CARINA
Comet Asteroid Relation INvestigation and Analysis

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Abstract: CARINA is a sample return mission to the near Earth D-type asteroid 2002 AT4. It will rendezvous with the asteroid and escort it along its orbit for a period of approximately one year. The mission aims to answer key scientific questions such as the relationship between asteroids and comets, the origins of life and water on Earth, and the evolution of the Solar System. Sampling is planned to be in a "touch and go" fashion, by means of a Bristle Sampler (BSA) for surface samples and a Harpoon Sampler (HSA) for sub-surface samples, both novel technologies to be applied. A crushable Earth Re-entry Capsule (ERC) is selected to bring back the samples. All mission designing details are described in this report.

Keywords: NEA, D-type asteroids, comets, sample return, coconut

1. INTRODUCTION

1.1 Small Solar System Bodies

Among the Solar System population, asteroids and comets are crucial elements to our understanding of the formation and history of our Solar System and the key processes and materials that shaped the origin of life on the Earth. Asteroids are rocky objects that can be a few metres to several hundred kilometres wide. Their composition ranges from primitive, those which have experienced the least processing since their condensation and accretion from the early Solar Nebula, to metallic asteroids hypothesised to be the cores of differentiated planetesimals. Their populations range from near-Earth to the Kuiper Belt. The asteroid population tells us the story of planetary accretion in the early Solar System and subsequent evolution. Comets are bodies thought to have formed in the outer Solar System; the Kuiper Belt (short period) and Oort cloud (long period), where there were more volatiles present for accretion. Thrown forward into the inner Solar System towards the sun, possibly by a gravitational perturbation, the volatiles on the surface of these comets sublime, creating dust and gas trails. These bodies which formed in the outer Solar System likely contributed to the volatile budget of the terrestrial planets, as they formed sunward of the hypothetical snow line. Studying these bodies can therefore give us an insight into our own evolution.

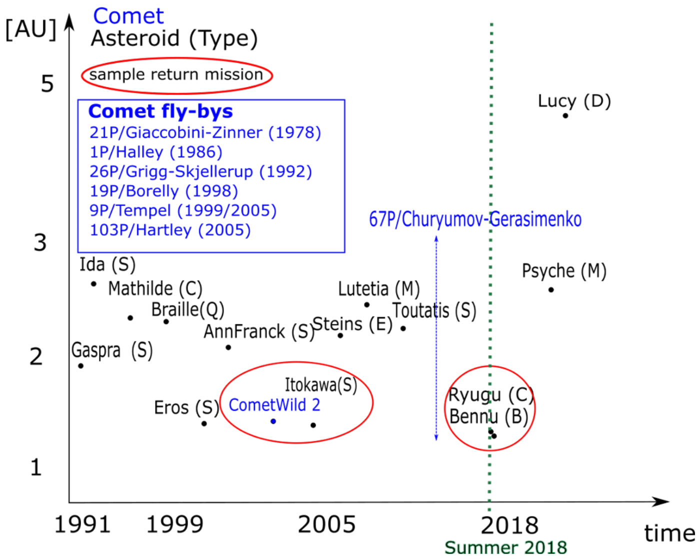

Fig. 1. Previous small body missions

1.2 Is there a Relationship between Comets and Asteroids?

Comets and asteroids may not, however, be distinct bodies. (Hicks et al., 2000) characterises two asteroids, 1996 PW and 1997 SE5, in comet-like orbits, but with no cometary activity. These were therefor suggested to be extinct comet nuclei. Additionally, some near-Earth objects (NEOs) originally classified as asteroids have been found to show intermittent cometary activity. One example is 3552 Don Quixote, which shows a coma and tail, but is in an Amor near-Earth orbit (Mommert et al., 2014).

If there are comet-like objects in near-Earth space such as Don Quixote, and we know that comets eventually cease being active, as in the case of 1996 PW and 1997 SE5, it is a reasonable hypothesis that there are some NEO extinct comets, that may have been identified previously as asteroids. This is not unexpected, as the activity of a short period comet is much shorter than its dynamical lifetime (Mommert et al., 2014; Morbidelli and Gladman, 1998; Levison and Duncan, 1997; Weissman et al., 2002).

