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Moonraker: Enceladus Multiple Flyby Mission

O. Mousis[1,2], A. Bouquet[1,3], Y. Langevin[4], N. André[5], H. Boithias[6], G. Durry[7], F. Faye[6], P. Hartogh[8], J. Helbert[9], L. Iess[10], S. Kempf[11], A. Masters[12], F. Postberg[13], J.-B. Renard[14], P. Vernazza[1], A. Vorburger[15], P. Wurz[15], D. H. Atkinson[16], S. Barabash[17], M. Berthomier[18], J. Brucato[19], M. Cable[16], J. Carter[1], S. Cazaux[20,21], A. Coustenis[22], G. Danger[2,3], V. Dehant[23], T. Fornaro[19], P. Garnier[24], T. Gautier[22,25], O. Groussin[1], L. Z. Hadid[26], J.-C. Ize[1], I. Kolmasova[27,28], J.-P. Lebreton[14], S. Le Maistre[23], E. Lellouch[22], J. I. Lunine[29], K. E. Mandt[30], Z. Martins[31], D. Mimoun[32], Q. Nenon[24], G. M. Muñoz Caro[33], P. Rannou[7], H. Rauer[9], P. Schmitt-Kopplin[34,35], A. Schneeberger[1], M. Simons[36], K. Stephan[9], T. Van Hoolst[23], J. Vaverka[28], M. Wieser[17], and L. Wörner[37]

[1] Aix-Marseille Université, CNRS, CNES, Institut Origines, LAM, Marseille, France; olivier.mousis@lam.fr
[2] Institut universitaire de France (IUF), France
[3] Aix-Marseille Université, CNRS, Institut Origines, PIIM, Marseille, France
[4] IAS, Institut d'Astrophysique Spatiale, Université Paris-Saclay, CNRS, Orsay, France
[5] Institut de Recherche en Astrophysique et Planétologie, 9 avenue du Colonel Roche, F-31028, Toulouse Cedex 4, France
[6] Airbus Defence & Space, France
[7] Groupe de Spectrométrie Moléculaire et Atmosphérique, UMR 7331, CNRS, Université de Reims, Champagne Ardenne, Campus Sciences Exactes et Naturelles, BP 1039, F-51687, Reims, France
[8] Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany
[9] Institute for Planetary Research, DLR, Berlin, Germany
[10] Dipartimento di ingegneria meccanica e aerospaziale, Universitá La Sapienza, Roma, Italy
[11] LASP, University of Colorado, Boulder, CO, USA
[12] Imperial College London, London, UK
[13] Institute of Geological Sciences, Freie Universität Berlin, Germany
[14] LPC2E, CNRS, Université Orléans, CNES, 3A avenue de la Recherche Scientifique, F-45071, Orléans Cedex 2, France
[15] Physics Institute, University of Bern, Bern, Switzerland
[16] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109-8001, USA
[17] Swedish Institute of Space Physics, Kiruna, Sweden
[18] Laboratoire de Physique des Plasmas, Ecole Polytechnique, Palaiseau, France
[19] INAF–Astrophysical Observatory of Arcetri, Florence, Italy
[20] Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands
[21] Leiden Observatory, Leiden University, PO Box 9513, 2300, RA Leiden, The Netherlands
[22] LESIA, Paris Observatory, CNRS, PSL Université, Sorbonne Université, Université de Paris, F-92190 Meudon, France
[23] Royal Observatory of Belgium, Brussels, 3 Avenue Circulaire, B-1180, Brussels, Belgium
[24] Institut de Recherche en Astrophysique et Planétologie, 9 avenue du Colonel Roche, F-31028, Toulouse Cedex 4, France
[25] LATMOS-IPSL, CNRS, Sorbonne Université, UVSQ-UPSaclay, Guyancourt, France
[26] Laboratoire de Physique des Plasmas (LPP), CNRS, Observatoire de Paris, Sorbonne Université, Université Paris Saclay, Ecole polytechnique, Institut Polytechnique de Paris, F-91120 Palaiseau, France
[27] Department of Space Physics, Institute of Atmospheric Physics of the Czech Academy of Sciences, 141 00 Prague, Czech Republic
[28] Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
[29] Department of Astronomy, Cornell University, Ithaca, NY, USA
[30] Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA
[31] Centro de Química Estrutural, Institute of Molecular Sciences and Department of Chemical Engineering, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal
[32] ISAE-SUPAERO, DEOS/SSPA, Université de Toulouse, France
[33] Centro de Astrobiología (INTA-CSIC), Ctra. de Ajalvir, km 4, E-28850 Torrejón de Ardoz, Madrid, Spain
[34] Max Planck Institute for Extraterrestrial Physics, MPI/MPE, Center for Astrochemical Studies, Garching, Germany
[35] Analytical Biochemistry (BGC), Helmholtz Munich, Ingolstaedter Landstrasse 1, 85764 Neuherberg, Germany
[36] Seismological Laboratory, California Institute of Technology, 1200 E. California Boulevard, Pasadena CA 91125, USA
[37] German Aerospace Center, Institute for Quantum Technologies, Ulm, Germany
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Abstract

Enceladus, an icy moon of Saturn, possesses an internal water ocean and jets expelling ocean material into space. Cassini investigations indicated that the subsurface ocean could be a habitable environment having a complex interaction with the rocky core. Further investigation of the composition of the plume formed by the jets is necessary to fully understand the ocean, its potential habitability, and what it tells us about Enceladus's origin. Moonraker has been proposed as an ESA M-class mission designed to orbit Saturn and perform multiple flybys of Enceladus, focusing on traversals of the plume. The proposed Moonraker mission consists of an ESA-provided platform with strong heritage from JUICE and Mars Sample Return and carrying a suite of instruments dedicated to plume and surface analysis. The nominal Moonraker mission has a duration of ∼13.5 yr. It includes a 23-flyby segment with 189 days allocated for the science phase and can be expanded with additional segments if resources allow. The mission concept consists of investigating (i) the habitability conditions of present-day Enceladus and its internal ocean, (ii) the mechanisms at play for the communication between the internal ocean and the surface of the South Polar Terrain, and (iii) the formation conditions of the moon. Moonraker, thanks to state-of-the-art instruments representing a significant improvement over Cassini's payload, would quantify the abundance of key species in the plume, isotopic ratios, and the physical parameters of the plume and the surface. Such a mission would pave the way for a possible future landed mission.

Unified Astronomy Thesaurus concepts: Enceladus (2280); Astrobiology (74); Saturnian satellites (1427); Habitable planets (695); Ocean planets (1151); Interdisciplinary astronomy (804)

1. Introduction

One of the most striking discoveries of the Cassini mission to the Saturn system is the direct observation of a plume (Dougherty et al. 2006; Hansen et al. 2006; Porco et al. 2006; Spahn et al. 2006; Tokar et al. 2006; Waite et al. 2006) emanating from Enceladus, a small (252 km radius) icy moon of Saturn, with multiple lines of evidence suggesting the plume is sourced from a subsurface liquid water ocean. The plume emanates from the geologically young South Polar Terrain (SPT; Dougherty et al. 2006; Hansen et al. 2006; Porco et al. 2006; Spahn et al. 2006; Tokar et al. 2006; Waite et al. 2006) through four main fissures dubbed the "Tiger Stripes." It consists mostly of water vapor and water-ice grains, as well as CO_2, CH_4, H_2, NH_3, and complex organics (Waite et al. 2006, 2017; Hsu et al. 2015; Postberg et al. 2018; Glein & Waite 2020). The ~100 jets from the surface (Porco et al. 2014) and a likely more diffuse emission (Spitale et al. 2015) are responsible for the replenishment of Saturn's diffuse E-ring and the Enceladus water torus (Hartogh et al. 2011).

