SOURCE
Subsurface Observation of Underground Reservoirs in the Ceres Environment

Students: F. Mota, K. Makhija, G. Oskarrson, M. Beaumont, F. Arch, C. Leca, A. Cremasco, K. El Bakkoury, N. El-Bez-Sebastian, M. Filipiak, V. Froehlich, J. M. Gómez-Limón, E. Klioner, J. Kramer, M. Vuori
Tutors: J. Loicq, O. Dhuicque

The origins of life on Earth remain among the most profound and unresolved scientific questions. Central to this mystery are two fundamental components: water and organic molecules. While both are essential prerequisites for life as we know it, their appearance on early Earth is still a matter of debate. Ceres, the largest Main Belt asteroid, bears organic compounds and is the only place in the inner Solar System that possibly harbors H_2O in a liquid form. Our mission, SOURCE, aims to investigate the origin of water and life on Earth by landing on Ceres, the largest extraterrestrial H_2O reservoir in the inner Solar System.

1. Introduction

The origin of life has captivated humanity since the dawn of civilization. **Water** is fundamental to life as we know it and is a central element in all scientific theories regarding the emergence of life on Earth [1]. However, the origin of water on our planet remains largely unresolved. Similarly, the presence of **organic molecules** is another fundamental requirement for prebiotic chemistry, and their origins remain unclear. Understanding how water and organic compounds appeared on Earth is therefore intrinsically connected to the broader question of life's origins.

In this report we present **SOURCE (Subsurface Observation for Understanding Reservoirs, Composition and Evolution in the Ceres Environment), a mission aimed at investigating the origin of water and life on Earth by landing on Ceres, the largest extraterrestrial reservoir of water in the inner Solar System**.

1.1. The origins of water on Earth

A key open question is whether Earth's water is of endogenous origin, exogenous origin, or a combination of both.

The endogenous hypothesis proposes that water was already present in the materials that formed the Earth - either trapped within minerals in the primordial mantle or adsorbed onto dust grains in the protoplanetary disk. [2]. Recent models suggest that water vapor could have condensed closer to the Sun than previously believed, a theory supported by isotopic similarities between Earth's water and predictions from solar nebula models. [3].

Conversely, the exogenous theory posits that asteroidal impacts delivered a significant portion of Earth's water. The deuterium-to-hydrogen ratio (D/H) of Earth's oceans closely resembles that of carbonacous chondrites [1], which are believed to have emerged from the outer Main Asteroid Belt [4].

Consequently, investigating the presence of H_2O and its isotopic ratios across the Solar System offers a direct approach to contrast the endogenous hypothesis against the exogenous hypothesis. For much of the 20th century, the Solar System was seen as a predominantly dry place, with liquid water thought to be largely confined to Earth. This perception has dramatically shifted in recent decades. Thanks to advances in space exploration and observational technologies, we now understand that water (whether as ice, vapor, or subsurface brines) is widespread across the Solar System. From the polar ice caps of Mars to the icy moons of Jupiter and Saturn to the comets of the Kuiper Belt, mankind has come to learn that water is no longer seen as a rare exception of a substance in space, but rather as a common planetary ingredient. This new paradigm not only reshapes our understanding of planetary formation, but it also broadens the scope for habitable environments beyond Earth.

1.2. Liquid water reservoirs in the Solar System: Towards the origins of life

The investigation of subsurface brines [2] and liquid water reservoirs in minor Solar System bodies is critical for advancing our understanding of the origins of life. These environments are hypothesized to be key settings for prebiotic chemistry, [5] offering unique conditions that may mirror those on early Earth where life's precursors emerged. Liquid water serves as a medium for chemical reactions that form complex organic molecules, such as amino acids and nucleobases. Subsurface brines, enriched with dissolved minerals and potentially organic compounds, provide stable, shielded environments

[1] A type of stony meteorite characterized by its high carbon content and primitive composition, meaning it hasn't been significantly altered by heat or other processes since its formation

[2] A high-concentration solution of salts in water

where these molecules can concentrate and interact, protected from harsh surface conditions like radiation and extreme temperatures [6].

As with water, the origin of related organic compounds on Earth remains uncertain. One hypothesis suggests that the same exogenic mechanisms—such as asteroid impacts—that may have delivered water to early Earth could also have transported organic materials [7]. Investigating the organic composition of liquid water reservoirs across the Solar System is therefore critical to testing this hypothesis and advancing our understanding of life's origins on Earth.

Exploring these environments also has broader astrobiological implications. Subsurface brines may exist on multiple Solar System bodies, providing a comparative framework to assess habitability across diverse settings. By analyzing their compositions - water, salts, organics, and potential energy sources - it is possible to constrain the conditions under which prebiotic chemistry occurs, not only on Earth but also in other potentially habitable worlds (Mars, icy moons, etc.).

1.3. Background on Ceres as a Target for Solar System Exploration

The largest object in the Asteroid Belt is the dwarf planet, (1) Ceres (see Figure 1). Ceres was discovered by Giuseppe Piazzi in 1801, becoming the first ever known Main Belt asteroid ever identified. It is roughly 946 km in diameter and orbits the Sun at ~ 2.7 AU (outer Main Belt) in an almost circular orbit (e = 0.09) and close to the ecliptic (i = 10°). Additionally, it rotates with a period of 9 hours and 4 minutes and has an axial tilt of 4°.

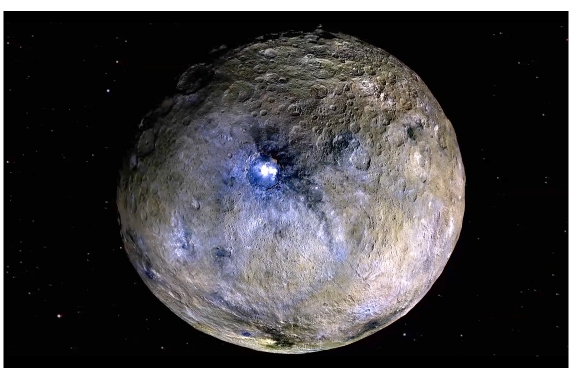

Figure 1. Ceres taken by Dawn's mission. Image credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA.

In 2014, ESA's *Herschel Space Observatory* unequivocally detected water vapor on Ceres. Ceres was then realized as the first-ever Main Belt asteroid confirmed to host water and a transient exosphere [8], a revolutionary discovery.

