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of the European Union

Erasmus Plus GeoPlaNet Strategic Partnership

IO 1 HABITABILITY TEACHING MATERIAL AND ASSESSMENTS

Leading organisation: Nantes Université, Laboratoire de Planétologie et Géosciences

Participating organisation: Universities of Padova, Chieti-Pescara, Coimbra and Porto

Habitability is a major issue in planetary geosciences. Its definition can vary from one discipline to another: - for astrophysicists, it is the area at a certain distance from the star where the surface temperature conditions of the planets around their star could be favourable to the presence of water in liquid form; -for planetologists, these temperature conditions favourable to liquid water can also be found under a thick layer of ice inside the ice satellites around the gaseous giants of our solar system.

Through this IO and the expertise of the various partners, we wish to offer a global vision of the current state of knowledge on this booming subject, which offers a new challenge for comparative planetology: to mobilize our expertise in the service of the habitability and study of terrestrial exoplanets (rocky or planet-oceans).

In order to share knowledge and good practices, and to train students and researchers on the topic, Nantes LPG has organised a **one-week intensive Thematic School on habitability in autumn 2022**. Partners did participate to the lectures and students from the whole partnership have attended this event.

→This activity has been supported by the **creation of teaching material on habitability by Nantes**, assisted by all partners.

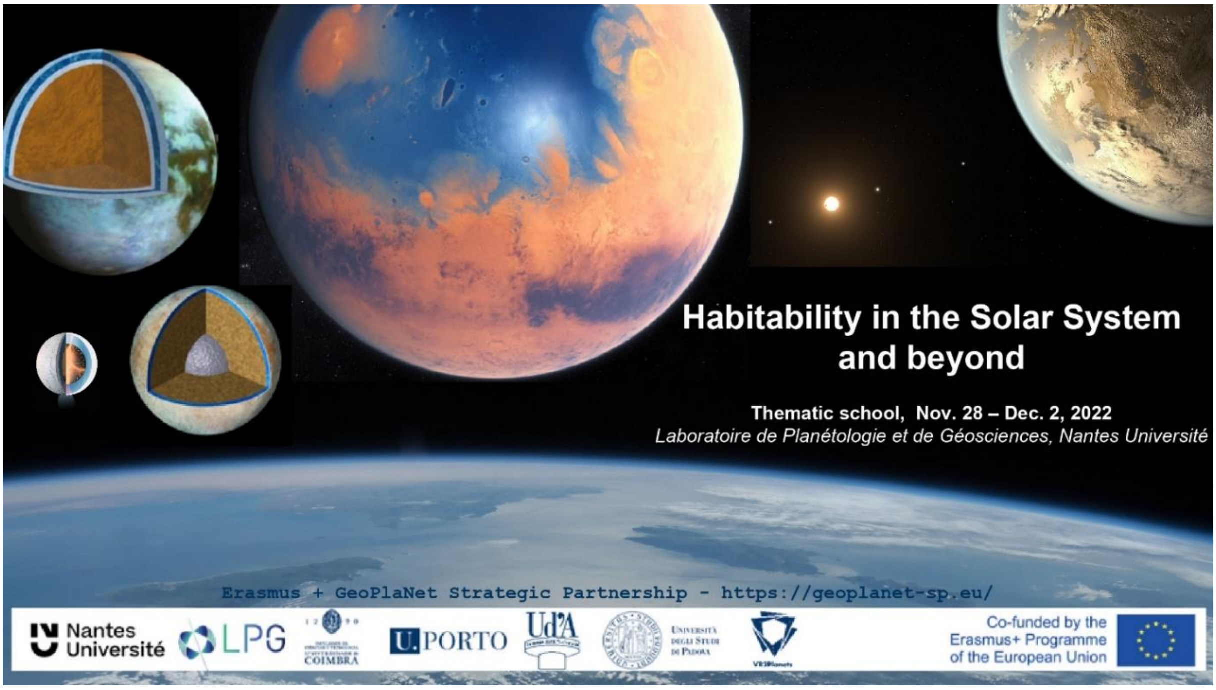
This Intellectual Output includes all teaching material relevant to the **preparation of the thematic school, and the assessment including :**
I - the specific programme designed by the Partnership to address the most recent challenges on habitability,

II - The pedagogical material relevant to the preparation, the dissemination and the educational recognition of the thematic school about habitability: **online courses and tutorials.** The courses will remain online on the GeoPlaNet websites and allow remote students and researchers to access a top-level overview on planetary habitability.

III - A list of pedagogical references designed to provide a strong background for participants prior to the event and reference for more in-depth study of themes.

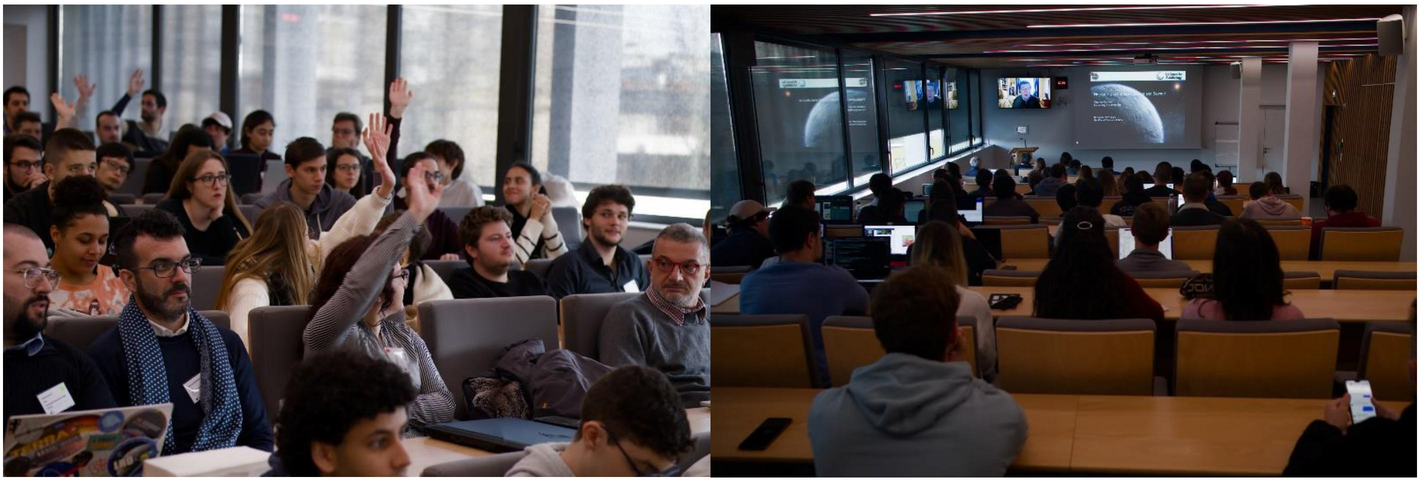
IV - The **assessment of student's group work** addressing the needs of educational recognition for students attending the school as part of their national education programmes

I - Programme designed by the Partnership



	Monday 28 nov.	Tuesday 29 nov.	Wednesday 30 nov.	Thursday 1 dec.	Friday 2 dec.
Chair	**Christophe Sotin**	**Laetitia Le Deit**	**Susan Conway**	**Gabriel Tobie**	**Gaël Choblet**
AM 1 9:00 - 10:30	Introduction & group project presentation	**Emergence of life on Earth** **Puri Lopez (visio)**	**ExoMars** **Jorge Vago**	**Structure and composition of icy worlds** **Olivier Bollengier**	**External solar system exploration: ESA/NASA** **Olivier Grasset**
AM 2 10:45 - 12:15	**Planetary habitability** **Charles Cockell (visio)**	**Organic matter on ancient Mars** **Caroline Freissinet**	VR/Group project	**Hydrothermal systems in Icy Worlds** **Yasuhito Sekine**	Group project
Lunch 12:15 - 13:00	**Lunch break – Poster sessions**				
13:00 - 14:00				**13:00** **Exoplanet Atmosphere Recipes** **Edwin Kite***	
PM 1 14 :00 - 15:30	**Aqueous environments on Early Mars** **Nicolas Mangold**	**Field Trip** Piriac/Penestin	VR/Group project		Group project presentation/evaluation
PM 2 15:45 - 17:15	**Current habitability on Mars** **Frances Westall**	**Field Trip** Piriac/Penestin	VR/Group project	VR/Group project	Closure
Evening	**Welcome party** **Poster presentation**	**Social event (Piriac/Guérande)**		**Conference, Museum** **"Les océans cachés des lunes de Jupiter et Saturne"** **Christophe Sotin****	

II - Pedagogical material: online courses and tutorials



- ➔ **All the videos are also available on the results section of the website:**
  https://geoplanet-sp.eu/en/results

Exoplanet Atmosphere recipes. Part I, by Edwin KITE
https://mediaserver.univ-nantes.fr/permalink/v126636b9a62ekno6zut/iframe/

Exoplanet Atmosphere recipes. Part II, by Edwin KITE
https://mediaserver.univ-nantes.fr/permalink/v126636b9ac00t53epec/iframe/

Outer Solar System Exploration by Olivier Grasset
https://mediaserver.univ-nantes.fr/permalink/v1266364ec088gy1dfa1/iframe/

Water-rock interactions: hydrothermal reactions, energy, and habitability of icy ocean worlds and beyond, by Yasu Sekine
https://mediaserver.univ-nantes.fr/permalink/v1266364e9cacnctd7bg/iframe/

Icy Worlds: Part I by Olivier Bollengier
https://mediaserver.univ-nantes.fr/permalink/v1266364e689ce07c2hg/iframe/

Icy Worlds: Part II by Olivier Bollengier
https://mediaserver.univ-nantes.fr/permalink/v1266364e6cf735bjavx/iframe/

Icy Worlds: Part III by Olivier Bollengier
https://mediaserver.univ-nantes.fr/permalink/v1266364e74afeq3sacq/iframe/

Search for life in the Solar System: Part I by Jorge Vago
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Search for life in the Solar System: Part II by Jorge Vago
https://mediaserver.univ-nantes.fr/permalink/v1266364e4440twwpew8/iframe/

Past habitable environments on Mars by Nicolas Mangold
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Planetary habitability: an introduction by Charles Cockell
https://mediaserver.univ-nantes.fr/permalink/v12641dc00c13uyq8345/iframe/

Emergence and early evolution of live on earth by Puri Lopez
https://mediaserver.univ-nantes.fr/permalink/v126636400a84dku31wv/iframe/

Mars: current habitability by Frances Westall
https://mediaserver.univ-nantes.fr/permalink/v12641dec3bd8ueesfot/iframe/

Organic matter on ancient and modern Mars. Into martian habitability by Caroline Freissinet
https://mediaserver.univ-nantes.fr/permalink/v12641dec476272frhob/iframe/

III - Pedagogical references

1) Habitability in the Solar System and Beyond (Charles Cockell, University of Edinburgh)

- The fate of the Earth in the far future : O'Malley-James JT, Greaves JS, Raven JA, Cockell CS 2015, In search for future Earths: Assessing the possibility of finding Earth analogues in the later stages of their habitable lifetimes. Astrobiology 15, 400-411.

- Saturn's moon Enceladus, liquid water outside the classic habitable zone in relation to tidal forces : Waite JH et al. 2009, Nature 460, 487-490.

- Microbiology of the Chicxulub crater - the effect of impacts on microbial habitability : Schulte P. et al. 2010, The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary, Science 327, 1214-1218; Cockel CS 2021, Shaping of the present-day deep biosphere at Chicxulub by the impact catastrophe that ended the Cretaceous, Front. Microbiol. 12, 668240.

- Lake of briny fluids below the south pole of Mars ? : Orosei R et al 2018, Radar evidence of subglacial liquid water on Mars, Science 361, 490-493.

- Studies on the counteracting effects of the perchlorate anion on enzime activity under pressure : Gault S., Cockell CS 2021, Perchlorate salts exert a dominant, deleterious effect on the structure, stability, and activity of alpha-chymotrypsin, Astrobiology 21, 405-412; Gault S, Jaworek MW, Winter R, Cockell CS 2020, High pressures increase alpha-chymotrypsin enzyme activity under perchlorate stress. Communications Biology 3, 550.