Cassini data revealed Enceladus as one of the most promising objects for habitability in the solar system (Hemingway & Mittal 2019; Cable et al. 2021; Hao et al. 2022). The composition of the icy grains containing various salts (Postberg et al. 2009, 2011) demonstrates a subsurface liquid source for the plume material, i.e., an internal sea that is in contact with a rocky core. Gravity measurements (Hemingway & Mittal 2019) and observations of the libration (Thomas et al. 2016) of the ice shell point to a global ocean under an icy crust of variable thickness (thinner under the SPT; see Figure 1) in contact with a rocky core of modest density made of porous rock and/or aqueously altered minerals. Detection of H_2 in the gas phase of the plume (Waite et al. 2017) and SiO_2 particles in E-ring grains (Hsu et al. 2015) are evidence of ongoing or geologically recent hydrothermal activity on Enceladus's seafloor resulting from alteration of minerals by water.

On Earth, seafloor hydrothermal vents provide chemical gradients that sustain life-forms in the absence of sunlight. On Enceladus, the composition of the volatile phase of the plume indicates that its subsurface ocean features chemical disequilibria that would be usable for metabolic reactions (Waite et al. 2017; Ray et al. 2021; Hoehler 2022). Mass spectrometry measurements in the plume also show the presence of various organic molecules over a wide range of masses (e.g., tentative detection of C_2H_6, CH_3OH, and C_8H_{18}; varied macromolecular organics with mass >200 amu, awaiting further characterization; Magee & Waite 2017; Postberg et al. 2018). Of the six elements commonly thought to be necessary for life (C, H, O, N, P, and S), only P and S have not been firmly detected at Enceladus, likely due to their modest abundance and the limitations of Cassini's instruments. The discovery of a strong thermal anomaly on Enceladus's icy surface and evidence of hydrothermal chemistry (hydrogen gas, silica nanoparticles, sodium salt–rich ice grains in the plume) along with the organics and liquid water suggest that habitable conditions could exist beneath the moon's icy crust.

The question of the age and formation scenario of Enceladus is also not completely solved (McKinnon et al. 2018), with lines of evidence indicating it may be as recent as 200 Myr (Ćuk et al. 2016; Neveu & Rhoden 2019). This has implications for the formation timeline of the Saturnian system, the materials available in the ocean, the extent of the rock–water interaction, and the lifetime of the ocean—and therefore the time available for life to emerge.

All of these discoveries and the related outstanding questions have recently led the 2023–2032 US National Academies' Planetary Science and Astrobiology Decadal Survey to recommend to NASA either a large (Flagship) or midsize (New Frontiers) mission whose aim would be to accomplish multiple flybys of Enceladus[38] prior to landing on its surface, in the case of the Flagship mission, in addition to a higher-priority Flagship mission toward the Uranus system. In this paper, we describe a proposal for a Saturn orbiter aiming at accomplishing several dozen flybys of Enceladus's SPT and called the Moonraker mission (see Figure 2). This proposal has been submitted in response to the European Space Agency (ESA) Call for a medium-sized mission opportunity (M-class Call) released at the end of 2021. It has been constrained by several limitations imposed by the M-class Call (limited budget, use of Ariane 62 (AR62), 12 yr cruise duration, limited international collaboration, and limited operation duration). The submission of a more ambitious version of this proposal is now envisaged to the upcoming ESA Call for a large-sized mission opportunity (L-class Call).

The paper is organized as follows. Section 2 summarizes the science goals of the Moonraker mission concept. The proposed mission and payload configurations are presented in Sections 3 and 4, respectively. The management structure of the proposed mission is detailed in Section 5. Section 6 is devoted to conclusions and prospects.

2. Science Goals

Through multiple flybys above the SPT and both in situ and remote measurements, the Moonraker mission concept addresses three main science goals. Figure 3 presents the science traceability matrix.

2.1. Science Goal 1: Habitability Conditions of Present-day Enceladus

Liquid water is only one of the conditions for life as we know it; metabolic energy and proper "building blocks" also need to be available in sufficient concentrations. The interface of the rocky core with the ocean is the most likely environment

[38] https://www.nationalacademies.org/our-work/planetary-science-and-astrobiology-decadal-survey-2023-2032

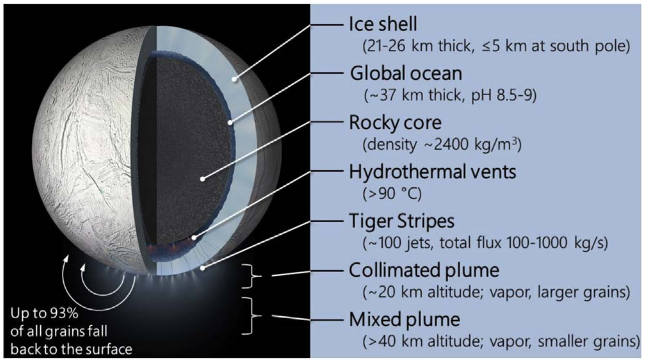

Figure 1. Main characteristics of Enceladus and its plume as currently understood. Reproduced from Cable et al. (2021), under CC BY license (https://creativecommons.org/licenses/by/4.0/). Background image: PIA20013 (NASA/JPL-Caltech).

to be habitable on Enceladus; the composition of the ocean and therefore the plume reflects the rock–water interaction. The measurements to be performed by Moonraker answer the following questions.

1. *How much chemical energy is available in the subsurface?* Without significant solar energy, complex chemical systems or even a hypothetical biosphere in Enceladus's ocean would have to rely on chemical energy. Cassini's measurements already indicated that methanogenesis is a viable reaction to sustain a potential biosphere (Hsu et al. 2015; Waite et al. 2017), but other yet undetected chemical species could be used for other metabolic reactions (Ray et al. 2021). To quantify this energy, the Moonraker mission would be able to measure the abundances in the plume (best proxy for the ocean itself) of key chemical species that could be used in metabolic reactions (e.g., CO_2, H_2, H_2S, sulfates, and O_2). The flux of charged energetic particles from Saturn's magnetosphere hitting Enceladus's surface also contributes to form oxidants (Teolis et al. 2017) that can be delivered to the reducing ocean due to constant burial by plume deposition that exceeds radiolytic destruction (Southworth et al. 2019; Ray et al. 2021); this delivery would help produce redox gradients. Moonraker would perform in situ measurements of the charged particle environment in the vicinity of Enceladus, allowing for calculation of the amount of oxidants thus formed on the surface.
2. *Are the elements necessary for life as we know it (CHNOPS) present, and in what forms and abundances?* While C, H, N, and O have been identified in Enceladus's plume, P- and S-bearing species are only tentatively detected, as phosphine and hydrogen sulfide, respectively, in the gas phase of the plume (Magee & Waite 2017). Phosphorus and sulfur may also be present in other chemical forms, such as phosphates (Hao et al. 2022) and sulfates, which would be refractory. Next-generation instruments on board Moonraker would be capable of detecting trace abundances of these key species in the plume, whether in the vapor or solid phase.
3. *What is the nature and extent of the interaction between the ocean and the rocky core?* Interaction between the ocean and the core not only provides chemical energy (Hsu et al. 2015; Bouquet et al. 2017; Waite et al. 2017), it can also produce a variety of organic compounds, ionic species, and heat to sustain the ocean over the age of Enceladus (Choblet et al. 2017). It is not clear at which stage of aqueous alteration the core currently is (Zandanel et al. 2021). Ocean–core interaction is also a key part in regulating the pH of the ocean (Glein et al. 2018; Glein & Waite 2020). Key measurements to understand the geochemistry of Enceladus include Ca, Mg, sulfates, and silica in icy grains. Organic compounds, in both the gas and solid phase, also represent a critical target, since they may reflect both Enceladus's initial inventory (leached by the ocean) and compounds synthesized through hydrothermal activity. Measurements in the plume can remove ambiguities left by the Cassini measurements and allow us to detect low-abundance compounds of interest, including putative biomolecules.