Just a year later, the *Dawn* mission by NASA reached Ceres and spent 3.7 years orbiting it. Its observations offered great insight into Ceres' aqueous nature.

Dawn data confirmed superficial H_2O presence [9], being the largest known water reservoir in the inner Solar System. Water ices might be in concentrations as high as ~ 90% near the crust, remnant of an old impure ocean [10]. Determining whether the water on Ceres shares a common origin with Earth's water (similar isotopic ratios) could provide compelling evidence supporting - or refuting - the hypothesis that Earth's water has a primarily asteroidal origin.

It has been recently proposed, based on *Dawn* gravitational evidence and thermal modelling, that large liquid water reservoirs may exist in Ceres' crust beneath the surface [11]. This possibility, in combination with the confirmed presence of organics [12], makes Ceres an invaluable asset in investigating prebiotic chemistry and its relation to the origin of life on Earth.

Furthermore, Ceres has been proven to be geologically active, contrary to what was previously thought. Outwellings of brines take place [13] at certain locations, exposing fresh material from beneath the surface, where it has likely laid protected. This implies that largely unaltered brines might be accesible at, or close to, surface level.

Therefore, Ceres was chosen as the mission target as it serves as a prime candidate to investigate the aforementioned fundamental questions, given its location and interior make-up. Its exploration will allow us to take **a major step towards understanding the origins of water and prebiotic compounds on Earth and ultimately, understanding the genesis of life**.

1.4. Probing the Origin of Water and Organics: The Case for Ceres

Data from the *Dawn* and *Herschel* data paint missions have provided invaluable knowledge into Ceres, but significant gaps remain. The following science objectives (SO) of the SOURCE mission are driven by the critical open questions outlined above:

- **SO1. Characterize the H_2O on Ceres and its relation to origin of water on Earth**: The *Dawn* mission (orbiter) could not measure the D/H ratio on Ceres, as it relied solely on remote sensing instruments and lacked the capability for isotopic analysis or direct access to water-bearing samples directly. Accurately detrmining this ratio would provide critical insights into Ceres' water origins, its role in volatile delivery across the Solar System, and its potential as a site for prebiotic chemistry, advancing our understanding of habitability.
- **SO2. Assess the current and past habitability potential of Ceres with relation to the origin of life on Earth**: The same argument applies to the resolution of organic compounds. *Dawn* had the capability (through infrared spectroscopy, measuring C-H absorption bands) of detecting broad organic signatures. Its limited spectral resolution, reliance on remote sensing, and lack of in situ analytical tools prevented it from resolving the exact molecular composition or complexity of these organics.
- **SO3. Determine the origin of the observed surface**

activity on Ceres: The driving mechanism for the unexpected geological activity on Ceres is still unknown. Impacts are hypothesized to trigger outwellings of internal brines [11], but endogenous seismic activity cannot be rueld out. Endogenous seismic activity could indicate ongoing cryovolcanism, suggesting active geochemical cycles that may sustain environments conducive to complex organic synthesis, unlike transient impact-driven processes.

- **SO4. Determine the internal structure and differentiation of Ceres**: The presence of substantial subsurface liquid H_2O reservoirs is still widely debated. All existing evidence supporting this hypothesis is derived from models based on indirect measurements, as *Dawn* was not equipped to perform magnetometric observations - an essential capability for confirming their presence with certainty If the presence of such vast subsurface waterbodies is confirmed, Ceres would become the closest ocean world to the Earth.

2. SOURCE mission

SOURCE is composed of an orbiter, a rover, and an impactor. There is an **absolute necessity to land on the surface and be able to traverse** in order for the scientific objective to be achieved. Additionally, detecting the magnetic signatures of potential subsurface water reservoirs necessitates ground-based measurements at multiple locations, thereby imposing the critical requirement for deploying a rover.

The spacecraft will launch on July 23rd 2036, perform a flyby of Mars by November 2042, and finally insert itself into orbit with Ceres in 2050.

The orbiter will first perform a global mapping (visual and infrared spectra) of the surface from an altitude of 396 km, with the goal of contrasting data collected during *Dawn* and identifying undiscovered regions with potential activity. This will allow us to map *regions of interest*, which will either be areas undergoing recent outwellings of fresh subsurface material, or Occator craters, in the case that no such new activity was uncovered.

Next, the orbit's pericenter will be lowered to an altitude of 10 km to enable detailed local mapping of the target region. This phase will include evaluation of the artificial impact event, which will inform the selection of a safe and optimal landing site for the rover.

From this orbit, the rover will be deployed on the surface of Ceres, and then the orbiter will enter *relay orbit*. Simultaneously with the orbiter, the rover will confirm or refute the presence of a subsurface ocean by measuring the magnetic field strength at the surface. Additionally, it will collect surface samples to determine the D/H isotopic ratio, organic composition, mineralogy, and crystallography of Ceres. The rover is designed for a minimum operational lifetime of thirty days post-landing, with the possibility of mission extension to analyze additional sampling sites if instrument functionality and solar panel performance remain sufficient.

3. Instrumentation

The mission carries a total of 16 instruments. Two of these, magnetometers and accelerometers, are equipped on both the orbiter and the rover."

3.1. Instruments on the orbiter and rover

- **Magnetometers** are deployed on both the orbiter and the rover to measure the magnetic field associated with Ceres. These measurements will help infer the presence or absence of an internal structure, such as a potential subsurface ocean. Its resolution is of 0.01 nT and necessitates 27 hours of consecutive measurement. It is based on THEMIS magnetometers [14]. Those measurements will be complemented by the GPR (see section 3.2), in order to obtain a well-rounded grasp of the differentiation and internal structure of Ceres.
- The **accelometers** are needed for the purposes of navigation and for the correction of the orbit and the facilitatation of the landing. Scientifically, it is used to infer gravitational perturbations and to determine the uniformity of Ceres' layers. They portray an accuracy of 10^{-9} m/s^2. It is based on ISA which is on Bepicolombo and on STIM300 which is on Juventas [15].

3.2. Orbit Instrumentation

The Orbiter has 7 instruments: two cameras, a copper impactor, an impactor shooter, a laser altimeter, a ground penetrating radar and an infrared hyperspectral camera.