- Transient habitable and uninhabited environments on Earth: Kelly L et al (2014), Pioneer colonists of the Eyjafjallajökull, Microbial. Ecology, DOI 10.1007/s00248-014-0432-3

- Laboratory experiments can be used to explore the decoupling between habitability and inhabitancy : Cockell CS, Hecht L, Landenmark H, Payler SL and

Snape M. 2018, Rapid colonization of artificial endolithic uninhabited habitats, International Journal of Astrobiology 17, 386-401; Cockell CS 2020, Persistence of habitable but uninhabitated, aqueous solutions and the application to extraterrestrial environments, Astrobiology, Vol 20, DOI : 10.1089/ast.2019.2179

- Habitable but uninhabited planets across the Universe ? : Cockell CS 2014, Habitable worlds with no signs of life, Phil. Trans. Royal Soc., 372, 20130082.

2) Past habitable environments on Mars (Nicolas Mangold, LPG, Nantes)

- Fluvial and alluvial environments : Luo and Stepinski, JGR 2009.

- Channel discharge from interior channels : Irwin et al, Geology, 2005

- Last activity often observed as surges : Goudge et al, 2021

- Alluvial fans extended within Hesperian and probably Early Amazonian epochs : Kite et al., 2017.

- Classification of channel pattern based on bankkfull discharge and gradient: Smith, 1993.

- Recent simulations suggest depositional processes as long as 500,000 years to develop the fluvial patterns observed at Aeolis Dorsa : Cardenas et al., 2021.

- Ground truth of fluvial/alluvial deposits on Mars : Shaler at Gale crater (Edgar et al., Sedeimentology, 2017), conglomerate at Gale crater(Williams et al., 2013).

- Mineralogy of mudstones from drills (CheMin) : Vaniman et al., 2014.

- A Habitable fluvio-lacustrine environment at Yellowknife Bay, Gale Crater, Mars : Grotzinger et al., 2014.

- Organic molecules in the Sheepbed Mudstone, Gale Crater, Mars : Freissinet et al, 2015.

- Deltaic and lacustrine environments : local drying out of the lake with mud cracks (Stein et al., 2018) and sulfate enrichments (Rapin et al., 2020).

- Outcrop Old Soaker : presence of mud cracks (Stein et al, 2018).

- Chemostratigraphy of fluvial and lacustrine sedimentary rocks at Gale Crater using ChemCam onboard the Curiosity Rover : Mangold et al, 2019.

- Clay mineral diversity and abundance in sedimentary rocks of Gale crater, Mars : Bristow et al., Sci. Adv., 2018.

- Dozen of delta from various sizes exist on Mars : Rice et al., 2011, Ansan et al., 2011.

- Map of deltas on Mars: De Toffoli, 2021.

- Map of paleolakes on Mars : Goudge, 2016.

- Sediments in Jezero crater : Fassett and Head, 2005; Goudge et al., 2015.

- Perseverance rover reveals an ancient delta-lake system and flood deposits at Jezero crater, Mars : Mangold, Science, 2021.

- Ground example of hyperpicnal flow at Gale crater related to rivers loaded by mud/grains : Stack et al., 2018.

- Detection of Melas Chasma lake by topography and morphology : Quantin et al., 2005.

- Detection of gypsum veins by Opportunity & Curiosity : Squyres et al., 2005; Nachon et al., 2014.

- Detection of Ca-sulfates veins on Mars : Nachon et al., 2017

- Detection of crystalline hematite within a vein : L'Haridon et al., 2020.

- Detection of sulfate deposits in many regions on Mars : Meridiani Planum (Arvidson et al., 2004), Candor Chasma (Mangold et al., 2008).

- Pedogenetic profiles form due to long-term action of aqueous alteration by weathering: example of pedogenetic profiles in Australia (Gaudin et al, 2011).

- Detection of Fe-Mg clays and Al-clays kaolinite in Mawrth Vallis region (Loizeau et al., 2007).

- Global map of potential weathering sequences : Carter et al., 2015.

- Coatings : specific micro-environments (Lanza et al., 2014, Lanza et al., 2015).

- Example of model coupling volcanic degasing, redox conditions, and climatic feedback to estimate how long liquid water was present on Mars : Wordsworth et al., 2020.

- Detection of phyllosilicates as a key mineral for surface and subsurface aqueous alteration : Carter et al., 2013.

- Thyrrena Terra : tens of craters with ejecta and central peaks (Ehlmann et al., 2009, Marzo et al., 2010).

- Deep crustal environments : astrobiological interest of deep subsurface geomicrobiology (Escudero et al., 2018).

- Impact-crater related hydrothermal systems : Newsom, 1993; Schwenzer and Kring, 2009).

- Sinter deposits, geyserite and concretions : Djokic et al., 2017.

- Detection of silica-rich concretions : Ruff, 2016, Ruff et al., 2016, Ruff et al, 2010.

- Detection of silica around Nili Patera volcano (Skok et al., 2008).

- Suite of hydrothermal minerals within Chasmata close to Tharsis volcanoes : Thollot et al., 2012.

- Lava-induced hydrothermal systems : Duhamel et al., 2022.

3) Mars : habitability and the search for extraterrestrial life from the geological point of view (Frances Westall, CNRS-Orléans)

- Radiation on Early Earth : Cockell and Raven, 2004.

- In situ origin of organic molecules : lightning in volcanic clouds in a CO2 atmosphere (Cleaves, 2020), crustal processes and hydrothermal vents (Baross + Hofman 1986, Russell and Hall, 1997).

- Extraterrestrial organic matter preserved in 3.33 Ga sediments from BarBerton, South Africa : Gourier et al., 2019.

- EPR of extraterrestrial carbon : Bourbin et al., 2013

- Elemental composition of rocks on early Earth : Venneman and Smith, 1999, Gale et al., 2013, Smithies et al., 2007.

- Biological periodic table : Nies, 2016.

- Mechanisms of metal resistance and detoxification taking place in Archaea, Bini 2019.

- Energy sources on the early Earth, Pascal et al., 2013.

- Scenarios for the emergence of life on Earth: exposed landmasses (Sutherland group, others),subaerial springs(Damer, Dreamer 2021, van Kranendonk et al., 2021), impact craters (Osinski et al., 2013, Sasselov et al., 2021),submarine environments - hydrohermal vents, sediments (Baross +Hofman, 1985, Russell and Hall, 1997, Martin et al., 2008, Westall et al., 2018, Hickman-Lewis et al., 2020), pumice rafts (Brasier et al., 2011), deep seated faults (Schreiber et al., 2012), radioactive beaches (Adam et al., 2016, Ebisuzaki, Maruyama, 2017), aqueous droplets (Saha et al., 2022).

- Emergence of life in hydrothermal vents : Martin and Russell, Phil. Tr. Roy. Soc. Lond. 2002.

- Evolution of habitability on Mars and the fate of life : Des Marais, 2010.

- Punctuated habitability : Cockell et al., 2012, Westall et al., 2013, 2015.

- Lakes, impact craters and cryosphere on Mars : Michalski et al., Nat. Astron. 2022, Osinski et al., 2013, Clifford et al., 2013, Mustard, Tarnas, 2021).

- Subsurface habitability on Earth today : Onstott et al., Astrobiology 2019.

- Mars subsurface habitability and groundwater upwelling : Michalski et al., Nat. Geosc., 2013.

- Geological evolution of Oxia Planum 1 : Fawdon et al., JGR Planets, 2022.

- Fossilized microbial filaments in hydrothermal veins in South Africa : Cavalazzi et al., Nat. Comm., 2021.

- Microbes in subsurface sediments : Parkes et al., Mar. Geol. 2014, Monty, Westall, Van der Gaast 1991.

- Chemotrophic microbes in a hydrothermal, nutrient-rich volcanic sample, Josefsdal Chert 3.33 GA, Barberton: Westall et al., 2015, Hickman_Lewis et al., 2020, Westall et al., 2006, Gourrir, Westall et al., 2019.

- Experimental alteration of basalt by chemolithotrophs : Kölbl, Front. Microbio, 2022.

4) Organic matter on ancient and modern Mars. Into martian habitability (Caroline Freissinet, LATMOS/IPSL)

- Similar past environmental conditions between Mars and the Earth (Mojziz et al., 1996 & 2001, Schopf et al., 2002, Westall et al., 2005 & 2015)

- Persistant liquid water (Bibring et al., 2006, Carter et al., 2010)

- Atmosphere, CH4 abundance (Webster et al., Science 2015 & 2018)

- Yellowknife Bay : lake deposit (Grotzinger et al. Science 2015)

- Cumberland drill : Detection of chlorine bearing organic molecules (Freissinet et al., JGR Planets 2015)

- Viking GCMS (Biemann et al., 1977)

- Re-analyzing of past missions : following SAM GCMS results (Guzman et al., JGR Planets 2018)

- Replicate Cumberland drill sample based on ChaMin mineralogy (Vanoman et al., 2014)

- Benzoic acid is a good candidate for the organic precursor of chlorobenzene at Cumberland in Yellowkinfe Bay (Freissinet et al., PSJ 2020)

- Low exposure time of Cumberland to galactic and solar cosmic rays (Farley et al., Science 2014).

- Presnce of Organic Carbon/carbonates in Gale CRater materials (Sutter et al., JGR 2017)

5) Emergence and early evolution of live on Earth (Puri Lopez-Garcia, CNRS & Univ Paris-Saclay)

- Microbial dark matter : Hug et al., Nature (2016)

- Hyperdiverse archea near life limits at the polyextreme geothermal Dallol area : Bellila et al , Nature (2019)

- Active microbial airborne dispersal and biomorphs as confoiunding factors for life detection in the cell-degrading brines of the polyextreme Dallol Geothermal Field : Bellila et al. (2022)

- Abiotic synthesis of amino acids in the oceanic lithosphere : Menez et al, Nature (2018)

- Synthesis of metabolic precursors catalyzed by Fe2+ : Muchowska et al, Nature (2019)

- Viruses : living or not living : Lopez-Garcia & Morrira, Nat Rev Microbiol (2009), Krupovic, Dolja, Koonin, Nat Rev Microbiol (2019), Kazlauskas, Nat Comm (2019)

- A hot, « autotrophic» origin of life : Martin & Russell (2003), Koonin & Martin (2005)

- Native iron reduces CO2 to intermediates and end-products of the acetyl-CoA pathway : Varma et al., Nature 2018

- Nonenzimatic metabolic reactions and life's origins : Muchowska et al., 2020

- Cell compartments : Monnar & Deamer (2002)

- RNA-peptide-lipid world ? Lombard et al., Nat Rev Microbiol (2012)

- The origin of biological membranes : Koga et al (1998), Koonin & Martin (2005), Wächtershäusser (2003)

6) Search for life in the Solar System (J. Vago, ESA)

- Review of the Viking landers' GCMS results : Navarro-Gonzalez et al.(2011)

- (Per)chlorates complicate the TV detection of organics : Steininger et al .(2012), Glavin et al. (2013)

- WISDOM Site characterization : Heggy and Paillou (2006)

- Organic compounds in Escherichia coli : Neidhardt and Umbarger, 1996)

- Dose rate from MSM vs depth : Hasslet et al. (2014)

- Radiolyse constant k measured by Kminek and Bada (2006)

- Increased stability of aqueous solutions : Hammmond et al. (2018)

7) Overview of the composition and structure of icy worlds (O. Bollengier, LPG)

- Historical perspective on alien oceans : Kuiper (1944)

- Tidal heating suggested as a major energy source for moons of giant planets : Peale et al. (1979)

- Life on seafloor at hydrothermal vents : Carliss et al. (1979)

- Phase diagram of water : Dunaeva et al (2010)

- Solar elemental abundances : Lodders (2020)

- The atmosphere of comets : Bockelée-Morvan and Biver (2017)

- Soluble fraction of chondrites : Fanale et al. (2001), Izawa et al. (2010)

- Primordial organic matter : Derenne and Robert (2010), Okumura and Mimura (2011)

- Mass analysis of E-ring particles : Postberg et al. (2018)

- Mapping of the 450 nm absorption Band on the surface of Europa : Trumbo et al. (2019)

- Gas hydrate structures : Hassanpouryouzband et al. (2020)

- Stability of gas hydrates : Choukroun et al. (2013)

- The structure of Titan : Néri et al. (2020), Sotin et al. (2021)

8) Water-rock interactions: hydrothermal reactions, energy, and habitability of icy ocean worlds and beyond (Yasu Sekine, ELSI, Tokyo Tech)

- Hydrothermal system on Earth : McCollom and Shock (1997), McCollom (2008)

- Available energy in Rainbow hydrothermal vent on Earth : Amend et al. (2011).

- Archaeal diversity and community development in deep-sea hydrothermal vents : Takai and Nakamura (2011)

- Energy-based habitability : Hoehler (2007)

9) Exoplanet Atmosphere Recipes (E. Kite, Univ. Chicago)

- Planets are numerous… and many have atmospheres : Madhusudhan et al. (2019), Winn & Fabrycky (2015), Hsu et al. (2020).

