CIRCE - Centaurs' Investigation, Reconnaissance and Compositional Exploration

Centaurs: A window into the building blocks of the Solar System

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Abstract

CIRCE is a large-class mission concept designed to study the Centaur object 29P/Schwassmann-Wachmann. Centaurs are small bodies located between the orbits of Jupiter and Neptune, which have not been visited by a spacecraft so far. Similarly to other comet and asteroid populations, Centaurs are remnants of primordial planetesimals and are of particular interest due to their transition from the trans-Neptunian object population into Jupiter-family comets. CIRCE will provide novel insights into the formation and dynamics of the Solar System by studying the physical and chemical characteristics of 29P to investigate the origin, evolution and activity drivers of Centaurs.

1. Introduction

Planetesimals, typically tens to hundreds of kilometers in diameter, form within a protoplanetary disc of gas and dust around a young star. Their composition and structure are shaped by both the location and timing of their formation within the disc, making them valuable records of the early Solar System and planetary system formation.

The most populated reservoirs of minor bodies in the Solar System are the Main Asteroid Belt, located between Mars and Jupiter (2–3 AU), and the Kuiper Belt (KB), situated beyond Neptune (>30 AU). However, the present-day distribution of these objects does not necessarily reflect their original formation locations. Over the past 4.5 billion years, gravitational interactions, primarily with the giant planets, have significantly altered their location within the Solar System. The main asteroid belt contains planetesimals (or their remnants) that originally formed both inside and outside the water ice line, resulting in a diverse population that includes both rocky and icy bodies. These objects now reside inside the current water ice line and have since lost most of their water and other volatiles within their surface layers. In contrast, the KB is composed of icy planetesimals that formed beyond the water ice line and thus preserve more primordial compositions. Their great distances from the Earth make them difficult to observe with ground-based telescopes and challenging to explore via spacecraft. To date, only a single Kuiper Belt Object (KBO), Arrokoth, has been visited during a New Horizon spacecraft flyby in 2019.

Another relevant population of active small bodies is the Jupiter Family Comets (JFCs), which typically evolve on orbits that bring them within the region interior to the water ice line. Their activity is generally attributed to the sublimation of water ice, and they are thought to have originated predominantly from the KB. Despite their origin in the KB, they get altered at their present location, making the reconstruction of their early evolutionary history particularly challenging. Multiple spacecraft missions have investigated objects of this class, with the most comprehensive being the Rosetta mission, which conducted an in-depth study of comet 67P/Churyumov-Gerasimenko between 2014 and 2016.

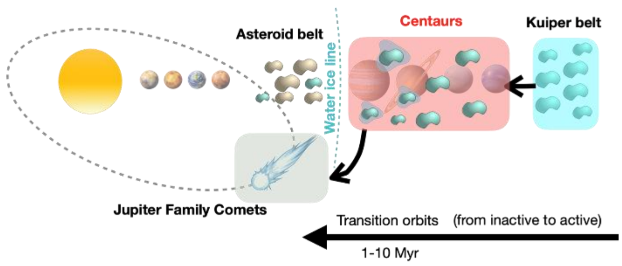

Figure 1: Schematic representation of the transitional pathways of Centaurs

Centaurs are expected to have formed in the protoplanetary disc of the Solar System, at distances between 5 and 40 AU from the Sun, where temperatures ranged from approximately 30 to 200 K [1]. These objects are especially interesting because they transition from the KB to JFCs, with perihelia beyond the orbit of Jupiter and aphelia within the orbit of Neptune [2]. Their orbits are dynamically unstable due to frequent gravitational interactions with the giant planets of the Solar System. Dynamical simulations suggest that the statistically most probable evolutionary pathway involves the inward migration of these objects from the outer to the inner Solar System (Fig.1) on timescales ranging from one to ten million years [2 after 3; 4]. It was theorized that the Centaurs go through a specific "gateway" to become JFCs [5].

The known population of Centaurs currently comprises around 250-400 objects of which approximately 20 % have shown cometary-like activity [2], particularly those with orbits interior to that of Saturn. The origin of this activity remains uncertain, as these objects reside beyond the water ice line, making water sublimation an unlikely mechanism. Understanding the physical and chemical evolution of Centaurs is therefore essential for constraining the properties of primordial icy bodies and bridging the knowledge gap between distant KBOs and processed comets observed in the inner Solar System.

So far, Centaurs have only been observed remotely, and no rendez-vous manoeuvre was done for a KBO. Thus, a dedicated space mission to a Centaur, being a former KBO, will be very valuable.

2. Science case

Aims of CIRCE:

- Explore the evolution from KBOs to JFCs with implications for Solar System formation and evolution
- Constrain planetesimal formation and differentiation with implications for planet formation
- Investigate comet activity beyond the water ice line with implications for the evolution of small bodies in the Solar System

2.1. Target object

After evaluating the scientific interest in studying a pristine object and the feasibility of a rendezvous manoeuvre for an in-depth study of multiple target objects, the mission target 29P/Schwassmann–Wachmann was chosen (Tab.1).

Table 1: Evaluation of potential target objects by a scoring system (lowest score 0-3 in red, medium score 4-7 orange, high score 8-10 green).

