The Calathus Mission

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D. Barros Caballero, N. Berge, C. Convenevole, Z. Dionnet, G. Duvieusart, F. Enengl, G. Fedorets,
F. Hessinger, B. Kedziora, A. Kiss, L. Kissick, J. Navarro Montilla, M. Novak, H. Petersson, K. Pump
Tutors: Günter Kargl and Cecilia Tubiana

ABSTRACT

With recent missions to asteroids, comets and icy moons, we have realized that the formation conditions of small bodies in the solar system may be more complex than previously thought. To know where and under what conditions an asteroid or comet formed, we would need to know its precise composition.

The Dawn mission discovered that the Occator Crater on Ceres has areas of salts ejected from its interior. The composition of these salts and their surroundings provides valuable information about the formation of small bodies in the solar system, as well as on the possibility of favorable conditions for life on Ceres in the distant past.

Calathus is a mission designed to travel to the Occator Crater to perform mass spectroscopy and take high resolution images of the surface, but most importantly it will bring samples of the salty surface material back to Earth. The spacecraft consists of an orbiter to map the crater, a lander equipped with a drill, a mass spectrometer, a thermal mapper and a second camera to be left on the surface as the collected sample rejoins the orbiter to return to Earth for analysis.

The Calathus mission aims to return a sample of a main asteroid belt body to contribute in research of the solar systems origin by characterizing Ceres' white spots.

1 INTRODUCTION

We here propose a sample return mission to the dwarf planet Ceres, to acquire a sample from a bright spot in the Occator Crater. We name the mission Calathus, after a basket used by the agriculture and fertility goddess Ceres, which she used to deliver grain to the people.

1.1 SCIENTIFIC BACKGROUND

The dwarf planet Ceres holds a unique position among the bodies of the inner solar system. Not only is it the largest body in the main asteroid belt, making up 30% of the entire belt's mass (Pitjeva & Pitjev, 2016), but it is also, to our knowledge, the only differentiated body in the inner Solar system comparable to carbonaceous bodies. Among the many discoveries made by the Dawn mission mapping the surface of Ceres, exceptionally bright spots in the Occator Crater called faculae have received special attention (e.g. de Sanctis et al., 2016) due to their unusual chemical composition, see Figure 1. These faculae are associated with impact-related fractures and cryovolcanism-associated domes (Buczkowski et al., 2016), both suggesting that their origin might be a result of upwelling of brines from beneath the crater surface.

The abundance of organic material on Ceres' surface and the presence of salts in liquid water at some point during its formation also raises the question of whether the conditions for the formation of life may ever have been present in the dwarf planet. These kinds of questions have also arisen for both Jupiter and Saturn's icy moons, although these are heated by tidal forces, whereas Ceres only relies on its leftover core heat.

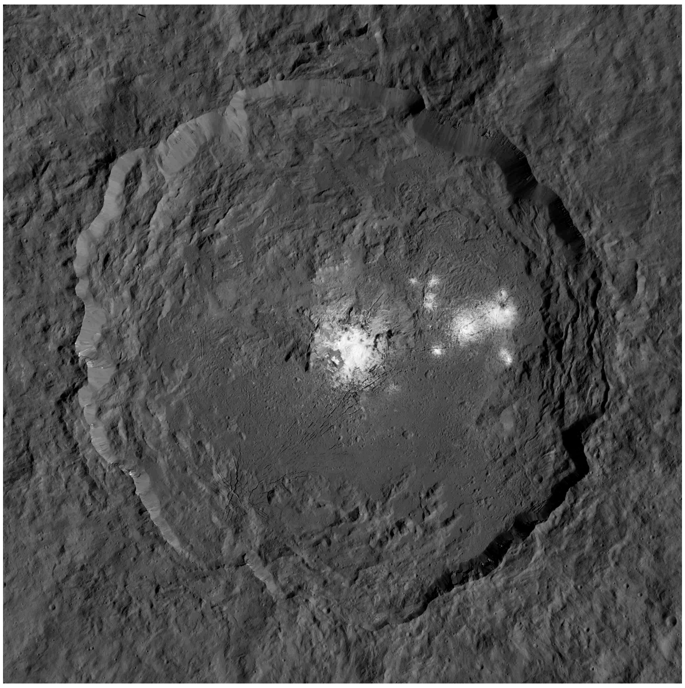

Figure 1: A close-up view of the Occator Crater with its faculae as imaged by the Dawn mission (NASA).

The surface of Ceres is similar to carbonaceous chondrites and can be classified as a C-type asteroid from spectroscopic observations (Larson et al., 1979). It also has a low bulk density, which implies high water content (McCord & Zambon, in press), and a combination of carbonates with other salt ions at the same sites (Carrozzo et al., 2018). This, in particular the presence of carbonates, is a strong indicator of Ceres having an aqueous nature with a subsurface cryosphere. Cryospheres of various types have already been inferred for Jupiter's moons Europa, Callisto, and Ganymede, while the NASA Cassini spacecraft directly observed water vapor plumes and salts from beneath the surface of Saturn's moon Enceladus (Waite et al., 2009).

While the salt carbonates on Ceres are concentrated in the Occator Crater, ammoniated phyllosilicates are ubiquitous across its surface (de Sanctis et al, 2015). Their presence signifies abundant chemical contact of surface minerals with the volatile ammonia at the dawn of the solar system (de Sanctis et al., 2015, 2016). The dynamical models of Vokrouhlický et al. (2016) argue that the migration of Ceres to the main belt is improbable but not impossible. This would require specific circumstances during the planetary instability scenario in the early formation stages of the solar system known as the grand tack (Walsh et al., 2011). It would also imply that many of the current C-type asteroids in the main asteroid belt could have migrated along with Ceres.