- Detection of exoplanet atmosphere : Beichman et al. (2014)

- Atmospheric data for TRAPPIST-1 : Agol et al. (2021)

- Overview of exoplanet atmosphere : Wordsworth & Kreidberg (2022)

- Contingency versus convergence : Carter (1983)

- Energy budget : Wordsworth et al. (2018), Margarita Marinova et al. (2005), Kite et al. (2019)

- Type of atmosphere needed for habitability : Nisbet & Nisbet (2008), Poudel et al. (2020)

- Possibility of non-water requiring life : Takai et al. (2008)

- Many exoplanets with too thin atmospheres for habitability : Forget & Bertand (2016)

- Many exoplanets with to. thick atmospheres for habitability : Yamila Miguel et al. (2016), Guillot et el. (2018)

- Temperature/pressure/composition profiles : for Neptune, Wictorowicz & Ingersoll (2007), for K2-18b, Charney et al. (2021)

- Questionable reports of phosphine at the cloud level of Venus' atmosphere : Trompet et al. (2021)

- Obliquity driven C02 exchange between Mars 'atmosphere, regolith and polar cap : Buhler & Piqueux (2021)

- Composition of exoplanets atmospheres : Olson et al. (2018), Catling & Zahnle (2020).

- Methane cycle on Titan : Lunine & Atreya (2008)

- Exoplanet volatile supply : Piani et al. (2021)

- Discovery of a planet around AU Mic, a 22 Myr-old star : Plavchan et al. (2020)

- Equilibrium condensation of a gas with the composition of the Sun : Zeng et al. (2019), Piani et al. (2020)

- Atmosphere sources: gas from nebula, de Pater & Lissauer (2010)

- Terrestrial planet formation : Marty et al. (2016)

- Planet gravity and distance-from-star regulate atmosphere rentention : Zahnle & Catling (2017), Wyatt et al. (2020)

- key processes in atmospheric escape : Zahnle & Catling (2009).

- Gravitational binding energy to thermal energy : Lewis & Prinn (2004)

- Key to whether atmospheres can escape over geologic time : upper-atmosphere temperature : Watson et al. (1981)

- A giant comet-like cloud of hydrogen escaping the warm Neptune-mass exoplanet GJ 436b! (2015)

- Metastable He : Spake et al. (2018)

- Atmospheric evolution on inhabited & lifeless worlds : Catling & Kasting (2017)

- Catastrophic destruction of rocky planets : Perez-Becker & Chiang (2013)

- Fate of planet's atmosphere : Zahnle et al. (2007), Lammer et al. (2018)

- Hydrogen-over-magma hypothesis : Bean et al. (2021)

- Atmospheres for low density sub-Neptunes : Rogers et al. (2015)

- Waterworlds hypothesis : Lugue & Pallé (2022)

- Gap in the radius distribution understood as a photo-evaporation valley driven by XUV-powered hydronamic escape of hydrogen : Owen & Wu (2017), Gupta & Schlichting (2019), Lee & Connors (2022)

- Removal of atmospheres and oceans by giant impacts: Kegerreis et al. (2020), Denman et al. (2020)

- Importance of solar wind erosion of atmospheres : Jakosky et al. (2018), Dong et al. (2018)

- Principles of Planetary Climate : Pierrehumbert (2010)

- Lunar volcanism produced by a transient atmosphere around the ancient Moon : Needham & Kring (2017)

- Why care about rocky-exoplanet water abundance and carbon abundance : Salvador et al. (2017)

- Transition between primary and secondary atmospheres : Wordsworth & Kreidberg (2022)

- Planet-formation era processes matter for exoplanet water and carbon abundance : Kite & Barnett (2020), Bower et al. (2022)

-« Earth cousins » : Kite et al. (2021), Bean et al. (2021), van Lieshout & Rappaport (2018), Kite & Ford (2018)

- Pressure-temperature-composition regimes of exoplanet atmosphere-silicate interfaces : Kite et al. (2021)

- Exotic « water worlds « ? : Tian & Ida (2015), Kimura & Ikoda (2022), Kite & Ford (2018)

- Sun-Neptunes : Benneke et al. (2019), Bezard et al. (2022), Benneke et al. (2019)

- Core straification/fuzzification : Liu et al. (2019), Nisr et al. (2020), Markham et al. (2022), Lichtenberg et al. (2021)

- Redox intro : Wordsworth et al. (2018)

- White dwarf FeO estimates : Doyle et al. (2020)

- Simple models suggest that sub-Neptunes have deep, long-lived magma oceans : Kite et al. (2020), Howe & Burrows (2015), Chean & Rogers (2016), Bodenheimer et al. (2018°, Vazan et al. (2018)

- Making endogenic waterworlds : Kite & Schaefer (2021), Ikoma & Genda (2006), Kimura & Ikoma (2020)

- High-molecular-weight atmosphere : Kite & Schaefer (2021)

- Effect of magma on atmosphere : Kite et al. (2020), Chachan & Stevenson (2018), Ikoma et al. (2006), Ormel et al. (2021)

- H2 dissolution into magma explains the radius cliff : « fugacity crisis » : Kite et al. (2019)

- Simple model of atmosphere evolution : Kite & Barnett, 2020.

- Exoplanet sub-Neptune atmosphere recipes : Kite et al. (2019), Kite et al. (2020), Kite & Barnett (2020), Kite & Schaefer (2021)

10) Outer Solar System Exploration (O. Grasset, LPG)

- Asteroid exploration science : Franchi et al. (2017)

- Voyage 2050 : Uranus and Neptune science : ESA white papers from Fletcher et al., and Guillot et al.

- Uranus & Neptune Trajectories with Jupiter flyby : NASA Ice Giant pre-decadal study final report (2017)
- Mission dedicated to Io : Thomas et al.
- Mission dedicated to Jupiter's radiation belts : Roussos et al.
- Missions dedicated to Europa : Prieto-Ballesteros et al., Blanc et al.
- Missions to Enceladus : Choblet et al., Sulaiman et al., Mitri et al.
- Missions to Titan : Rodriguez et al., Sulaiman et al., Mitri et al.
- Plume diving maneuver by an aerial-aquatic aircraft : Liang et al. (2013)

11) Les océans cachés des lunes de Jupiter et Saturne (C. Sotin, LPG)

- Echanges océan - source thermale : Russell et Nitschke (2017)
- Magmatisme induit par effet de marée sur le plancher océanique d'Europe : Behounkova et al (2021)
- Tiger stripes d'Encelade (Porco et al, 2006)
- Production de chaleur au pôle sud provenant des tiger stripes : Spencer et al (2006)
- Coeffcients de degree 2 du champ de pesanteur d'Encelade : Iess et al. (2013)
- Composition des geysers d'Encelade : Glein et al (2015) et Hsu, Postberg, Sekine et al (2015), Affholder et al (2012), Barge and Rodriguez (2021)
- Modèle de noyau poreux d'Encelade : Choblet et al (2017)

IV – Assessment: students' group work

The group work carried out by the Partnership's students focused on 4 main themes related to habitability:

1 - exploring the habitability on the Martian icy mid- latitudes,

2 - searching for habitable environments on Ceres,

3 - characterizing the habitability of Triton,

4 - life detection on Enceladus

Mission Concept White Paper

Exploring habitability on the Martian icy mid-latitudes

Yellow Team (AUBRY Camille – Touvin Lindsey – Guenneguez Melanie
PaLOMa - Past life On Mars

1. General goals of the mission in relationship with our target

The main objective for the mission is to search the evidence of past or present life underground with the focus on the past life remnants. Water ice glaciers were targeted for the research due to high potential to preserve organic prints. Besides, air bubbles inside can provide information about sealed organic matter entrapped in them. Nevertheless, the possibility of aquifers remaining at the bottom of the icy layer could also provide equivalent information.

2. List the main scientific objectives of the mission

Over the next decade, the main scientific questions are based on the search for life outside the Earth. The sites identified as having high potential will be based on features that are likely to harbor traces of biosignatures. The exploration phase will search for these traces and analyze the ground environments. In parallel with this objective, understanding the structure of the body to enable the development of future manned missions will be one of the objectives.

In this context, several scientific questions arise. In order to know whether life could have developed in the past on Mars, we need to understand the geological and mineralogical history of the planet in order to be able to reconstruct the environment over time. Once these initial questions have been answered, it will be important to examine the possible presence of underground water reservoirs, in particular aquifers. Finally, we will have to ask ourselves about the presence of organic and chemical signs and the possible preponderance of stable isotopes characteristic of life.

3. Science investigations

a. Landing site on the Martian icy mid-latitudes

On the poles CO_2 ice is dominant and are not relevant for the purpose of this mission. Also, equator zone lacks stable ice deposits. Instead, conditions are very different at mid latitudes, which are rich in water ice. Mid latitude zone of 30°–45° in northern hemisphere was chosen by the mission architecture team due to the pressure conditions that affect landing.

Location for landing should correspond to several criteria such as ice affected by a past geodynamical active environment. The choice of the area of interest was made based on the heat flux and crust thickness maps (Figure 1A) [4]. To manage these objectives, the western hemisphere of the planet shows high enough level of heat flux. In addition, a largely faulted zone covered with craters is present on this hemisphere at the targeted latitudes. Several craters within the area have glaciers inside and the largest of them is ~31km of diameter (Figures 1B, C). It presents typical structures constructed by ice like eskers. The selection of the largest possible crater within the area is also dependent on the landing conditions, because of the ellipse size. Also, the crater floor should be as flat as possible.
It can be assumed that the thickness of the largest deposits on top of the glacier in the chosen range of latitudes should not exceed 3 meters [5]. More precise data about the thickness could be assessed after the Mars Ice Mapper mission. Also, precise information could be received in situ using ground penetrating radar data from the rover.

From regional point of view, the chosen crater is located near North East of Tharsis formation. The crater belongs to Early Hesperian volcanic unit, the age of the formation is close to 3,5 Ga. At the same time the crater is close to Noachian – Hesperian boundary (Figure 1D), meaning sampling of both units is possible. Based on the position next Kasei Valley [3] there is a possibility of aquifer be presented in the targeted region.

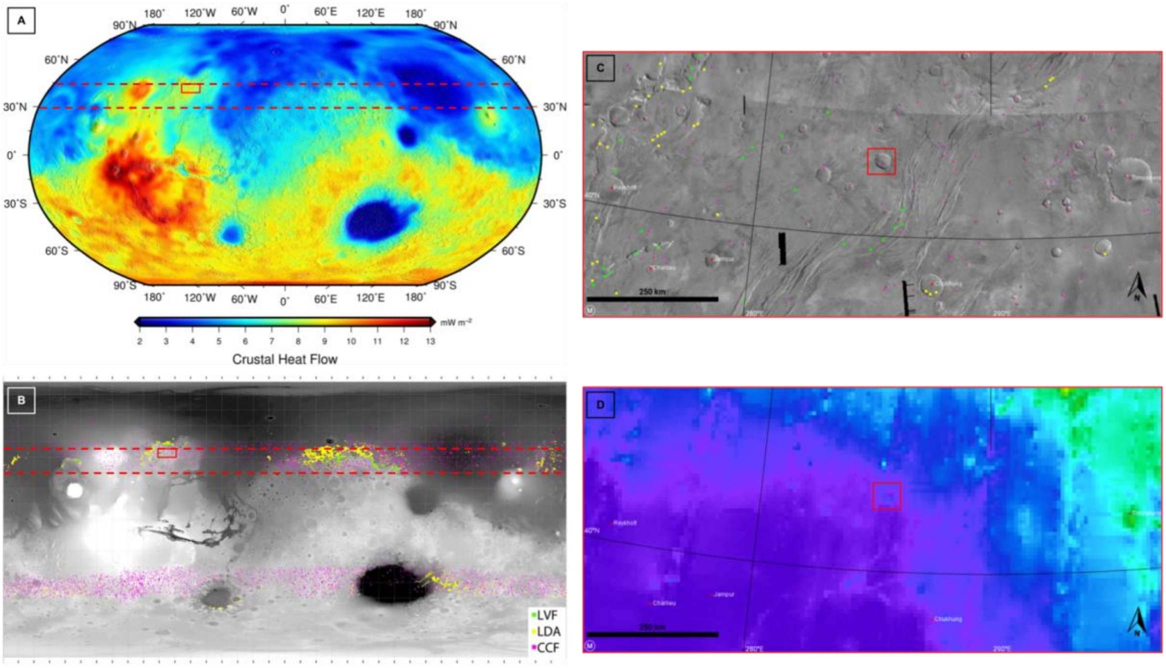

Figure 1: Characteristics used to focus on the landing site. (A) Heat flux map (B) Glaciers map (C) Biggest crater with a glacier (D) Geological map around the crater in (C).

b. Mission concept and scenarios

The mission will be a rover class mission in order to obtain the necessary mobility to characterize the target area. Ejected from the atmosphere, the rover will have a landing system consisting of 2 parachute phases: a supersonic parachute and a pair of subsonic parachutes (Figure 2), in the same style as the Perseverance rover [8]. This technique is based on the need to present a landing zone with a radius of 8 km [6], which in our case is much smaller than the target crater of about 32 km in diameter.