Name	Scientific Interest (60%)	Size (20%)	Accessibillity (20%)	Total Score
29P/Schwassmann -Wachmann	„Gateway" Region, study transition Centaurs, most active	~60 km	Hard	8.6
2060 Chiron	Study remnants of KBOs, more pristine surface, ring system	~200 km	Very hard	7.8
P/2019 LD2	Very young comet, will become JFC in 2063	<2.4 km	Easy	4.2
174P/Echeclus	Show unusually low CO levels	~60 km	Hard	5.2

As 29P is a Centaur in the "gateway" region [6], CIRCE can study a highly active transitional object, before it crosses the ice line. In 2002–2014, 64 outbursts were identified for 29P [7]. Remote observations by the James Webb Space Telescope (JWST) showed heterogeneous outgassing in a way that makes 29P also a potential contact binary of 60 km in diameter [8]. Compared to New Horizons' observations of Arrokoth (36 km in diameter), 29P could be the largest contact binary ever explored, giving hints about the formation processes of early small bodies.

2.2. Science objectives

CIRCE aims to answer the following scientific objectives with the according science requirements (Tab.2).

SO1: ***How did the icy planetesimals form and evolve?***
SO2: ***Which processes drive the activity of Centaurs?***

Table 2: Science requirements grouped by science topics.

Topic	Science requirements
Composition and chemistry	**SR-010:** The bulk composition of the surface and shallow sub-surface of a Centaur shall be assessed. **SR-020:** The chemical composition of the coma/exosphere of a Centaur shall be identified. **SR-021:** Isotopic reservoir of key elements shall be identified.
Physical geology, topography, and thermal state	**SR-030:** Physical characteristics on the surface of a Centaur shall be mapped. **SR-090:** The thermal state of a Centaur shall be characterised.
Activity, outgassing, and spin evolution	**SR-031:** Outgassing patterns, outburst events and their temporal evolution shall be investigated. **SR-040:** The dynamic state of a Centaur and its evolution due to outgassing events shall be analysed.
Interior structure and gravity field	**SR-050:** The interior mass distribution of a Centaur shall be investigated.
Electromagnetic and plasma environment	**SR-060:** The magnetic state of a Centaur shall be explored. **SR-070:** The interaction with the interplanetary magnetic field shall be investigated. **SR-080:** Interactions of a Centaur's magnetic field with the solar wind shall be investigated.
Dust and particle environment	**SR-100:** The dust in the coma/ring of a Centaur shall be characterised.

3. Payload

To fulfill our scientific objectives, we propose the following suite of instrumentation with specific Technology Readiness Levels (TRLs).

Table 3: Instruments of the Circe mission. Sources for the images from top to bottom: 1. RTOF reflectron; Universität Bern, 2. MIRMIS, 3. Prettyman 2021, 4. Janus/Juice, 5. Colangeli 2006, 6. Barbaglio et al. 2012, 7. ESA, SENER, 8. & 9. Rosetta.

<table>
<tr><th>Instrument TRL Heritage</th><th>Description</th></tr>
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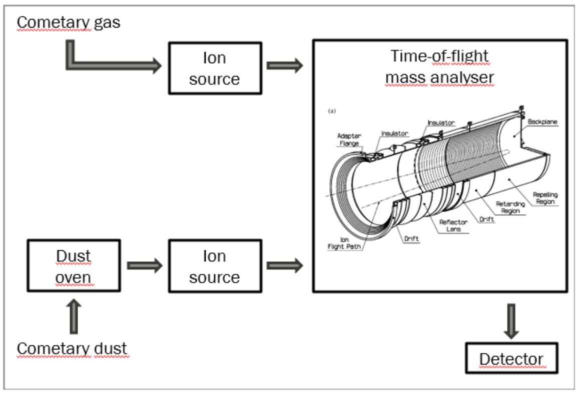
Time-of-flight Mass Spectrometer [MS] TRL 4
ROSINA & COSAC (Rosetta)



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The mass spectrometer [9, 10] is proposed to be a combined time-of-flight (TOF) for gas and dust. A detection mass range of 1-300 amu with resolving power above 10000 Full Width at Half Maximum (FWHM), in a dynamic range of 108 and pressure range of 10-6 – 10-17 mbar shall be achieved to identify coma and dust volatiles. For calibration, ambient pressure shall be measured to complement the TOF measurements.

- **Ram pointing**: Gas & dust volatile measurements,
- **Any pointing**: Reference ambient pressure measurement

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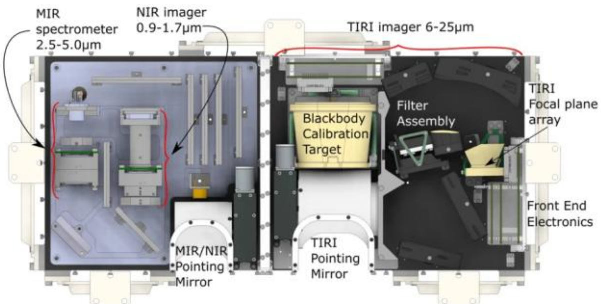
Infrared and Theremal Spectrometer [NIR + MIR + TIR] TRL 5 MIRMIS (Comet Interceptor)



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The infrared and thermal spectrometer [11] range includes near-infrared [NIR] 0.6-1.7 μm with field of view (FOV) 6.7 x 5.4°, mid-infrared [MIR] 2.5-7 μm with FOV 0.286° circular, and thermal infrared [TIR] 6-25 μm with FOV 9 x 7°. [NIR] and [MIR] shall enable the detection of water-ice; (hyper-) volatile ices (e.g., CO, CO_2, CH_4, N_2, O2, and HCN); minerals (e.g., pyroxenes, olivines, and phyllosilicates); and organics (e.g., amino acids, lipids, polymers). From the [TIR], we shall be able to study the coma by observing a star occultation, produce a temperature map and infer the thermal inertia. The spectrograph will need its own radiator.