It should also be noted that the dating of Jupiter's formation provides evidence of two spatially and compositionally distinct reservoirs forming on either side of the gas giant – hydrated carbonaceous bodies further out, and dehydrated non-carbonaceous bodies closer to the Sun (Morbidelli et al. 2016; Kruijer et al., 2017). Ceres, with a semi-major axis of 2.77 AU, currently lies just outside the dehydrated realm of the primordial snowline at 2.70 AU. After Jupiter's formation, destabilisation and re-organisation of its orbit lead to a mixing of these reservoirs to the present-day homogeneity (Kruijer et al., 2017). This could explain Ceres' volatile-rich crust despite its position relatively close to the Sun in the main asteroid belt.

As a summary, we here identify two scientific domains where further investigation of Ceres is required:

1. Were the ingredients for life present in the subsurface of Ceres?
2. Where did Ceres form in the solar system?

1.1.1 Previous and upcoming missions

Our proposed Calathus mission to Ceres stands on the shoulders of half a century of in situ and sample return missions. The Dawn mission, which one could consider a precursor or scout mission for Calathus, has collected nearly all currently known physical information about Ceres. The recent Rosetta mission with its lander Philae to the comet 67P/Churyumov-Gerasimenko serves as a source of both scientific and technological inspiration. Other results that are scientifically interesting for the Calathus mission have been obtained by the Cassini mission during its flight through the plume of Enceladus (Waite et al., 2017). We also anticipate results from the upcoming Jupiter Icy Moon Explorer (JUICE) mission to the Jovian system.

There are multiple lessons to be learned about sample acquisition from the Phobos-Grunt and upcoming Luna-27 and InSight missions. Other counterpart missions are the OSIRIS-REx sample return mission from asteroid (101955) Bennu, the mission Hayabusa2 to asteroid (162173) Ryugu and anticipated Mars sample return missions.

1.2 MISSION PROFILE

The goal of our mission is to launch a probe from Earth to Ceres. The spacecraft Calathus consists of four segments: the orbiter, the orbiting sample (OS), the propulsion platform and the surface module, see Figure 2. The latter three parts comprise the lander Piazzi. We will be using ion thrusters and a Mars fly-by to reduce the required fuel mass and make the launch feasible. Ceres' orbit averages 2.77 AU from the Sun, and 110 m^2 of solar panels will power the spacecraft on the way there.

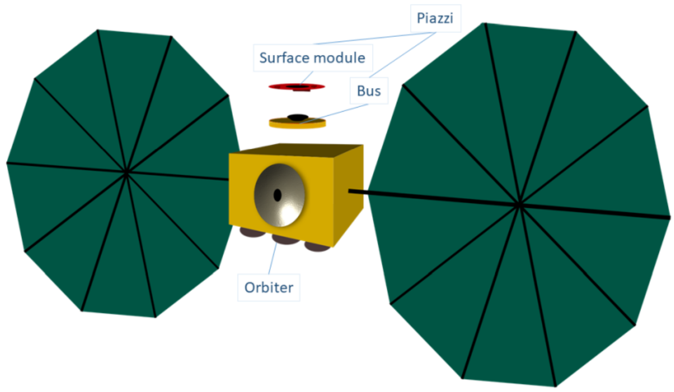

Figure 2: Exploded view of the Calathus spacecraft and its segments.

When the probe enters Ceres' proximity, it will perform an orbital insertion and map the Occator Crater faculae, sending the gathered data to Earth for analysis and landing site selection. Once an adequate landing spot is selected, the lander will decouple from the orbiter. It will use chemical engines to deorbit and safely land on the surface, photographing the surface during the descent.

On the surface, batteries will power the lander while it performs several operations. The first and most important operation will be the acquisition of four samples of Ceres' surface. The necessary instruments will be located at the end of a robotic arm, which will also carry a camera for Earth-based decision of the exact sampling location. We will use titanium brushes to remove the uppermost space-weathered layer of the surface that may have been contaminated by the engines' exhaust, and a drill with different power increments to collect the samples. Once the sample is collected, the arm will place it into a basket in the bus. The process is then repeated three times for as many samples, with a fourth repetition placing a sample into the onboard mass spectrometer to determine Ceres' D/H-ratio and relative abundances of volatile subsurface material. When finished, the arm will perform a 360° horizontal rotation to capture a panorama from the landing site.

Once all operations on Ceres' surface are done, the propulsion platform will launch the OS with the sample basket on board, detaching from the landing structure, lifting off and leaving the rest of the instrumentation on Ceres. The OS will perform a rendezvous and dock with the orbiter, which will capture the basket with an arm and put it into the reentry capsule. The orbiter will then leave Ceres' orbit to return to Earth, again with ion propulsion, ending with an atmospheric reentry of the capsule on Earth. The capsule will be retrieved on the ground, brought to a curation facility where preliminary tests will be done, before distributing sample material to laboratories across the world.

The total spacecraft has a volume of 2.5 x 2.5 x 3.3 m and a wet mass of 5569 kg.

2 SCIENCE

2.1 SCIENTIFIC QUESTIONS

The scientific questions identified for the Calathus mission are as follows:

1. What is the nature of the bright material on Ceres' surface?

The exact mineralogical composition of the faculae on the surface of the Occator Crater cannot be resolved through remote sensing observations. The spectroscopic observations from Dawn indicate the presence of various carbonates ranging from natrite, natron, magnesite, calcite and dolomite, to even more exotic species such as rhodochrosite (Carrozzo et al., 2018), but their spectroscopic bands inseparably overlap. A sample return from the faculae will resolve the respective abundances of the components present in the bright material, from which the nature of their subsurface parent reservoir can be characterized.

2. Are the ingredients for life present in the subsurface of Ceres?

The faculae in the Occator Crater are among the most accessible retrievable materials that originate from subsurface cryospheric reservoirs, falling into the same category as Europa and Enceladus. By investigating the residual material from this reservoir, we can probe the organic and chemical composition of an uncharted primordial environment.