The rover will then be equipped with 6 wheels to ensure the rover's stability and mobility inside the crater [7] even if the latter has a relatively flat surface. The instruments and the rover itself will be powered by a set of solar panels [7] that should sustain the mission. In order to prevent dust from blocking the panels and reducing the efficiency of energy collection, we propose the incorporation of a solar collector system. To facilitate the various measurements that will be carried out, all the instruments will be designed for measurements towards the ground and not towards the sides of craters. This is an engineering legacy from the various rovers already present on the surface of Mars: Curiosity and Perseverance [6].

This will be a flagship mission with a budget between ExoMars and Perseverance (\$1.2 billion < x < \$2.7 billion) [6]. Indeed, the concept of this mission is largely based on that of the ExoMars mission but introduces new instruments. In order to limit the budget, a lot of existing data, notably from the Exo Mars probe sent into orbit around Mars in 2003, will be used to characterize potential sites for future exploration.

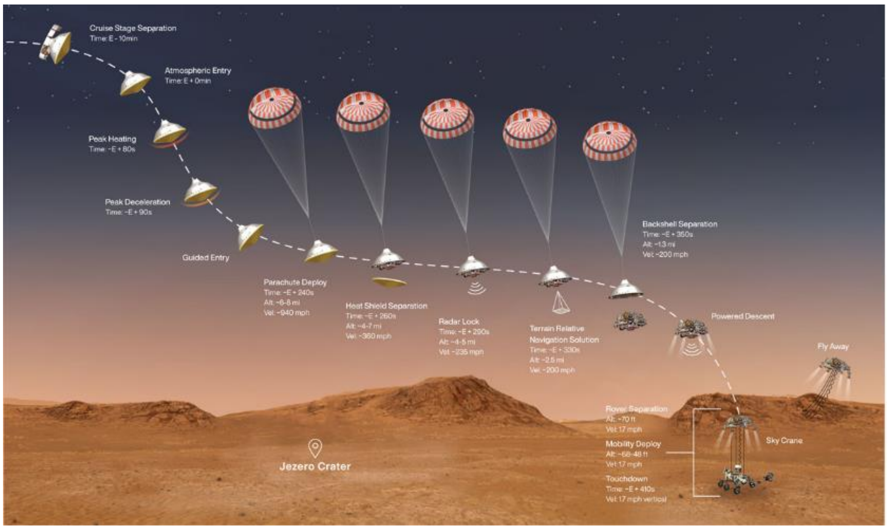

Figure 2: Perseverance rover entry, descent, and landing profile [8]

c. Instruments used for the mission

Various instruments will be used to meet our main objective: to search for evidence of past or present life underground. Some instruments will be inherited from past missions, some will be modified from past uses and some will be completely new.

Heritage technology

Hazard Avoidance Cameras, Navigation Cameras aid in autonomous navigation and obstacle avoidance. Science Cameras/Close-Up Imager (CLUPI) aim to take color images, analyze the elemental composition of vaporized materials, and provide close-up views of the minerals, textures, and structures. Descent Imager provides a high resolution and true color video of landing.

Neutron spectrometer (like ADRON-RM in Curiosity rover) aims to find optimal sites for drilling. The Autonomous Detector of Radiation of Neutrons is a neutron spectrometer which will look for subsurface hydrogen in the form of bound water or water ice and hydrogen-bearing compounds such as hydrated minerals. Main objective is to search for biosignatures and biomarkers such as major soil neutron absorption elements (Cl, Fe, S, Ti, etc.) or hydrogen content (free or bound water). The principles and design are inherited directly from the DAN instrument, but with a reduction of mass.

Drill (like ExoMars drill): It is composed of a drill tool equipped with position and temperature sensors, a set of extension rods designed to penetrate a maximum length of 2 meters, a rotation-translation group, a drill box structure, and a back-up drill tool in case of a problem. It is devised to acquire soil samples in a variety of soils types. Its main function is to penetrate the soil, acquire a core sample, extract it, and deliver it to the inlet of the Rover Payload Module, where the sample will be distributed, processed, and analyzed by the Analytical Laboratory Drawer (Raman, X-Ray spectrometers). A minimum number of 17 samples shall be acquired and delivered by the Drill for subsequent analysis. It samples the ice without melting it with a multistore technology. The drill unit and assembly, integration, and verification (AIV) approach will be compatible with the class IVb planetary protection directives applicable to the mission.

Ground-penetrating RADAR (such as WISDOM radar) The ground-penetrating radar allows to obtain a high-resolution 3D map of the subsurface and to identify the most promising location for drilling. The method consists in measuring the propagation delay and the amplitude of reflected waves by a sudden transition in the electrical parameters of the soil. By analyzing these reflections, we can reconstruct a stratigraphic map of the subsurface to understand the local distribution and state of H_2O. This instrument is inspired from the WISDOM radar located on ExoMars [1].

➢ *Transfer technology*

Thermal Emission Imaging System (like THEMIS) is a multispectral imager allowing to determine the distribution of minerals and quantify the physical properties of morphological features observed in high-resolution images. We will use the THEMIS data-set from the 2001 Mars Odyssey mission.

Micro X-ray fluorescence spectrometer (technology transfer): X-ray fluorescence will provide information about the reconstitution of paleoclimatic variations and dynamics, hydrological conditions by trapped micro-debris ice and dust analysis. It is also best suited for chemical bio-signatures, for any kind of elemental pattern or feature that may originate from microbial metabolism such as organic compounds so-called CHNOPS and elements such as Mg, Ca, Na, K and Fe which are essential minerals nutrients for life. The X-ray fluorescence spectrometer is suggested to be mounted at the end of the rover's robotic arm.

RAMAN spectrometer (technology heritage and transfer: SHERLOC) is a non-destructive chemical analysis aimed to detect both organic and mineral phases and is very sensitive to carbonaceous matter and bio-molecules. It is thus particularly suited for the detection of bio-signatures and bio-markers such as complex organic matter (CH_2, CH_3, NH_2) or Amino-acid associated with present or ancient life.

➢ New technology

Transient electromagnetic (TEM) is a geophysical exploration technique in which electric and magnetic fields are induced by transient pulses of electric current and the subsequent decay response measured. Depending on subsurface resistivity, induced current, receiver sensitivity and transmitter-receiver geometry, TEM measurements allow geophysical exploration below the surface. It enables the characterization of subsurface including the eventual presence of an aquifer, volcanic dykes and sills, salty layers, and porous layers.

4. Summary

The concept of a rover mission is far from being a revolutionary model, Mars 2020 and Mars Science Laboratory are projects that integrate the search for traces of life on Mars. Inspired by the success of these models, we propose a similar system in never-before-explored Martian sites: the icy mid-latitudes. This mission will be a first of its kind in terms of its exploration site and the provision of new measurement equipment such as a magnetometer. The example of this mission will serve as a precursor to more effective studies of other bodies in our solar system with icy surfaces. However, this mission is still very expensive, but the success of the latest missions to explore the Martian surface gives it a certain advantage.

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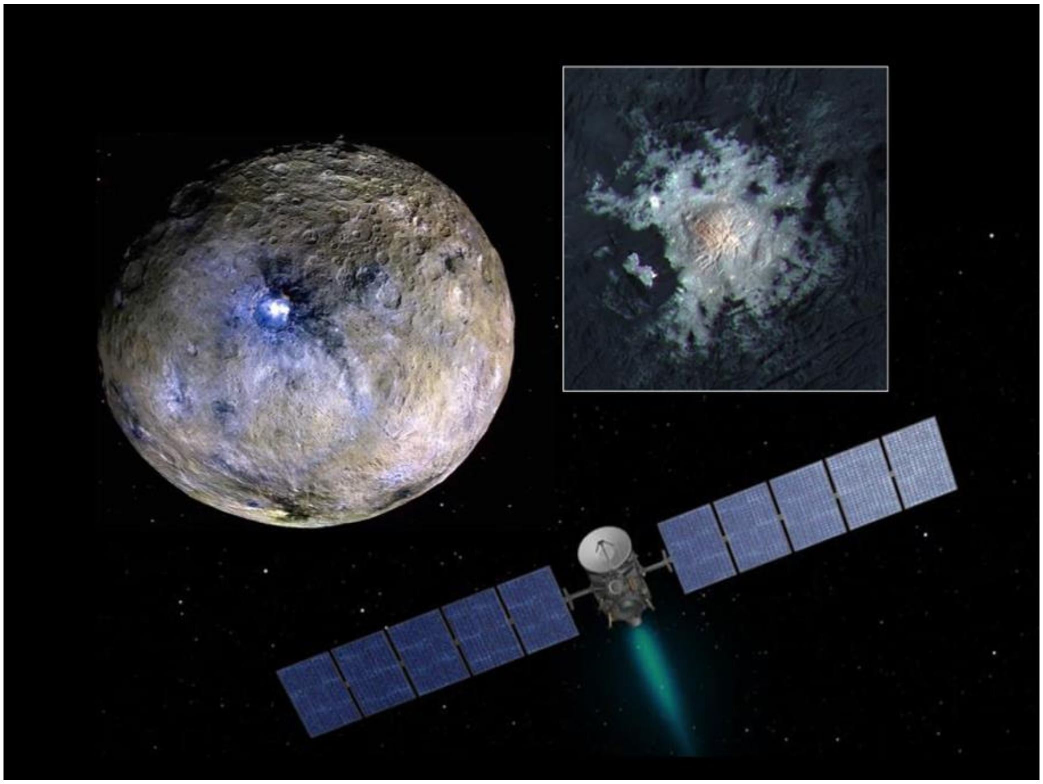
Nantes Université

Mission Concept

Searching for habitable environments on Ceres



MOTTE Mikael Andreas Caccia M2 IMPG
02/12/2022

Contents

I. General goals of the mission

Dwarf planet Ceres (*Figure 1*) is a compelling target for future exploration because it hosts at least regional brine reservoirs and potentially ongoing geological activity. As the most water-rich body in the inner solar system, it is a representative of a population of planetesimals that were likely a significant source of volatiles and organics to the inner solar system.

This mission's main target is a better characterization and understanding of Ceres in its structure and composition.

This will be accomplished through the following goals :

- **Goal A** : investigate the subsurface origin of the fresh emplacements on Ceres;
- **Goal B** : investigate organic matter on Ceres and possible implications for habitability;

1. *Investigate the subsurface origin of the fresh emplacements on Ceres*

The results from DAWN mission show promising evidence for ongoing activity at Cerealia Facula crater (Castillo et al, 2022). Seeking additional evidence for brine exposure at Occator Crater (*Figure 2*) would inform on the mechanisms that drive recent and current activity. Furthermore, a new mission would make it possible to observe landscape modifications that occurred since the DAWN mission. New images with a better resolution will allow us to look for changes in the distribution of bright material.

More insight over the ongoing mechanisms that occur on the surface of Ceres would give crucial information of the understanding of the dynamics of the inner layers of this body. This information could then be applied to the study of other planetary bodies and further increase our knowledge of the forces and systems that rule our Solar System.

