



Saturn atmosphere Investigation of Rings and ENceladus (SIREN)



Team Yellow

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ABSTRACT The Saturnian system has been the target of four previous space missions and has generated high scientific interest due to its dynamic atmospheric properties and its many moons, some of which are key targets for the search for habitability. The SIREN mission is designed to study these environments, focusing on three main science goals. Firstly, the mission aims to study Saturn's atmospheric composition to further understand its formation and evolution. Secondly, it aims to study the Saturnian ring and moon formation and evolution as a proxy for accretion processes in protoplanetary discs. Lastly, the mission will study what chemical processes shape Enceladus' potentially habitable subsurface and surface environment. The orbiter will perform multiple flybys of Enceladus at different altitudes crossing the plume to unambiguously characterise its chemical composition as a probe of this moon's pristine interior material. After that, the orbiter will perform close observations of the A and B rings. The Saturn atmospheric entry probe (ARGO) will carry out measurements during a 90-minute descent to characterize the atmospheric composition down to an altitude of 20 bar. We present an overview of the science goals of the mission and the instruments required to achieve those, the mission phases, and a description of the orbiter spacecraft and ARGO. Finally, we describe the overall expected scientific gain of the mission.

1. INTRODUCTION

Since the invention of the telescope in the early 17th century, our knowledge of the Solar System has been ever-changing. Galileo Galilei discovered two of the four known giant planets in our solar system, Jupiter and Saturn, in 1610. Uranus and Neptune were discovered roughly 170 and 230 years later, respectively. Since the dawn of the space age, the knowledge of these planets and their moons has been increased considerably by four space missions.

In 1979, the first spacecraft to flyby Saturn, Pioneer 11, provided the first information about the mass, interior, atmosphere, moons, and the rings of Saturn. A few years later, Voyager 1 and 2 made their flybys of Saturn and even more information was collected, in particular of Saturn's rings and its moons. In 2004, the fourth spacecraft, Cassini-Huygens, entered the Saturnian system. The spacecraft observed Saturn and its moons for more than 13 years, discovering among others methane lakes on Titan, a kilometre long plume at the south pole of Enceladus, and small moons within the rings of Saturn.

With the Voyage 2050 campaign by the European Space Agency (ESA), new proposals for missions to the giant planets are to be expected, within the scientific area of "Moons of the Giant Planets". To that effect, our multidisciplinary group of engineering and science students has designed the SIREN: Saturn atmosphere and Investigation of Rings and ENceladus mission that proposes the exploration of the Saturnian system as a followup of the extraordinary

discoveries by the Cassini-Huygens mission. In particular, the Saturnian atmosphere will be explored with ARGO: Atmospheric Research and Gas composition Observer, while the rings and Enceladus' plume are to be explored through dedicated flybys.

2. SCIENCE CASE

SIREN will investigate the formation, evolution, and habitability of the Saturnian System. We build on the knowledge acquired by previous missions, such as the Cassini-Huygens probe that investigated the system from 2004 to 2017 [Matson, et al. (2002)].

2.1. STATE OF THE ART

I. *Saturn's atmosphere.*

Saturn's atmosphere has a rich and complex composition, which is essential for the understanding of the formation process of giant planets. Spectral data collected by the Cassini mission revealed that Saturn's atmosphere is composed mainly of hydrogen (88%) and helium (11%), with traces of CH₄, NH₃, H₂O and hydrocarbons [Sánchez-Lavega, 2011]. The characterization of the vertical distribution of these volatiles is crucial as it provides clues about the initial conditions of the Solar System and the accretion processes of light materials in the atmospheres of gas giants. Models of gas giant formation suggest that Saturn was formed in a region rich in ice and volatile materials, facilitating the rapid accretion of a critical mass of hydrogen and helium [Irwin, 2009]. The analysis of isotopes and noble gas abundances across different layers of

Saturn's atmosphere would improve our understanding of the processes of accretion and planetary migration. Isotopic ratio measurements, and in particular the deuterium to hydrogen (D/H) ratio, are markers of a possible origin of Saturn in the outer regions of the protoplanetary disk [Sánchez-Lavega, 2011]. Nevertheless, the condensable nature of the key volatiles on Saturn's atmosphere (NH₃, CH₄, H₂O, H₂S) prevent remote-sensing characterization of Saturn's atmosphere [Irwin, 2009]. Saturn's atmosphere also provides a framework for studying extreme atmospheric conditions. Supersonic winds reach speeds of 1800 km/h, influenced by rapid rotation and a complex internal structure as well as seasonal changes and extreme temperatures have been detected by Cassini [Garcia-Melendo et al., 2011]. Giant storms, such as the Great White Spot observed from Earth, exhibit violent atmospheric dynamics and intense chemical interactions [Sánchez-Lavega, 2011]. However, the understanding of these extreme phenomena and their connection to the planetary interior remains limited without in situ measurements.

II. Saturn's Ring Environment

The processes behind the formation of small bodies in Saturn's icy rings are mainly linked to accretion and collisions. Cassini observations revealed fine structures in the inner rings as well as shepherd planetesimals such as the Pan or Daphnis moons inside the A ring [Buratti et al., 2019]. These observations indicate a dynamic interaction between fine particles and small planetesimals. Planetary accretion models explain the formation of centimetre-sized dust by coalescence of fine particles and the formation of sub-kilometric planetesimals by successive collisions leaving a core dense enough to accrete the residual dust under the effect of gravity. The growth from centimetre to the sub-kilometre scale is incompletely described by accretion models, due to the so-called "metre-size barrier". As dust particles grow in size through coagulation, they acquire increasingly greater relative velocities to other nearby particles, as well as a systematic inward drift velocity that leads to destructive collisions, thus limiting the growth of aggregates to a maximum size in scales close to 1m [Birnstiel et al., 2011]. In the outer rings, the interactions of charged particles and dust play a crucial role in the overall dynamics of the ring system. Enceladus, an icy moon of Saturn, releases water ice particles in an active plume that forms Saturn's diffuse E ring. Cassini detected these particles, charged by electromagnetic fields, which contribute to the plasma environment of Saturn's system [Gombosi et al., 2010]. Saturn's magnetosphere interacts with the charged ring and Enceladus plume particles. Magnetic fields trap charged particles, changing their trajectory and facilitating their accretion [Holmberg, M. 2015]. These electromagnetic and gravitational interactions studied by Cassini need to be further explored in order to understand the accretion processes of metric rocks and the composition and movements of plasma in the Saturnian environment.