- Two **wide-field cameras** are used to do global mapping of the surface after arriving on Ceres. By contrasting against Dawn, global mapping we will be able to detect areas of recent activity. Afterwards, areas of interest (chosen based on the global mapping) will be locally imaged. The global mapping is done with a resolution of 40 m/pixel at 396 km altitude. Local imaging is done with a resolution of 1 m/pixel at 10 km altitude. It has a field of view of 12x12°, and will operate in the visible (240-720nm). Local imaging will be used to define the rover's landing site. Additionally, a resolution ~ 50 times better than Dawn will allow us to better characterize the activity region and determine the size of the crater created by the copper impactor (proxy for surface strength and compostion). The instrument is based on OSIRIS on board the Rosetta mission [16].
- **The Laser Altimeter** (L.A) performs local topographic mapping by measuring the surface elevation with a horizontal accuracy of of 7 cm and a vertical accuracy of 1 cm. Potential rover landing sites will be surveyed using the Laser Altimeter (L.A.) to identify the optimal landing area. Altimetry data will also assess the depth of the crater formed by the impactor, providing insights into the

structural strength of the surface material and, indirectly, its ice content. Additionally The instrument is based on heritage from OLA on board of OSIRIS-REX [17].

- The **Ground Penetrating Radar** (GPR) detects different layers and measures their depth. The GPR will be used locally, before and after impact, to assess the influence of a collision on Ceres on its subsurface. It will also provide crucial insight into the possibility of presence subsurface liquid water reservoirs. It will measure 5 km deep, with a vertical resolution of 150 m. The instrument is based on MARSIS radar which is on Mars Express [18].
- The **infrared hyperspectral camera** will perform spectral mapping of Ceres, both globally and locally at areas of interest - including the impact site following collision with the copper impactor. Its objectives include detecting complex organic compounds and mapping their distribution. Additionally, the camera will be used to detect and obtain spectra of Ceres' exosphere by observing the Sun and standard stars. Its spectral range is 0.9-5.0 μm, and spectral resolution 0.20 μm. At such wavelength, the thermal tail of Ceres blackbody spectrum will start to show, allowing for the realization of the surface temperature as well. Its spatial resolution is 6.55 m/pixel at an altitude of 10 km, and of 259 km/pixel during global mapping. The instrument is based on the camera VIMS that was used for CASSINI [19].

3.3. Impactor

- The **impactor** consists of a solid 2 kg copper ball. It will be used to see if we can induce endogenic activity from collision, as well as uncover new material underneath the surface. It will make possible the study of a newly formed crater. The prediction is that it will be thrown onto Ceres with a veocity of 200 m/s and create a $\sim$ 3 m diameter crater. The impactor launcher is a pneumatic system consisting on 1.5 L of He at 50 bar. It will be used to shoot the copper impactor. There are no heritage based instrument. It will be developed, until it reaches Technology Readiness Level (TRL) 5, by the end of phase B. There are no heritage based instrument. It will be developed, until it reaches Technology Readiness Level (TRL) 6.

3.4. Rover instruments

The rover is tooled by seven instruments, two for navigational purposes (the wide field camera and the wheel camera), and five as scientific payloads, mass spectrometer, XRD-L chip, a sampler/drill, Raman spectrometer, and IR spectrometer. It will allow the rover to serve as an autonomous laboratory. The drill will retrieve the samples on the surface and subsurface, and place them in the carrousel. The carrousel will then prepare and redistribute them for study under the different instruments.

- The **mass spectrometer** determines the composition of the samples analyzed. It derives the D/H isotopic ratios from the samples' spectra, in brines and hydrated minerals. Moreover, it characterizes the molecular composition of subsurface water if detected. It has a range of 50-1000 amu, a resolution of 1 amu, and a sensitivity of 10 ppb. This instrument is based on MOMA/COSAC on ExoMars [20].
- **X-Ray Diffraction** (XRD) with an **L-chip** allows for the detection of mineral crystal structure on samples. It will also detect phase differentiation, degrees of crystallinity and assist with determining the compositions of active regions. The range of the XRD is of 4° to 55° 2θ, with a resolution of 0.3° 2θ. It is based on the CheMin on Curiosity's rover [21].
- The **drill** retrieves subsurface samples, up to 30 cm in depth, and a sample of 30 mm^3. It is based on the drill SD2 that was on Rosetta's lander Philae [22]. This choice was motivated by the similarities of the surfaces, 67P and Ceres, in comparison with Mars.
- The **Raman spectrometer** is essential to determine the brines mineralogy. It measures the minerals abundances, for subsurface samples the degree of crystallinity, and phase identifications of ices. It has a spectral resolution of 10 cm−1, and spectrally ranges from 90 to 4000 cm^{-1}. It is based on RAX which is on the MMX mission [23].
- The **Infrared spectrometer** is a critical tool as it provides for the detection and characterization of complex organics, volatiles, salt hydrates and ices in the surface and subsurface of Ceres. It ranges from 0.9 up to 3.6 μm, with a spectral resolution of 0.20 μm. The IR spectrometer is based on MicrOmega-IR which is on ExoMars [24].
- The **Wide field camera** serves navigational purposes, alongside outreach. It will ensure the safety of potential sampling sites, and will assist with operational tasks on the rover. It has a resolution of 1 m/pixel. It operates in the visible (0.4-1.1 μm) It bases its heritage on the PanCam on ExoMars [25].
- **Pressure sensors** will aid in detecting upwellings and outgassing events associated with the release of volatiles. They offer an accuracy of 10 Pa and a precision of 1 Pa. It is based on the instrument MEDA which is on Perseverance [26].

4. Mission Analysis

The goal of the mission analysis is to develop a feasible transfer strategy and an orbital design to support robust science operations at Ceres. The SOURCE mission aims to reach and land on Ceres, whose orbit around the Sun has a semi-major axis of 2.77 AU. The developed mission profile of SOURCE is outlined in Figure 2.