3. What role do small body cryospheres play in the search for life?

With the discovery of subsurface oceans on Europa and Enceladus, our original idea of small, hydrosphere-bearing worlds as anomalies has changed. The traditional definition of the habitable zone based on liquid water on the surface is challenged. Ceres' cryosphere only has minor surface activity, which might indicate a no longer active world. Still it is one of the most accessible examples of these icy worlds, making it a prime target for the exploration of this class of bodies.

4. What is the nature of Ceres' carbonaceous material?

Characterizing the carbonaceous material on the surface through thorough mineralogical analysis will give more insight concerning the pressure and temperature under which Ceres was formed. The precise birth conditions of these elements will pinpoint Ceres in context of the formation of the solar system.

5. Where did Ceres and other C-type asteroids form?

If Ceres indeed formed in the gas giant region, the planetary migration process must have resulted in a substantial portion of current C-type asteroids migrating inwards to the main asteroid belt. Learning about the exact formation circumstances of Ceres would constrain the acceptable variations of the grand tack early instability scenario of giant planets in the Solar System.

6. Did C-type small bodies contribute to the delivery of Earth's water?

Various measurements of deuterium/hydrogen (D/H) ratios from objects around the solar system have not revealed the mystery behind the origin of water on Earth. Based on previous measurements, C-type asteroids have the D/H-ratio most similar to that of Earth. The D/H-ratio of volatiles near Ceres' surface provides a link between icy moons and C-type asteroids.

2.2 SCIENTIFIC OBJECTIVES

The identified science questions have been quantified to include the following scientific objectives:

1. To characterize the organic, carbonaceous surface material.
2. To determine how and under what conditions the Occator Crater faculae carbonates formed.
3. To investigate the chemical composition of the Occator Crater carbonates to determine their formation conditions.
4. To investigate the morphology of carbonate grains to determine their formation conditions.
5. To characterize the bright material in the faculae to tell us about the conditions (such as habitability) within the cryosphere reservoir of Ceres.
6. To relate the characterization of SO_3 to other cryosphere-bearing worlds such as Pluto and Ganymede.
7. To investigate how the organic material has evolved under aqueous conditions.
8. To determine the temperature and pressure under which minerals on Ceres were formed.
9. To compare the surface properties of Ceres to those of D-type asteroids.
10. To date the carbonaceous material, carbonates and ammoniated phyllosilicates.
11. To measure the D/H-ratio and relative abundances of volatiles on the surface of Ceres.
12. To compare the properties of Ceres to icy moons.

2.3 SAMPLE RETURN

In order to fulfill all but the last two of the scientific objectives, we require the following sample analysis methods:

1. X-ray diffraction for determining the mineral or chemical structure of the sample.

2. Gas chromatography mass spectroscopy for the identification of the insoluble organic phase.
3. Infrared spectroscopy for identifying spatial distributions of organics and minerals and the link between them.
4. Electron microprobing for elemental composition.
5. Scanning electron microscopy for determining the sample microstructure.
6. Thermal ionization mass spectrometry for calculating the age of the components, by means of calculating ratios of radioactive isotopes.

All mentioned methods require large, massive and extremely high precision instrumentation, which is not feasible to accomodate on a spacecraft. Sample return allows these complex methods to be carried out on Earth to a scientifically permissible level of accuracy. Furthermore, returned samples allow the material to be characterized and compared by research laboratories across the world. Returning samples also provides material for future generations of scientists to utilize methods and techniques not yet invented. Notable for this mission is the possibility that Ceres is a parent body for certain clans of carbonaceous chondrites, as spectra of Ceres made from Earth and by Dawn are similar to the spectra of such meteorites found on Earth (e.g., Larsen et al., 1979; Ehlmann et al., 2018). Returned samples would enable the high precision techniques used for studying meteorites to be applied to samples from Ceres, contextualizing the origin of carbonaceous chondrite meteorites.

The main priority of the sample return is the retrieval of the white carbonate material from the Occator faculae. As dark color organic matter and ammoniated phyllosilicates are ubiquitous on the surface, it is highly likely that they will also be present at the landing site. In the unlikely case of the sample containing exclusively white material, we nevertheless have the capability of answering the majority of our scientific questions.

2.4 IN SITU MEASUREMENTS

In addition to the sample return, some measurements need to be performed on-site. This pertains primarily to volatile substances, as they are not transportable to Earth within the scope of this mission. The onboard mass spectrometer will characterize the D/H-ratio of any volatiles and relative abundances of gases exposed during the drilling of the samples. Detailed mapping of the landing site will be performed, which can be used to create topographic maps. A thermal mapper will perform temperature variation measurements of the landing site. We will also characterize the landing and sample sites with cameras and the surface strength of the sampling site jointly with the drilling operation.

3 PAYLOAD

3.1 ORBITER

3.1.1 Orbiter camera

The Calathus orbiter will have a high resolution, narrow angle camera for choosing a landing site, as well as to provide us better information about Ceres' surface. The Dawn mission already mapped Ceres with a resolution up to 3.3 m / px achieved on it's closest fly-bys. The camera on the orbiter will build on heritage from the OSIRIS Narrow Angle Camera (NAC) on the Rosetta mission (Keller et al. 2007). Since our mission will be more than ten years into the future, we will replace the CCD from the NAC with a more modern one with 4096 x 4096 pixels. This gives an angular resolution of 9.3 µrad/px for the NAC's 2.20° x 2.22° field of view (FOV). This will allow us to perform a mapping of the Occator Crater at a resolution of less than 1.1 m/px from a distance of 100 km. This is an improvement of factor three from the Dawn images. We would then go to lower orbits, mapping the faculae and landing site in even higher resolution. We would not require as many filters as the 14 the NAC carried, but will do with 3 filters in the visible spectrum, as well as the Hydro and Fe_2O_3 filters from the NAC. The mechanical shutter on the NAC is too slow for taking clear pictures at the predicted orbital speeds, so we envision exchanging it for an electrical shutter capable of exposure times down toward 1 ms.