III. Enceladus

Enceladus harbours a potentially habitable liquid ocean beneath its icy crust sustained by tidal forces exerted by Saturn [e.g., Choblet et al., 2017]. The surface ice layer varies in thickness, being the thinnest (5-18 km) at the south pole and the thickest at the equator (30-60 km) [Cadek et al., 2019]. However, these values rely on modelling without verification

by measurement. At Enceladus' south pole, ice grains originating in the subsurface ocean are ejected into space through multiple fractures [Porco et al., 2006]. This active region is called the "Tiger stripes". The ejected ice and dust form a plume that extends 10 000 km into space. The Cosmic Dust Analyzer (CDA) onboard the Cassini spacecraft analysed the ejected material and revealed that the ocean is alkaline (pH 9-12 [Glein et al., 2015]), moderately salty (mostly 0.5 - 2 %, [Postberg et al., 2009, 2011]) and contains most elements required for life as we know it on Earth (CHNOPS) [Postberg et al., 2018a]. The presence of sulphur compounds is inferred, but remains to be validated [Peter et al., 2024]. N- and O-bearing organic compounds up to high molecular masses have been identified [Postberg et al., 2018a, Khawaja et al., 2019]. However, the mass resolution of the CDA did not allow for an unambiguous characterization of these organics. The gas phase of the plume was analysed by the Ion and Neutral Mass spectrometer (INMS) and contained mostly water vapour, but also NH₃, CO₂ and potential hydrothermal products like CH₄ and H₂ [Waite et al., 2006, 2017]. Their presence suggests ongoing hydrothermal activity at the core-ocean interface - a potential energy source for life as we know it on Earth [Hsu et al., 2015]. Nevertheless, both the INMS and CDA lacked sufficient resolution to unambiguously measure isotopic ratios (e.g., ¹²C/¹³C ratio as biosignature) and sufficient mass range to detect complex organics that could serve as biosignatures (e.g., amino acids in biotic abundances).

The south pole surface of Enceladus is continuously buried by fresh material as 90% of the ejected ice grains fall back and do not escape to form Saturn's E-ring [Villanueva et al., 2023]. In contrast, the northern hemisphere is heavily cratered indicating older surface ages [e.g., Crow-Williard et al., 2015]. In such areas, the surface ice is exposed to radiation and oxidised compounds such as molecular oxygen may form by radiolysis and diffuse into the subsurface ocean [Ray et al., 2020].

Data obtained by Cassini suggest a habitable environment in Enceladus subsurface ocean. However, further investigations are needed to constrain the environmental parameters that may limit life as we know it on Earth.

2.2. SCIENTIFIC OBJECTIVES AND REQUIREMENTS

G1. Study of Saturn's formation and evolution reflected in its atmospheric composition

G1S1. What is Saturn's tropospheric volatile composition and vertical profile?

Due to the condensable nature of volatiles in Saturn's cold atmosphere, remote sensing observations are not able to constrain volatile abundances [Hanel et al., 2003]. Hence, the only available molecular abundance constraints for Saturn are those of H₂, He and CH₄. SIREN is going to perform in situ measurements of the vertical profiles of both volatile and gas species and cloud structure. Measurements will be conducted with a vertical resolution of 0.5 km, from a pressure of 0.5 bar up to 20 bar, corresponding to the bottom of the H₂O cloud layer. This will allow the retrieval of chemical abundances (NH₃, H₂O, CH₄, H₂S, He, Ne, Ar, Kr, Xe) and relative isotopic ratios in Saturn's atmosphere [Irwin, 2009], proxies to the planet's formation history and interior composition.

G1S2. What is the structure of Saturn's atmosphere?

The vertical and latitudinal structure of Saturn's atmosphere is poorly constrained below the first cloud layers [Irwin, 2009]. SIREN will observe the atmosphere in high spatial and spectral ($R > 1000$) resolution and characterise its layers. Radio occultations of the spacecraft from the planetary atmosphere will allow the estimation of vertical profiles of temperature, density and static stability [Ando et al., 2018]. The mission will study atmospheric dynamics through cloud tracking measurements, which will provide wind speed measurements at distinct latitudes and altitudes [Machado et al., 2017]. Additionally, it will monitor the temporal variability of the weather layer with Thermal, NIR and UV-VIS spectroscopy. Coordinated remote sensing observation during the probe's descent will allow for a comparison with ground truth measurements and provide a general context to the descent site.

G2. Study of the Saturnian ring and moon formation and evolution as a proxy for accretion processes

G2S1. What are the processes behind small bodies formation within Saturn's rings?

The *Metre-size Barrier* is a persistent problem in Planet Formation Models. Cassini's observation of Saturn's tiny moons showed that they record a complex geologic history with groove formation caused by tidal stresses and accretion of ring particles. SIREN is going to use Saturn's ring system as a natural laboratory of protoplanetary accretion by observing the particle formation and destruction within Saturn's rings at the metre scale: the mission will study the A-B ring system during at least 100 orbits, achieving images with a high spatial resolution of 1-10 m/px. Wide field observations of the rings will also be performed, allowing us to carry out ring seismology and constrain the interior mass repartition of Saturn.

G2S2. What are the interactions of charged dust and particles from Enceladus within the Saturnian magnetosphere and rings system?