The method of a comet becoming extinct is not well understood. One theory suggests a non volatile crust can form on the surface, which can repress subsurface volatiles from subliming, rendering the comet inactive. These non volatile grains are left behind or launched from the surface of the comet as volatile gas and dust sublimes from the surface (Weissman et al., 2002). Figure 2 shows this process visually: on extinct comets we might find a crust of non volatile material covering subsurface ice or hydrous minerals, and sampling both would give us a way of testing whether this method is accurate.

D-Type Asteroids All three examples mentioned, Don Quixote, 1996 PW and 1997 SE5, have been grouped into the D-type asteroid taxonomy based on their visible and near infrared (VNIR) spectral slopes Hicks et al. (2000); Mommert et al. (2014). Figure 3 shows the VNIR spectra for Don Quixote, which is featureless but has a steep red slope characteristic of D-type bodies.

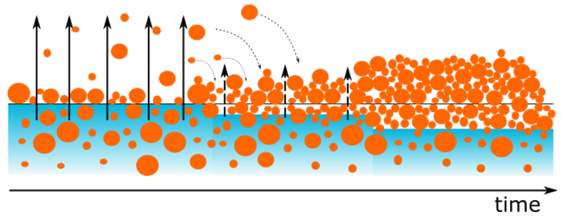

Fig. 2. A diagram showing the method of asteroid 'quenching'. Non volatile materials are redeposited on an surface, and subsurface volatile materials are depleted.

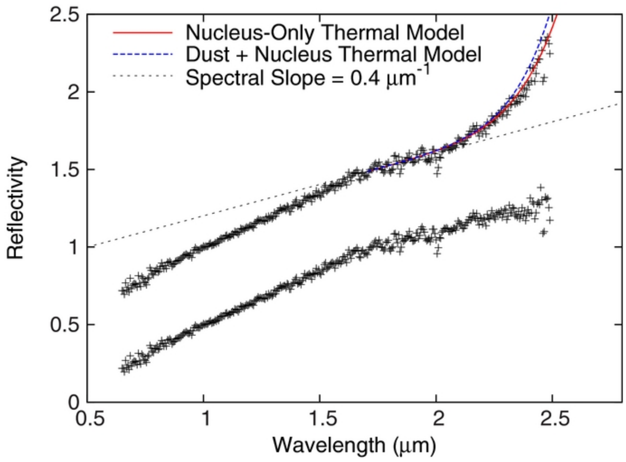

Fig. 3. IRTF SpeX spectrum of Don Quixote. The steep slope at longer wavelengths in the upper plot is assumed to be due to thermal emission from the nucleus and contributions from the coma dust (fits the thermal models). The lower plot shows the same spectrum, offset, from which this tail has been subtracted Mommert et al. (2014); Thomas et al. (2014).

The asteroids in the D-type taxonomy have typically been assumed to have formed in the outer Solar Nebula, in areas rich in condensed volatiles. They are considered among the most primitive of the asteroid population, and contain abundant volatiles and organics (Barucci et al., 2018). Any bodies in the inner Solar System were thought to be thrown forward by movement of the Giant Planets (Levison et al., 2009; Morbidelli et al., 2015).

If D-type near-Earth asteroids could represent extinct comets, they offer us a unique opportunity to investigate the method of how a comet becomes inactive. Additionally due to their volatile and organic content, they may have played a role in our planet's evolution.

2. SCIENCE OBJECTIVES AND REQUIREMENTS

We believe studying a near-Earth D-type asteroid will contribute to the following science questions.

- How did the Solar System evolve and how did planetesimals form?
- What is the origin of life on Earth?
- Is there a relationship between asteroids and comets?

We have divided these questions into achievable objectives for the CARINA mission to a near-Earth D-type asteroid.

(1) Characterise a near Earth D-type asteroid.