- **Nadir pointing**: detection of surface ices, mineralogy, organics by NIR/MIR spectroscopy, Temperature mapping by TIR emission
- **Off-nadir pointing**: coma thickness measurement by stellar occultation

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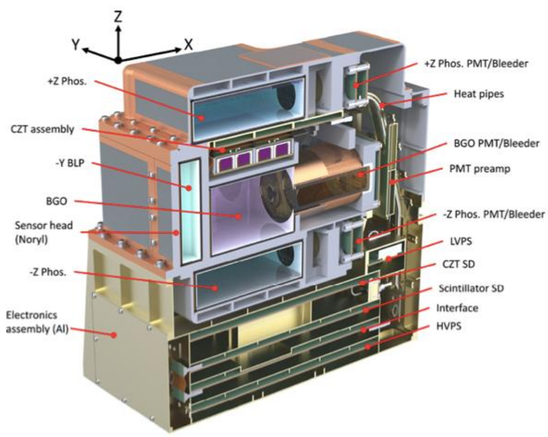
Gamma and Neutron Detectors [GND] TRL 7 GRaND (Dawn)



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The instrument [12] consists of a Bismuth Germanate scintillator with a resolution of ~10% Full Width at Half Maximum (FWHM) at 662 keV, Cadmium Zinc Telluride semiconductor with 3% FWHM at 662 keV, 2 x Boron-loaded plastic scintillator, and a Phosphor sandwich used for neutron detection. The [GND] unit will be capable of remote mapping of the subsurface (up to 10-25 cm deep) atomic composition by detection of gamma rays and neutrons produced by interactions between galactic cosmic rays and 29P. Approximate sensitivities for the sensors are 1000-10000 ppm for O, Si, Fe, Ca, Al, Mg, Ti atoms; 1000-5000 ppm for C atoms and 100-200 ppm for H atoms. The detectable energy range is 0.1-10 MeV and the sensors are operated in a temperature range of -20 to 30°C thanks to an active thermal control system.

- **Nadir pointing:** Remote mapping of specific elements

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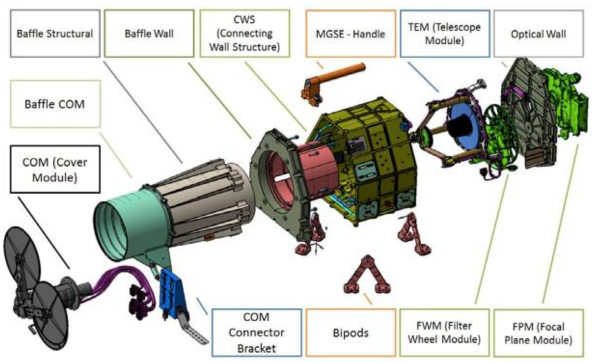
<td>Optical Imager [NAC] TRL 4 JANUS/JUICE

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<td>The optical imager [13] shall be adapted to operate at 6 AU, where solar illumination is only around 3% of that at 1 AU. To achieve the required signal-to-noise ratio (SNR) while maintaining exposure times compatible with the spacecraft's velocity during orbit, the aperture will be enlarged to enhance light-gathering capability. As a result, the instrument currently stands at a TRL of 4. The Narrow Angle Camera [NAC] shall characterise the 3D shape of 29P using stereophotogrammetry, with a FOV of 1.72 × 1.29° and a spatial resolution of 1000 m. Surface mapping will be performed at 100 m resolution, and morphological features larger than 10 m - such as fractures, craters, and boulders - shall be analysed in the visible spectral range. The [NAC] will require additional thermal control and will be equipped with a dedicated heater to ensure operability at 233–243 K.

• Nadir pointing: Mapping of shape, surface features, rotation state
• Off-nadir pointing: Side-looking imaging for stereoscopic measurements and increased ground coverage</td>
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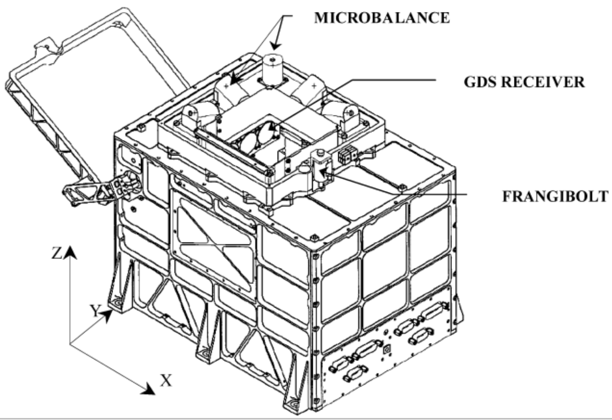
<td>Dust Impact Analyser [DIA] TRL 7 GAIDA (Rosetta)

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<td>The Dust Impact Analyser [14] includes a grain detection system, impact sensor and microbalances. From measuring the impact effects of particles, the instrument shall characterise the dust flux evolution and dynamical grain properties in position and time of particle > 10 µm size, particle velocity < 300 m/s and particle momentum of 6.5 x 10-10 – 4.0 x 10-4 (kg m)/s.