Cassini started to characterise the generation of plasma from Enceladus' plume and its interaction with Saturn's magnetic field; while it discovered the locations of the sources and the sink, the way the charged particles engage with Saturn's ionosphere is still unknown. The motion of these particles in the Saturnian System (e.g. energy, direction) and what they consist of are key questions for understanding the interaction between particles in this system and constraining the formation and evolution of the planetary environment. In an effort to answer them, SIREN will measure the Plasma environment, the Electric Field and the Magnetic Field of the Saturnian System. Additionally, the mission will search for possible Ion Cyclotron Waves in the magnetic field and UV emission produced by the interaction between the solar wind and the rings particles.

G3. Study of the chemical processes that shape Enceladus' potentially habitable subsurface and surface

G3S1. What is the structure and composition of the plume, including prebiotic chemistry, biosignatures, isotopic ratios and hydrothermal products?

Enceladus' plume is composed of gas and ice particles that form from the subsurface ocean and are ejected into space [Porco et al., 2006]. SIREN will analyse the plume

material during flybys, thereby revealing the ocean composition (including potential biosignatures and hydrothermal products) and providing new insight into the ocean's habitability. Additionally, the mission will study the asymmetry of the plume, the ice grain densities and size distribution. The composition of the ice grains will be measured with a 1 Da resolution and up to >500 Da, while the gas phase will be analysed with a 1 Da resolution up to >200 Da. This will cover relevant mass ranges for identification of biotic or abiotic abundance ratios of amino acids and fatty acids [Klenner et al., 2020, Dannenmann et al., 2023] and complex organic compounds that quantify the extent of hydrothermal activity in the ocean through geothermometer techniques such as the C_2H_4/C_2H_6O ratio as a probe of hydrothermal system temperature [Robinson et al., 2023].

G3S2. What is the structure and composition of Enceladus' surface on a global and local scale?

Enceladus' heterogeneous surface crater distribution between the North and South hemispheres showcases a significant age difference between the two regions, due to the surface deposition of expelled plume material while also suggesting active generation of tectonic features [Crow-Williard et al., 2015]. Cassini mapped Enceladus' surface with a resolution of 50 m/px at their closest encounter and studied the minor compound's chemistry of the moon's icy crust, which was however poorly constrained due to insufficient SNR (*Signal to Noise Ratio*) [Postberg et al., 2018b]. SIREN will perform hyperspectral surface maps of the surface, reaching a spectral resolution power $R > 1000$ and a spatial resolution of 6 m/px. The mission will measure the ice grains' chemical composition as well as their cohesiveness in order to prepare for a future lander mission. In relation to this, SIREN will analyse the terrain features and ground elevation and it will search for active and passive geomorphology.

G3S3. How does Enceladus sustain a global liquid ocean?

Physical libration measurements based on Cassini data indicate a global liquid ocean although its preservation is questioned by thermal models [Thomas et al., 2015]. Thus, the question remains which process prevented the ocean from freezing, considering the possibility that tidal forces due to Saturn's gravity might generate more heat than previously indicated by numerical models. SIREN will measure the tidal deformation of the Enceladus and perform a study of the surface, to detect signals of the presence of a subsurface ocean, specifically monitoring for surface features such as tilted blocks and acquiring an IR thermal map of the surface to study temperature variations that could point to geothermal activity.

Radar measurements will allow the identification of the ice-ocean interface and the thickness and structure of the ice layer. Finally, SIREN will measure compositional differences of ice grains originating from individual jets in order to investigate whether they originate from the same ocean or, possibly, from water pockets in the ice shells.

3. MEASUREMENTS AND INSTRUMENTS

SIREN's payload will be divided between the instruments that are going to be installed on the probe and those that are going to operate on the spacecraft.

3.1. PROBE INSTRUMENTS

- I. The *Mass spectrometer* is able to measure the mass-to-charge ratio of one or more molecules in a sample. This instrument will inherit its design from Galileo's NMS and it will measure the molecular composition and the gases vertical abundance profiles in Saturn's atmosphere. It will operate with a resolution optimised for the detection of isotopic ratios and a sensitivity of 1 ppm.
- II. The *Nephelometer* measures light scattered from the atmosphere, allowing to constrain aerosol properties (e.g. particles sizes, number densities and indications of non-sphericity). The instrument is inspired by Galileo's NEP and it will study Saturn's atmospheres and its clouds in an altitude range going from 0.5 bar up to 20 bar, with a vertical resolution of 0.5 km.
- III. The *Net Flux Radiometer*, which will be based on Galileo's NFR, will measure the vertical profile of upward net radiation fluxes in five spectral bands, spanning from solar to far infrared wavelengths. This will allow the detection of sinks of the planetary radiation from which we will be able to retrieve the presence of clouds in Saturn's atmosphere.
- IV. The *Atmospheric Sensing Instrument*, inspired by Huygens' HASI instrument, will measure the vertical profile of Saturn's physical atmospheric characteristics such as temperature, pressure, winds speeds and downward velocity.
- V. The *Helium Abundance Detector* will inherit Galileo's HAD design and its aim in the SIREN mission will be to measure the relative abundance of helium as a function of altitude in Saturn's atmosphere, with a sensitivity of 100 ppm.

3.2. ORBITER INSTRUMENTS

- I. The *UV-VIS Spectrometer* will observe Saturn's atmosphere in high spatial resolution, allowing for cloud tracking, and it will measure both the composition, structure and migration of Enceladus' plume as well as the composition of the moon's surface material through reflectance measurements in the 55.8 - 190 nm spectral range. The instrument is based on Cassini's UVIS but will improve on its spectral resolution, aiming at achieving a resolving power $R > 1000$.
- II. The *NIR Spectrometer* will be based on Rosetta's VIRTIS instrument and it will condense a spectral imager with a higher spectral resolution spectrograph, operating in a 1 - 5 μm range with a spectral resolving power $R > 1000$. It will allow for the measurement of the composition of both Enceladus' plume and surface, observing it with a spatial resolution of 5 m/px at a 25 km distance.
- III. The *Thermal Infrared Spectrometer* will be used to achieve an infrared map of Enceladus' surface in order to study the surface temperature variation and detect any geological activity. The instrument will reprise Europa Clipper's E-THEMIS' design and it

will perform measurements in the 5 - 100 μm range with a thermal resolution of 0.1 K.