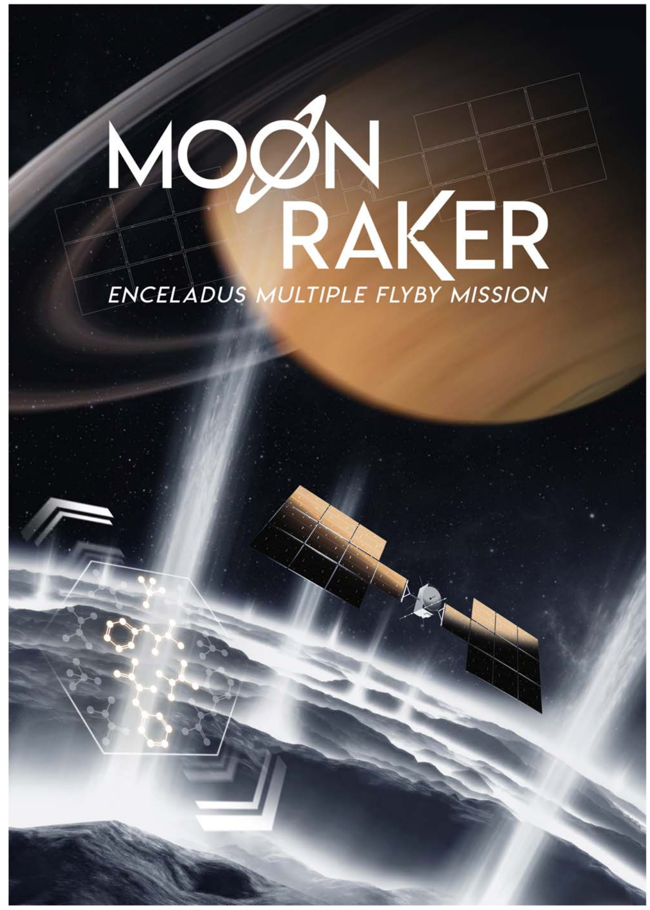

Figure 2. Artist view of the Moonraker mission concept. Note that the geometry adopted for the image does not reflect reality. Enceladus orbits in the ring plane. The plume sources are at most 20° of the south pole (Porco et al. 2014) and do not extend as far as 45° as suggested by the rendition.

2.2. Science Goal 2: Communication between the Subsurface Ocean and the Surface through the SPT

There are still many standing questions about the exact mechanisms generating the plume and their stability over geological timescales (Spencer et al. 2018). The exact form of the emission (distribution of vapor and icy grains between the jets, Porco et al. 2014, and the more diffuse "curtain" source, Spitale et al. 2015) is still not fully determined. New observational constraints are required to understand what regulates the plume,

Science Goals	Science Objectives	Measurement requirements: Physical parameter	Measurement requirements: Observables	Instrument	Progress with regard to available data
I. Habitability conditions of present-day Enceladus	1. Determine the abundances of key species related to habitability (CHNOPS, pH and redox state, hydrothermal interactions, organic inventory)	A. Mixing ratio in the plume with respect to water	H_2, CH_4, CO_2, NH_3, CO, N_2, H_2S, PH_3, ^4He, ^{40}Ar, volatile organics	INMS	Sensitivity > 50000 x Cassini INMS M/ΔM > 50 x Cassini INMS
				SWI	Allows remote measurements of the whole plume
		B. Abundance in icy grains	Refractory organics: HMOC, amino and fatty acids	HIFI, INMS, SWI (some organics such as AA condensed on grains)	HIFI: M/ΔM > 100 x Cassini CDA (distinction of inorganic ion clusters); 3.85 km/s flyby velocity prevents organic fragmentation SWI allows for detection of some organics condensed on grains
			Salts (incl. Mg, Ca, Na, K), carbonates, sulfates, SiO_2, phosphates		
		C. Energetic particles altering the surface	Abundance and energy of ions and electrons	Plasma spectrometer	M/ΔM for ions = 5 x Cassini CAPS Time resol. =45 x Cassini CAPS E/ΔE = 10 x Cassini CAPS
	2. Key properties of Enceladus' hydrosphere	A. Structure of the interior	Gravity field	Radio science	Close flybys at 3.85 km/s and <100 km altitude (at least 5 dedicated RS flybys, vs only 3 in Cassini)
II. Communication between the ocean and the surface through the South Polar Terrain	3. Determine the mechanisms of production of the plume	A. Size, distribution, shape of vents and fractures, temperature distribution	High resolution imaging	Camera	Multiple close flybys at 3.85 km/s and <100 km altitude
			Heat flux mapping	SWI	Multiple close flybys at 3.85 km/s and <100 km altitude, pixel 4 times smaller than Cassini CIRS, sensitivity to T as low as 20K
			Ions + charged grains in fine structure jets	Plasma spectrometer	M/ΔM for ions = 5 x Cassini CAPS Time resol. =45 x Cassini CAPS E/ΔE = 10 x Cassini CAPS
		B. Relative abundance and spatial distribution of the vapor and solid phase in the plume, variation over time	Abundance + size distribution of icy grains	HIFI, Nephelometer	HIFI measures flux, density, velocity No nephelometer on Cassini Large number of 3.85 km/s flybys provide spatial resolution and allow for monitoring over time of plume variations
				Plasma spectrometer	
			Velocity distribution of icy grains	HIFI, Nephelometer	
			Abundance, distribution of water vapor	INMS, SWI	Large number of 3.85 km/s flybys provide spatial resolution
			Gas kinematics	SWI	
III. Origin of Enceladus in the context of the formation of Saturn's system	4. Measure the isotopic and chemical composition of key tracers in the plume that are related to the origin of Enceladus	A. Relative elemental abundances	Ar, Ne, Kr, Xe $/H_2O$	INMS	Sensitivity > 50000 x Cassini INMS
		B. Isotopic ratios	$^{14}N/^{15}N$, $^{12}C/^{13}C$, $^{16}O/^{18}O$	INMS, TLS	INMS M/ΔM > 50 x Cassini INMS TLS
				SWI	Gives value for whole plume
			D/H in H_2O, CH_4, NH_3	INMS, TLS, HIFI (grains D/H), SWI	M/ΔM for INMS (> 50x Cassini INMS) and HIFI (>100 x Cassini CDA) removes ambiguity (D/H in H2O) or enables detection (other isotopes), INMS sensitivity (>50000 Cassini INMS) enables detection of low-abundance species, TLS
			$^{38}Ar/^{36}Ar$	INMS	
			^{82}Kr, ^{83}Kr, $^{86}Kr/^{84}Kr$		
			^{129}Xe, $^{131}Xe/^{132}Xe$		

INMS = Ion and Neutral Mass Spectrometer. HIFI= High Ice Flux Instrument. SWI= Sub-mm Wave Instrument. TLS = Tunable Laser System.