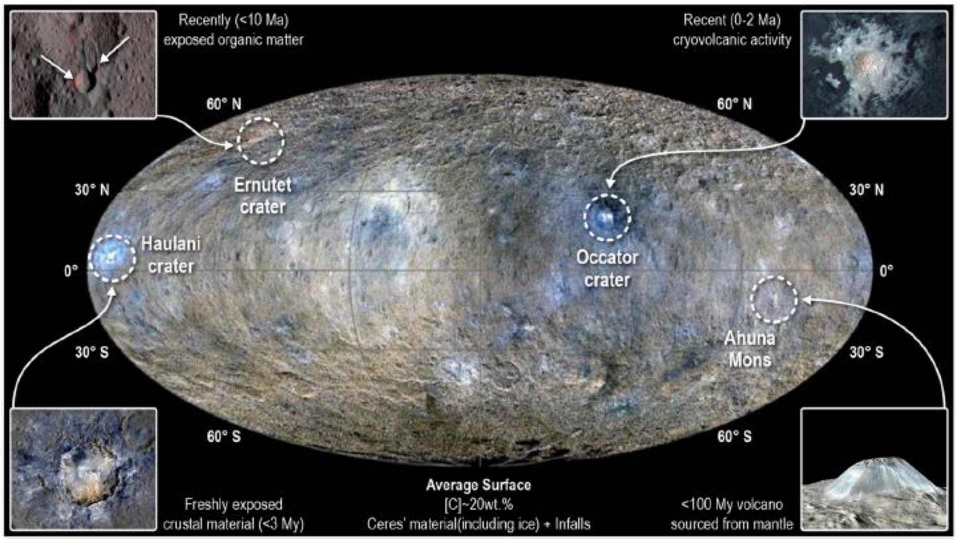


Figure 1 : Global map of Ceres with the main scientific points of interest. (Castillo et al, 2022).

2. Investigate organic matter on Ceres and possible implications for habitability

As emerged from spectral data from DAWN mission, Ceres is rich in organic matter, possibly coming from the outer Solar System (Castillo et al, 2022). For this reason, it is safe to assume that Ceres regolith contains super-chondritic concentrations of carbon. However, information is lacking about the nature of that material and whether it was accreted early on, processed inside Ceres, and/ or formed in-situ.

Determining the inventory of organic compounds falls under the theme of understanding the availability of biogenic elements and their evolution and interactions over time.

In the specific, Occator evaporites likely contain rocky material and organic matter that has evolved on top of regolith material and can help assess the long-term evolution of organic compounds. This information would be of major interest for understanding prebiotic systems.

These two main goals, will be accomplished with the following scientific objectives (*table 1*) :

Goal A	*Goal B*
– Define the depth of the brine reservoir	– Assess the abundance and distribution of the organic matter on Ceres
– Define the composition and properties of brines	– Measure the environmental conditions on Ceres
– Investigate the formation and the dynamical history and evolution of fresh emplacements	– Identify the origin and evolution of organic matter

Table 1 : Main scientific objectives for each main goal

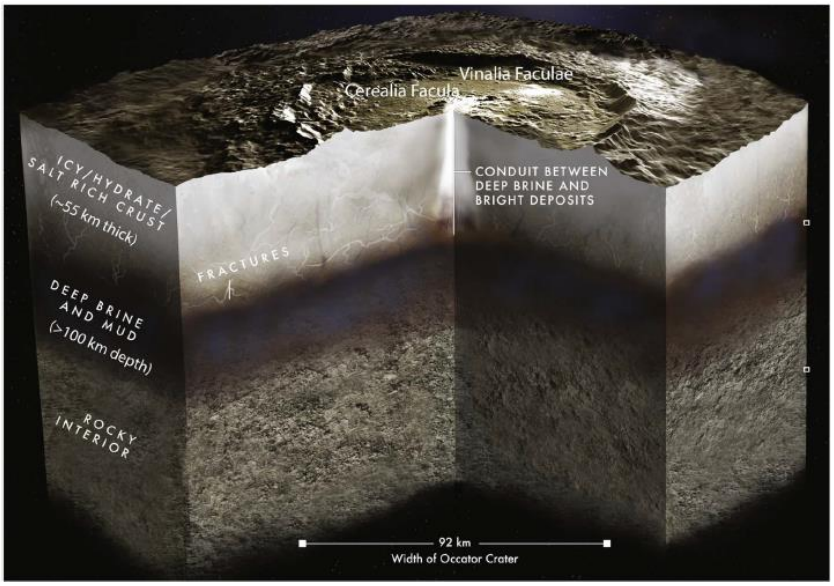


Figure 2 : Geophysical context for the geological site investigated by this study. (Castillo et al, 2022).

II. Investigate the subsurface origin of the fresh emplacements on Ceres

To address the first goal of the mission, we propose the following scientific objectives:

- **Define the depth of the brine reservoir;**
- **Instruments** : Electromagnetic Sounding;

The first objective of the mission is to define the depth of those features to characterize if there is a global ocean in the subsurface of the asteroid or just plums. This information could allow us to understand if those features come from a single event, or if they are a part of the geological activity of the body. Furthermore, it will be possible to determine if those deposits participate to the evolution of the cooling down of Ceres. Electromagnetic sounding is the best approach to make the measurements because of the high inductive response of a salty water.

- **Define the composition and physical and chemical properties of brines;**
- **Instruments** : Raman, XRD, mass spectrometer, Sample Collector (driller/shovel);

We will get better knowledge about the compounds and their distribution in the subsurface layers. This information will give us clear understanding on how this body has been formed and its state of differentiation from CI chondrites. To reach this goal, some analyses are required. First, Raman spectroscopy will give us information about the chemical structure and the chemical behavior of the deposits. XRD analysis will provide a quantitative approach of the chemical composition. These two instruments provide complementary measurements and the GC MS, which is a powerful tool to directly analyze samples from the ground. All together we will get isotopic measurements of the compounds.

- **Investigate the formation and the dynamical history and evolution of fresh emplacements;**
- **Instruments** : High resolution stereo camera, specific isotopic measurements, IR mapper, electromagnetic sounding;

We want to have a clear understanding on the mechanisms of material exchange between the interior and surface provided by the cryovolcanism using high resolution stereo camera and IR mapping. These methods of observation are aimed to identify structures on Ceres surface and their distribution.

Next, we want to determinate the geomorphology of the deposits using electromagnetic sounding and precised images of the surface with high resolution stereo camera to interpret the landscape modifications which will allowing us to determine if there was recent activity.

For the final investigation of the formation, evolution, and dynamic history of the fresh emplacements, an inventory of the components (mineralogy, isotopes) is important to identify the relationship between mineral and chemical phases. To achieve this goal, IR mapping of the study area is important to get the distribution of petrological components and interactions between the rock surface layer and water.

III. Investigate organic matter on Ceres and possible implications for habitability

To address the second goal of the mission, we propose the following scientific objectives:

- **Assess the abundance and distribution of the organic matter on Ceres;**
- **Instruments** : Raman, GCMS, NMR spectroscope, Spectral Sensor;

Evidence for long chain aliphatic compounds have been observed in Ernutet Crater. However, information is lacking on the nature of the material and its distribution (Castillo et al, 2022). In order to get a thorough understanding, information is needed about the variety and concentration of the organic matter (OM), the isotopic ratio to understand the fractionation and distribution of the OM and their variation through time. To analyze and quantify the variety of OM we will use Raman and Mass Spectroscopy and Spectral Imagery from the orbiter will be used to pin point targets. The Mass Spectrometer can then also be used to quantify the isotopic ratios at each target. Comparisons can then be made by looking at OM found in carbonaceous chondrites to understand the change in their nature which is key to understanding the habitability of Ceres' oceans.

- **Quantify the physical and chemical conditions of the environment on Ceres;**
- **Instruments** : Raman, isotopic fractionation(GCMS);

Dark materials within the Occator Crater are trapped within the evaporates which are distinctive of aluminum-rich clays unique to the area (Castillo et al, 2022). In these brine regions, organics have been found in association with carbonates and it's suggested that the organic matter evolved deep within the interior (Castillo et al, 2022). We must analyze this substance in order to determine the long-term evolution of organic compounds on Ceres (Castillo et al, 2022).

We will use a land rover equipped with Raman Spectroscopy, Mass Spectrometer, and XRD. Raman will identify the organic compounds, while Mass Spectrometry will do the isotopic analysis to detect their nature. Isotopic ratios of $^{13}C/^{12}C$ are critical to discover the origins of the organics and their degree of maturation (Castillo et al, 2022). XRD will give a clear idea about the environments that host the organics. Together these analyses will address a full composition inventory that includes mineralogy, elemental, and isotopic species of the organic compounds and their petrological phases between the mineral phases (Castillo et al, 2022).

- **Determine the origin and evolution of organic matter;**
- **Instruments** : Mass spectroscopy, Raman spectroscopy and XRD;

The origin of organic matter on Ceres' surface is now debated (whether exogenic or endogenic?) since it has been suggested that the surface regolith contains exogenic materials. We will constrain the origin and evolution of organic matter based on in-situ measurement data of Raman Spectroscopy, Mass Spectrometer, and XRD analyses. Findings of organics co-existing salt-rich materials could support the possibility of endogenic origin.

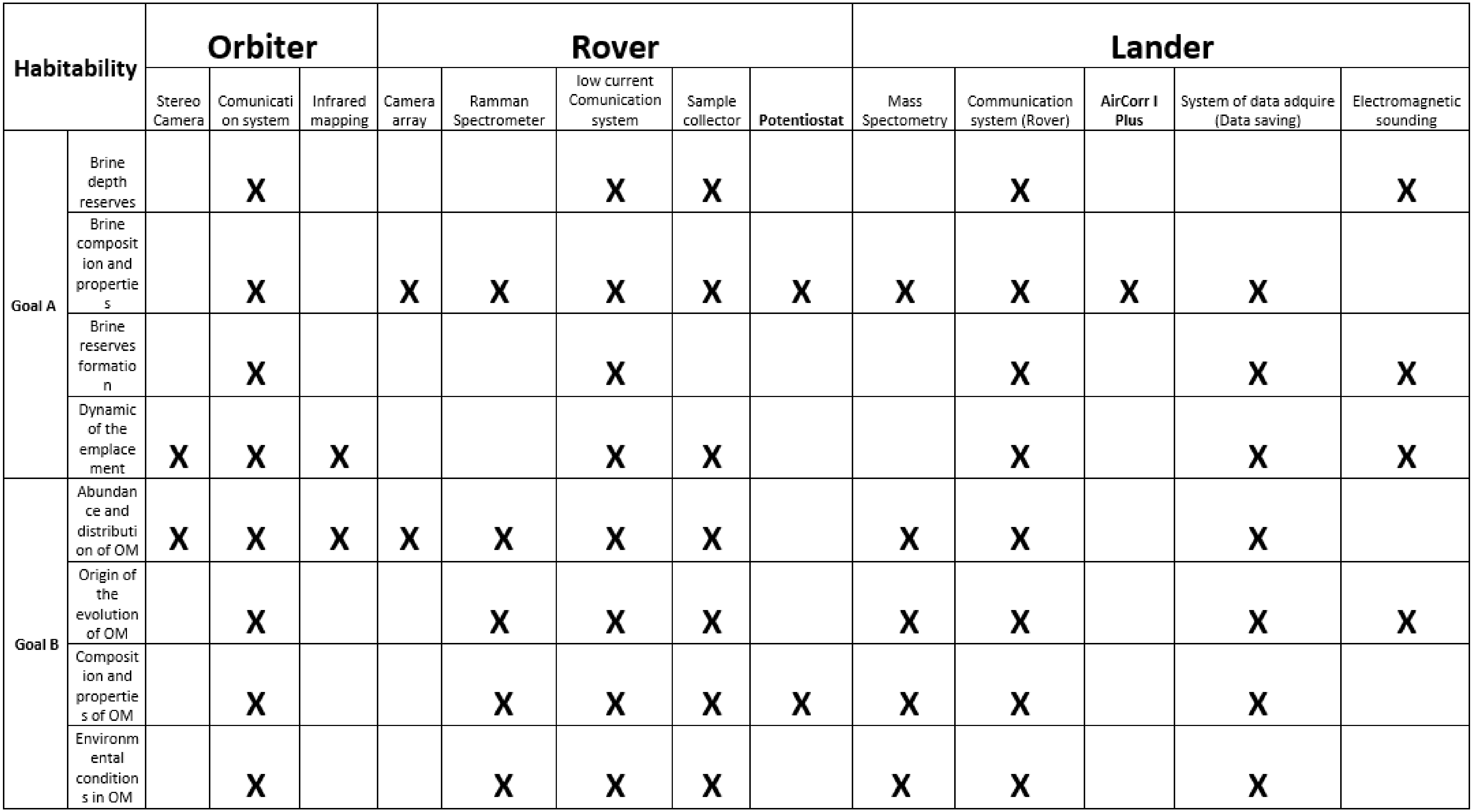
IV. Payloads and instruments

The mission will require tree majors payloads (*Image 1*) :

- **The Dawn-like Orbiter** that will provide the geophysical measurements with electromagnetic sounding and high-resolution images with stereo cameras and IR imager. The orbiter will also collect the data from the lander and the rover and will be the link between Ceres and the earth;
- **The Phoenix Lander** will be the "laboratory" of the mission. This payload will be able to carry precises chemical and isotopic analyses with Raman, XRD, mass spectrometer and the new AirCorr I Plus system. It will be able to provide geophysical analyses of the landing site with electromagnetic sounding;
- **The MMX Rover** will be used to collect sample from the area of investigation thanks to a drill system, in relation with the orbiter that could point some interesting places. The samples will be then returned to the lander for analyses. To be sure that areas of investigation will be interesting, the rover will be able to do some Raman analyses and will carry the new potentiostat;

Image 1 : illustration of the payloads (Left to right : Dawn-like Orbiter, The Phoenix Lander, and the MMX Rover

All the instruments that the mission will carry are listed in the *table 3* just below. The *table 4* regroup the instruments and their characteristics. Some limitations were identified before selecting the instruments : the Energy (Power, charging time), weight, data transmission, operation, price, and materials.