- IV. The *VIS Camera* will inherit JUICE's JANUS' design and it will obtain high resolution images of Saturn's rings and Enceladus' surface and plume in a 350-1050 nm spectral range. In particular it will be able to reach a spatial resolution of 10 m/px during the observation of the rings.
- V. The *Ion and Neutral Mass Spectrometer*, based on MAVEN's NGIMS, will measure the composition of the volatile fraction of Enceladus' plume and of the plasma. It will operate in a 1-200 Da mass range, with a mass resolution of 150-300 m/ Δm and an abundance precision of 1 ppm.
- VI. The *Impact Ionization Mass Spectrometer* is able to, in addition to measuring the mass-to-charge ratio of molecules, detect properties of individual particles such as their charge, speed, mass and flight direction. The instrument is inspired by Europa Clipper's SUDA and it operates with a resolution and range optimised for the study of complex organics. It will measure Saturn's plasma density, energy and composition and it will also analyse the compositions of Enceladus' plume and surface material. In particular it will focus on the measurement of compositional differences in the ice grains ejected from individual jets in proximity of the moon's surface.
- VII. The *Ice Penetrating Radar* will probe Enceladus' ice shell for the interface between the ice and the subsurface ocean and it will measure the ice layer's thickness, study its internal structure and detect any liquid pocket within the ice shield. The instrument will be based on JUICE's RIME, characterised by a 16 m dipole antenna operating at a 9 MHz frequency and able to reach a 9 km penetration depth. Our instrument aims to reach depths superior to 18 km through technical improvements, in order to properly study the ice shell in both the north and south hemisphere.
- VIII. The *Laser Altimeter* is able to measure the altitude of an observed point on the planetary surface by transmitting laser pulses towards the surface and measuring the time lag between the start and return pulses. It will inherit JUICE's GALA design and it will be able to study the morphology of Enceladus' surface, mapping the terrain's features and elevation with an altimeter accuracy of up to 1 m.
- IX. The *Radio Science Experiment*, based on JUICE's 3GM, consists of a movable radio antenna (for radio tracking) and an Ultra Stable Oscillator (USO). It will estimate the vertical profiles of Saturn's atmosphere, tracking temperature, density and static stability. Additionally, it will be able to measure the extent of Enceladus' subsurface ocean.
- X. The *Magnetometer* measures changes in the magnetic field. Its design will be inspired by JUICE's JMAG: it will be equipped with three sensors, two for the measurement of the magnetic field's orientation and direction and one for the field's strength. SIREN will use the magnetometer to look at interactions between charged particles and Saturn's magnetosphere.

- XI. The *Top-Hat Analyser*, based on BepiColombo's MIA instrument, will measure the energy distribution of ions in Saturn's environment which has never been looked at by Cassini-Huygens. It will use the spin motion of spacecraft to observe three-dimensional ion distribution. It will permit us to understand the interaction between Saturn's magnetosphere, the rings and the solar wind, contributing to the study of its atmosphere.
- XII. The *Electric Field Antenna* will inherit JUICE's LP-PWI's design with a nearly equivalent length of antennas. The Debye length reach will be sufficient to look at the charge separation within the electrostatic field at a distance of six Saturnian radii. SIREN will analyse potential variations, plasma waves and charged particles, helping to understand the electromagnetic interactions and dynamics of the Saturnian System.

4. MISSION ANALYSIS

To achieve the mission objectives a transfer to Saturn is necessary, which requires an escape velocity of approximately 12 km/s [Rocchi and Khan]. Due to the limitations in our launch capabilities, achieving such a velocity requires the use of Gravitational Assists (GAs). This method generally implies a series of gravity-assist manoeuvres at the inner planets, which leads to a series of disadvantages. For example, finding a transfer that involves different bodies can be challenging and limits the launch date due to the need for a specific configuration of the planets involved. Secondly, gravitational assists performed around Venus may increase the spacecraft's requirements for thermal protection.

Therefore, the SIREN mission makes use of Solar Electric Propulsion (SEP) systems, and more specifically, of the NASA Evolutionary Xenon Thruster, which was previously employed in missions such as DART. This system has a specific impulse of 4190 s for an initial mass of 6900 kg. With this propulsion method, the need for Venus GAs is eliminated, leading to greater flexibility of the launch date (approximately one launch date per year).

After launch, starting with the escape velocity provided by the launch vehicle, the spacecraft is inserted in a 1:1 resonance orbit with the Earth around the Sun. A series of alternating SEP manoeuvres and Earth encounters inserts the spacecraft in a heliocentric transfer to Saturn with a duration of 8.8 years. The total ΔV employed for this transfer amounts to 2989 m/s.

4.1. SOI AND PROBE PHASE

Prior to the arrival to the Saturnian system, the SEP propulsion module is detached from the spacecraft. The tour phase makes use of the chemical propulsion system of the orbiter.

The spacecraft follows an intersecting trajectory with Saturn. 20 days prior to arrival at Saturn, the probe (ARGO) is deployed and a ΔV is applied by the spacecraft to raise the periapsis and avoid collision with Saturn.

Upon arrival at Saturn's atmosphere, the probe goes through an entry phase of approximate duration of 2 minutes. Then, a drogue chute is followed by a main chute deployment to slow down the probe. Finally, the probe begins the descent phase of approximately 90 minutes in which the scientific measurements are performed, ranging in altitudes from 0.5 to 20 bar.

