Titan. In the case of a lander, whilst the NASA Dragonfly mission will further our understanding, here

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[7] https://www.planetary.org/articles/chinas-plans-for-outer-solar-system-exploration

we specifically suggest the investigation of lake sediments, a very different type of landing environment which will not be studied by Dragonfly. However, in order to fully meet the goals, the mission design should include a Titan orbiter, a reconnaissance phase and an autonomous hazard detection and avoidance system to ensure targeted and safe landings on selected terrains, and a mothership that provides enough power to allow a diverse range of measurements.

- For either an Enceladus or Titan mission, we strongly suggest that flybys of both these moons should be carried out. Any planned mission to the Saturnian system should involve Enceladus plume flybys, and an additional Moon Tour focusing on at least those moons considered to potentially host a liquid subsurface. With the recent finding of Mimas likely being a young evolving ocean world, special attention should be given to a larger number of close Mimas flybys.
- A lander on Europa at this time appears not feasible. With the upcoming JUICE and NASA Europa Clipper missions, a lander on Europa would be a minimum requirement to substantially further our knowledge of this body. However, based on current technological restrictions this seems not plausible. This does stress the importance of further technological advancements. The Expert Committee would like to note that the adoption of the double launcher proposal was introduced relatively late in the Expert Committee's activities and that a complete study of how a double launch would affect a Europa lander mission was not carried out.
- The Expert Committee also notes that the availability of radioisotope power and heating options (RTGs and RHUs) would make a dramatic improvement to each of the mission profiles investigated, allowing for more resources (e.g., power, and data), and a longer lifetime of each mission, e.g., the lifetime of the lander could be increased from weeks to years, while at the same time increasing the scope and capability of its scientific payload.
- The Expert Committee notes that a sample return mission from a moon of the giant planets would likely have enormous scientific returns. However, the limitations of current technology, knowledge of the target bodies, and cost, mean that this type of mission is regarded as beyond the scope of the L4 mission. Nevertheless, there should be a further dedicated study of this type of mission in the future.

Any of the most promising options of the L-class mission concepts presented in this study, with launch in the early 2040s, would revolutionize our understanding of the habitability and the assessment of the presence of biosignatures on the moons of Saturn, and would guarantee ESA leadership in the science theme "Moons of the Giant Planets".

Acknowledgments

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