• Nadir pointing: Characterisation of dust flux evolution and grain dynamic properties</td>
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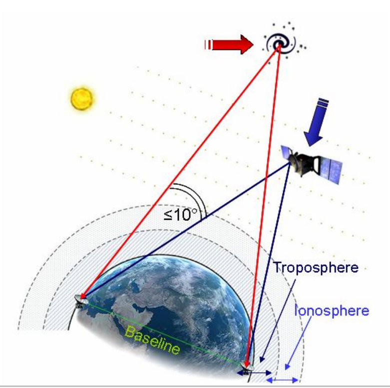
<td>Radioscience – Delta DOR

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<td>Radioscience analyses changes in a spacecraft's radio signal as received on Earth, using Doppler shifts and precise timing between two ground stations. For 29P, we will use Delta-DOR to study the gravity field by tracking how the object's mass affects the spacecraft's velocity. Beyond the sensitivity of the antenna, an accurate timekeeping device is critical to achieve the necessary precision in the measurements.</td>
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<td>Plasma Package [PP] TRL 7 Rosetta Plasma Consortium
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<td>The Plasma Package [PP] consists of three instruments: a 3-axial fluxgate magnetometer [MAG], a Langmuir Probe [LAP], and an Ion and Electron Sensor [IES]. This package aims to, first of all, study the remnant field (if it exists) and the interplanetary magnetic field and solar wind interaction. Furthermore, it is going to measure the plasma density variations, flow velocity, and the particle energy and its direction. The magnetometer will measure in the range ±1000 nT with a step size of 0.015 nT and will be placed on a boom to avoid interference with the other instruments, as well as the Langmuir Probe, placed on another boom measuring the electric field to 8 kHz. The Ion and</td>
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	Electron Sensor will be able to measure in the energy range of 3 eV/e to 30 keV/e with a FOV of 90 x 360°. • **Any pointing**: Detection of a potential remanent magnetic field, detection of a potential induced magnetic field and interaction with the interplanetary magnetic field, detection of a potential bow shock and magnetic bubble

4. Mission design

4.1. Key mission drivers

The mission is driven by:

- **Operational uncertainties:** unknown rotational dynamics and unknown gravitational field
- **Data generation and communication complexity:** large data production during scientific modes and low data link due to large distances from Earth
- **Long total mission duration (transfer and operations):** Degradation of spacecraft components, reliability of spacecraft components
- **Limited power availability:** limited power generation at 6 AU

4.2. Mission phases and orbits

The envisioned nominal mission timeline includes ten phases:

0. Prelaunch (launch campaign) in August 2043;
1. Launch and Early Operation Phase (LEOP) of 3-4 weeks;
2. Commissioning phase, including 4 months of operational and 2 weeks of science commissioning phase;
3. Cruise phase (Earth-Mars) for 2 years;
4. Mars gravity assist;
5. Cruise phase (Mars-29P) for 10 years;
6. Post-LEOP phase commissioning phase of 1 month;
7. Nominal mission phase of 2-3 years (starting upon arrival at 29P, in 2055);
8. Extended mission phase 6 years;
9. Decommissioning phase 6 months.

4.2.1 Transfer Trajectory to 29P

The transfer to 29P employs a low-escape speed, low-thrust trajectory that enables a smooth outward spiral from Earth orbit, assisted by a single gravity assist at Mars, prioritizing mission flexibility. The S/C is scheduled to launch on 19 August 2043 with a C_3 of ~6.7 km^2/s^2, initiating a low-thrust Earth departure phase. The propulsion system operates at 0.2 N continuous thrust with a specific impulse of 1710 s. After approximately 800 days, the S/C performs a Mars gravity assist to adjust its heliocentric trajectory. The transfer continues with a mix of thrust arcs and ballistic coasting phases, converging on the orbit of the Centaur after a total time of flight of 12 years. The complete trajectory requires a Δv of ~15 km/s, and results in an arrival mass of 1650 kg from an initial launch mass of 3613 kg. Fig. 2 portrays the ecliptic projection of the selected transfer.

One of the key advantages of the proposed trajectory design lies in its flexibility. The combined use of low thrust and low Earth escape speed extends the viable launch window to approximately 2 months, significantly relaxing launch-related constraints. In addition, 29P's near-circular heliocentric orbit and the short synodic period of the Earth–Mars system (~2.1 y) further enhance the frequency of launch opportunities. Suitable transfer windows occur frequently, mirroring this synodic cycle, and facilitate mission rescheduling in the event of delays. This architecture enables efficient trajectory re-optimization and robust recovery planning without fundamentally altering mission scope, offering a reliable and repeatable path to rendezvous with 29P.