3.2 THE LANDER PIAZZI

3.2.1 Lander cameras

To map the terrain around the sample during descent, heritage from the Rosetta Lander Imaging System (ROLIS) is used, previously carried by Rosetta's lander Philae. The camera is mounted on the bottom of Piazzi, and consists of a miniaturized CCD camera and four independent arrays of light emitting diodes (LEDs) in visible and near-infrared wavelength ranges to illuminate the image field. The detector, a Thomson TH7888A with front side illuminated frame transfer CCD, has a 1024 x 1024 pixel active area. One moveable and four fixed lenses project a square field of view of 57.7° x 57.7° on the CCD, which corresponds to a resolution of 0.98 mrad/px. Therefore, an object 30 cm away can be mapped with a resolution of 0.33 mm/px. The ROLIS Imaging Main Electronics (IME) is the interface to the lander and restricts the operational temperature range to -50°C to +60°C, whereas its camera head electronics can go down to -150°C with minimum power consumption.

A second camera set on the robotic arm of the lander is used to put the immediate sample area in context. The model is heritage of the InSight Mars lander Instrument Deployment Camera which is a flight spare of Mars Science Laboratory (MSL) Navcam Serial Number 210. These MSL cameras were converted from grayscale to colour by using a Bayer colour filter array version instead of the previous detector. It will then operate in the visible light range. The detector has a 1024 x 1024 pixel active area. The angular resolution is 0.82 mrad/px at the center of the FOV, with a 45° x 45° FOV. Since this camera system has been utilized previously on Mars landers, it is qualified for the temperature ranges on a mission to Ceres.

3.2.2 Thermal mapper

An infrared mapper is used to complement the characterization by the cameras of the bright material around the landing site. The infrared mapper measures the temperature variations, so a temperature profile can be made of the immediate area around the sample. The thermal mapper is based on heritage of the MASCOT radiometer MARA on the Hayabusa2 mission. The instrument's FOV is 10°. The sensor in use is a miniaturized thermal radiation sensor, model TS-72M, by the Institute of Photonic Technologies, Jena. The expected absolute brightness temperature accuracy of the instrument is 2 K operating at low temperatures (100 K – 400 K).

3.2.3 Sampler

The requirements for the Calathus mission are to collect three samples, each with a volume of 4 cm^3 (roughly 10 g) that shall return to Earth. The samples shall be collected at a minimum depth of 50 mm. In addition, one sample of 0.5 cm^3 shall be delivered from the surface to the on-board mass spectrometer. The sample collecting process must maintain the temperature below -20°C to keep the volatile materials. Due to the limited information available about Ceres' surface, the system will be capable to work in different types of soil: solid with compressive strength up to 20 MPa, and loose with high and low adhesion. Finally, all sampling areas will be cleaned from materials contaminated by the solar wind, space dust or lander thrusters.

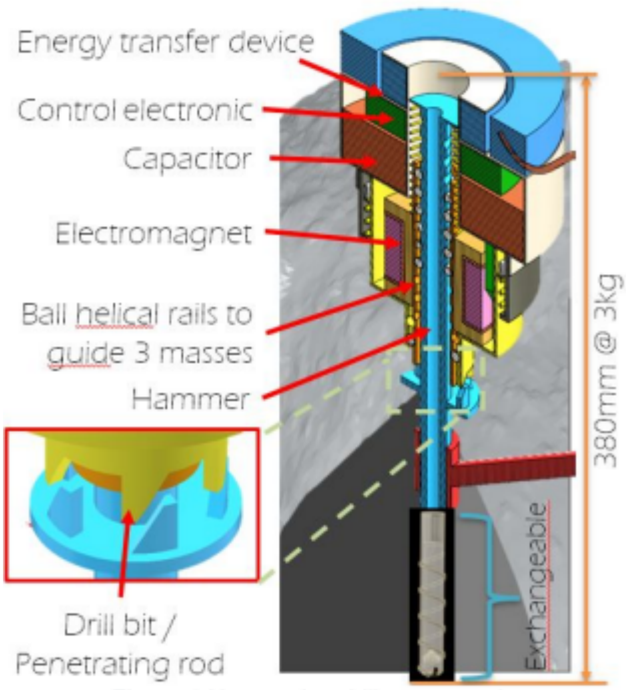

Figure 3: Hammering drill cross-section

The sampling system is equipped with the four following instruments: a hammering drill to collect samples, a camera to provide feedback, a mechanical brush to clean the immediate sampling area and a manipulator to operate all declared instruments.

The hammering drill, see Figure 3, is based on the principle of a reluctant electromagnet, located inside the device, generating strokes whose energy is transformed to torsional and linear movement of the drill. Therefore it generates much less heat on the drilling end in comparison to a conventional driller and can still penetrate highly compressed regolith, rock and ice. By splitting the device into three parts, it can operate on microgravity bodies and requires support only during the initial phases of operation.

A detachable sampling container made of hardened titanium with diamond inserted at the bottom also plays the role of a drilling bit. The container will return to Earth with the sample inside.

A DC motor will drive the brush and have bristles made of titanium in order to remove even solid contaminated material. The 2-meter long manipulator will be based on already available systems with profound space heritage having Technological Readiness Level (TRL) 9.

3.2.4 Mass spectrometer

Piazzi will have a mass spectrometer to perform analysis on volatiles (such as water, carbon monoxide and noble gases), light elements (carbon, nitrogen and oxygen) and light organic compounds. It is crucial to do these measurements in situ, as part of the volatiles would be lost during the travel back to Earth. After the collection of three samples for the return capsule, we are going to collect one last sample and carry out mass spectrometry measurements. A small laser will heat this sample, and the resultant gas will be analyzed to extract its chemical composition and isotopic ratio. For instance, the D/H ratio will be obtained to be compared to that of other bodies of our solar system (Hallis, 2017). We will also take advantage of the measurement of light elements. We are going to use an instrument developed for Mercury exploration (Rohner et al., 2017). As this setup was designed for a space mission it has a low mass (0.5kg) and power consumption (3W), but also high performance. It can reach a mass resolution better than $\Delta m/m$ = 600 and 30‰ for isotopic compositions.