During this scientific phase, the probe must communicate with the orbiter, which requires a continuous line of sight. The orbiter arrives at its pericenter inside the Saturnian rings, where the Saturn Orbit Insertion (SOI) ($\Delta V = 633$ m/s) manoeuvre is performed. This point is critical for the mission as the scientific retrieval is done while the manoeuvre is performed.

The SOI manoeuvre inserts the orbiter in an orbit around Saturn which intersects Titan. By performing multiple Titan GAs, the inclination of $\sim 14^\circ$ is reduced to about 0.3° and the periapsis is raised to outside the rings.

4.2. ENCELADUS PLUME PHASE

By using the Titan GAs, the orbiter is inserted into a 1:7 resonant orbit with Enceladus, with Enceladus located approximately at periapsis. At passage at Enceladus every 9.6 days, the orbiter crosses the South pole plume at different altitudes, i.e., different orbital inclinations. These inclination changes are achieved through Titan GAs when the orbiter's orbit intersects that of Titan. By performing 75 flybys of Enceladus, the estimated ΔV (accounting for a $\Delta V = 5$ m/s of station keeping per orbit) amounts to 373 m/s. It is important to notice that the distance to Titan during GAs is not sufficient for most scientific objectives, which means that these encounters are considered only gravitational manoeuvres.

4.3. RING STUDY PHASE

Once the Enceladus scientific phase is finished, the orbiter begins its transfer to achieve the orbit needed for the ring scientific phase. The desired orbit requires close distances above and below the A and B rings. This implies a large eccentricity and a small inclination angle, with the crossing points of the equatorial plane of Saturn at periapsis and apoapsis. To transfer into this orbit, the spacecraft employs multiple Titan GAs that lower the periapsis to inside the rings and adjust the inclination to $\sim 0.15^\circ$. The instrument specifications constraints the maximum altitude over the rings, while the safety concerns limit the minimum distance to the rings. These two main constraints lead to an altitude of ~ 600 km above the ring plane and a maximum relative velocity. In Figure 1, the trajectory of the orbiter is shown, indicating the points at which the constraints are respected for the A (red) and B (blue) rings. The ΔV of this phase amounts to 745 m/s.

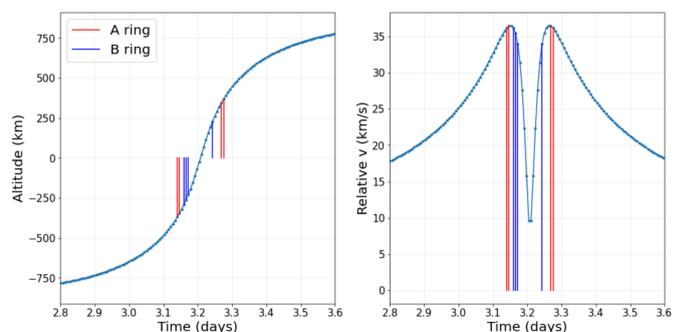


Figure 1: Altitude and relative Velocity with respect to Saturn's Rings during ring science phase.

4.4. DISPOSAL

The mission ends with the orbiter entering the atmosphere of Saturn. From the orbit followed during the ring study,

transitioning into a collision orbit with Saturn implies lowering the periapsis, which can be done by subsequent Titan GAs at apoapsis.

The goal is to follow the planetary protection principles to avoid accidental collision with the rings or moons of Saturn.

4.5. ADDITIONAL SCIENTIFIC PHASES

The mission can be extended at different phases if allowed by the mission constraints including system degradation, ΔV budget, and data budget, among others. The main extension consists of increasing the number of Enceladus flybys and ring passes. Additionally, since the apoapsis of most orbits extends further than Titan, opportunistic intersection with other moons can be taken advantage of for further scientific retrieval by accounting with the data budget restrictions per orbit.

4.6. MISSION TIMELINE

The mission begins with launch in 2038 after a twelve-year development period. The interplanetary phase has a duration of 8.8 years. Afterward, there is a transition phase of approximately two weeks to enter the Enceladus science phase. This phase includes 75 orbits with a total duration of approximately 600 days. A transition phase with subsequent Titan flyby's follows for an approximate duration of fifteen days. The ring science phase includes 100 orbits, which leads to an approximate duration of 640 days. The total mission duration is approximated to be fourteen years.

5. SPACE SEGMENT

The space segment of the SIREN-ARGO mission consists of 3 main elements: the transfer vehicle, the orbiter spacecraft and the atmospheric probe. These elements are described below.

5.1. TRANSFER VEHICLE

The SIREN Transfer Vehicle (STV) in Figure 2 is based upon previous spacecraft and transfer module designs such as the BepiColombo Mercury Transfer Module (MTM) and the Lucy spacecraft.

Electric propulsion is provided by the STV using Xenon thrusters comparable to the ones used in NASA's DART mission, presenting a high specific impulse of 4190s [Shastry et al., 2017]. To be able to power the thrusters, the STV employs a pair of solar panels with a total power generating area of 83 m².

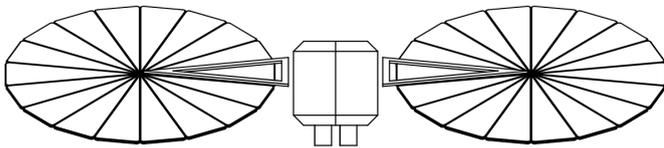


Figure 2: SIREN Orbital Transfer Module (OTM)

5.2. ORBITER

The Orbiter is constructed upon a hexagonal satellite bus structure carrying all science instruments and operation subsystems as well as propulsion, communication, and power systems. In order to protect exposed delicate or vulnerable subsystems from potentially hazardous high-energy particles during the passage of Enceladus's plume, a circular plate is mounted on top of the spacecraft, facing prograde direction in flight. Figure 3 depicts a sketch of the orbiter spacecraft, including the dipole antenna of the Ice Penetrating Radar and

the Magnetometer boom as well as the electric field probes and the atmospheric probe ARGO that is to be deployed into Saturn's atmosphere.