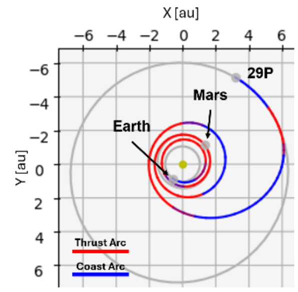

Figure 2: Transfer trajectory to 29P

4.2.2 Injection and Target Orbits around 29P

Upon arrival at 29P, the spacecraft will be injected in a high-eccentricity (0.72) capture orbit. Since scientific requirements fix the semilatus rectum (p) of the orbit to 230 km (corresponding to an altitude of 200 km above the surface), the eccentricity of the capture orbit is limited by the apocenter distance. Due to 29P's small gravitational influence, an excessive apocenter distance would result in a very low local escape velocity, making the spacecraft highly susceptible to external perturbations (e.g., solar radiation pressure or third-body effects), which could cause it to escape 29P.

During the capture orbit, an appropriate change of plane manoeuvre will be applied to acquire the desired inclination (77°) with respect to the equatorial plane (orthogonal to the rotation axis) of 29P. From this point, the spacecraft will transition through a sequence of three elliptical orbits (survey, high, and low orbit). The first three orbits (capture, survey, high) are characterized by the same value of p. Consequently, the impulsive manoeuvre for transitioning between these configurations will be applied in correspondence of p. The transition between high and low orbit is obtained with a burn at the apocenter, lowering p to 80 km (50 km above the target surface). A schematic representation of the operation orbits around the target and corresponding impulsive transition cost between adjacent orbits is provided in Fig. 3.

The availability of low-thrust propulsion can be exploited for stationkeeping around the object. The cumulative Delta-v that must be provided by the propulsion system to compensate for solar radiation pressure, outgassing-related perturbations, and gravitational perturbation due to Jupiter and Sun has been computed for each orbit over a period of 6 months, never exceeding 2.6 m/s.

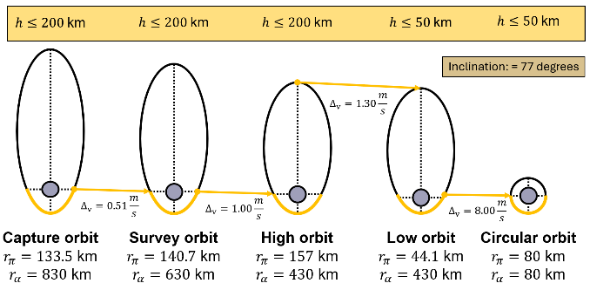

Figure 3: Target Orbits around 29P

4.2.3 Mission End-of-Life and Decommissioning

For the end-of-life phas, deorbiting strategies compliant with planetary protection guidelines were assessed. In accordance with ESA's Planetary Protection Policy, 29P is classified as a **Category II** object. Therefore, the surface may be impacted without extensive contamination prevention measures. Accordingly, a **controlled impact on 29P** has been selected as the end-of-mission scenario. This approach minimizes mission complexity and propellant demands while enabling the collection of valuable in-situ data during the final descent. The spacecraft will execute its terminal operations with batteries fully charged and its high-gain antenna pointed toward Earth to transmit final measurements from onboard instruments during the last descent phase (30 to 60 min).

4.3 Observation strategy

Upon arrival, CIRCE will orbit around the target through its initial capture orbit. Subsequently, the S/C will transition to a survey orbit where the condition of the system will be assessed. During this phase, unknown parameters, such as the direction and rate of the body's rotation, will be determined. Simultaneously, data obtained from ground-based observations will be confirmed and corrected where needed. The spacecraft's optical imager, the plasma package, and infrared mapping, will take global scans at lower resolution, capturing the first overview images to provide a preliminary characterisation of 29P. In parallel, the on-board plasma package will conduct measurements which may observe events such as bow shock, possible due to the activity of the small body. Additionally the mass spectrometer is expected to start taking measurements along the flight direction. Based on the results of these assessments, the parameters of the subsequent High, Low and Circular orbits will be refined and adapted accordingly.

Once the High and Low orbits parameters are confirmed, the science collection phase will start in High orbit. All instruments are expected to make significant contributions to the characterization of the coma, the nuclei, the surface and the sub-surface composition. Similar measurements will be performed during the Low Orbit with better accuracy. As a result, specific topographic features including cracks, cliffs, and surface irregularities will be detected and mapped with higher resolution. In this orbit, CIRCE's instruments will monitor outgassing activities, where the computer vision algorithm will command the AOCS subsystem to direct its instruments to point towards outburst locations. This mode involves higher risks and demands a lot of power, but is crucial to collect further information about 29P's activity drivers. After the low orbit science measurement phase is complete, the spacecraft will be directed towards the circular orbit, collecting additional crucial high resolution images with short revisit time for the entire surface, high fidelity gravity field, and nuclear spectrometry measurements. Finally, the S/C will be directed to the ground to transmit a variety of high-data-rate, time-resolved science measurements in the moment before the crash. The collision will occur on the Sun-facing side of 29P to optimize power consumption and communication. High-cadence measurements from instruments such as the Plasma and Ion sensors, IR spectrometer (sequential spectroscopy), and magnetometer will provide important insights into surface properties and coma composition. The effects of the impact will be observed from a distance with the James Webb Space Telescope.