Habitability		**Orbiter**			**Rover**					**Lander**				
		Stereo Camera	Comunication system	Infrared mapping	Camera array	Ramman Spectrometer	low current Comunication system	Sample collector	**Potentiostat**	Mass Spectometry	Communication system (Rover)	**AirCorr I Plus**	System of data adquire (Data saving)	Electromagnetic sounding
Goal A	Brine depth reserves		**X**				**X**	**X**			**X**			**X**
	Brine composition and properties		**X**		**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	
	Brine reserves formation		**X**				**X**				**X**		**X**	**X**
	Dynamic of the emplacement	**X**	**X**	**X**			**X**	**X**			**X**		**X**	**X**
Goal B	Abundance and distribution of OM	**X**	**X**	**X**	**X**	**X**	**X**	**X**		**X**	**X**		**X**	
	Origin of the evolution of OM		**X**			**X**	**X**	**X**		**X**	**X**		**X**	**X**
	Composition and properties of OM		**X**			**X**	**X**	**X**	**X**	**X**	**X**		**X**	
	Environmental conditions in OM		**X**			**X**	**X**	**X**		**X**	**X**		**X**	

Table 3 : list of the instruments and their roles for each goal of the mission

Instruments	**Specifications**
HRSC Stereo Camera 2.3 m/pixel	1.9kg ; 2.3 m/pixel
Comunication system Orbiter	High Gain UHF antenna 30kg
Infrared mapping	IR camera, resolution 50m/ pixel ; 1Kg
Hardware / Software System	Microcontrollers, 0.1 Kg
Camera array	4 Low resolution camera wheels - 4 to explore camera 0.35 Kg
Ramman Spectrometer (5-10 um spacial resolution for Organic Compounds)	3.11 Kg, 16.6W, 2 cameras check material
Comunication system Rover-Lander	high gain antenna, Low gain and high gain antenna 1 kg
Sample collector	0.2 Kg
Potentiostat	**0.02 kg**
Gas Chhromatography - Mass Spectometry	10 kg
Communication system Lander	UHF, low gain, and high gain antenna, 25kg
AirCorr I Plus (Temperature, RH, Air corrosion)	**0.3 kg**

Table 4 : List of the instruments and their specifications weight and resolution (Was not added the solar energy source and the exoskeleton which is a part of the obligatory weight)

V. New technology

We proposed two new instruments : the **potentiostat** to obtain the curve of redox in the seawater of CERES and the multisensing system **AirCorr I Plus** to obtain the values of the environment (Temperature, RH, Air Corrosion).

The potentiostat let us know information about the interaction of the salts dissolved in seawater with some material, obtaining information about the composition of the seawater (Segura et al, 2020). On the other hand, the AirCorr I plus, gives us information about corrosive environments, oxygen presence, temperature, and relative humidity.

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Winter School - Habitability Week

Assessing the habitability of a unique KBO, Triton

Since the one flyby of Voyager 2 in 1989, no other mission has been sent to observe Neptune and its satellites. However, with the small amount of data acquired and the approximately 40 % of the moon that has been imaged, Figure 1, it is no doubt that Triton seems to be a very good candidate for habitability. Additionally, Triton has a retrograde orbit indicating its possible Kuiper belt origin. This particularity must be responsible for an enriched composition of carbon and nitrogen compared to other icy moons. More, the potential plumes observed at the surface and the ice shell-like crust and induced features seem to indicate ongoing active processes and a potential liquid ocean.

I – Generals Goals

- **G1: Triton, a Kuiper Belt Object with an Ocean?**

Among all the icy moons already known inside the solar system, many of them are now considered to be ocean worlds. Although not extensive, several characteristics of Triton point to the likelihood that it may host a subsurface ocean (tidal heating history associated with KBO capture, extremely young surface, and large apparent surface heat flux, plumes), but further investigation is required to demonstrate the current presence of an ocean.

- **G2: Triton, a habitable active world?**

Explore ongoing re-surfacing processes (cryo-volcanism, plumes, melt/crystallization water ice shell, …) and their impacts on the interior-surface exchanges are key research questions to understand to what extent is Triton a viable place with habitable conditions for the emergence and the sustainability of life.

Figure 1: Photo of Triton taken by Voyager 2 (only 40% of the moon is visible) - NASA.

II – Scientific objectives

The chief scientific objectives of new missions to study the ice giants and their moons were well described in the 2003 Planetary Decadal Survey's call for the exploration of Pluto and small KBOs (Simon et al. 2018), namely:

- Map the surfaces of these bodies in three dimensions to determine their photometric properties, geologies, and geophysical expressions;
- Map the surface compositions of these bodies to determine their surface and interior compositions and compositional variegation;
- Assay their atmospheric compositions, vertical structures, escape rates, and solar wind interactions;
- Determine their densities;
- Assay their satellite and rings systems for content;
- Map the surfaces and surface compositions of their satellites;
- Search for intrinsic magnetic fields.

Within this context, our main scientific objectives propose to answer the following questions (Figure 2):

- Does Triton have a global subsurface ocean underneath its icy crust? Is it sufficiently thin to drive/feed the observed plumes on its surface?
- Is the possible subsurface ocean salty enough to allow the measurement of an induced magnetic field? Can this salinity be compatible with the presence of life?
- For such a distant icy world, does the heat budget (radiogenic heat plus tidal heating: thermal energy) allow for the sustainability of life in the subsurface? Are the energy sources sufficient to sustain life in the hydrosphere?
- Which geological processes have been responsible for the large-scale resurfacing of the satellite, and the high variety of geological terrains? Are these processes (convection, possible material exchange, active core) still ongoing? Are they compatible with habitability?
- Does the oxidant potential of the coupled atmosphere/surface/ionosphere contribute to the habitability of the boundary surface/interior with the possible creation of tholin-like organics in the haze and transfer to the subsurface ocean?

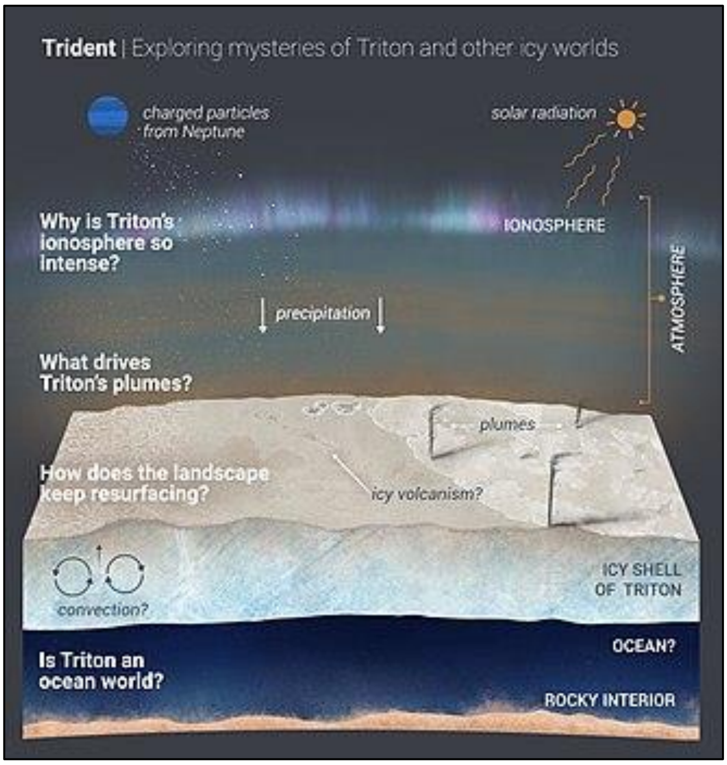


Figure 2: Potential description of Triton surface/interior/atmosphere exchanges – NASA.

III – Science investigation and associated instruments

We present in this section the payload necessary to investigate the scientific objectives considering a spacecraft and a potential lander. The subject of budget limitations will be discussed in the following section. The scientific objective, the acquisition needs, the characteristics, and the origin of each instrument are presented in detail.

A) Spacecraft Instruments

Ground Penetrating Radar: radar sounder optimized for the penetration of the Triton's surface which is covered by ice up to a depth of 9 km. Radar can also perform "radiometry," allowing the radar to help determine the temperature of what it observes. It also has a third mode called "scatterometry," which allows the instrument to see smoothness and roughness at a molecular scale. Indeed, Radar can overcome Titan's haze which would hide its surface from most instruments.
Requirements: multiple profiles for targeted regions with less than 50 km spacing, penetration depths of 1-9 km, and vertical resolution of 30 m to 1% of target depth. (Nitrogen ice cap, cryo-volcanism, paleolakes).
Heritage Instrument: *RADAR* from the Cassini mission.
Characteristics: Mass = 41.43 kg / Operating Power = 108.40 W / Data Rate = 364.8 kbyte/s / Cost = 160 M$

Hyperspectral camera (UV-VIS-SWIR-MIR): the hyperspectral camera will play a role in the characterization of the composition of the surface by looking at the absorbance peaks in many wavelengths of the ice. This camera should be able to look for global high-resolution imaging in a large range of wavelengths (0,3-2,5um) and albedo to be sure to look at every area of interest of the possible element of the surface.
Requirements: multiple flybys to cover most of the surface of the moon and to have an idea of the global composition of the surface.
Heritage Instrument: *HRSC (High-Resolution Stereo Camera)* from the Mars Express mission.
Characteristics: Mass = 19.6 kg / Operating Power = 45.7 W / Data Rate = 11.5 kbyte/s / Cost = 19 M$

Laser altimeter: transmits laser pulses toward planetary surfaces that measure the round-trip time of the light pulse between emission and the returned surface reflection to determine the distance of the spacecraft concerning the surface. This will investigate, classify, and constrain the ages of tectonic and cryovolcanic activity and landforms to determine properties such as the location of deforming regions and the thickness of deforming layers by creating a global topographic map.
Requirements: multiple flybys to cover most of the surface of the moon.
Transfer Instrument: *TRALA* - adapted from GALA (JUICE) and BELA (BepiColombo).
Characteristics: Mass = 15 kg / Operating Power = 50 W / Data Rate = 1 kbyte/s / Cost = 43 M$

Magnetometer: Measures the strength and direction of the magnetic field in its vicinity. It is necessary to define magnetic field models, as well as to assess their temporal variability. The instrument will measure the magnetic field of both Triton and Neptune to understand the interaction between the bodies. These measurements are crucial to study the location and composition of the potential subsurface ocean in Triton. The study of Triton's magnetic field could also be an indicator of the salinity of its potential oceans, a question which is a key factor in determining their habitability.
Requirements: multiple orbits over time to follow the time and spatial evolution of the magnetic field of Neptune and its impact on Triton.
Heritage Instrument: *MAG* from the Cassini mission.
Characteristics: Mass = 3 kg / Operating Power = 3.1 W / Data Rate = 3.6 kbyte/s / Cost = 37 M$

Plasma measurements: Neptune's magnetic field transports plasma (as charged particles) from Neptune's ionosphere and Triton itself. Triton's generated magnetic field and magnetic signal are both distorted by the plasma. These measurements will investigate the density, temperature, and movement of plasma near Triton.
Requirements: Multiple flybys to have a global overview of the plasma.
Heritage Instrument: *PIMS* from the Europa Clipper mission.
Characteristics: Mass = 1.4 kg / Operating Power = 1.3 W / Data Rate = 0.032 kbyte/s / Cost = 80 M$

Radiofrequency telecommunication system: Excluding the seismic study, the best way to study the interior of the body is through the estimation of the gravity field. Using the Doppler shift created by variation of spacecraft velocities on the frequency of the Earth-Orbiter radio link with a high-gain antenna, the gravity field of Triton can be reconstructed. Combined with the topographic data, the gravitational potential variation can also be deduced as well as the tidal heating and the tidal deformation of the body. This experiment will provide essential information on the internal structure and the presence and stability of a liquid layer below the ice shell (Deboy et al 2003).
Requirements: multiple flybys to cover most of the surface of the moon.
Heritage Instrument: *REX* from the New Horizon mission.
Characteristics: Mass = 0.16 kg / Operating Power = 1.6 W / Data Rate Sent = 2 kbyte/s / Cost = 56 M$