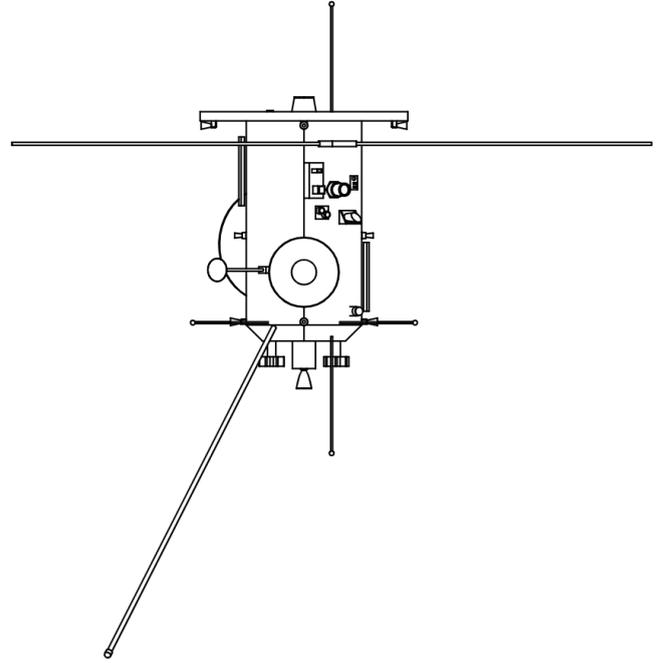


Figure 3: SIREN Orbiter Spacecraft side view.

I. Thermal Control

The aim of the thermal control subsystem (TCS) is to maintain all the spacecraft and the payloads within their required operational (or at least survivability) temperature during each mission phase. The mission heritage of Cassini-Huygens [Gibbs, 1996] and similar missions like Juice [Deschamps et al., 2023] or the NASA mission concept Enceladus Orbiter [Spencer et al., 2010], have been considered as a starting point to design what is required to meet the thermal requirements.

Components	Margin [%]	Total Mass [kg]	Power [W]
MLI Blanket	10	45.97	-
Thermal Surfaces	10	1.71	-
Thermal Straps	10	18.96	-
Radiators	10	25.68	-
Heaters	10	1.85	12
Thermistors	10	3.02	31.2

Table 1: Thermal control elements of SIREN.

At this stage of the design, since they are the most demanding components, only the instrumentation of the payload has been considered. Two different ranges of temperature are retained to ensure that all the instruments will be operational: 150 to 161 K for the IR instruments (60 to 90 K for part of the NIR Spectrometer) and 280.15 to 290.15 K for the others. A preliminary radiator area has been performed following [Wertz et al., 2003], resulting in 3.08 m² area of radiators for the orbiter. Table 1 summarises the elements of the thermal control system.

As a preliminary configuration, the dissipated heat from the RTGs will be partially redistributed through the spacecraft

using some heat circuits linked to the radiators (for example using some different conductive material to propagate the heat). The idea is to take advantage passively of the huge amount of dissipated heat by the RTGs to provide the heat necessary to maintain the temperature of the different components constituting the spacecraft. This leads to a few challenges:

- The way to control the heat flux coming from RTGs.
- The heat circuit through the spacecraft.
- The management of the temperature of the two different payload volumes, especially the coldest one.

These challenges require a more in depth analysis in a later stage of the development.

II. Attitude Determination and Control

The attitude determination and control subsystem (ADCS) aims to orient and stabilise the spacecraft during each phase of the mission. The approach taken is based on proven techniques used in past missions like Cassini-Huygens, NASA's concept mission Enceladus orbiter, Rosetta and Juice. Sensors to determine the attitude of the orbiter in space include a total of six sun sensors, two star trackers and two Inertial Measurement Units (IMU).

In order to modify and stabilise its attitude in space, the orbiter features a set of four reaction wheels and a total of 12 reaction control thrusters with 20 N of thrust, four for each axis. While the spacecraft is stabilised about three axes, four reaction wheels are installed in a redundant configuration that retains full control authority in case one reaction wheel fails. [Markley et al., 2014].

III. Power

The orbiter's power system was sized based on the driving modes of the spacecraft. These occur when the spacecraft is conducting scientific measurement with its instruments and when transmitting the gathered data back to Earth as seen in Table 3. However, the Saturnian orbits are in the order of days while the windows to use instrumentation are no more than 5h per orbit. Additionally, access to deep space ground stations is a valuable commodity therefore there will be large periods of downtime in each orbit. This has enabled the hybrid power system that is being operated.

Unsurprisingly a radioisotope thermal generator has been chosen as the primary power source as the solar intensity at Saturn rules out solar arrays however what is slightly out of the ordinary is the chosen isotope. Americium is much more accessible than Plutonium in Europe and considering this is an ESA mission, keeping key technologies in our own hands is a worthwhile investment. As well as this, the half-life of Americium is 5 times longer than Plutonium, falling by only 7 Watts over 15 years of operations. The downside of Americium is that it is less efficient and so the power output will be supplemented by 50 kg of lithium ion batteries to enable operation during critical modes. This saves about 250 kg of total mass and halves the amount of expensive radioisotopes required, lowering cost as well.

The principle of charging batteries with an RTG and discharging during critical phases will be tested on NASA's Dragonfly mission to Titan. Using a worst case scenario, there is 420 W of excess power generated over the course of a single orbit which allows the 12.5 kWh batteries to recharge fully after each pass.

IV. Communications

The communications architecture of the SIREN orbiter is composed of two different cassegrain antennas and the radiofrequency electronics necessary for the correct working of the subsystem. Both antennas have been sized based on the amount of scientific data expected to be gathered.