The most efficient operational mode sequence to pursue once the spacecraft is in orbit were analysed, to ensure the well-being and success of the mission. Hence, three operational sequences were defined, each including a distinct combination of spacecraft activities. Each of the following orbits corresponds to one iteration of a sequence. Firstly the Science Collection sequence focuses on acquiring data from the surface and coma using CIRCE's onboard payloads, whilst enabling the downlink of critical data collected (Figure …). Dissimilarly the Communication and Charging sequence focuses only on the downlink of scientific data and battery recharge. Lastly, the Service sequence, which is designed to perform internal or ground-directed maintenance tasks, software updates, reaction wheel desaturation, and other operations that require maintenance of the spacecraft's health and functionality.

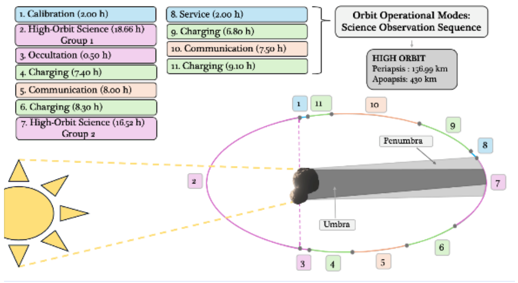

Figure 4: Science Collection sequence of payload Operational Modes for spacecraft in High Orbit.

Note that the most constraining operation mode in terms of power consumption and data storage is the Outgassing special scenario, consisting in the spacecraft changing orientation in order to face the outgassing source and activity, investigating areas of volatile release or venting. If this happens during Science Mode the on-board computer will command the AOCS to automatically point the Z+ deck towards the outburst, altering the typical Science Collection sequence, and allowing for an even more efficient battery recharge and downlink. Furthermore, occultation will aid the observation of the Centaur's close environment and gain insights on the composition of the coma, with the only downside of reducing the effectiveness of other instruments during that time due to its orientation.

2.5. CONOPS: High Orbit Example

This requires a well structured sequence of Science Collection orbits, followed by Communication and Charging Orbits, and Service Orbits. The orbits arrangement was further optimized to take into account additional constraints such as time intervals between large downlinks, and minimize the number of orbits needed.

Given the smaller orbital period in the Low and Circular Orbit, the science operation time in that phase is expected to be shorter. Therefore, the estimated maximum duration for High, Low and Circular orbits science operations is approximately 3 years.

4.4. Critical technology

Combining the instrumentation to analyze cometary gas and dust into a single time-of-flight mass analyzer will require substantial development. The optical imager, critical for the success of the mission, needs to have its TRL increased beyond 4. In particular, the aperture and detector must be revised.

Ensuring a sufficient and stable power supply at the target will require large and highly efficient solar panels. Adequate mechanisms for sun-tracking which maximize solar radiation input while maintaining the structural integrity of the spacecraft will require substantial development.

5. Spacecraft design

For the spacecraft design presented below and related budgets, the ESA Margin philosophy for science assessment studies is followed [18]. For power and mass, off-the shelf components use a 5% margin if they require no further modification and a 10 % otherwise. New components use a 20 % margin. A system margin of 20% is applied for the mass and 30% for the power. Propellant masses were assigned an initial 20 % margin plus an additional 10 % uncertainty margin and 2 % residual margin.

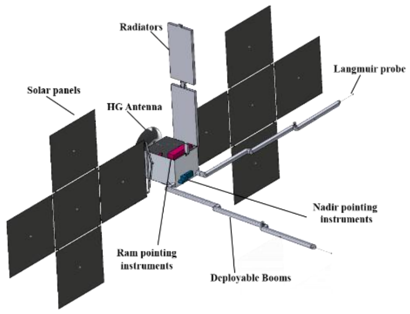

Figure 5: Deployed configuration of the CIRCE spacecraft.

5.1. Communications

The spacecraft (S/C) will use a communication system with a single 2.5-meter High-Gain Antenna (HGA) [16] and 0.5-meter Medium-Gain Antenna (MGA) [17] based on the JUICE Mission. Operating in Ka-band, it supports a downlink rate of 260 kbps and Uplink is maintained at 1.2 Mbps. During an average 8-hour daily contact window, the system transmits up to 7.48 Gbit/day, with a link margin exceeding 18 dB. The MGA with X-band is used for Command and Control and backup, it supports an Uplink of 60kbps and a Downlink of 10kbps.

The ESA Deep Space Antenna network will serve as the ground segment, including 35-meter stations at Cebreros (CEB1), Malargüe (MLG1), and New Norcia (NNO1). NASA's 70-meter DSN antennas in Goldstone, Madrid, and Canberra provide backup coverage. Communications operate in the Ka-band at 32.0 GHz downlink and 34.5 GHz uplink.