Figure 3. Moonraker science traceability matrix.

possibly including the opening and closing of vents (Ingersoll & Nakajima 2016; Ingersoll & Ewald 2017). Aside from the intrinsic interest in understanding the generation of the plume, it is a crucial piece of context to interpret the data gathered from its composition and establish a link with oceanic composition. A deeper understanding of the SPT and its evolution with time is invaluable for possible future landed missions (e.g., MacKenzie et al. 2021). The Moonraker mission concept addresses the following questions related to the plume generation.

1. *What is the size, distribution, and shape of the vents and fractures from which the plume emanates, and what is the temperature distribution?* Our understanding of the morphology and size of the vents is limited by the capabilities of the Cassini spacecraft payload. Observations have provided only upper limits for vent size. Different models predict different channel widths with different predictions, such as vents shutting off after a few years (Ingersoll & Nakajima 2016) or nearly

insignificant endogenic heat emission between the fractures (Kite & Rubin 2016). The study of the morphology of the vents and the associated heat flow (including the likely background emission between the stripes) would allow us to constrain plume emission models. The variation in the width of the stripes (spatial variation as well as opening/closing with time) needs to be observed at high resolution; models predict the evolution of these openings on a timescale of years (Spencer et al. 2018). The total heat flow and its distribution would allow us to quantify the effect of condensation in the vents. Moonraker would perform remote observations at a high spatial resolution to draw a new picture of the emission zone.
2. *How are vapor and ice grains distributed in the plume? How has the plume evolved since the Cassini measurements?* The distribution and velocity of the gas phase and ice grains, as well as the size distribution of the ice grains, are critical parameters that models of plume generation must reproduce. The spatial distribution of vapor and solid sources (and correspondence to surface features) is another outstanding question (Spencer et al. 2018). Moonraker would combine in situ and remote observations across many flybys to understand the plume production mechanism and its evolution with time.

2.3. Science Goal 3: Origin of Enceladus in the Context of the Formation of Saturn's System

Possible formation scenarios for Enceladus include a primordial formation along with the other satellites, late formation from ring materials, or recent (100–200 Myr ago) formation due to a catastrophic event in the Saturnian system (McKinnon et al. 2018). Distinction between these scenarios requires quantification of various tracers, such as noble gases and their isotopic ratios, and their comparison to known measurements in the other satellites and objects indicative of the early solar system (e.g., chondrites and comets). Their quantification with Moonraker measurements would allow us to address the following questions related to Enceladus's origin.

1. *Which volatile tracers are primordial, and which are evolved? How do the tracers compare to early solar system objects and other Saturnian system bodies? How old is Enceladus?* Noble gas abundances and isotopic ratios of noble gases, carbon, nitrogen, oxygen, and hydrogen are all tied to the reservoir from which the building blocks of Enceladus came. Comparison of these data with those already measured by Cassini-Huygens in Titan (Ar, Kr, and Xe abundances; D/H in CH_4; and $^{14}N/^{15}N$) would indicate if the building blocks of the two moons originate from the same material reservoir or followed distinct formation paths. Moonraker would perform measurements at Enceladus to remove the existing ambiguities and detect species that were under the limits of detection of Cassini.

3. Proposed Mission Configuration

In this section, we first depict the proposed end-to-end Moonraker mission profile. We then provide a description of the spacecraft design; finally, we discuss the needed technology requirements.

3.1. End-to-End Mission Profile

3.1.1. Interplanetary Trajectory

Our analysis has been performed assuming that the launcher for M-class missions would be an AR62 rocket with a launch capability of ∼2650 kg for a departure at 3 km s^{-1} at the optimum decl. (low S latitude). A launch capability of ∼2185 kg for velocities in the 3.2 km s^{-1} range should be available up to a decl. of ∼23° (N or S). The proposed baseline mission trajectory, considering a launch in 2036 March with a velocity of 3.23 km s^{-1} at a decl. of 21°.8 N, is then as follows.

1. EVEES trajectory: one swing-by of Venus (V), followed by a first Earth (E) swing-by to initiate a 3 yr orbit and a second Earth swing-by setting the spacecraft on a transfer trajectory to Saturn (S). No deep space maneuver would be required.
2. Arrival at Saturn in 2048 May, with a relative velocity of 5 km s^{-1} and a decl. of 6°.7.

Two backup opportunities have been identified, with launch in 2036 October and 2038 March and arrival dates at Saturn in mid-year 2048 and 2050, respectively. The proposed baseline mission would use the AR62 launcher.

3.1.2. Saturn Orbit Insertion and Early Tour Phases

Satellites of Saturn orbit close to the equatorial plane, with a large angle to its orbital plane (26°.7). However, an arrival at Saturn less than 3 yr after the northern summer solstice (2045 November) results in declinations lower than 10° for the nominal and first backup opportunities. A standard pump-down sequence 383 days long could then be implemented.

1. Titan flyby before Saturn orbit insertion (SOI) at an altitude of 1000 km, out of Titan's atmosphere. This flyby reduces the magnitude of the SOI maneuver, improving the mass budget. However, it may not be completely outside Titan's atmosphere, implying some uncertainty about the induced drag and trajectory perturbation, and a source of uncertainty for the SOI. Post-flyby adjustment for the SOI trajectory might be needed.
2. SOI at pericenter (365,000 km from the body center): ∼850 m s^{-1} for 5.25 km s^{-1} (explicit solution; the optimum requires adjusting the pericenter distance as a function of decl.).
3. First orbit: 18:1 (287 days) with a large pericenter raise maneuver (PRM; 250 m s^{-1}).
4. Second Titan flyby: 3.35 km s^{-1} (optimum for the science mission).
5. Pump-down sequence at Titan. A series of orbits of decreasing periods—3, 2, 1, then 2/3 Titan periods (15.95 days)—could be achieved with Titan flybys at altitudes higher than 1000 km (beyond the upper layers of the atmosphere of Titan). The Titan flyby following the 2/3 orbit sets the spacecraft to an orbit with a period close to 8 days, initiating the science phase with a first flyby of Enceladus.