Thermal imager: A thermal imager could help the team address some relevant questions, such as the surface distribution of the main species, and the connection between geology and composition. LEISA works with two filters: the first, sensitive to wavelengths in the range from 1.25 to 2.5 micrometers, will give us general thermal composition mapping at a resolution of something like 10 km/pixel (this value held for Pluto and Charon). The second filter uses a well-known transition of the N2 molecule (alpha to beta transition at 35 K) to detect dependent changes in the spectral structure of this molecule. This will in turn provide surface temperature maps.
Requirements: multiple flybys to cover most of the surface of the moon.
Heritage Instrument: *LEISA* from the New Horizon mission.
Characteristics: Mass = 6 kg / Operating Power = 3.7 W / Data Rate = 9.8 kbyte/s / Cost = 43 M$

B) Lander Instruments

Seismometer: to constrain interior structure. Seismology can investigate icy ocean worlds at depths greater than just the ice shell thickness and might also reveal the presence of local heterogeneities within the ice shells. If these pockets are analogous to aquifers and subglacial lakes on Earth, they can be suitable for a habitable environment.
Requirements: Landing on a flat and loose surface.
New Instrument: *SEISMOMETER* inspired by the proposal Joint Europa Mission.
Characteristics: Mass = ~17 Kg / Operating Power = ~2.2 W / Data Rate = ~0.8 kbyte/s / Cost = ~60M$

Sample analysis platform: to study the water and nitrogen ice. The objective is here to perform a chemical analysis of dissolved oxygen, pH, conductivity, and NH^{4+}, NO^{3}, Ca^{2+}, K^{+}, Cl, and NO^{3} concentrations to define the potential habitability of Triton's environment and search for large organics molecules (proteins, lipids, etc.). It will carry three life-detection instruments working in the liquid phase: multi-probe immunoassay (MPAS); Multiparametric probe (MPP); VISTA (Volatiles In Situ Thermogravimetric Analyzer).
Requirements: Landing on a flat surface in an area of interest.
Transfer Instrument: *TAWL* Triton Astrobiology Wet Laboratory – adapted from MECA (Phoenix).
Characteristics: Mass = 23 kg / Operating Power = 42 W / Data Rate = 4 kbyte/s / Cost = 100 M$

Miniaturize weather stations: to study temperature, pressure, and wind speed and direction. The objective is here to perform a follow-up of the evolution over time of the temperature, the pressure, and the wind on Triton's surface and their impact on habitability. Winds of N2 are a possible explanation for the movement of the plumes at the south pole. It will carry three instruments a barometer, an anemometer, and, a thermometer.
Requirements: Landing in an area of interest.
Transfer Instrument: *TWT Temperature and Winds for Triton* - adapted from TWINS (InSight).
Characteristics: Mass = 1.2 kg / Operating Power = 12 W / Data Rate = 0.7 kbyte/s / Cost = 24 M$

C) Payload summary

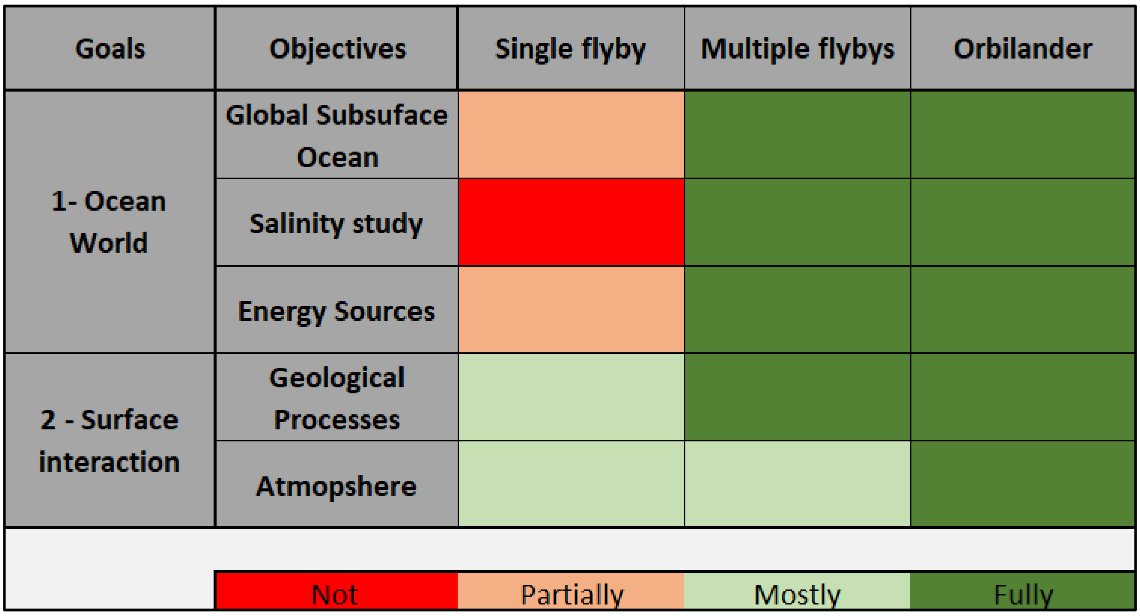
Payload characteristics	*Orbiter*	*Lander*
Mass (kg)	86.59	41.2
Operating Power (W)	380.7	5.5
Peak Data Rate (kbyte/s)	213.8	56.2

IV – Mission concept

A) Architecture of the various missions

In terms of the possible mission, we present here 3 potential architectures to respond to our scientific objectives. First, a single flyby mission seems not sufficient to fully answer all the questions and will lead us to the same kind of data we already have. On contrary, multiple flybys will allow us to collect a better range of data, but also to cover the global surface of the planet, and answer fully almost all our scientific questions. Even if it answers fully all the questions, the last proposition, an oriblander, seems a little bit too early since we didn't discover the global surface of the moon.

Table 1: Summarize of the proposed missions



Goals	Objectives	Single flyby	Multiple flybys	Orbilander
1- Ocean World	Global Subsufface Ocean	🟧	🟩	🟩
	Salinity study	🟥	🟩	🟩
	Energy Sources	🟧	🟩	🟩
2 - Surface interaction	Geological Processes	🟢	🟩	🟩
	Atmopshere	🟢	🟢	🟩
	🟥 Not	🟧 Partially	🟢 Mostly	🟩 Fully

B) Budget class

Establishing a budget for a space mission of this magnitude is not easy. Few missions have made trips to Neptune to date, and we suffer from the lack of data on which to base our calculations. It should also be noted that the need for quality information requires the sending of instruments with sufficient precision and therefore requires careful logistics both in terms of space and power supply. All these parameters make the budget difficult to predict. We have based our budget as best we can on the price of different instruments and/or similar missions. The minimum budget for the instruments is 500 M$ to which we will have to add numerous expenses like the launch (estimated to be 500 M$), the communication, the operating, the delays, and other potential worries during the development (that can go up to 500 M$). All these parameters lead us to, at least 1.5 billion dollars missions such as ESA's L-size missions or NASA's New Frontiers programs.

Payload characteristics	*Orbiter*	*Lander*	*Launch*
Cost (M$)	438	184	500

V – Summary

Triton is the largest moon of Neptune; it was seen during a flyby by the Voyager 2 mission. It is an unusual icy moon because it is the only moon with a retrograde orbit with a possible origin in the Kuiper Belt Object. Today one of the biggest questions in space exploration is the habitability potential in the solar system. There has been a recent interest in Jovian and Saturnian icy moons to assess this subject, but other important bodies have been left behind because of their distance. Today, 60% of Triton surface remains unknown but interesting surface features such as possible geysers and ice-crust in the southern hemisphere have been observed. The concept mission addresses exploration for a subsurface ocean and habitable conditions. The research requires geophysical measurements and remote observations. The instruments aim to study the surface and the first kilometers of depth. The use of a ground penetrating radar, plasma measurements, and next-generation remote sensing devices are the highlight of orbit analysis. Although a hybrid mission (orbiter and lander) is not the most viable, it is the one that will provide us with the most information about Triton with a combination of in-situ analysis instruments and geophysical measurements.

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VII – Contacts

ada.abboud-oropeza@etu.univ-nantes.fr,
camille.delarue@etu.univ-nantes.fr,
mathis.pinceloup@etu.univ-nantes.fr,
simon.gouzy@etu.univ-nantes.fr,
yann.musseau@univ-nantes.fr,
up201704548@edu.fc.up.pt,
pliniosborges@gmail.com,
emavalente@ua.pt,
luigi.gisolfi@studenti.unipd.it,
nasser.aminizadkovij@studenti.unipd.it,
simone.pascucci@studenti.unich.it,
nicolekaterin.diasmarques@studenti.unich.it,
gianluca.chiarolanza@unich.it

Life Detection on Enceladus

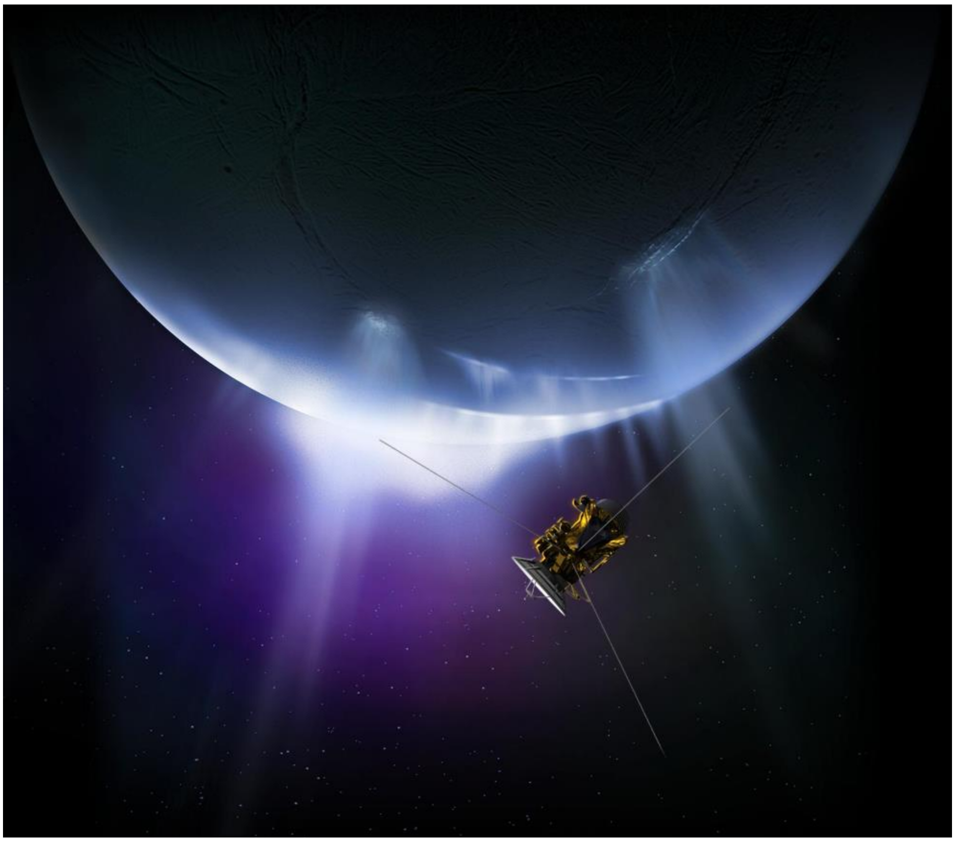
Space mission proposal: En-Cell-Adus

BARBEY Mathieu

KBIDI Samuel

M2 EPS

Supervised by ROSENBLATT Pascal



I- Introduction

Enceladus is a satellite of Saturn, with a diameter of around 500 km, making it the sixth moon of Saturn by size. Enceladus is mostly covered by fresh ice, making it one of the most reflective bodies of the solar system. Most of the surface of the moon is young and presents tectonically deformed terrain. Thanks to the Cassini spacecraft, we know today Enceladus hides a global ocean with an ice shell above. The Cassini mission yielded a tantalizing discovery by revealing the presence of ice plumes at the South Pole of the moon. Recent models linked the presence of the plumes to an anomaly of the heat flux at the South Pole, linked with hydrothermalism at the surface of the core.