(2) Determine the timescales of accretion and planetesimal formation.
(3) Characterise the mixing of elements the protoplanetary disk.
(4) Link characterisation to potential meteorite analogues.
(5) Investigate the organic material.
(6) Investigate the volatile content.
(7) Evaluate whether D-types could represent extinct comet nuclei.
(8) Investigate activity quenching as a 'comet killer
(9) Determine whether asteroids and other comets are related; are they separate bodies or do comets, D-type asteroids and C-type asteroids represent a continuum.

Many of these objectives cannot be achieved without laboratory analysis of returned samples from a near-Earth D-type asteroid. Further details follow below.

2.1 Solar System Evolution

As D-types represent some of the most primitive material in the Solar System, they will likely tell us about the very early stages of planetesimal formation. Objectives (1) to (4) should contribute knowledge to this stage. Requirements to achieve these objectives include determining a global and near-subsurface compositional map, a measure of volume, mass and density of the bulk target, and an evaluation of the magnetic field. This will require optical cameras, VNIR and thermal infrared (TIR) spectrometers, a high frequency radar and a magnetometer on the spacecraft.

Additionally analysis into the ¡mm and $< \mu$m scale structure and mineralogy will tell us details about processing and alteration on the asteroid. This is only possible with laboratory analysis, such as scanning micro-computed tomography (μ-CT), electron microscopy (SEM), transmission electron microscopy (TEM) and electron microprobe analysis (EMPA). Isotopic measurements will also tell us about elemental and chemical composition of the asteroid, and these measurements are also only possible to a high precision using techniques such as Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). Another consideration is the possibility of keeping some of the sample for improved future techniques and further arising questions.

2.2 Origin of Life

As the source of volatiles and potentially organics to the terrestrial planets is likely extraterrestrial, it is very interesting for us to study bodies which are rich in these components. As we know this to be the case for D-type asteroids, we want to find out whether they played a role in our planet's evolution. As a result, we aim to complete objectives (5) and (6).

Spectroscopic analysis should provide preliminary identification of absorption and emission bands due to the presence of volatiles and organics. The spacecraft should also carry a mass spectrometer to do initial characterisation of volatiles in the collected sample. This is to ensure there is no alteration of potential volatile products once the sample is in the return capsule. Most analysis of composition and content should however be conducted through laboratory experiments such as nano secondary ion mass spectroscopy (nanoSIMS), nuclear magnetic resonance (NMR) analysis and circular polarisation spectroscopy, which will be particularly important for determining chirality.

2.3 Asteroid Comet Relationship

CARINA offers us an opportunity to test whether asteroids and comets are similar bodies or distinct. As near-Earth D-type asteroids could be extinct comets, this gives us an opportunity to study the method in which comets are rendered inactive. Objectives (7), (8) and (9) will contribute to answering this question. We particularly want to focus on comet quenching, and this requires a sample from both the regolith and the subsurface, where there might be some more cometary-like material still present.

To achieve these objectives, compositional maps and physical maps determined from orbit can be compared to data from other missions such as Rosetta, OSIRIS-REx and Hayabusa2. Additionally important will be laboratory measurements of the returned samples, as the exact same experiments and conditions can be replicated from analysis on Stardust, OSIRIS-REx and Hayabusa2 samples. These will likely include μ-CT, SEM, TEM, EMPA, LA-ICP-MS, Raman spectroscopy, X-ray absorption spectroscopy (XAS) and other techniques.

2.4 Measurement Requirements

Optical camera should be able to build maps at a distance of 5 km from the target at a resolution of 20 cm, and local maps from a distance of 1 km at a resolution of 1mm. Spectral ranges for the VNIR and TIR spectrometers should cover 25000 - 2325 cm$^-1$ (0.4 - 4.3 μm) and 2325 - 333 cm$^-1$ (4.3 - 30 μm), at a precision of 10 cm$^-1$. The radar should have a resolution of 1 m x 1 m and should penetrate to 10 m. The magnetometer should be able to measure remnant magnetism to an accuracy of 1 nT. The mass spectrometer should cover the mass/angle range 10 - 200 m/z, and have a detection limit of 5 permille.