3.1.3. Science Phase

To perform multiple flybys over the south polar region of Enceladus, an orbital period in resonance with its 33 hr orbital period has to be selected. On this basis, we opted for an orbit with a 6:1 orbital period (8.22 days). This period is slightly larger than the 1:2 resonance with Titan (7.97 days). Every two orbits, Titan moves forward by 11°.2, more precisely, 10°.5 due to precession. After 30 orbits (157°.5 forward motion), Titan begins to catch up with the alternate apocenter (180° of phasing away), but one could still implement more than 20 Enceladus flybys with minor Titan perturbation in between before Titan gets close to the apocenter again (see Figure 4). A grazing encounter scheme has been selected, resulting in the slowest possible encounter velocity (∼3.85 km s^{-1}) and minimizing the impact of precession on the encounters and orbit maintenance costs. Therefore, a mission segment would be constituted by a Titan-to-Enceladus transfer on an orbit with a period slightly larger than the 6:1 resonance after the first Enceladus flyby, leading to 21–24 Enceladus flybys. At the end of this segment, the spacecraft could be disposed of at Titan, or a new segment could be initiated using Titan flybys. Given the specific interest of the southern high latitudes, all flybys have been set over the south polar region, with the first two flybys at an altitude of 200 km (to be compared to the ∼1500 km plume height) and the next flybys at 100 km or lower at the end of the nominal mission or during an extended mission. The latitude could, however, be varied to fit scientific requirements, e.g., to perform at least five dedicated radio-science flybys. The nominal Moonraker mission would have a duration of ∼13.5 yr, with 189 days allocated for the science phase, assuming a 23-flyby segment.

Regarding end of mission, Planetary Protection (PP) considers Enceladus as a Category III target (Fisk et al. 2021), implying that this moon is not appropriate for crashing the spacecraft. Only some specific landing conditions in the case of a descent module would be compliant with the Planetary Protection Policy (see Neveu et al. 2022 for details). The proposed scenario would be spacecraft destruction during entry in Titan's upper atmosphere. Other options to be considered would be to crash on an intermediate-sized moon that has lower PP categorization or delivery to a moon-free orbit around Saturn (a strategy similar to Juno's end of mission at Jupiter). Destruction in Saturn's atmosphere would be too expensive in terms of energetic cost.

3.1.4. ΔV *Budget for Evaluating Mass Margins*

The deterministic and stochastic mission ΔV are found to be 1410 and 118 m s^{-1}, respectively. The corresponding breakdowns are given in Table 1.

Cleanup costs would be negligible for Enceladus flybys given its very low gravity potential. With a velocity change of up to 10 m s^{-1}, a very large guidance error of 10 km only results in a difference of ∼0.3 m s^{-1} for the orbital velocity after the flyby. Flybys of Titan at an altitude of 10,000 km or more would be implemented when initiating a segment. The velocity change is larger (400 m s^{-1}) than for Enceladus, but a 10 km guidance error also leads to a difference of ∼0.4 m s^{-1}. Therefore, only the six close flybys of Titan would be considered to require significant cleanup costs.

The total ΔV is then 1528 m s^{-1} (1604 m s^{-1} with a 5% margin). A two-segment mission, for a total of 45 flybys of Enceladus over a 463 day mission, could be obtained for a deterministic ΔV cost of 150 m s^{-1} instead of 60 m s^{-1} if remaining propellant allows. The following section considers only a one-segment mission (23 flybys).

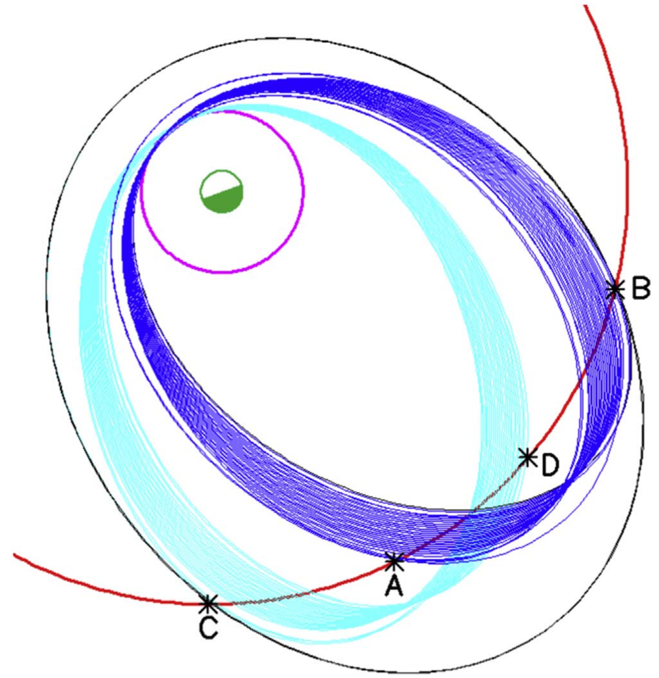

Figure 4. Forty-five flybys of Enceladus distributed over two segments (one segment for the nominal mission + one segment for an extended mission). Mission scheme: a first segment (dark blue; A: departure from Titan outbound, B: return to Titan inbound) provides 23 grazing flybys of Enceladus (magenta) over the south polar regions. For an extended mission, a 2:3 inbound–outbound orbit (black) could initiate a second segment (light blue) with 22 flybys shifted 30° clockwise. C: departure from Titan. D: return to Titan for disposal or transition to a new segment initiating a new extended mission.

Table 1
Breakdowns of the Deterministic and Stochastic Mission ΔV

Deterministic ΔV	
Launch window	50 m s^{-1}
Cruise	200 m s^{-1} (440 and 100 m s^{-1} for the two opportunities)
SOI and pump-down	1100 m s^{-1} (to be improved after optimization)
Nominal mission	60 m s^{-1} (including disposal by collision with Titan after one segment)
Stochastic ΔV	
Flyby cleanup during the interplanetary phase	40 m s^{-1}
SOI + PRM	30 m s^{-1}
Titan flybys	48 m s^{-1} (8 m s^{-1} per flyby for JUICE)

3.2. Spacecraft Design

The structure of the platform would be mission-customized, with a strong heritage from JUICE. The design of the primary structure would be first driven by the central cylinder housing the propellant tanks and interfacing with the launcher and the need to support the large solar panels, as well as the JUICE-like 2.5 m diameter High Gain Antenna (HGA). This results in large support surfaces available to accommodate the payload instruments, the platform sensor, and the other aerials, i.e., the Medium Gain and Low Gain Antennas (MGA and LGA), thrusters' pods, and main engine. The propulsion would be similar to that of JUICE but with downsized propellant tanks and a single pressurant tank, in line with mission ΔV and orbit control needs. The building blocks of our platform would be mostly inherited from JUICE. These elements have been considered in support of the mass and power budget consolidation. The main differences with respect to JUICE to meet the programmatic constraints of an M-class mission are as follows.

1. There would be no dedicated NAVCAM, as this functionality would be shared with the payload camera. As for JUICE, the processing algorithms of the NAVCAM images would run on the platform command and data management unit (CDMU).
2. There are two Star Tracker heads instead of three on JUICE.
3. European inertial measurement unit (IMU) Astrix 1000 family class would be operational and implemented in place of the US IMU of JUICE.
4. The communication system features only the *X*-band chain of JUICE. The steerable JUICE MGA would be replaced by a smaller antenna supporting minimum communications at Saturn and a few kbps during the hot inner cruise of the early transfer phase between Earth and Saturn.
5. Due to the lower amount of solar and battery power to be managed, the digital conditioning system of JUICE's power conditioning and distribution units (PCDUs) would be replaced by a standard analog maximum power point tracking system. A single battery module from JUICE instead of five meets the spacecraft needs.
6. A couple of input/output (I/O) boards would be removed from the data management remote interface unit, in line with the reduced number of interfaces to manage. The embedded science mass memory of the CDMU would also be of reduced capability to match the downlink capability of the communication system operated at Saturn.