5 MISSION

5.1 LAUNCH

The Calathus mission will begin with a launch from Kourou, French Guiana, using the Ariane 64 rocket. The spacecraft's wet mass at launch is 5569 kg, and the dimensions, seen in Table 1, allows for a dual launch configuration. The targeted Δv is 10.6 km/s in the Earth inertial frame, which allows us for a good start on the trajectory to Ceres.

	Inner dimensions of Ariane 64	Outer dimensions of spacecraft
Diameter [mm]	4460	2000x3000 mm, diagonal 3606
Height [mm]	3660	3500

Table 1: Dimensions of Ariane 64

5.2 ORBIT

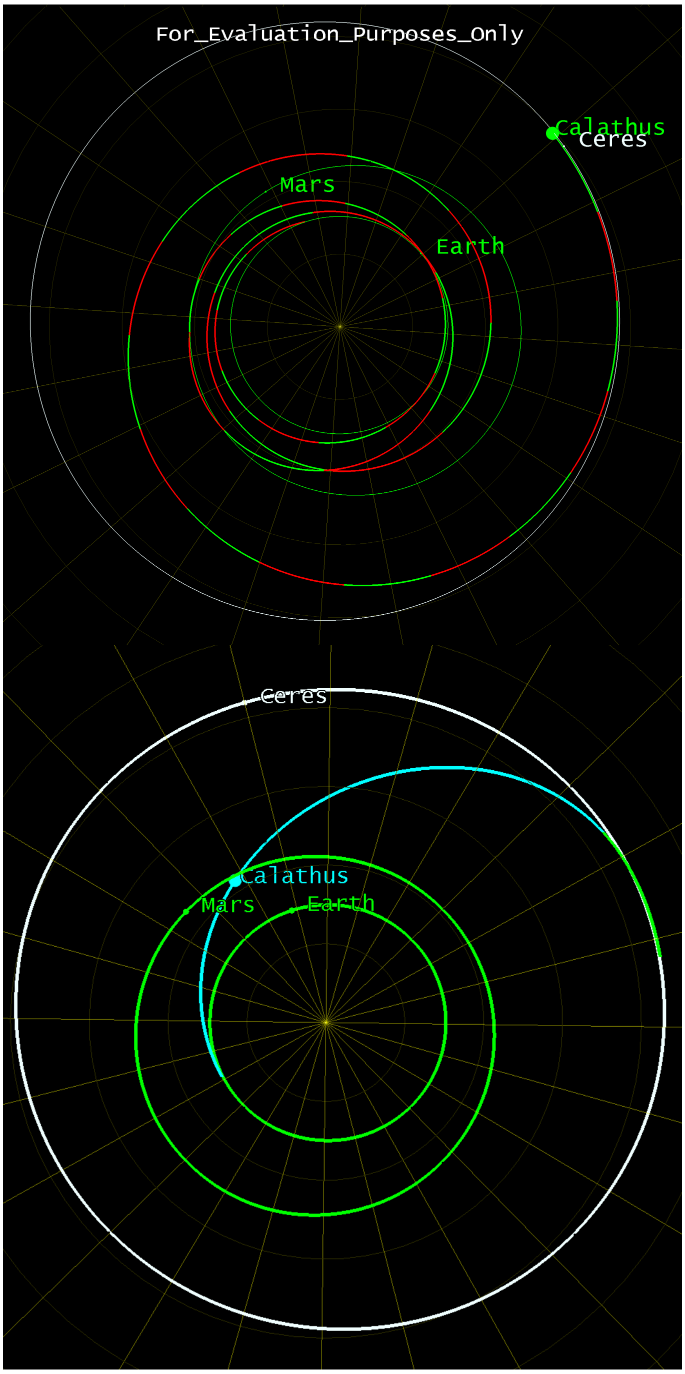

Figure 4: The outbound (top) and inbound (bottom) trajectory.

The Δv for a Lambert transfer from Earth to Ceres is above 11.6 km/s plus escape velocity, which is far above the capabilities of chemical propulsion. Therefore ion propulsion was selected, and a trajectory made with the Pagmo Optimizer was chosen using a maximum thrust of 1.2 N at 1 AU and a Mars gravity assist. We can see the full mission orbit in Figure 4. The red and green alternate arcs are the part of the trajectory in which we have electric propulsion. The light blue arcs are when we do not fire our ion engines. After the journey to Ceres we have an insertion into a circular orbit from a parabolic one. We increase the inclination gradually until we reach Ceres' inclination. Then we lower our orbit twice with a Hohmann maneuver to take high-resolution images of Ceres' surface. After having done ancillary science for 404 days, we descend with the lander and collect the samples. Then we turn on the ion engines to provide thrust for 149 days. The final part of the journey will not use propulsion. We catch the Earth and have a reentry at a relative speed of 11 km/s.

5.2.1 Mapping

While orbiting Ceres, the orbiter camera will first spend three months mapping the whole Occator Crater at an altitude of 100 km, with a mapping distance of maximum 120 km. The resolution at this height is at least 1.11 m/px, which results in approximately 4600 images of around 4000 m x 4000 m.

After this, mapping is done at an altitude of 40 km for two months to cover the faculae with a better resolution for selecting a landing site. The resolution of these images will be less than 0.56 m/px. When a landing site is chosen, a final mapping is done over 5 days with resolutions smaller than 0.28 m/px at an altitude of 20 km, maximum distance 30 km, collecting about 50 images of the immediate landing area.