5.2. Structure

The main structure of CIRCE is a rectangular box with dimensions of 2.0 × 1.5 × 1.8 m. A detailed view of the deployed configuration is shown in Fig. 5. At the center of the S/C is a 900-liter Xenon tank, surrounded by all other internal components. To enhance structural integrity, the interior is divided into separate compartments by aluminum walls. The S/C is designed to meet the pointing requirements of all onboard instruments, particularly those that must be positioned 10 m away from the main body. This requirement is addressed through the use of two booms. Since two sides of the spacecraft are occupied by the HGA and the thrusters, both booms must be deployed in specific directions. To accommodate these booms, the two solar arrays and the deployable radiator within the limited space of the Ariane 64's short fairing (which has a diameter of only 5.4 m) complex deployment mechanisms have been developed to enable a compact stowed configuration.

5.3. Mass budget

The preliminary mass budget for CIRCE, summarized in Tab.3, was estimated bottom-up by inferring the mass of the components for each subsystem from heritage hardware. The Xe and N_2H_4 propellant mass was derived from the delta v budget, as can be seen in Tab.4.

Margins were applied in accordance with the ESA margin philosophy for science assessment studies [18]:

- Off-the-shelf components were assigned a 5% margin if they required no further modification and a 10% margin otherwise.
- New components were given a 20% margin, which was also applied to the launch mass.
- The xenon (Xe) and hydrazine (N_2H_4) propellant masses were assigned an initial 20 % margin plus an additional 10 % uncertainty margin and 2 % residual margin.

Table 3: Mass budget of the CIRCE mission

Item	Mass [kg]	Margin [%]	Mass w/ margin [kg]
Payloads	98	5-20	110
AOCS	88	5	92
EPS	539	5	566
TCS	57	5	60
Structures	363	5-20	429
Communication	35	5	37
Avionics	68	5	71
Total dry mass	1363	20	1635
Xe propellant	1495	20 + 10 early stage + 2 residuals	1973
N2H4 propellant	5	100	10
Launch mass with 20% margin			4341
Wet mass at arrival with 20% margin			1645

5.4. Electrical power system

A driving factor for the design of the EPS is the need to balance between a high power demand for the electrical thrusters at distances of up until 6 AU and performing scientific operations around 29P. For power generation, several options with RTGs, solar cells and hybrid approaches were explored. The trade-off performed based on power per unit of mass (after efficiencies and losses), thermal aspects and costs/programmatic concerns concluded that solar cells were the optimal option.

Table 4: Power budget under different operation modes

Item	Propulsion mode	Outgassing Activity	Communication
Payloads	43.32	143.1	0
AOCS	3247.44	125.79	125.79
EPS	10.5	10.5	10.5
TCS	0	262.5	105
Comms	9.03	3.01	301
Avionics	9.6	9.6	9.6
TOTAL	3319.89	554.5	551.89
TOTAL w/ System Margin (30%)	4315.86	720.85	717.457

Solar panels were sized according to the most power intensive mode, which is the propulsion mode at a distance of 3 AU with a power consumption of 4.3 kWh, resulting in a solar panel area of 113.95 m^2. For energy storage, 5x Li-ion batteries with a capacity of 10560 kWh are used. To increase the lifetime of the batteries, a depth of discharge between 80 % and 20 % is used, meaning that EPS can store 6336 kWh of electrical energy. Estimates for the power conditioning units are also included. A preliminary version of the power budget can be found in Tab.6, showing the most power intensive modes that were identified during the study.

Table 5: Sizing of the solar panels

Item	Propulsion at 3 AU	Propulsion at 6 AU	Outgassing Activity
Solar Constant	1367	1367	1367
Distance AU	3	6	6
Efficiency	0.25	0.2	0.18
Power Consumption [W]	4327	800	411
Required solar panel area [m^2]	113.64	105.34	105.48

5.5. Propulsion

5.5.1. Main Propulsion System

To reach its target, CIRCE will require a main propulsion system capable of delivering a total delta v of 19.53 km/s and a thrust of 200 mN, within a power budget of 4.0 kW. Therefore, the main propulsion system will consist of three Busek BHT-1500 Xe Hall effect thrusters [19]. These thrusters, currently at TLR 6, may work under several modes. For the objectives of this mission, the relevant characteristics may be found in Table 7. Only two of the units will be active throughout the transfer, maintaining the third one as a backup in case of misfire. Similar engines have been qualified to endure 7200 on/off cycles [20], which allows for intermittent battery charge and thrust stages throughout the transfer beyond the orbit of Mars, optimizing the power required to reach the target within the generation constraints given by the growing distance to the Sun.

Table 6: Operation modes of the main thrusters

Power (W)	Thrust (mN)	Total Isp (s)
1000	68	1615
1500	101	1710

5.5.2. Reaction Control System (RCS)

The RCS shall perform all the manoeuvres after being captured by the target, including the orbital transfers and the stationkeeping manoeuvres. It will also act as the actuator system for the AOCS.

The system will consist of 16 ArianeGroup hydrazine chemical monopropellant thrusters, capable of delivering 20 N at a specific impulse of 226 s each [21]. These components have performed successfully to several previous missions, including Planck (2009), yielding a TRL of 8.