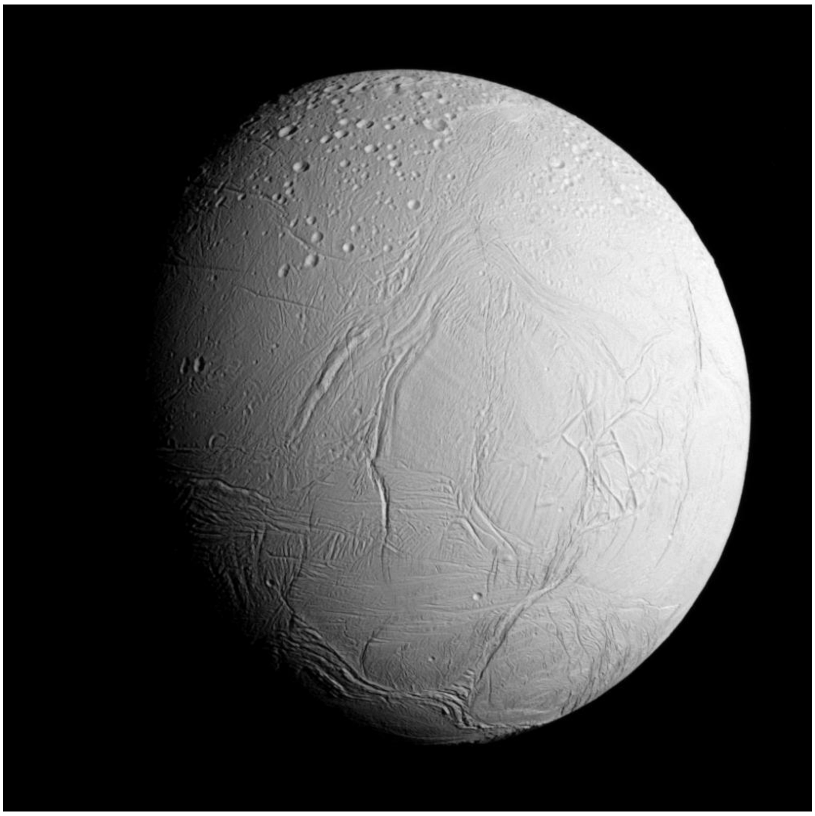


Figure 1: Enceladus suface taken by Cassini. Tiger stripes are on the lower left, close to the terminator. Credit: NASA/JPL-Caltech/Space Science Institute

With our current knowledge about Enceladus and icy moons, it’s possible to think of this moon as a potential world where life can emerge, thanks to the chemical interactions between the rocky core and the ocean. The analysis of these plumes revealed, thanks to flybys of Cassini, between 6.5 and 17.5 km/s relative to Enceladus, the composition of the ejected ice grain constituting the plumes (Waite and al 2020 [3], [6]). The cosmic dust analyzer instrument revealed a composition rich in salts and silicates, with the presence of many organic molecules. Thanks to the detection of organic molecules such as Carbon chains organics and Methane, we know that Enceladus can sustain potential life present within the subsurface ocean. However, the cosmic dust analyzer on board Cassini couldn't decipher more complex molecules such as amino acids, and we are still left with a lot of unknowns after the end of the mission in 2017.

We know today Enceladus has a habitable environment but not if life is present. The purpose of this space mission proposal is to answer this crucial question: does Enceladus possess life forms beneath its ice shell, or not? This question is addressed in the Decadal survey 2023-2023, and is a main research axis in planetary science.

II- Main scientific objectives

To answer this crucial question, we propose to proceed in four steps. The first step is to analyze in situ material and try to identify evidence of life in ice particles projected outside the moon by the plumes. We plan to collect surface deposits of fresh ice which will fall on the surface, but also to catch the ice particles as they do fall back. About 90% of the particles actually do fallback, and they are usually the heaviest ones, containing the most promising heavy organic molecules (Morgan.L and al 2016 [4]), which motivates our choice of a surface mission compared to a high altitude flyby. The second step will be to deduce the composition of the subsurface ocean, and to try to detect biosignatures and/or molecules strongly associated with the presence of life, with in situ analysis. The third step will be to obtain a time series of these analyses to verify if the composition of the ocean, and the concentrations and presence of molecules are constant in the time and space. The last step will be to evaluate the overall indications of life, similar to the approach of the ELF proposal (figure 2), and obtain ocean properties like the pH or the salinity. With these properties, a life probability score will be established, giving the likeliness of the presence of life on Enceladus. We can consider as indicators of life enantiomers, fatty acids like glycine, methane or ethane with propane, the isotopic ratio of C/H and CHNOPS atoms, as an indicator of the presence of life. Enantiomers can be a good indicator, because the presence of one enantiomer in majority would not correspond to what we expect of abiotic processes, where we would have a racemic distribution.

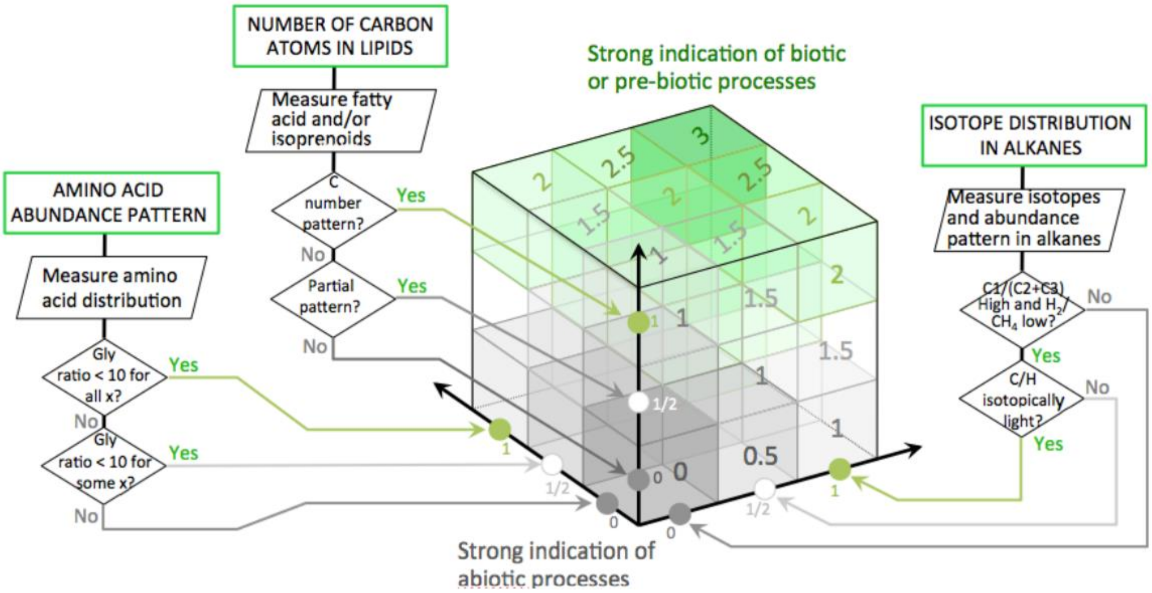


Figure 2: ELF's three distinct tests for life are as universal as possible, and seek properties of life that are inherent in its essential nature. Positive results for all three would strongly argue for life within Enceladus. Morgan L. & al . (2016)

Glycine is interesting because this fatty acid is preserved from cosmic radiation. Additionally, as the constant matter deposits from plumes accumulate quickly, a drill will be able to access this molecule at a very shallow depth (several millimeters only). About the detection of Methane, ethane, and propane, we need to be careful. These gasses can be produced by inorganic processes, so we can't rely solely on these. However, if the ratio $CH_4/C_2H_6+C_3H_8$ is high, it could be a good indicator for the presence of Life [6]. It's the same problem for the isotopic ratio C/H. It can have an inorganic origin but bacteria preferentially select carbon-12 to produce methane instead of carbon-13, so if we can decipher between those too, we could obtain a very strong indicator for the presence of life. The last indicator which could be used are the CHNOPS (Carbon, Hydrogen, Nitrogen, Oxygen, Phosphorus, Sulfur) complex molecules. The presence of molecules containing C, H, O and N are already confirmed by Cassini but finding complex molecules containing phosphorus and sulfur will be a strong indication of biotic or pre-biotic processes. In addition to these indicators, it will be possible to refine the composition and some properties of the ocean compared to the data acquired by Cassini, like for example it's salinity, pH, it's fine elemental composition, the oxidation state of chemical species and to which degree chemical energy is available for potential life. Refining our knowledge about these parameters will permit us to build a "Life likeliness" score, which comforts us about the fact that Enceladus ocean has the capacity to create or sustain a life, and could motivate eventual future sample return missions. However, we decided to not try a sample return for this mission because of the high possibility of degrading our samples during the return trip, because of the high radiation levels present in the interplanetary medium, which can destroy organic matter. By the way, the amount of fuel needed to leave the Saturnian system and go back to Earth will be gigantic, and out of the current rocket launching capabilities. It could be interesting to consider this hypothesis when the technology will be able to counter radiation, and the launching capabilities and/or propulsion technologies will be more advanced.

III- Mission architecture and instruments

The mission is structured in two parts. We will have an orbiter with most of the scientific baggage, and a lander to collect samples of the surface and return to deliver them to the orbiter.

The instruments aboard the orbiter are divided in two main instrumental suites. The first instrumental suite, mostly dedicated to remote sensing and optical analysis of the surface and plumes, is composed of a multispectral camera, of a spectral range between 400 and 2500 nm, in addition to an optic camera and a laser altimeter to determine the best landing site around the South Pole. The second instrumental suite, dedicated to the analysis of surface samples, is composed of two main instruments. Firstly, a Raman spectrometer is proposed to prospect the variety of molecules present in the sample. The second instrument is a mass spectrometer, like the MASPEX developed for Europa Clipper, to characterize a wider range of molecules than the RAMAN spectrometer, and confirm and quantify the organic molecules detected with the latter one. In addition, an oven will be present in case we need to heat the samples, to melt ice for example. We hypothesize that an oven could permit to simulate the environment of the subsurface ocean and permits the detection of a wider range of organic molecules compared to the frozen samples.

To obtain the samples with the lander, we chosed a mission architecture which rely on a quasi-satellite orbit around Enceladus, furthermore described in Kawakatsu & al. (2016) [7]. This orbit permits us to be within the vicinity of Enceladus, without worrying about large fuel expenditures throughout the mission to maintain the orbit. By the way, the Δv necessary to reach the surface from this orbit is minor compared to a classical Saturnian orbit (Neveu.M and al, 2020 [2]), opening the possibility of multiple landings, and consequently analyze multiple samples from different locations. The lander will be equipped with a long-duration battery, similar to the one used onboard Philae. This technology gives us a 60 hours window to land on the surface of Enceladus, collect samples and bring them back to the orbiter. Another advantage of the battery is that it's lightweight compared to solar panels or a RTG, limited cost compared to the addition of a second RTG, and it will still provide power in the shaded areas of the moon, would the lander land in one of these areas.

The mission of the lander is divided into three phases. The first phase is the landing. The lander will be equipped with a laser retroreflector, to always track it's position relative to the orbiter. A descent camera will be present to be sure the lander succeed to land on a suitable surface. To avoid contamination of the surface that will be sampled by rocket engine exhaust during descent, the lander will perform a cutoff maneuver at a certain height from the surface, and will perform a free fall to the chosed landing site. The low gravity of Enceladus (0,113 $m.s^{-1}$) could let the lander land safely with the use of shock absorbers or crush cores in the landing legs.

The second phase consists in sample collection. After the landing, the lander will use two instruments to collect samples. An automatic coring sampler like the ones used in Antarctica to collect ice rods, and an umbrella-like appendage to collect particles of the plumes that do fall back on the moon. This collector presents the advantage to analyze the heaviest particles and freshest particles of the plumes that do fall back shortly after ejection.

The third phase consists in the taking off to rejoin the orbiter in quasi satellite orbit. The low gravity of Enceladus permits it to perform this maneuver quite easily. The most technically challenging part of the mission would be the automatic orbital rendezvous with the orbiter, a procedure never done before, especially at such a distance from Earth. Indeed, the signal travel time with Earth from the Saturnian system is around 70 minutes. We propose a minimum of two sample returns, but this number can be reevaluated considering fuel expenditures.

Conclusion:

Thanks to the Cassini mission, we currently know that Enceladus has a subsurface ocean with the presence of some organic molecules. However, Cassini left us with more questions than answers about the potential presence of life inside of this ocean. With this mission proposal, we can unveil crucial details about the composition and the eventual presence of life in Enceladus subsurface ocean, which would be, if confirmed, the biggest breakthrough of planetary sciences in history.

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