Launch: The mission starts with a launch from Kourou, French Guiana, using the *Ariane 64* rocket with a characteristic energy of $C_3 = 12\,\mathrm{km^2\,s^{-2}}$. The performance of Ariane 64

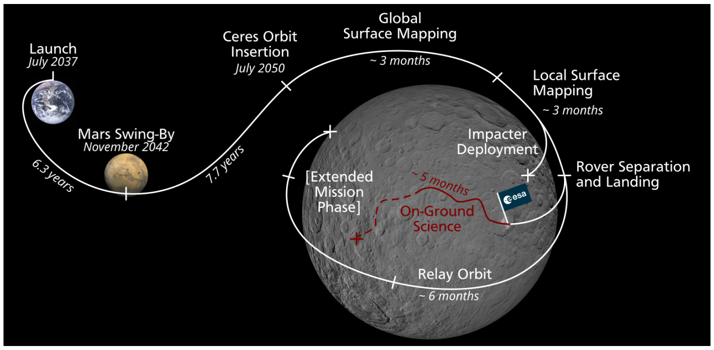

Figure 2. Sketch of the mission profile

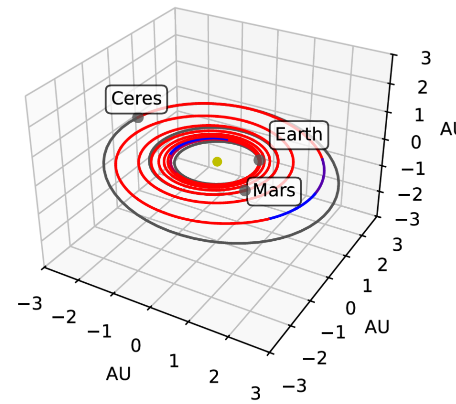

Figure 3. Plot of transfer orbit in the heliocentric frame

allows for launching up to 5.65 t at this C_3 [27], which is compatible with the SOURCE launch mass of 4.961 t (5.1.8).

Transfer: A Lambert transfer from Earth to Ceres using chemical propulsion is discarded due to the high Δv, and consequently, the large propellant mass required. Instead, electric propulsion is selected for its significantly higher efficiency (specific impulse), enabling a more mass-effective transfer. Additionally, a Mars gravity assist is included, based on Tisserand's graph, to enable efficient targeting of Ceres from Earth. An optimization with pykep and a sequential quadratic programming algorithm is performed to find a low-thrust trajectory, minimizing the propellant mass while satisfying mission constraints as minimum dry mass, maximum C_3, and Time of Flight (TOF) limited to 15 years [28–30]. The selected dates of launch, Mars flyby, and arrival at Ceres are listed in Table 1. The launch window in 2036 extends for one month, and a backup 1-month launch window in May 2037 provides additional flexibility.

Table 1. Transfer from Earth to Ceres

Event	Date
Launch	23 July 2036
Mars flyby	November 2042
Ceres arrival	July 2050

The spacecraft uses four RIT-2X ion thrusters (two operative, two redundant) for the transfer, providing a total thrust of 150 mN at 5 kW power. The total Δv required for the transfer is 14.64 km/s, corresponding to 1.65 t of Xenon, and the total TOF is 14 years. This long transfer time is due to the relatively large mass-to-thrust ratio. Figure 3 shows the transfer trajectory.

Global Mapping Orbit: The first nominal science phase at Ceres requires global surface mapping at a resolution of 40 m px^{-1}, using the camera mentioned in 3.2. This is achieved using a circular polar orbit with an altitude of 396 km. The Δv required for *Ceres Orbit Insertion* is 205 m s^{-1}, considering the circularization from the parabola with $v_{\text{inf}} = 10\,\text{m}\,\text{s}^{-1}$ and the change of plane of 20° as a margin. With one image every 10 minutes, and considering the illumination and 100% margins, a global coverage is achieved after 80 orbits, corresponding to 38 Earth days.

Local Mapping Orbit: To obtain high-resolution images (1 m px^{-1}) of the landing site, a maneuver of $\Delta v = 41.55\,\text{m}\,\text{s}^{-1}$ lowers the pericenter to 10 km above the region of interest. The copper impactor is deployed during this phase. The low orbit allows to compare the surface before and after the impact. This phase lasts approximately 3 months, with a Δv allocated for station-keeping of 30 m s^{-1} (to counteract $J_2 \approx 10^{-7}\,\text{km}\,\text{s}^{-2}$)

Separation and Landing: The rover is deployed at the pericenter of this orbit, through a landing platform equipped with thrusters to ensure a safe landing. The Δv required for landing is 510 m s^{-1}.

Relay Orbit and On-Ground Science: Post-landing, both the orbiter and rover continue to operate in parallel. While the rover fulfills all its science objectives on the surface, the orbiter acts as a communication relay between the rover and Earth. The *Relay Orbit* is designed in 1:1 resonance with Ceres' rotation period (9.07 hours), phased with the rover's dayside, and maximizing the communication window. The maneuver required for semi-major axis change and apsidal rotation is $\Delta v = 75.7\,\text{m}\,\text{s}^{-1}$. The rover is expected to operate on surface for at least 20 days. Since the Relay Orbit showed to be stable for at least 20 years, a mission extension is possible after the achievement of the minimum science requirements. At the end of the mission, both the orbiter and the rover will be safely decommissioned.

The total Δv budget, including ESA standard ECSS margins, is summarized in Table 2. Applied margins include: 5% on deterministic maneuvers, 100% on stochastic maneuvers, 20% for landing, 35 m s^{-1} for Mars gravity assist, 30 m s^{-1} to account for launcher uncertainties.

5. System

A mission to Ceres presents several significant challenges regarding the design of the spacecraft system. The vast distance from Earth demands robust communication systems, including large antennas, while the low solar intensity sets the

Table 2. Total Δv budget (including ECSS margins [31])

Propulsion system	Δv m s^{-1}
Orbiter (electric propulsion)	15437
Orbiter (chemical propulsion)	442
Lander	612

need for extensive power generation capabilities. Operating a rover adds further complexity, especially due to the relay communication via an orbiter, since data transmission is limited by orbital visibility windows, and the difficulties of surface deployment in Ceres' low-gravity and geologically complex terrain environment. In the following section, the system architecture for orbiter, lander and rover are described.

5.1. Orbiter

5.1.1. On-Board Computer (OBC)

The OBC subsystem handles command transmission, processing and execution, telemetery gathering and preparation as well as data exchange between the orbiter's subsystems and instruments. The orbiter is expected to generate approximately 1.3 GB of data every 24 hours, including a 20% margin. The general outline of the OBC architecture is shown in Figure 4.