Using the 3G28 or 3G30 solar cells of JUICE and considering the loss of efficiency (about 5% due to the majority carrier effect) in the colder operating environment, a 143 m^2 Mars Sample Return (MSR) array (total area) at 10 au from the Sun delivers about 380 W (to be compared with 900 W delivered by the JUICE 84 m^2 solar array at 5 au), enabling an M-class spacecraft.

Preliminary mass and power budgets are presented in Tables 2 and 3. A payload of 50 kg consuming 50 W over 3 hr, i.e., 150 Wh during each Enceladus flyby, would be allocated to the payload. System margins of 25% (mass) and 30% (power) are achieved on top of estimates. The energy budget would be balanced with 4 hr of communications per day considering a JUICE-based system featuring a 2.5 m diameter HGA and the JUICE *X*-band telemetry chain. The amount of data downloaded to Earth varies between 0.9 and 1.3 Gb between two Enceladus flybys separated by 8 days as a function of Earth/Saturn distance, to be allocated between the different instruments.

3.3. Technology Requirements

No new technology development has been identified for the spacecraft, in line with the requirements for an M-class mission. Tailoring to the Saturn environment is to be performed for the solar array and solar cells. The absence of eclipses during the multiple orbits prevents the occurrence of surface temperatures as low as experienced on JUICE. The characterization first aims at securing power and energy budgets.

4. Payload Configuration

The scientific requirements discussed in Section 1 are addressed with the suite of scientific instruments listed in Table 4. This list includes a mass spectrometer, tunable laser system, high ice flux instrument, nephelometer, plasma spectrometer, submillimeter-wave instrument, camera, and radio-science experiment. The total mass of the scientific payload would be 39.7 kg (with an allocation of 50 kg in the mass budget). This payload has been scaled to meet the specifications of an AR62 launch as provided by ESA. In case a more powerful AR version would be available for launch, the payload could be revised accordingly. The present configuration also enables additional science to be performed at Titan during the multiple approaches of the Moonraker spacecraft.

In the following, we provide a short description of each instrument with their technology readiness and heritage.

4.1. Moonraker Ion and Neutral Mass Spectrometer

The M-INMS measures the composition of the neutral gas and the thermal ion population at the location of the spacecraft. In this configuration, the mass spectrometer would be provided by the University of Bern, Switzerland. This group has considerable space hardware experience and, in particular, built the mass spectrometers RTOF and DFMS of the ROSINA experiment for Rosetta (Scherer et al. 2006; Balsiger et al. 2007), the Neutral Gas Mass Spectrometer (NGMS) instrument for Luna-Resurs (Wurz et al. 2012; Hofer et al. 2015), and the Neutral Ion Mass Spectrometer (NIM) instrument of the Particle Environment Package (PEP) experiment on JUICE (Föhn et al. 2021). The proposed mass spectrometer is a time-of-flight (TOF) mass spectrometer. It thus measures a full mass spectrum at once with a mass resolution of $M/\Delta M$ up to 5000. The nominal and extended mass ranges are 1–300 and 1–1000 amu. The integration time for a mass spectrum could be adjusted between 0.1 and 300 s to optimize the spatial resolution of the measurements, as well as the sensitivity of the mass spectrometric measurements over a very wide altitude range along the flyby trajectory. The proposed mass spectrometer is comprised of an ion-optical system and an electronic box. The ion-optical system would be based on the RTOF instrument and the electronics on the NIM instrument on JUICE, which serves a very similar application (mass spectrometry during flybys of the Jovian moons). All subsystems have flight heritage; thus, the combined system has a technology readiness level (TRL) of 6.

4.2. Tunable Laser System

The instrument would be provided through a consortium composed of the Universities of Reims (GSMA-CNRS) and Aix-Marseille (LAM-CNRS). The instrument would be based on near-infrared antimonide laser diode absorption

Table 2
Mass Budget Derived from the JUICE Avionics and MSR Solar Generator for a 50 kg Science Payload to Enceladus Using A62 with a 25% System Margin on the Platform Dry Mass

Mass	kg	Heritage
Launcher capability	2185	AR62 ($V_\infty = 3.3$ km s^{-1})
Spacecraft max. launch mass	2125	Launcher capability—60 kg adapter
Propellant:		
—Orbit maneuvers	850	1604 m s^{-1} (incl. 5% margin), 320 s Isp
—Attitude control	25	Allocation with margin
Spacecraft max. dry mass	1250	
Payload	50	Allocation
System margin	250	25% of spacecraft dry mass
Platform dry mass	950	Best estimate
Structure	185	15% of spacecraft dry mass (best estimate)
Solar arrays	340	MSR
Harness	50	5% of spacecraft dry mass
Propulsion	120	JUICE architecture with one pressurant tank and two 800 L bipropellant tanks
Thermal	40	Allocation
AOCS	70	*4× reaction wheels*, *2 STR*, 2× Astrix IMU, *2 Sun sensors*
Communication	60	*X-band system including HGA and 2 LGAs*, one 2 axes MGA 200 bps at Saturn
Power	60	*2× battery modules*, 1× customized PCDU, 1 axis solar array drive assembly
DMS	25	*CDMU* with limited SSMM, *RIU* with reduced I/O capabilities

Note. Italics denote direct heritage from JUICE. AOCS = altitude and orbit control system. DMS = data management system. Isp = specific impulse.

spectroscopy to provide concentration measurements of selected molecular species. The laser beam is propagated through the molecular gas, where it is partially absorbed, the laser wavelengths being tuned to match accordingly with a rovibronic transition of the targeted molecules. The gas concentration is retrieved from the measurement of the amount of absorbed laser energy using an adequate molecular model (Zeninari et al. 2006). Hence, the sensor yields in situ measurements of gaseous abundances inside the plume of Enceladus, with a typical relative accuracy within a few percent. It would be a heritage of the former TDLAS instrument (Durry et al. 2010) launched within the framework of the Russian Martian mission Phobos-Grunt to provide measurements of C_2H_2, H_2O, CO_2, and their isotopologues (Le Barbu et al. 2006a, 2006b; Durry et al. 2008; Li et al. 2009) from the in situ pyrolysis of a Phobos soil sample. Therefore, the TRL of the TLS is around 8 (Durry et al. 2010). One should also mention that an upgraded version of the TDLAS developed and led by IKI/Roskosmos was ready to be launched within the framework of the Exomars-2022 Martian mission (Rodin et al. 2020).

4.3. High Ice Flux Instrument

HIFI would be provided by the Laboratory for Atmospheric and Space Physics at Colorado University. It would be an impact-ionization TOF mass spectrometer that is optimized for measuring Enceladus plume ice grains. Plume grains strike an iridium impact plate at flythrough velocity, yielding a cloud of neutral and ionized species; HIFI measures the small resulting fraction of ionized species. Complementary cation and anion spectra allow determination of the composition of the salt- and organic-rich grains. The spectrometer has an $M/\Delta M$ of ∼3000 and would be able to detect organic and salt analytes in the grains' icy matrix at ppm concentrations. The considered mass range extends up to more than 2000 amu. The HIFI instrument comprises two subsystems: a mass analyzer (MA) and an electronics box. The MA uses an electric field to extract ions created by impacting grains. The MA comprises two identical mass spectrometers: MA1 (cations) and MA2 (anions). The electronics box reads out the analog signals from the sensor head and controls its other components. HIFI would be the latest generation in a line of successful dust analyzer instruments: Giotto PIA at comet Halley (Kissel 1986), Stardust CIDA at comet Wild 2 (Kissel et al. 2004), CDA Cassini at Saturn (Srama et al. 2004), and Europa Clipper SUDA (to be launched in 2024). It represents a large performance improvement over the similar ENIJA instrument (Srama et al. 2015) considered in the the E2T (Mitri et al. 2018) and ELF (Reh et al. 2016) proposals. All HIFI subsystems are at TRL 6 and above, having been demonstrated in relevant environments via ground testing of high-fidelity prototypes or operation in space; the remaining integration involves standard interfaces and engineering development.