2.5 Sample Requirements

In order to achieve our scientific objectives, a return sample is necessary. We require a sample from the surface and from the near subsurface. These two samples will have a minimum mass of 12 g (6 g from the regolith and 6 g from the near subsurface) and a optimal mass 2.2 kg (1.1 kg from the regolith and 1.1 kg from the near subsurface).

Surface and Subsurface Temperature In order to evaluate the temperature of the subsurface on our target asteroid, which would inform us with regards to sample requirements and return sample capsule design, we modelled the regolith of a hypothetical D-type asteroid for a variety of rotation rates. In order to find possible volatiles in an asteroid, the sampling location must have a temperature around 225K (Dyar et al., 2010).

The temperature depends on the bodys thermal properties, rotational properties and the heliocentric distance (Michel and Delbo, 2010). The maximum (sub-solar) temperature was calculated, taking the albedo of D-types

asteroid as a range between from 0.02 to 0.05 (Darling and Schulze-Makuch, 2016; Delbó and Harris, 2002; Bowell et al., 1989; Dymock, 2007). The emissivity (ϵ) for asteroids is assumed to be 0.9 (Delbó and Harris, 2002).
Using the Energy 2D software (Xie, 2012), a rough estimation of the subsurface temperature has been done. It is assumed that D-type asteroids have approximately the same density of regolith as a C-type asteroid, measured $1.3 \pm 0.2\ g/cm^3$ (Herique et al., 2017). The thermal conductivity of the carbonaceous chondrite Cold Bokkeveld (CM2) is $0.5\ W/m/K$ and the heat capacity $C_p = 500\ J/Kg/K$, which could be considered a satisfactory analogue for the surface of D-type asteroid (Fujiya et al., 2013; Yomogida and Matsui, 1983).

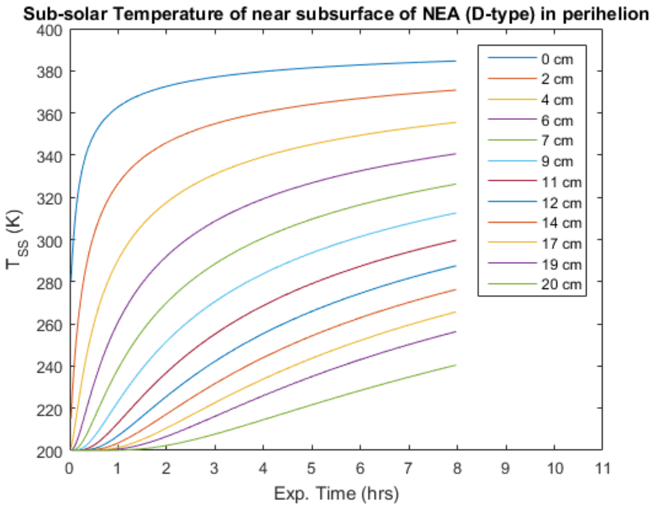

Fig. 4. Results of simulations

Skin depth is additionally calculated, using $ds = (2k/\rho c\omega)^{1/2}$ (Spencer et al., 1989). For a rotation of 2.2 hours, (Winkler et al., 2012), the ds is $0.11\ m$ and for a rotation of 6 hours, (Gil-Fernández et al., 2008), the ds is $0.18\ m$. Typical skin depth values for asteroids are $10^{-3} - 10^{-2}\ m$ (Bottke, 2002). Also, it can be concluded that from 15 to 20 cm of depth chemisorbed water could be found, if there is.

Target Selection We focused the study on targets which are hypothesized to contain volatiles, organics and be carbonaceous. Preference was given to targets which were assured to be D-types, although the near-Earth population of accessible D-type targets is small. Two primitive near-Earth bodies were chosen for feasibility analysis

- Asteroid 2002 AT4

AT4 is a Near Earth Asteroid classing as a D-type due to its large slope and its red VNIR spectrum. As a D-type it is thought to have formed in the outer Solar Nebula and thus to contain volatiles and complex organic molecules. 2002 AT4 satisfies all scientific and engineering requirements, which makes it the perfect target for our mission.