5.3 LANDING ON CERES

The lander Piazzi will detach from the orbiter to descend to the surface of Ceres. The spacecraft will be orbiting at an altitude of 20 km, making the Δv requirement of this procedure 419 m/s. Piazzi will determine its altitude by using an onboard radar. A landing camera will be used to contextualize the obtained sample. Once Piazzi has landed, the orbiter fires the electric propulsion engines with a 36.23 m/s Δv to reach a 100 km orbit.

When all the scientific measurements are performed, the bus fires its chemical propulsion engines with a 371 m/s Δv to reach the same orbit as the orbiter. For security reasons, the bus and the orbiter will be separated by at least 10 km which corresponds to an orbit angle phase of 91° or greater. Then the OS is separated from the propulsion platform, which fires the engines one last time to separate from the OS orbit.

For the moment, we envisage one of the flatter areas in the faculae Vinalia and Cerealia for the landing site on Ceres, as we are concerned about avoiding steep slopes and fractures. The final decision will be taken once we have the results of the mapping from the orbiter.

5.4 RENDEZVOUS

The rendezvous phase takes place during the following 24 hours. OS radio beacons allow the orbiter to approach it using the ADCS. Figure 5 shows the rendezvous system (RVS) based on a Mars Sample Return mission design which allows taking the orbiter sample (OS) from the orbit and fixing it inside the Reentry Capsule (RC). Lidars will detect the OS with less than 0.5 m accuracy during the rendezvous. Once the OS is inside the cone, a robotic arm blocks the entry.

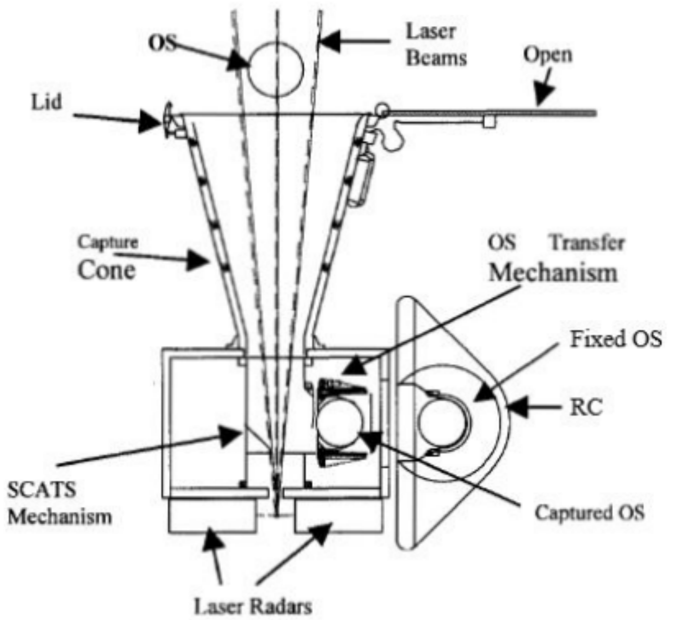

Figure 5: The rendezvous system of Mars Sample Return Spacecraft Systems Architecture (Price et al., 2000).

5.5 RETURN TO EARTH

A reentry capsule (RC) containing the OS is used to assure a -20°C thermal environment of the samples during Earth reentry.

The reentry sequence is done in four different stages. Beyond 10^6 km from Earth, the orbiter tracks the Earth using its navigation systems and the NAC. Then attitude corrections are made to reach the most precise trajectory for landing. At less than 40,000 km, the RC is separated from the orbiter. During the separation the RC is spine up for stabilization reasons with a reentry velocity of 11 km/s. Finally, while the orbiter disintegrates in the highest part of the Earth's atmosphere, the RC starts a calculated reentry trajectory to reach ground in the Australian Outback with a velocity of less than 41 m/s. During the reentry, the RC is tracked by two 0.7 W radio beacons powered by 260 g of lithium batteries.

The design proposed is a reentry capsule based on the technology developed for the Mars Sample Return mission. As shown in Figure 6, a thermal protection system isolates the samples from the temperatures greater than 2500°C that will be reached on the surface of the RC. Energy absorption material will protect the OS from the deceleration of more than 2500 G at the impact with ground.

No parachute or attitude control is used in this design. Tests already done shows that even in the worst-case scenario of an 180° angle of attack, the RC will reorient to nose-forward

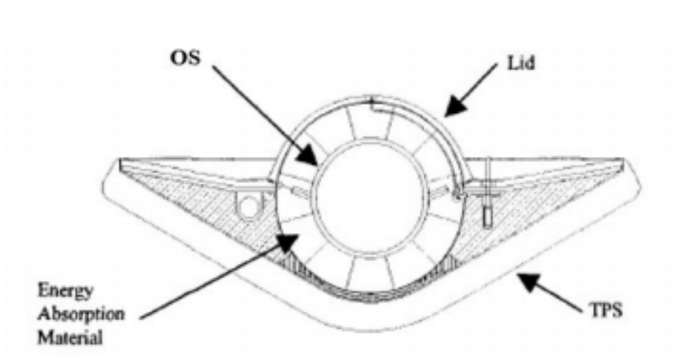

Figure 6: The reentry capsule (Price et al., 2000).

5.6 SAMPLE CURATION

Once the sample has landed on Earth, it will be retrieved and brought to the EuroCare facilities in the UK, via refrigerated transport at temperatures below -20°C. At the EuroCare facilities, the basket and two of the three sample capsules will be opened in a refrigerated and atmosphere controlled containment chamber. The chamber will be built to Planetary Protection standards to avoid any contamination of the sample by terrestrial life, contamination of Earth by Cererian material, or chemical alteration of the sample. When analysis has mapped any risk and ensured there is no danger of contamination, the opened sample material will be characterized and cataloged, before half of it is distributed to laboratories after a review of their proposed utilization.