4.4. Nephelometer

The instrument, named Light Optical Nephelometer Sizer and Counter for Aerosols for Planetary Environments (LONSCAPE; Renard et al. 2020b), would be provided through a consortium composed of the Universities of Orleans (LPC2E-CNRS) and Aix-Marseille (LAM-CNRS). The instrument provides the scattering function at several angles of the particles that cross a laser beam inside an optical chamber. By doing so, LONSCAPE performs measurements of the concentrations and typologies of the particles for 20 size classes in the 0.1–30 μm range. The counting is performed at small scattering angles, where the scattered light is mainly dependent on the diffraction and thus not sensitive to the refractive index. The typology is retrieved from the scattering properties at several angles by comparison with laboratory measurements. The team has developed instrumentation for particle detection, in particular under stratospheric balloons (Renard et al. 2020a) and in nanosatellites (Verdier et al. 2020), with current TRL 6–7 for space applications. Also, some studies have been conducted for an

Table 3
Energy Budget of the Mission Achieved with the MSR Solar Array and 500 Wh Battery Range

Power	Quiet Cruise	Communication Sessions	Science: 0.5–1.5 hr before and after C/A	Science: C/A ± 30 minutes		
Duration (hr)	20.0	4.0	2.0	1.0		
Solar arrays	380	380	380	0	W	
Total w/margin	353	503	380	489	W	
System margin	81	116	88	113	W	30% specified system margin
Net total	272	387	293	377	W	
Payload	0	0	50	50	W	
Propulsion	5	5	5	5	W	
Thermal	70	50	50	50	W	
AOCS	75	75	100	180	W	
Communication	35	160	35	35	W	
DMS	45	50	60	60	W	
Power	42	47	43	47	W	95% (30 W + regulation efficiency)
Delta % solar arrays	27	−123	0	−489	W	
Delivered to battery	26	0	0	0	W	95% BCR efficiency
Needed from battery	0	515	0	515	Wh	95% BCR efficiency
Recharge capacity	515	0	0	0	Wh	Between communication session/after flyby

Note. The power system supports 3 hr of science at each flyby around closest approach (C/A) and 4 hr of communication per day with Earth. BCR = battery charge regulator.

Table 4
Suite of Scientific Instruments

Instrument	Mass (kg)
Moonraker ion and neutral mass spectrometer (M-INMS)	6.2
Tunable laser system (TLS)	2
High ice flux instrument (HIFI)	4
Nephelometer	1
Submillimeter-wave instrument (SWI)	8
Camera	12
Radio-science experiment	2
Plasma spectrometer	4.5
Total mass	39.7

application to aerosol detection in the upper atmosphere of Venus (Baines et al. 2021).

4.5. Submillimeter-wave Instrument

The SWI would be provided by a consortium led by the Max Planck Institute for Solar System Research[39] and corresponds to a passively cooled tunable heterodyne spectrometer covering the frequency range of 1065–1275 GHz. The local oscillator chain consists of a 25 GHz band frequency synthesizer. Its output signal is tripled to 75 GHz where it is amplified with an *E*-band amplifier. Three frequency doublers produce a signal of a few mW at 600 GHz, fed to a subharmonically pumped mixer. The spectrometer backend consists of a chirp transform spectrometer with 1 GHz bandwidth and 100 kHz spectral resolution. The resolving power of the instrument is above 1×10^7. The receiver is coupled to a telescope with a 29 cm primary mirror. The spatial resolution of the telescope is about 1 mrad. The SWI would be based on the JUICE-SWI instrument, mounted into the JUICE satellite in 2021 August. However, due to the mass constraints and different scientific objectives of Moonraker compared to JUICE, a number of components would be descoped: the 600 GHz receiver, along- and cross-track actuators, and autocorrelator spectrometers. All components of the Moonraker SWI are TRL 8.

[39] https://www.mps.mpg.de/planetary-science/juice-swi

4.6. Camera

The camera for Moonraker would be provided by a partnership between the University of Aix-Marseille (LAM-CNRS) and the Institute for Planetary Research of DLR. The DLR, LAM, and their partners have many years of experience in the design of optical imaging instruments and their key components for planetary science missions (Mars-Express (PI), Rosetta-Lander (PI), DAWN, Hayabusa-II, ExoMars (PAN-CAM-HRC), and, recently, JUICE (Co-PI)). The camera would be a straightforward telescope combined with a scientific VIS/NIR CMOS- image sensor (based on JUICE-JANUS) and their associated electronics (Della Corte et al. 2014). The typical angular resolution that could be achieved is 15 μrad pixel^{-1}. Because the SPT is expected to be in the dark of polar winter during the science phase, the illumination due to Saturn's glow will have to be quantified to provide a better assessment of the camera design. To do so, a wide dynamic range is required. The key components of the camera are TRL 8. In our spacecraft design, this camera would also be used as a navigation camera.

4.7. Radio-science Experiment

Doppler tracking of the spacecraft during flybys (preferably via the HGA) would provide the determination of the gravity field and the orbits of the moons (Iess et al. 2014; Durante et al. 2019). In the Moonraker mission concept, gravity is the only available tool to constrain the interior structure of the Saturnian satellites. The precise knowledge of Enceladus's orbit is crucial to characterize the dissipative processes in the Saturnian system. The Doppler data would be produced at the ground antenna via a two-way coherent link. The measurements use the onboard radio communication system (RCS), without the need for dedicated equipment. If the RCS includes the Integrated Deep Space Transponder (IDST) developed by ASI and ESA, to be flown on NASA's VERITAS mission to Venus, *Ka*-band tracking becomes possible, providing a significant enhancement of the data quality and the determination of the interior structure. Indeed, *Ka*-band radio links (32.5–34 GHz) are nearly immune to plasma noise, the main limitation to Doppler measurements in *X*-band tracking systems (7.2–8.4 GHz). The IDST could be a contribution of the Italian Space Agency to Moonraker or provided by ESA as the onboard transponder, a system element. The IDST, which would be based on the digital technologies developed for the BepiColombo MORE investigation, also enables range measurements accurate to 1–4 cm (Cappuccio et al. 2020), thus providing very precise data on the orbits of the moons.