5.1.2. Propulsion

The SOURCE mission employs a hybrid propulsion system, composed of three electric-ion thrusters for the interplanetary transfer and twelve chemical bipropellant thrusters for in-orbit maneuvering and RW desaturation, particularly liquid Monomethylhydrazine and Nitrogen Tetroxide (MMH/NTO) thrusters, for a long-duration mission to Ceres. The system is based on the heritage of past missions such as Deep Space 1 [32] and Dawn [33], which successfully operated ion engines near small bodies. It leverages the high-efficiency, low-thrust performance of ion propulsion for interplanetary travel, while chemical thrusters provide high-thrust capabilities for orbit insertion, momentum dumping, and fine attitude control. The main functions of the propulsion subsystem are identified in Table 3.

Table 3. Propulsion Functions and Their Roles (information obtained from [34])

Propulsion Function	Role
Orbit insertion	Transition from interplanet trajectory to orbiting Ceres
Orbit maintenance	Maintain stable orbit despite perturbations such as radiation, pressure, etc.
Attitude control	Unload reaction wheels using thrusters
Orbital stability	For collision avoidance, debris avoidance

5.1.3. Structure

The orbiter was designed to maximize the internal capacity while remaining within the spatial constraints of the Ariane 64 launch vehicle. Its final dimensions are 3200 mm × 3200 mm × 4000 mm.

Both, the orbiter with the lander, and the rover structures, utilize space-grade materials to achieve high mechanical strength with minimal mass and serve as radiation shielding. The external structure comprises aluminum 6061-T6 honeycomb sandwich panels, selected for their strength-to-weight ratio and structural reliability. Carbon fiber composite components are used internally to secure sensitive systems, chosen for their accessible manufacturing process, adaptable to complex designs and vibration-damping properties.

During launch, the spacecraft is exposed to various dynamic loads, including accoustic pressure, sine (steady-state) and random vibrations, shock, and quasistatic forces. The structural design is designed to withstand these conditions to ensure the system's integrity throughout ascent.

5.1.4. Attitude & Orbit Control System AOCS

The orbiter's AOCS has 2 star trackers, 2 scientific cameras as well as twelve sun sensors as reference sensors. The reference sensors provide a fixed position without information on where the spacecraft is going, the sun sensors are primarily intended to orient the orbiter towards the Sun in case of navigation failure. The star and Sun trackers are mounted such that there is one on each side of the orbiter. The scientific cameras serve as navigation cameras when oriented towards the surface of Ceres. For inertial sensors, the orbiter is equipped with two Inertial Measurement Units (IMU) which can measure change in position and attitude. Combined, the reference and inertial sensors provide the orbiter the ability to determine its attitude. The position will be done using radar-ranging and vision-based positioning with Dawn reference imagery.

The orbiter's attitude is controlled using four Reaction Wheels (RWs) arranged in a redundant 3+1 configuration. Each RW provides an angular momentum capacity of 4 N·m·s. Three wheels are mounted orthogonally to control pitch, yaw, and roll, while the fourth is mounted at a 45° angle to provide redundancy in the event of a wheel failure.

To desaturate the reaction wheels, for orbital maneuvres and more intensive attitude control the orbiter is equipped with twelve Reaction Control Thrusters (RCS).

5.1.5. Communication system

The communication subsystem on the orbiter consists of one high-gain antenna (HGA) with a diameter of three meters and one medium-gain antenna (MGA) with a diameter of 0.5 meters. The antenna configuration is derived from heritage hardware developed for **ESA's JUICE (Jupiter Icy Moons Explorer)** mission [35]. The HGA is installed in a fixed ori-

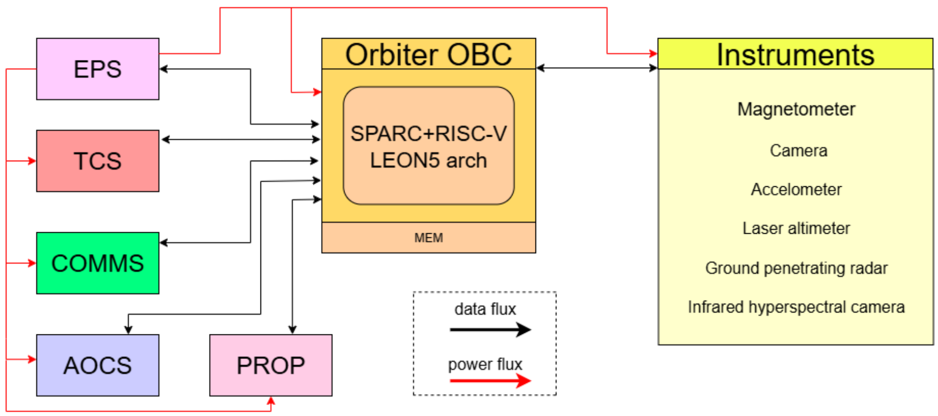

Figure 4. Data exchange between the On-Board Computer (OBC) and the following subsystems: Electrical Power System (EPS), Thermal Control System (TCS), Communications (COMMS), Attitude and Orbit Control System (AOCS), and Propulsion System (PROP), as well as instruments. Additionally, it illustrates how each of these subsystems and instruments is powered by the EPS.

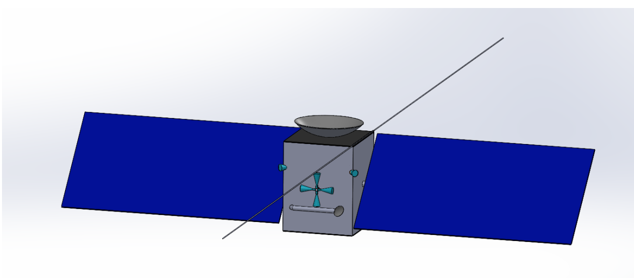

Figure 5. Illustration of the orbiter

Table 4. Link Budget Summary for Ka- and X-bands for both Uplink (U/L) and Downlink (D/L) Paths.

Band: **Up-/Downlink:** **Antennatype:**	**Ka** **D/L** **HGA**	**X** **U/L** **HGA**	**X** **D/L** **HGA**	**X** **D/L** **MGA**
f [GHz]	32	7.2	8.7	8.7
Data Rate [Mbps]	1	0.5	0.1	0.008
Margin [dB]	2.6	10.5	2.6	7.8

entation on the spacecraft, whereas the MGA is mounted on a movable mechanism that allows for active pointing. Downlink communication to the Ground Station shall be carried out using the HGA across two frequency bands: telemetry data will be transmitted in the X-band at 8.7 GHz, while scientific data shall be downlinked in the Ka-band at 32 GHz. Table 4 shows the corresponding data rates. In case of AOCS-failure, the MGA can send telemetry via the X-band.