One fixed 2.5 m High Gain Antenna (HGA) and one movable 0.5 m Mid Gain Antenna (MGA) both of them are placed in the sides of the orbiter. The HGA will be used as the main antenna, both for Earth communications using X-Band and for the downlink of data science using Ka-Band. The HGA also includes a UHF-Band antenna for the communications with the atmospheric probe during phase 1 of the Science Operations. The movable MGA will be used during the manoeuvres of the spacecraft if the HGA can not be pointed to Earth.

Link Budget					
Antenna	Freq. Band	P (Tx) [W]	Data Rate [kbps]	P (Tx) [W]	Data Rate [kbps]
HGA	X	40	8.62	200	43.1
	Ka	40	80.2	200	421.3
MGA	X	50	0.42	120	10.6
ARGO	UHF	10	8.2	20	16.4
		<i>Min.</i>		<i>Max.</i>	

Table 2: Link Budget

The Link Budget has been done taking into account the Data Budget, Table 2, and both the best and worst case scenario of the Power Budget, Table 5, of SIREN orbiter.

Different estimations have been done to measure the transmission time of the science data in order to prove that all the data gathered could be successfully transmitted.

- Data generated by orbit: 5.02 ± 0.01 Gbits.
- Period of the smallest stable orbit: 6.4 days during phase 2.
- Conjunction time between Earth and the spacecraft.
- Usual ESTRACK communication window: 8 hours.

The time needed to transmit the scientific data, using Ka frequency band, and with the different data rates provides an estimated range of time of transmission between 3.7h and 18.5h. In the worst case scenario, where the spacecraft lacks power, it would take 72h or 3 days of 8h communication windows for the total transmission of the science data.

The time available for each communications period would be around 5 days, time that would comply with the worst case scenario for transmission.

V. Propulsion

The orbiter will include a Bipropellant Propulsion System, allowing for performing manoeuvres in the Saturn system. As a baseline, a Ariane group 400 N Bipropellant Apogee Motor was selected. It operates on MMH as a propellant and MON-3 as a oxidizer, achieving Isp value of 320s. The propulsion system will include all required tanks, valves, and sensors including redundancies, reducing the probability of single point failures in this key system.

VI. Structure and Mechanisms

The exact configuration and materials (both for primary and secondary) structures has to be prepared in future development process, by taking into account both numerical simulations as well as structural models testing.

The mechanisms used on the orbiter include a pointing mechanism for the MGA, magnetic boom deployer, radar boom deployer, and an electric field probe deployer. Furthermore, the optic instruments (camera, laser altimeter) and spectrometers will have protective shutters to protect the instrument apertures during on-ground processing, launch and non-operation phases.

The spacecraft will need to be qualified in an environmental test campaign, ensuring that it is able to withstand loads and vibrations related to the launch.

VII. On-Board Data Handling

The collection and efficient transmission of the scientific data is an important part of the mission. This is due to the large number of instruments on the SIREN orbiter. Some of these instruments have different compression rates, resulting in an overall mean compression rate of 1.6.

The different orbits performed by the spacecraft during the Science Phase [Section 4] are expected to generate 4.8 Gbits per Saturn orbit. On top, a flyby over Enceladus would add 0.21 Gbits of data generated and the flybys over the Rings 0.23 Gbits. This results in a total amount of 5.01 Gbits or 5.03 Gbits including a 10% margin, as referred to in Table 3.

Mission Phase	Data Budget		
	Data Gathered 10% Margin	Lossless Compression Rate	Memory Budget
Atmospheric Probe Total Phase 1	3.02 [Mbit]	1.25	10 [MB]
Saturn + Enceladus Per Orbit in Phase 2	5.01 [Gbit]	1.6	1.2 [TB]
Saturn + Rings Per Orbit in Phase 3	5.03 [Gbit]		

Table 3: Data Budget

A 1.2 TBytes memory has been selected for the spacecraft for various reasons. The first one is the data gathering during the normal operations due to the performance of the spacecraft, the second one is the possible flybys over the different moons in the Saturnian system for the extended mission that are not budgeted above.

5.2. THE ATMOSPHERIC PROBE - ARGO

The atmospheric probe ARGO has been designed to measure the atmosphere of Saturn. In the following two subsections the mission profile and the design parameters for ARGO are presented.

I. Mission Profile

Upon release from the orbiter, ARGO coasts for a duration of 20 days, before reaching the atmosphere of Saturn at around 700 km above 1 bar altitude. The entry of Saturn’s atmosphere starts with an entry angle of -25° and an entry velocity of 36 km/s. After the atmospheric entry phase, which lasts about 2 minutes, the drogue chute deploys. The drogue chute will

serve as a means of stabilisation and further deceleration of ARGO. When reaching a transonic velocity of around Mach 1, the back shield will be released and dragged away by the drogue chute. The main chute is deployed shortly after the release of the back shield and subsequently the heat shield is jettisoned. The descent module, consisting of the pressure vessel with instruments, will remain attached to the main chute while it descends into the deeper atmosphere. The main chute limits the probe’s speed to 50 m/s. From this point in time, at around an altitude where Saturn’s atmospheric pressure is about 0.5 bar, the scientific measurements start and are relayed directly back to the orbiter over the UHF (Ultra High Frequency) radio link, where the orbiter is above 20° elevation as seen from the probe. Measurements are taken every 10 seconds, which means a measurement is made every 500 m.

The descent phase is expected to last 90 minutes; the probe will have descended 270 km below the 0.1 bar altitude level of Saturn’s atmosphere, which is expected to be below the water cloud layer. Here the probe will lose contact with the orbiter and implode, ending the descent phase of the probe.