6 SPACECRAFT DESIGN

The spacecraft Calathus consists of the following segments: the orbiter, and the lander Piazzi, made up of the orbiting sample (OS), the propulsion platform and the surface module. The orbit insertion at Ceres will be followed by the separation of the orbiter from the rest of the spacecraft, which descends to Ceres' surface. After the completion of all measurements and the successful acquisition of the sample, the propulsion platform will use its chemical propulsion system to leave Ceres' surface and
to take the sample into orbit, where it be captured by the orbiter and transferred into the reentry capsule. This is followed by a transfer back to Earth and the atmospheric reentry.

6.1 THERMAL CONTROL

In order to meet the temperature requirements of on-board electronic components, instruments and the collected sample, the spacecraft Calathus is equipped with temperature sensors, carbon-fibre radiators, louvers and electric heaters. It also features multi-layer insulation and a golden coating to be able to deal with the very different thermic situations on the journey to Ceres.

During the so-called "hot case", which describes a situation in which Calathus is only 1 au away from the Sun and its solar panels are perpendicular to the incoming sunlight, the radiators protect the spacecraft from overheating by radiating off up to 46 kW. During the "cold case" the electric heaters compensate the negative heat balance by producing more than 230 W of thermal energy – for example during eclipse at Ceres.

6.2 ATTITUDE AND DETERMINATION CONTROL (ADCS)

Two separate ADCS systems are required for the Calathus mission, one on the orbiter and on the Piazzi lander. The attitude control of both modules necessitates the use of thrusters and reaction wheels together. Monopropellant RCS thrusters are used to desaturate the reaction wheels.

The main driving factor for determining the reaction wheel features is the scanning speed required to map the surface of Ceres from the orbiter, as the camera must be pointed towards the crater. Based on the trajectory of the orbiter, its inertia and the characteristics of Ceres' motion it was calculated that the orbiter will have an angular velocity of 0.53 mrad/s, and as a result an angular momentum of 2.39 Nms. Subsequently, an example of reaction wheel was chosen: the model RSI 4-75/60 by Rockwell Collins. For actuating the three rotational degrees of freedom we have utilized six reaction wheels, making the system highly redundant.

In the case of the lander, the main driving factor was the necessity of a 90° tilt before landing within a timespan of one hour, which determines the angular velocity of 0.44 mrad/s. For this case the calculated angular momentum is around 0.018 Nms, and a potential model was found: the RWP050 by Blue Canyon Technologies. This model shall provide required angular velocity within a few seconds.

6.3 TELECOMMUNICATION AND LINK BUDGET

The communication system is driven by the payload data rate requirements, and for deep space missions also by mass requirements. On ground we will use ESA's ESTRACK network. For up- and downlink of status and telecommand data we use low gain antennas (LGA) in the X-band. For efficiency the LGAs are also used to get the data from Piazzi. For data downlink the Ka-band is used to enable fast data transfer with the high gain antenna with gimbal.

The operation has two critical phases concerning the data rate: First the mapping phase requiring 5.9 Gb data per orbit with a visibility window of 1.633 hours per orbit, resulting in 1.27 Mb/s *[1] of needed data downlink. Second the 69 minute descent of Piazzi with 2.32 Gb and 2.71 Gb of data resulting in 0.55 Mb/s and 0.67 Mb/s* for Piazzi and the orbiter respectively, resulting of a data transmission rate through the orbiter of 1.22 Mb/s†. For the descent, an internal backup memory is used to store the data, plus new mapping data for up to four orbits. See Table 2 for an overview of the data rates.

	X down (3 kbit/s)	X up (8 kbit/s)	Ka down (1.3 Mbit/s)	X Piazzi to orbiter (2 Mbit/s)
Frequency [GHz]	8.415	7.16	32	8.44
Bandwidth [MHz]	10	10	100	10
D_Antenna [m]	0.2	35	1.3	0.1
EIRP [dB]	44.6	103.67	68.45	12.94
Margin [dB]	6.001	10.795	5.722	32.543

Table 2: Data transfer rates.

6.4 ONBOARD COMPUTING

Data handling is one of the key aspects to control the spacecraft and deliver sufficient data rates for scientific data to be sent to Earth. The estimated amount of data generated per orbit is expected to be from 1.008 Mbit/s during mapping and until the descent of Piazzi. During this time the data bus of the orbiter and Piazzi must handle 2.01 Mbit/s and 1.12 Mbit/s respectively. Therefore, both systems are equipped with a SpaceWire bus.

Despite the ADCS and allocation of incoming data, Calathus does not need fast processing. Due to this almost all radiation proof processors can be used off the shelf. For the orbiter a RAD750 is sufficient, for Piazzi GR LEON3FT is used.

During descent the data rate created by the orbiter and received from Piazzi is, as seen above, higher than the maximum data rate the orbiter can send. Therefore, part of the incoming data is stored in the internal memory of the orbiter. The needed capacity is 0.3 Gb during the actual descent. As a worst case scenario, it is assumed that the orbiter has no contact with Earth for four orbits, which results in a total of 2.63 Gb of data to be stored. Therefore we use a 3D Plus 4 Gb FLASH NAND for Calathus.

6.5 POWER MODES

For the Calathus mission, the main power consumption modes are highlighted in Table 3. During the launch on an Ariane 64 rocket, the orbiter and Piazzi will be in a launch mode limiting their power consumption. Two operational modes are highlighted for the orbiter. Operational mode 1 where Ceres surface characterization is done using the NAC, and operational mode 2 where Piazzi has landed.

The Piazzi spacecraft has two main consumption modes, the landing mode and the operational mode. The operational mode consists of the close-up characterization of the surface, the sampling and the in situ measurements. Also, both the orbiter and Piazzi have a safe mode in case of failures compromising the mission. In this mode the

* Including 20% margin

† Including 20% margin

spacecraft turns off all the systems except the on-board computer, the thermal and telecommunications and only sends housekeeping information.