As a ground station, selected stations from ESA's ESTRACK network, specifically those stations equipped with both X-band and Ka-band capabilities, shall be used. The primary candidates are the deep space antennas in Cebreros (Spain), Malargue (Argentina) and New Norcia (Australia), each featuring a 35-meter dish. The mission shall be operated from the European Space Operations Centre (ESOC) in Darmstadt, Germany.

5.1.6. Power

Power generation is achieved using JUICE-type solar panels [36]. These are sized (126 m^2) based on the power consumption at cruise, which is around 5 kW (mainly due to the propulsion system), and by taking into account their degradation over time.

A total battery capacity of 15000 Wh will provide sufficient energy to power the orbiter during the eclipse phase when orbiting around Ceres (this phase is more energy-consuming than the Launch and Early Orbit Phase). The power consumption of each subsystem during this phase is shown in Table 5.

Table 5. Power Budget of the Orbiter - Average Power [W]

Subsystems	**Daylight**	**Eclipse**
ADCS	120	120
Coms	100	10
OBC	30	30
Thermal	25	200
Solar Drive Mechanism	10	0
Instruments	185	55
Total Power (incl. 20% margin)	**564**	**505**

5.1.7. Thermal Control System

A hybrid passive-active thermal management strategy was implemented, tailored separately for the Orbiter and the Rover. This configuration ensures efficient regulation of both internal heat loads generated by onboard electronics and external thermal fluxes from the spacecraft's environment.

The Orbiter's thermal control system relies on a combination of radiative surfaces and active heating elements to maintain temperature stability. A radiator, with a surface of 6.4 m^2

Table 6. Operational temperatures of the subsystems of the orbiter

Subsystems	Operational Temperature [°C]
Power	(-50, 70)
AOCS	(-20, 50)
OBC	(-40, 60)
COMM	(-20, 60)
Payload	(10, 30)

is distributed across the spacecraft, positioned to achieve balanced thermal rejection, particularly during hot-case when the internal temperature is 303 K. During cold-case scenarios the temperature is 283 K, so electric heaters are used to provide to 104 W of supplementary thermal power to prevent critical components from falling below their minimum operational thresholds. To mitigate excessive thermal losses through the radiators in these conditions, a louver system with a surface area of 2.52 m^2 is deployed. These adjustable louvers dynamically reduce heat dissipation by controlling the effective radiating area. Among the payload instruments, the onboard infrared hyperspectral camera operates within an extremely narrow cryogenic temperature range of -218.15°C to -213.15°C . To maintain this environment, the instrument is enclosed in a dedicated cryocooler integrated into the thermal architecture. This ensures that the camera remains within its required operating conditions while minimizing thermal impact on neighboring subsystems. In addition, a distributed network of thermistors and thermostats continuously monitors the thermal state of vital subsystems. This sensor-driven system enables autonomous thermal regulation by activating heaters as needed to preserve functional temperature margins.[37]

5.1.8. Mass budget

The mass budget summarizes the distribution of mass across the orbiter and rover subsystems. The total allowable mass is constrained by the payload capacity of the Ariane 64, which provides a maximum launch mass allocation of 5600 kg for this mission. A system-level margin of 20% has been applied, as per industry standards.

The current estimated dry mass of the orbiter, including the payload, integrated rover, and a 20% system margin, is approximately 2268 kg. The corresponding wet mass, accounting for all propellant and consumables, is estimated at 4811 kg. With instrumentation this is 4961 kg, including margins.

5.2. Lander

The lander's purpose is to land the rover on the surface of Ceres. The lander navigation includes 2 IMU units, LiDAR for height measurement, and three navigation cameras (2+1 for redundancy). The lander is further equipped with a redundant set of batteries to power the navigation suite and the on-board computer. The thruster set includes 8400N thrusters mounted

Table 7. Mass Budget of the Orbiter

Subsystems	Mass [kg]
ADCS + Propellant	209.9 + 754
Communications	38.6
OBS + Harness (5% of Sys. Dry Mass)	81
Thermal	95
EPS	434.5
Propulsion + Propellant	230 + 1650
Structure	400
Solar Array Mechanisms	16.6
Total Dry Mass (incl. 20% margin)	1806
Total Wet Mass (incl. 20% system margin)	**4210**

in pairs facing four directions, as well as four small 1 N thrusters. These thrusters are monopropellant 400 N thrusters. The lander's structure is a aluminium construction with some steel reinforcement, where appropriate. Figure 6 depicts the lander configuration, the lander is 2005 mm x 1900x650 mm in size with the ramp folded up. The lander's estimated dry mass, including a 20% system margin, is approximately 139.6 kg. The corresponding wet mass, which includes all the propellant needed for the landing maneuver, is estimated to be 303.6 kg. Once the lander has reached the surface, the ramp will be unfold and the rover will be deployed.

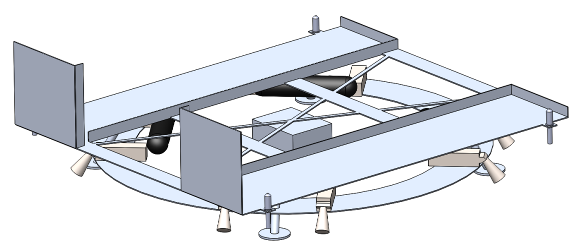

Figure 6. Illustration of the lander.

5.3. Rover

5.3.1. Onboard Computer (OBC)

The OBC system of the rover is comprised of a design similar to that of the orbiter's OBC, and it is responsible for the control of both, the rover subsystems and instruments.

5.3.2. Navigation and Wheel System

The navigation of the rover includes the usage of IMUs, LiDARs, and visual cameras. The path-planning is performed in combination with in-orbit data on-ground. The rover is then programmed to drive autonomously according to the planned path with an estimated surface speed of up to 5 cm/s.