- Asteroid 2001 SK_{162}

Our secondary target would be SK162, another NEA to be believed have affinities to D-type. It also has been classified as a T- and X-type based on VNIR spectra also and thus,though fulfilling our requirements, it is more suitable as a plan-B target.

Scientific objectives :

Target	Class	Volatile	Carbonaceous
2002 AT4	D	Yes	Yes
2001 SK162	D, T, X	No	Yes

Engineering objectives :

Target	ΔV(km s^{-1})	Inclin.(°)	a(AU)
2002 AT4	5.55	1.5	1.8
2001 SK162	5.57	1.6	1.92

2.6 Mission goals

Based on our science case, CARINA's goals for a successful would be to:

- Have a rendezvous with a near-Earth D-type asteroid and escort it along a part of its orbit.
- Return a regolith and a sub-surface sample and document the sampling site.
- Characterize and map a D-type asteroid.

3. PROPOSED PAYLOAD

3.1 Mapping Camera (MAC)

The main objective of the Mapping Camera is to obtain a shape model of the NEA with an accuracy of 1 m in height and horizontal direction. The shape can be obtained if the entire asteroid is included in one MAC image while the spacecraft is in a distant orbit (5km), which also allows for global characterization of the target. MAC images are also used for determining the rotation rate of the body. Its wide field is suitable for search of any potential 'moons' around the main target. Finally, the MAC may also be utilized for navigation purposes, in particular during the approach phase.

3.2 Sampling Camera (SAC)

The SAC is capable of imaging the surface with a 20 cm resolution, providing the high resolution needed to identify possible landing sites. These images will be used for characterisation of the surface topography and morphological features, the generation of a digital terrain model of some regions, analysis of regolith fragmentation and accretion history and the bulk composition of the body. The SAC imaging will bring complementary details of the shape model obtained with the MAC imaging and a close characterisation of any moon that might be discovered. Finally the SAC may also be used for space craft navigation during sampling.

3.3 VIS and NIR Spectrometer

Spectroscopy is a major tool used to characterise the composition of asteroids, to derive their surface mineralogy, to connect the mineralogical composition with the surface morphology and so to map the complete surface of the body. Spectra at different spatial resolution are needed to identify mineralogical provinces on the asteroid surface.

Most of the interesting minerals have electronic and vibration absorption features in their NIR reflectance spectra. Organic materials expected on primitive type may be more difficult to identify and so will require higher resolution. The complete surface of the asteroids will be imaged in the visible and near-IR wavelength range from 25,000 - 2325 cm $^{-1}$ (0.3 to 4.3 μm) and with at a precision of 10cm^{-}1. It will have a spatial resolution on the order of metres to characterize the mineral properties of the surface.

3.4 Thermal Infrared Spectrometer

TIR spectroscopy provides information on the surface mineralogy, particularly silicates and organics, the surface temperature, thermal inertia and properties of the regolith. The compositional information complements the data obtained from VNIR spectrosocopy and provides global context for the returned samples. Spectroscopic data is used to compute surface temperature distribution which can constrain the surface thermal inertia and regolith particle size, which will be useful for the sample site selection. In addition, they provide valuable information for determination of sizes and albedos from optical and IR observations of unresolved NEOs using the radiometric method and study of the Yarkovsky effect.

3.5 Mass Spectrometer

The Mass spectrometer experiment is designed to establish the identity, abundance and isotopic compositions of major, minor and trace components. This isotope ratios are measured and referenced to well established standard material. The next following should be measured:
1) Major volatiles (CO, CO_2, H_2O, NH_3).
2) Minor/Trace volatile species (CH_3OH, CH_4O, etc).
3) Non-volatile or refractory species (CHON, silicates, dust)

3.6 High-Frequency Radar (HFR)

The aim of a monostatic high frequency radar is to investigate the shallow subsurface of the asteroid down to a few tens of meters depth with meter resolution. This resolution will allow us to understand the structure of the regolith, size distribution, depth, stratigraphy and heterogeneities, which would give better constraints on the process of regolith formation and evolution, and its thermal state. Furthermore, knowing the state of the regolith around the sampling site gives us the vertical context of the sample, and the geological area it fits. In order to achieve our scientific goals, a resolution of one meter in the horizontal and vertical planes is required, as well as a penetration depth of one meter: we are therefore using a similar instrument to the High Frequency Radar (HFR) designed for the AIM mission with a frequency range of 300 – 800 MHz.