II. The Probe Design

ARGO’s design was strongly influenced by the ESA CDF (Concurrent Design Facility) studies “EPIG” [ESA, 2019a], “ICE Giants” [ESA, 2019b], and “PEP” [ESA, 2010]. It consists of a descent module, which is a pressure vessel holding the instruments, a parachute system (drogue and main) as well as a TPS (Thermal Protection System) that encapsulates the pressure vessel and parachutes, consisting of a front heat shield made of HEEET (Heat shield for Extreme Entry Environment Technology) and back shield. The heat shield is a design driver and dictates a probe diameter to 1.25 m in diameter with a half-cone angle of 45 degrees.

ARGO is expected to generate 280 bps reaching a total amount of data of 3.02 Mbits, applying 10% margin, during its whole mission. Several of its instruments perform lossless compression using different rates, resulting in a mean compression rate of 1.25 as given in Table 3. During the entry phase in phase 1, ARGO won’t be able to send data to the spacecraft during the 2 minute descent due to plasma forming around the probe, resulting in the addition of a 10 Mbyte memory for its storage. Right after entering the transonic phase, the stored data will be transmitted directly to the spacecraft using a UHF communication system [see Table 2].

The design leads to a total probe mass of 420 kg, of which half (210 kg) is taken up by the heat shield, and 6% (24.5 kg) is taken up by the instruments. A system margin of 20% was applied to the whole system, except for the TPS, for which a 25% margin was taken. A total heat load of $1.7e9 \text{ J/m}^2$ and a maximum heat flux of 115 MW/m^2 were assumed from the previous studies mentioned before, for which the TPS was sized. Finally a total battery capacity of 1150 Wh is supplied by the batteries.

5.3. SPACE SEGMENT OVERVIEW

An overview of the mass budget and power budget of the space segment is presented in Tables 4 and 5.

	Mass Budget		
	Basic Mass [kg]	Margin	Total Mass [kg]
Launcher Limit	6900	-	-
Launch Mass	6851.99	-	-
Spacecraft Dry mass	3931.62	-	-
Transfer Module Wet Mass	1761.19	-	550,03
Propellant Mass (Electric)	500.03	10%	-
Transfer Module Dry Mass	1009.30	20%	-
Orbiter Wet Mass	4586,80	-	-
Propellant Mass (Bipropellant)	2154,85	10%	2370,33
Orbiter Dry Mass	1847,05	20%	2216,46
Probe	420	20%	504
Mean subsystem level margin	-	17%	-
Mean component level margin	-	14%	-

Table 4: Mass Budget

Orbiter Subsystem Power [W]	Power Budget in Phases			
	Enceladus	Data trans.	Orbit	Saturn
Payload	302	0	0	330
AOCS	96	96	39	96
Communications	0	315	0	0
Command	53	53	53	53
Propulsion	0	0	11	0
Power Conditioning and Distribution Unit (PCCU)	95	95	95	95
Thermal Control	38	38	38	38
System Margin (20%)	117	119	47	122
Total	699	715	281	732

Table 5: Power Budget

7. LAUNCH AND GROUND SEGMENT

In this section the launch and ground segment are presented.

7.1. Launch segment

For the launch of the SIREN mission the Ariane 64 was selected. The Ariane 64 rocket is developed by Arianespace and had its maiden flight on July 9th 2024. As of writing, the launch mass of Ariane 64 is 6900 kg onto an Earth escape trajectory with an escape velocity equal to 2.5 km/s [Arianespace, 2021]. The spacecraft's configuration was designed such that it fits within the fairing of the Ariane 64.

7.2. Ground segment

The ground segment used during the mission will be the ESTRACK Deep Space Antennas (DSA), with the optional use of NASA's Deep Space Network (DSN) as a backup. The usage of the ground segment is estimated to be about 3h/day for routine operations and ~19 h/week for science downlink.

The operations will be conducted by the European Space Operations Center (ESOC), and the collected data will be stored at the ESAC Science Data Center (ESDC).

8. PROGRAMMATICS

8.1. COST

The cost of the mission is estimated to be 2.082 B euro, which, assuming a 10% inflation, will lead to a future projected cost of 2.29 B euro.

The costs are divided into 5 different categories, namely industrial costs (1200 M), ESA project team (300 M), mission operations and science operations (180 M), launch (150 M), and contingency (252 M).

With this cost the mission falls within ESA's large (L-class) classification.

8.1. RISK ANALYSIS

Risk analysis was performed for the mission, allowing for identification of several potential risks. All of those were evaluated in terms of their likelihood, cost/schedule impact and severity, and mitigated where needed.

Most notable risks were related to: (I) the RTG availability, maturity and potential environmental damages, (II) the potential subsystem failures (deployment mechanisms, AOCS) complicating fulfilment of scientific objectives, and (III) the possible influences of Enceladus' plume on the orbiter during flybys.

8.2. OUTREACH

Outreach is a key factor to bring the technological and scientific advancement produced by ESA missions such as SIREN to the public. This includes outreach to stakeholders, as well as to private people, as they are the ones ultimately investing their taxes into the projects. Further than that, ESA follows the goal of educating students of all ages. To fulfil this goal of making space accessible for all, different measures shall be taken.

A. Social Media

Updates on the mission shall be uploaded on social media platforms such as X (formerly known as Twitter) and Instagram. Posts could include making educational series about the scientific and technical basics of the mission, as well as mission updates.

B. Educational talks at universities and high schools

This point mainly serves the purpose of making students aware of their respective options with regard to specific ESA courses, such as the young graduate trainee program.

9. CONCLUSION

The mission SIREN proposes the exploration of the Saturnian system. With the help of 17 instruments distributed on an orbiter and the probe ARGO, the mission will push scientific knowledge about the composition of Saturn's atmosphere, its ring system, and its moon Enceladus. With its ambitious scientific requirements, the L-class mission will encourage technological advancement and push the European economy forward. SIREN will be decommissioned after 14 years of mission duration and send data for ~3.5 years. The results will help understand the formation of the Solar System and its giant planets, and possibly advance our knowledge on the Habitability of nearby ocean worlds.

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