5.3.3. Structure

The rover measures 7000×1200×550 mm in dimension. A lightweight suspension system integrates the wheel system bringing the total height of the rover to 975 mm with the wheels deployed. In addition, the rover features six deployable solar panels equipped with lightweight mechanisms which allow for the orientation control of the panels, maximizing energy generation during surface operations. The CAD model illustrating the mechanism is depicted in figure 7.

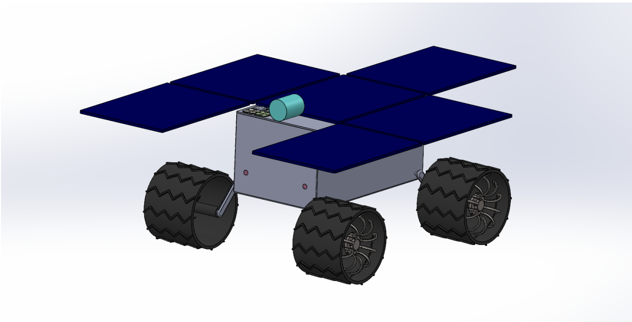

Figure 7. Illustration of the rover.

5.3.4. Communication system

The rover is equipped with a 4×4 cm X-band patch antenna with a half power beamwidth of $\theta_{-3dB} = 21°$. This provides a communication window of approximately 35 minutes/orbit. The link from the orbiter to the rover achieves a data rate of 0.5 Mbps. The uplink from the rover to the orbiter operates in the X-band as well, reaching data rates of 5 Mbps, which corresponds to approximately 1.4 GB of data/orbit. Table 4 provides a detailed overview of the communication link between the orbiter and the rover, including key parameters such as transmission frequency, data rate, and signal margin in both directions.

Table 8. Link Budget Summary for X-band for both Uplink (U/L) and Downlink (D/L) Paths.

Band: **Up-/Downlink:** **Antennatype:**	**X** **D/L** **LGA**	**X** **U/L** **LGA**
f [GHz]	8.7	7.2
Data Rate [Mbps]	0.5	5
Margin [dB]	18.7	13.1

5.3.5. Power

Steerable solar panels of 4 m^2 are used to power the rover in science mode (see the power consumptions of each mode in table 9) during daylight.

The rover will be able to sustain three Ceres days (27 hours) in safe mode without power generation using a total battery capacity of 5600 Wh. This also enables the rover to cover the necessary distance and perform the measurements while relying on less than half of the total battery capacity.

5.3.6. Thermal Control System

The Rover's thermal control system is adapted for the challenging surface atmosphere, characterized by large thermal gradients due to the planetary diurnal cycle and minimal atmospheric insulation. A radiator area of 2.84 m² is used to dissipate excess heat under sunlit conditions, while passive insulation strategies, including multi-layer insulation (MLI) and thermally resistive materials, minimize conductive and radiative losses. Localized electric 50 W heater ensure instrument survival. To complement this setup, a 0.28 m² louver surface is integrated into the rover to reduce radiative losses during cold-case scenarios which have a temperature of 240 K, thereby improving energy efficiency and maintaining thermal equilibrium. A network of thermal sensors monitors real-time temperature distributions, supporting closed-loop thermal control throughout the mission timeline [37].

Table 9. Power Budget of the Rover - Average Power [W]

Subsystems	Moving	Science	Sleep Mode
Wheels Motors	67	3.3	0
Coms	10	50	10
OBC	15	15	15
Thermal	35	35	14
Solar Panel Mechanism	10	10	0
Instruments	24	60	12
Total Power (incl. 20% margin)	**193**	**208**	**62**

Table 10. Operational temperatures of the subsystems of the rover.

Subsystems	Operational temperature [ºC]
Power	(-40, 40)
COMS	(-40, 40)
Payload	(-33, 0)

5.3.7. Mass budget

Table 11. Mass Budget of the Rover

Subsystems	Mass [kg]
Communications	1
OBC + Harness (5% of Sys. Dry)	26
Thermal	40
EPS	91
Structure + Wheel System	47
Mechanisms	10
Instruments	27
Lander system + Propellant	143 + 139
Total Dry Mass (incl. 20% system margin)	462
Total Wet Mass (incl. 20% margin)	**601**

The rover's current estimated dry mass, including its payload and a 20% system margin, is approximately 319 kg.

6. Cost estimation

An estimation of the cost of the mission is presented in Table 12. The mission is classified as an ESA class L mission.

Table 12. Cost estimate

Element	Cost [M€]	Nat. Contr. [M€]
Launch (Ariane 64)	130	
Spacecraft + Lander	650	
Rover	300	
Instruments (Orbiter)		70
Instruments (Rover)		80
Mission Operations	90	
Science Operations	60	
ESA Mgnt.	190	
Contingency	213	
Total CaC	**1 633**	**150**

7. Risks and mitigation techniques

The risk analysis identified potential threats across the mission profile, scientific objectives, and operational systems. Key risks and corresponding mitigation strategies include the following:

1) **Mission delays leading to cost overruns** — To mitigate this, contingencies have been incorporated, including budgetary margins and flexibility in transfer options.
2) **Inaccuracies in orbital transfers affecting the ΔV budget** — Margins have been added to the ΔV budget to absorb such deviations.
3) **Accelerated degradation of solar cells reducing power generation** — To address this, margins in power generation capacity have been included.
4) **Premature battery degradation** — This could compromise system performance or result in mission loss. To mitigate, redundant battery systems are included and generous performance margins are built in.
5) **Failure in subsurface sample collection** — As this is a core science objective and a key differentiator from previous missions, extensive pre-launch testing is planned at analogue environments such as the LUNA lunar analogue facility to ensure robustness of the sampling system.

8. Descoping options

Descoping options were chosen in terms of impact on the science vs. mission cost reduction. The science objectives and subgoals are listed by priority.

The first descoping option would be the micro-impactor. It answers one sub-goal of the third science objectives, meaning the determination of activity on Ceres and if it can be induced by impacts.

Another descoping that can be done is reducing the sampling sites. This will decrease the diversity of terrains analyzed. Similarly, there is the possibility to only do surface samples and not subsurface. The internal layer composition would not be known anymore, yet the mission will be able to detect them using other instruments (radar, magnetometer and accelerometer).

A further reduction of the instrument suite could further descope the mission and reduce costs.

9. Conclusions

SOURCE, thanks to its orbiter, rover and impactor, will be able to uncover the possibility of a subsurface ocean on Ceres. If said ocean exist, it will characterize it, as well as the activity on Ceres, and its internal structure.