Mode	Total power consumption (W)
CALATHUS	
Launch	120
Travel	32629
Operational 1	649
Operational 2	681
Safe	405
Rendezvous	679
Re-entry	515
Sum	**35,676**
PIAZZI	
Launch from Orbiter	108
Operational	169
Take off	94
Safety margin	51
Sum	**422**
TOTAL	**36,098**

Table 3: Power modes.

In terms of power generation, the orbiter will have 110 m^2 of solar arrays at its disposal, producing more than 20 kW of electric power near Earth and 4 kW when orbiting Ceres. Also, 15 kg of lithium batteries deliver 3 kWh of electrical energy to the different subsystems. For Piazzi, 30 kg of lithium batteries that deliver 6 kWh enable the spacecraft to perform all technical and scientific operations.

7 RISK AND COST

7.1 RISK

Here we discuss the main risks of the Calathus mission and classify them into severity from 1 to 5 (5 for the worst case) and likelihood from remote (A) to near certain (E). The combination of these two classifications lead to a rating from very low (green) to very high (red), see Table 4.

The fatal case for this mission would be to not bring the sample back to Earth safely. In this scenario the mission goal would not be achieved. The likelihood is C that one of the steps of collecting and handling the sample fails or is not correctly performed. The severity of this would be 5. The combination relates to a high risk. ESA is currently working on a Mars sample return and new technologies will be developed in the coming years. We anticipate that the likelihood classification will lower to level B before Calathus launches, which would lead to a reclassification of the risk to a medium level.

As the sampling site cannot be mapped in advance, there is a possibility of not being able to retrieve matter other than salts from the Ceres faculae. We rate this as likely but not severe (1C), because even with only salts it is possible to fulfill the majority of the scientific requirements.

Another risk is that the ion engines will not work properly, which could lead to an incorrect orbit. This could also lead to not achieving the mission goal of bringing back a sample.
This risk is rated with a severity of 5 and a likelihood of A, which gives a summarized low risk. This technology is already at a technical readiness level (TRL) of 7, and before Calathus will launch it might have become TRL 9, as ion engines are flown by current missions (e.g. BepiColombo).

In addition there is the risk of contaminating the Earth. We rate this a low risk (3B). Planetary protection needs to be planned accurately, and laboratories are working on their research techniques. Missions like Hayabusa2 and OSIRIS-REx will likely improve our containment procedures, which will lower the risk likelihood.

Severity						
	5	Low	Medium	High	Very High	
	4					
	3	Very Low				
	2					
	1					
		A (remote)	B (unlikely)	C (likely)	D (highly likely)	E (near certain)
		Likelihood				

Table 4: Risk classification matrix.

7.2 COST

A rough estimation of the costs leads to a 1.5 billion euro mission, which by ESA classifications would be an L class mission, see Table 5.

	Mechanical	Electrical	Payload	Total [M€]
Orbiter	140	1090	60	1290
Lander	25	45	11	81
Reentry	40	-	-	40
Operations	-	-	-	126
Launch	-	-	-	90
SUM				**1501**

Table 5: Mission cost estimate.

The most expensive part is the orbiter, because the cost estimate is calculated by multiplying correction factors (depending on complexity) by the dry mass. The costs lower when payload or techniques are already tested and used.

7.2.1 Descoping options

To lower the mass and costs, it would be possible to remove the thermal mapper or the mass spectrometer. This leads to less context information, but the mission goal is still achievable. However, this will decrease the costs only very little, as the costs are driven by the structure and electrical architecture of the orbiter, especially by the solar panels. It is possible to work on a lighter structure of the solar panels but this could add a safety risk.

7.3 PLANETARY PROTECTION

According to the planetary protection (PP) guidelines, the Calathus mission is a class V-RER (Restricted Earth Return). This implies that our spacecraft must be thoroughly sterilized before launch, that launch from both Earth and Ceres, as well as Earth reentry, must be reviewed and approved by a PP officer. Any returning hardware that has directly or indirectly come in contact with Ceres must be either sterilized or contained for reentry.

Moreover, the sample will be required to be curated in a facility capable of preventing any risk of Earth contamination during sample analysis and distribution. This is planned to be done by the curation facility EuroCare, which will be ready by the end of this mission.

8 OUTREACH

Outreach for space missions is an important for public acceptance and support. It is necessary to inform people about what is planned and what is going on at the moment. In addition, good outreach can arouse interest and persuade young people to become engineers or scientists. The Calathus mission will therefore be present on different social media platforms (Facebook, Instagram), and we will have live tweets and messaging during every important mission event.

In addition, it is possible to prepare lessons for schoolteachers, visiting schools and offer open-door days. One such activity we prepared was 'Taste Ceres: a hands-on activity where younger audiences can 'create' the interior structure of Ceres through analogous materials. These include chocolate sauce in place of a mud-rich mantle, caramel cereal in place of rocks rich in complex organic matter and an edible clay in place of ammoniated phyllosilicates. This provides an entertaining and educational means of explaining the structure of Ceres to small children.

9 CONCLUSION

The discovery of bright spots on Ceres with the Dawn mission has raised a lot of questions concerning the composition of carbonaceous material and the issue of the past astrobiological potential of Ceres. On the other hand the models for formation and evolution of small bodies in the solar system, in particular the origin of Ceres, and more generally C-types asteroids, could be constrained by characterizing the organic material. The proposed sample return mission Calathus could lead to a breakthrough in these two scientific domains.

From a technological point of view, the Calathus mission could serve as a precursor to a sample return mission from a Galilean moon of Jupiter. In particular, Europa is specifically mentioned in ESA's Cosmic Vision as a target for the future due to its astrobiologically exceptional interest. While such a mission is currently unfeasible, stepwise maturing of technology would make that endeavor closer to actuating.

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