3.7 Magnetometer

The magnetometer objective is to measure any global and local magnetic fields, or remnant magnetism during the whole local mapping phase of the mission. There is limited knowledge from previous magnetic field observations of primitive bodies, and characterizing it would improve our grasp of asteroid formation and the evolution of the magnetic field in the solar system. The magnetometer should have an accuracy of 1 nT to be able to estimate the local magnetization of the surface material for decimeter-sized magnetic domains granularity. The sensitivity should be better than 0.1 nT.

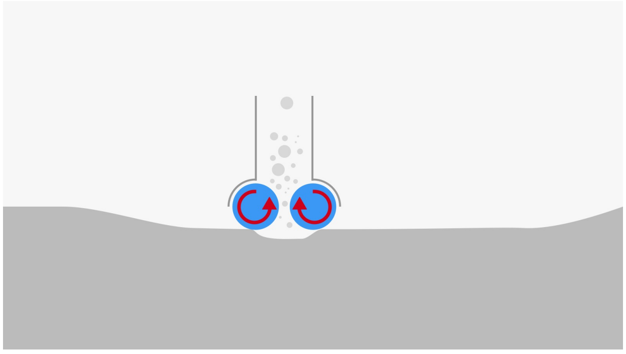

Fig. 5. Bristle sampler artist impression

3.8 Radio Science Experiment

The goal of doing radio science is to get an estimation of the mass and density of the target body when a good shape model is available. The spacecraft can be treated as a "test particle" falling in the gravity field of the planetary system with its velocity along the line-of-sight to the tracking station measured by Doppler effect. Gravity experiments are based on determining the motion of the satellite in response to the variations in mass distribution within a planet, and this method has been extended to small bodies. Combined with camera and altimeter determination of the mass; centre of mass, gravity field, shape, rotation axis and moments of inertia can be measured.

3.9 Sampling Mechanisms

Bristle Sampler (BSA) The BSA, as seen in figure 5, is the basic mechanism to collect surface samples of the regolith. It has the capability to collect 300 g of material. It uses two brushes which rotate and brush the sample into a storage box. It was proposed for Phobos and has a TRL of 3-4 (Allegranza et al., 2014).

Harpoon Sampler (HSA) The HSA, as seen in figure 6, collects sub surface samples. Tests with different materials have shown a penetration depth of up to 24cm. The harpoon has two shells, the outer shell will stay in the asteroid and the inner one will be pulled back out, along with the sampled subsurface regolith. Each harpoon has the possibility of collecting 280 g. The technology has a TRL of 4 (Wegel and Nuth, 2012).

4. SYSTEM REQUIREMENTS AND SPACECRAFT DESIGN

4.1 Attitude Orbit and Control System

The most important pointing requirement is the pointing of the X-Band Antenna. For this we defined the following requirements

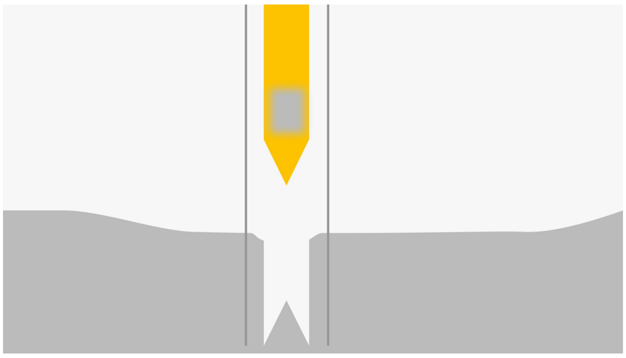

Fig. 6. Harpoon sampler artist impression

- 700 arcsec pointing accuracy
- 70 arcsec knowledge accuracy
- 0.1 mNm disturbance

4.2 Propulsion

The propulsion system consists of the main engines for the transfer orbits and the attitude and control thrusters considered in Section 4.1. Low thrust electrical propulsion is considered for this spacecraft as initial computations showed excessive propellant mass in the case of high thrust options. Therefore, the highly efficient and reliable T6 engines employed for BepiColombo will be used in this mission, with some modifications taking into account probable technological improvement during mission development. Its characteristics are shown in Table 1. The system mass is taken from (Hutchins et al., 2000) by considering an array of 4 thrusters with only 2 thrusting at the same time and 2 propulsion power units in order to obtain maximum reliability.