References

[1] Westall and Brack. The importance of water for life. *Space Science Reviews*, 214(2):50, 2018.

[2] Wilde et al. Evidence from detrital zircons for the existence of continental crust and oceans on the earth 4.4 gyr ago. *Nature*, 409(6817):175–178, 2001.

[3] Sato et al. On the water delivery to terrestrial embryos by ice pebble accretion. *Astronomy & Astrophysics*, 589:A15, 2016.

[4] Alexander et al. The provenances of asteroids, and their contributions to the volatile inventories of the terrestrial planets. *Science*, 337(6095):721–723, 2012.

[5] Cable et al. The science case for a return to enceladus. *The planetary science journal*, 2(4):132, 2021.

[6] Vance. et al. Geophysical investigations of habitability in ice-covered ocean worlds. *Journal of Geophysical Research: Planets*, 123(1):180–205, 2018.

[7] Chyba and Sagan. Endogenous production, exogenous delivery and impact-shock synthesis of organic molecules: an inventory for the origins of life. *Nature*, 355(6356):125–132, 1992.

[8] Küppers et al. Localized sources of water vapour on the dwarf planet (1) ceres. *Nature*, 505(7484):525–527, 2014.

[9] Prettyman et al. Extensive water ice within ceres' aqueously altered regolith: Evidence from nuclear spectroscopy. *Science*, 355(6320):55–59, 2017.

[10] Pamerleau et al. An ancient and impure frozen ocean on ceres implied by its ice-rich crust. *Nature Astronomy*, 8(11):1373–1379, 2024.

[11] Raymond et al. Impact-driven mobilization of deep crustal brines on dwarf planet ceres. *Nature Astronomy*, 4(8):741–747, 2020.

[12] De Sanctis et al. Localized aliphatic organic material on the surface of ceres. *Science*, 355(6326):719–722, 2017.

[13] Nathues et al. Recent cryovolcanic activity at occator crater on ceres. *Nature Astronomy*, 4(8):794–801, 2020.

[14] Craig et al. THEMIS Ground-based magnetometer arrays and their education and public outreach potential. In *AGU Spring Meeting Abstracts*, volume 2004, pages SM22A–03, May 2004.

[15] Iafolla et al. In Lysiane Mornas and Juoaquin Diaz Alonso, editors, *A Century of Relativity Physics: ERE 2005*, volume 841 of *American Institute of Physics Conference Series*, pages 453–457. AIP, June 2006.

[16] Keller et al. Osiris - the scientific camera system onboard rosetta. *Space Science Reviews*, 128:433–506, 02 2007.

[17] Daly et al. The OSIRIS-REx Laser Altimeter (OLA) Investi-

gation and Instrument. , 212(1-2):899–924, October 2017.

[18] Orosei et al. Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) after nine years of operation: A summary. , 112:98–114, July 2015.

[19] Brown et al. The Cassini Visual and Infrared Mapping Spectrometer (VIMS) Investigation. In Christopher T. Russell, editor, *The Cassini-Huygens Mission*, page 111. 2004.

[20] Brinckerhoff et al. Mars Organic Molecule Analyzer Mass Spectrometer for 2018 and Beyond. In LPI Editorial Board, editor, *Concepts and Approaches for Mars Exploration*, volume 1679 of *LPI Contributions*, page 4236, June 2012.

[21] Grotzinger et al. Mars Science Laboratory Mission and Science Investigation. , 170(1-4):5–56, September 2012.

[22] Finzi et al. SD2 How To Sample A Comet. , 128(1-4):281–299, February 2007.

[23] Schröder et al. In-Situ Raman Spectroscopy on Phobos: RAX on the MMX Rover. In *51st Annual Lunar and Planetary Science Conference*, Lunar and Planetary Science Conference, page 2019, March 2020.

[24] Vaitua et al. MicrOmega IR: a new infrared hyperspectral imaging microscope or in situ analysis. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 10566 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 105662B, November 2017.

[25] Griffiths et al. The Panoramic Camera (PanCam) Instrument for the ESA ExoMars Rover. In *European Planetary Science Congress 2006*, page 26, January 2006.

[26] Rodriguez-Manfredi et al. The Mars Environmental Dynamics Analyzer, MEDA. A Suite of Environmental Sensors for the Mars 2020 Mission. , 217(3):48, April 2021.

[27] Roland Lagier. *Ariane 6 User's Manual*. Arianespace, issue 2, revision 0 edition, February 2021. Senior Vice President, Chief Technical Officer.

[28] C H Yam, D D Lorenzo, and D Izzo. Low-thrust trajectory design as a constrained global optimization problem. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 225(11):1243–1251, 2011.

[29] Dario Izzo. esa/pykep: Major update., November 2017.

[30] Gill et al. Snopt: An sqp algorithm for large-scale constrained optimization. *SIAM Journal on Optimization*, 12(4):979–1006, 2002.

[31] European Space Agency. Margin philosophy for science assessment studies. Technical Note SRE-PA/2011.097/, ESA, SRE-FM, SRE-P, ESOC & D-TEC, ESTEC, Noordwijk, The Netherlands, December 2014. Issue 2, Revision 0, Status: N/A.

[32] NASA History Office. NASA History: Deep Space 1 Validated the Promise of Ion Thrusters, 2015. Accessed: 2025-07-16.

[33] NASA History Office. NASA History: Deep Space 1 Validated the Promise of Ion Thrusters, 2015. Accessed: 2025-07-16.

[34] Grotzinger et al. Mars Science Laboratory Mission and Science Investigation. , 170(1-4):5–56, September 2012.

[35] Vázquez et al. Two-axis antenna pointing mechanism qualification for juice mission – dual-band medium gain antenna. *Proceedings of the 45th Aerospace Mechanisms Symposium, NASA Johnson Space Center*, 214(2):573–586, 2020.

[36] Kroon et al. Solar arrays for jupiter missions: Europa clipper and juice. Presented at the Space Power Workshop, April 2019.

[37] J. R. et al. Wertz. *Space Mission Analysis and Design*, chapter Specific Chapter Title or Number (if known), pages 409–429. Microcosm Press and Kluwer Academic Publishers, El Segundo, CA and Dordrecht, The Netherlands, 3 edition, 1999.