4.8. Plasma Spectrometer

The instrument would be provided by a consortium under the responsibility of the University of Toulouse (IRAP-CNRS). The formed international consortium has solid institutional experience and outstanding mission heritage, including BepiColombo/MEA and MSA, MAVEN/SWIA, JUICE/JDC, and Cassini/CAPS (Young et al. 2004; Sauvaud et al. 2010; Delcourt et al. 2016; Wittmann et al. 2019; Saito et al. 2021), to thoroughly address the scientific objectives of the plasma spectrometer. The instruments consist of an electron and negative ion spectrometer (1–30 keV q^{-1}), together with an ion mass spectrometer (1–40 keV q^{-1}, $M/\Delta M = 40$ for $<$15 keV q^{-1}) with shared LVPS and DPU. The current TRL for the plasma spectrometer is 5 at minimum for all of its elements and would be planned to reach TRL 6 by the end of Phase A.

5. Management Structure

The Moonraker mission concept is proposed as an ESA-led mission, with a contribution to the science payload by NASA. Participating in the elaboration of the Moonraker proposal is one industrial company, Airbus Defense and Space. The international consortium for the Moonraker mission concept involves the platform, as well as the science instruments and investigations. After selection by ESA, the European industrial partner would be responsible for developing the platform within the international consortium. The Moonraker instrument payload is provided by instrument PI teams from ESA's member states and NASA scientific communities. Payload funding for ESA's member states is provided by national funding agencies, while the US payload contribution would be funded by NASA. The lead funding agency for each PI team is either the PI National Funding Agency for a European-led PI team or NASA for a US-led PI team.

6. Conclusion

The Moonraker mission concept has been submitted to the ESA Call for a medium-sized mission opportunity released in 2021 December. It consists of an ESA-provided platform with strong heritage from JUICE and MSR and carrying a suite of instruments dedicated to plume and surface analysis. The nominal Moonraker mission concept includes a 23-flyby segment and has a duration of ∼13.5 yr, with 189 days allocated for the science phase. It can be expanded with additional segments, if needed, to satisfy the science objectives. The ESA review indicated that the needed budget is larger than the maximum one at disposal for medium-sized missions (550 million euros), and that the mission profile is instead tailored to match that of a large-sized mission in terms of budget (∼1 billion euros) and mission design (need of a rocket more powerful than AR62, 12 yr cruise duration, extended international collaboration, and significant operation duration).

The submission of an extended Moonraker proposal is currently envisaged for the next ESA Call for a large-sized mission, including science both at Enceladus and Titan, which would fit the "Moons of the giant planets" priority defined for L-class missions in the Voyage 2050 program. The Moonraker mission concept corresponds to one of the top priorities of the future New Frontiers 6 and 7 calls proposed by the 2023–2032 US National Academies' Planetary Science and Astrobiology Decadal Survey. Enceladus is also considered as the second-highest priority new Flagship mission for the decade 2023–2032 recommended by this panel, with the highest priority attributed to the Uranus Orbiter and Probe.

In case Ariane 64 could be envisaged, additional mission capability would be considered (e.g., extension of the payload, such as the addition of a magnetometer, or more propellant to increase the orbital phase duration). The additional available launch mass could be considered to piggyback an additional contribution (to explore the Saturn system) from another space agency.

If selected, such a spacecraft would also provide important follow-up science at Titan after the Dragonfly mission. Flybys of Titan are already a part of the initial mission profile, although at a high altitude. The additional fuel available could allow for closer flybys, enabling mass spectrometry measurements in Titan's atmosphere. Such a mission concept would have to overcome any potential contamination between the successive flybys of Titan and Enceladus. To do so, M-INMS could contain a bake-out heater designed to heat the ion source up to 150–300°C for at least 24 hr. This ion source bake-out heater would clean the ion source of any contaminant deposited there and originating from the spacecraft. It would also remove any chemical heritage from prior measurements, such as the Titan atmosphere. Such an ion source bake-out system is standard for neutral gas mass spectrometers as illustrated by the ROSINA/Rosetta experiment but also by the NGMS instrument for Luna-Resurs and the NIM on the PEP of JUICE. If the ion source bake-out heater would still be considered insufficient, then a hermetically sealed instrument could be flown, with the seal only broken at Enceladus. In addition, the risk of contamination of the HIFI instrument would be almost zero, given the fact that it is more or less in a vacuum-tight housing with a tiny aperture and a target fully isolated from the ambient atmosphere. The HIFI team is also currently investigating the possibility of keeping the target warm during flybys to prevent ice grains from sticking and slowly evaporating.

A larger science payload should be considered, with the inclusion of radar and a magnetometer. The addition of a magnetometer would allow us to use the reported tidal variations in plume activity to explore Enceladus's inductive response to the resulting time dependence of the background magnetic field arising from the moon–magnetosphere interaction. This would place a constraint on global ocean thickness and salinity. This instrument would also allow for additional science related to Saturn's magnetosphere and Titan's ionosphere. Ice-penetrating radar would also allow for further understanding of the communication of Enceladus's ocean with its surface, as well as help establish bathymetry maps of Titan's lakes and seas. An additional module to be dropped at Titan, such as a small entry probe or minisatellite, could be considered as well.

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ORCID iDs

O. Mousis https://orcid.org/0000-0001-5323-6453
A. Bouquet https://orcid.org/0000-0001-8262-9678
N. André https://orcid.org/0000-0001-8017-5676
G. Durry https://orcid.org/0000-0002-5255-8554
P. Hartogh https://orcid.org/0000-0002-9550-6551
J. Helbert https://orcid.org/0000-0001-5346-9505
L. Iess https://orcid.org/0000-0002-6230-5825
A. Masters https://orcid.org/0000-0002-7209-7732
F. Postberg https://orcid.org/0000-0002-5862-4276
P. Vernazza https://orcid.org/0000-0002-2564-6743
A. Vorburger https://orcid.org/0000-0002-7400-9142
P. Wurz https://orcid.org/0000-0002-2603-1169
M. Berthomier https://orcid.org/0000-0001-6235-5382
J. Brucato https://orcid.org/0000-0002-4738-5521
M. Cable https://orcid.org/0000-0002-3680-302X
S. Cazaux https://orcid.org/0000-0003-0320-3578
A. Coustenis https://orcid.org/0000-0003-3414-3491
G. Danger https://orcid.org/0000-0002-5689-0853
V. Dehant https://orcid.org/0000-0002-9516-8572
T. Fornaro https://orcid.org/0000-0001-7705-9658
T. Gautier https://orcid.org/0000-0002-9794-5056
O. Groussin https://orcid.org/0000-0002-8997-3815
L. Z. Hadid https://orcid.org/0000-0002-8587-0202
I. Kolmasova https://orcid.org/0000-0002-1704-3846
S. Le Maistre https://orcid.org/0000-0002-9524-9479
E. Lellouch https://orcid.org/0000-0001-7168-1577
J. I. Lunine https://orcid.org/0000-0003-2279-4131
K. E. Mandt https://orcid.org/0000-0001-8397-3315
Z. Martins https://orcid.org/0000-0002-5420-1081
D. Mimoun https://orcid.org/0000-0002-3427-2974
G. M. Muñoz Caro https://orcid.org/0000-0001-7003-7368
P. Rannou https://orcid.org/0000-0003-0836-723X
H. Rauer https://orcid.org/0000-0002-6510-1828
P. Schmitt-Kopplin https://orcid.org/0000-0003-0824-2664
M. Simons https://orcid.org/0000-0003-1412-6395
T. Van Hoolst https://orcid.org/0000-0002-9820-8584
J. Vaverka https://orcid.org/0000-0003-2177-0955
M. Wieser https://orcid.org/0000-0002-1760-210X

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