Table 1. Modified T-6 Engine

Force [N]	I_{sp} [s]	Power [kW]	System mass [kg]
0.2	4000	4.0	138.8

4.3 Telecommunication Subsystem

The telecommunication subsystem (TT&C SS) is responsible for providing the spacecraft with the ability to receive, detect and process the telecommand (uplink), as well as performing range and range rate measurements, telemetry modulation and transmission. The system operates in X-band during the uplink and in X- or Ka-band (8.2 GHz, 18 GHz) during the telemetry (downlink). One high gain antenna (HGA) will be used for scientific data (highly demanding phase), telemetry and housekeeping in X- or Ka-band during downlink. One medium gain antenna (MGA) will be used during up/downlink in the X-band for long distance telemetry, housekeeping and emergency far from Earth. Furthermore two low gain antennas (LGA) operating in the S-band will be used for the emergency case, redundancy and omni-directional communication close to Earth. Three ESA deep space ground stations are chosen as the ground stations (CEB1, NNO1, MLG1). A data rate of 60 $\mathrm{kb\,s^{-1}}$ and 300 $\mathrm{kb\,s^{-1}}$ with a transmission power of 170 W and 125 W respectively using a HGA diameter of 1.7 m and a ground receive antenna diameter of 35 m has been used as input parameters in the downlink budget. According to the budget the system is capable of delivering a transmission data rate of 822 $\mathrm{kb\,s^{-1}}$ and 151 $\mathrm{kb\,s^{-1}}$ respectively for the inputs mentioned above.

4.4 Thermal Design

The thermal system is designed to fulfill the temperature requirements of the different spacecraft components. By considering the spacecraft to consist of two nodes, main body and solar panels, a model was derived to calculate the spacecraft temperature during the different mission phases. In the cruise phases, the solar radiation and the internal heat dissipation will be the dominating heat sources affecting the spacecraft. In the vicinity of the asteroid, the albedo radiation is taken into account as well. During each phase an average distance from the Sun is assumed. Using a combination of passive and active thermal control systems it will be possible to keep the overall spacecraft temperature within 272 - 314 K. The total radiator size will be 3.5 m^2, covered with louvres to adjust thermal radiation to space. In addition a 290 W heater will ensure that the sample to be returned is stored at a constant temperature, and that key systems maintain their operational temperature.

4.5 Mass Budget

The mass budget is consistent with the cost.

Table 2. Budget over dry mass with 20 % margin.

Object	margin [%]	mass [kg]
Data handling	5	67.55
Communication	5	103.01
Thermal	10	63.65
AOCS/GNC	5	29.19
Power	5	136.50
Propulsion	5	229.74
Structure	20	143.25
Harness	5	62.67
ERC	20	35.68
Payload	20	57.1
Total Mass	**20**	**928.35**

5. MISSION PROFILE AND OUTLINE

5.1 Pre-launch ground based observations

As both AT4 and SK162 are in the smaller range of NEO asteroids with diameters of 150-380 m and 1.5 km respectively they have yet to have be accurately characterised. With the planned launch windows there is ample time for further ground observations, as shown in figures 7 and 8. Supporting in the observation is the NEOcam, which is planned for launch by NASA in 2021.