5.6. Attitude control & determination system

AOCS for CIRCE uses primarily COTS components which have previously flown on comparable deep space missions. 4x reaction wheels placed in a redundant tetrahedron configuration are used to control the orientation of the spacecraft. These are also complemented by the set of sixteen hydrazine thrusters described above. Apart from their role in orbit adjustment and station keeping around 29P, these thrusters are also used for attitude control and desaturating the reaction wheels. For attitude determination and guidance purposes, a combination of sensors is used. These are 3x star trackers, 4x sun sensors and 3x LASER gyroscopes. The overall architecture provides sufficient reliability, can meet the pointing needs of different instruments and can also meet the requirements for spacecraft operations.

5.7. Thermal system

To design the Thermal Control System (TCS) for the spacecraft, two mission scenarios representing the thermal extremes, commonly referred to as the "hot case" and the "cold case", were analysed. The hot case occurs shortly after launch when the spacecraft is located approximately 1 AU from the Sun. In this scenario, the primary heat inputs include direct solar radiation, Earth-reflected sunlight, terrestrial infrared emission, and internal heat generated by spacecraft systems such as thrusters and onboard electronics. To maintain thermal balance and meet the specific thermal requirements of the onboard instruments, the spacecraft will be enveloped in Multi-Layer Insulation (MLI) comprising 20 layers of 2-mil-thick aluminized Kapton. Additionally, deployable passive radiators with an approximate surface area of 9 m² will be employed to dissipate excess heat. The cold case corresponds to a mission phase during which the spacecraft is in eclipse behind the celestial body 29P, at a heliocentric distance of approximately 6 AU. Under these conditions, the infrared radiation received from 29P is minimal, and the primary thermal input is the internally generated heat within the spacecraft. To minimize thermal losses, the TCS will utilize MLI and radiators. Nevertheless, some heat dissipation is inevitable. To ensure that critical systems and instruments remain within their survival temperature limits, supplemental heating will be provided through onboard heaters.

5.8. Data budget & on-board computing

To meet the memory requirements of the mission's scientific experiments, reference missions such as JUICE and Rosetta were analyzed. The primary contributors to the data volume were the camera and the Thermal and Infrared Spectrometer, producing data at approximately 60 Mbit/s and 150 Mbit/s, respectively. Assuming a lossy compression ratio of 12:1 for the camera and a lossless 3:1 compression for data from the other instruments, the total data volume was estimated based on the instruments' maximum data rates, expected operational durations, and the time spent in various orbits around 29P. Based on this analysis, the On-Board Computer (OBC) was calculated to require a minimum of 1 TB of storage. To ensure margin and enable 40 days of continuous data collection while not exceeding 60%, a total storage capacity of 2 TB was selected.

5.9. Cost breakdown

The costs of the mission were estimated using the ESA Academy Cost Model [22], taking into account the TRL of the different subsystems and components as well as launcher and operations. A 20% margin was added as a contingency. Tab.1 provides a breakdown of the total costs by category. Our estimations place CIRCE in the lower end of the L class category, although it may be considered as a high-end M class in an optimistic scenario.

Table 7: Cost budget for the CIRCE mission

Segment	TOTAL (M €)
Total platform hardware & software	113
Total spacecraft system level activities	185
Total payload instruments -S/C	196
ESA project management	62
Launch	130
Operations	192
TOTAL EXCLUDING MARGINS	878
Risk margin (20 %)	**176**
TOTALS + RISK MARGIN	**1,054**

Table 8: ESA cost budget for the CIRCE mission

Segment	TOTAL (M €)
Total costs for ESA without margins	682
Total costs for ESA with margins (20 %)	819

6. Risks

Table 9: Risks for the CIRCE mission

Mission Risks	Name	Justification	Mitigation
R1 (highly likely)	Unstable dynamics of 29P, incompatible with stable orbit	Orbiting 29P may be unfeasible if its rotation state is unstable.	Characterise the object's dynamics through a stepwise approach (e.g. a survey orbit). Update the mission plan before initiating proximity operations. If a stable orbit is not possible, conduct multiple hyperbolic arcs to provide high resolution observations of selected areas with slower coverage.
R2 (near certain)	Unpredictable outburst activity	Unexpected outgassing and dust release during low orbits may disrupt navigation, contaminate instruments or damage the spacecraft.	Monitor activity and outbursts from a distance (e.g., during survey orbit). Approach only regions with low outburst activity. Increase distance if significant outbursts occur.
R3 (unlikely)	Missing the launch window	Possible delays due to e.g. bad weather or development setbacks.	Include schedule margins, large launch windows and a plan for backup launch windows.
R4 (unlikely)	Cost overrun	Potential cost increases due to delays, e.g., missing the launch window or extended spacecraft integration and testing phases.	Request additional funds at the earliest sign of cost overruns to prevent project delays or compromise.

7. Descoping options

- Plasma Package: linked to OR-170 with a low priority level of 2 but the related science can not be covered by other instruments
- Dust Impact Analyser: linked to OR-200 with medium priority level of 3 and the science could partially be achieved by spectrometry and imaging

8. Conclusion

CIRCE will be the first mission to study a Centaur in-situ and aims to understand the origin and evolution as well as the activity processes of Centaurs. 29P is an excellent target object to orbit around to fulfill our scientific objectives. We are confident that CIRCE would have a high value for the field of space science and look forward to the realization of such a mission.

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