5.2 Launch Windows and Overall Mission Trajectory

In order to reach the preferred target, the European Ariane 62, which consists of 2 main liquid stages and 2 solid boosters, has been selected because it can provide enough mass at launch, necessary for a feasible sample return

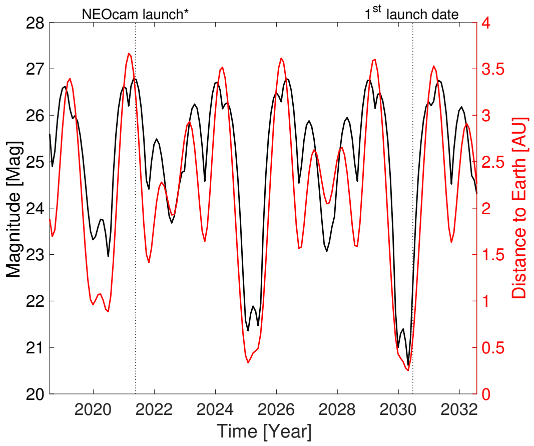

Fig. 7. 2002 AT4 orbit with respect to Earth.

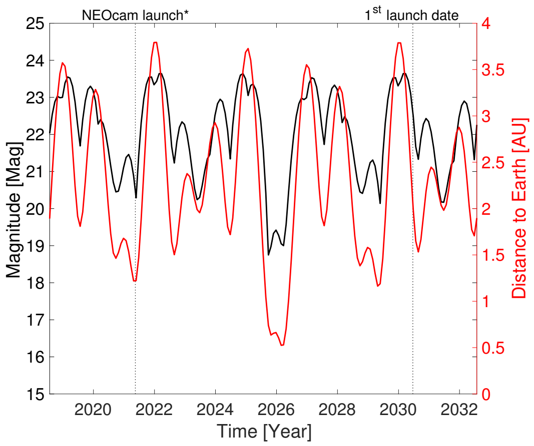

Fig. 8. 2001 SK162 orbit with respect to Earth.

mission. A direct injection can be used to deliver the spacecraft into the heliocentric transfer orbit. The mission will be launched from European launchpad in Kourou (Guiana Space Centre).

An initial study of the possible trajectories has been carried out by taking into account chemical propulsion. Nonetheless it has been stated that mission objectives could be better satisfied by using electric propulsion, in particular two T6 engines (section 4.2), with a flyby of the Earth. Therefore, some simulations, performed with Pagmo (Biscani et al., 2018) to identify a potential launch window, are shown in Table 5.2.

Table 3. Launch Window

Launch Date	Mission Duration	ΔV
29/06/2030	6.95 years	9.43 km/s
12/08/2033	6.45 years	9.68 km/s
31/08/2035	6.73 years	13.55 km/s

5.3 Asteroid Stay and Operations

The mission profile includes a total stay time escorting the asteroid of 7 months with an operation profile consisting of different phases: (1) Arrival, (2) Approach, (3) Orbiter Operations, (4) touch and Go campaigns and (5) Departure. During the arrival and approach phases, the systems are checked. Starting with the global and local mapping phases, the orbiter conducts its observation campaign to select its sampling site.

In order to retrieve the samples, a touch and go system is proposed. The spacecraft will perform a descent towards a pre-selected landing site. This poses challenging requirements for the GNC system binaries as highly irregular asteroid shapes can generate complex gravitational fields. Possible abort scenarios have to be accommodated. As a solution, an adaptive autonomous hazard detection and avoidance system with terrain absolute and relative navigation could be employed. Advanced techniques to deal with this include convex optimization guidance (Pinson and Lu, 2017). This would impose strict requirements on the on-board computer which can be accounted for in this preliminary design phase, but the enhancement of safety and accuracy would be significant. Alternatively, simple guidance systems can be used at this stage in order to obtain some initial estimates on the trajectory and propulsion requirements.

The spacecraft first turns the solar panels 25^o upwards, providing clearance from possible boulders or slopes. It then proceeds by performing a propulsive landing using its AOCS thrusters to decelerate from orbit. 8 meters before touchdown, the thrusters are turned off and a free-fall is performed in order to avoid ground contamination (Dworkin et al., 2017). Once the accelerometers detect a ground impact at approximately 6 cm/s, the upper thrusters are turned on in order to avoid a rebounce and attach the spacecraft to the ground, providing active damping in combination with the landing legs. The sample retrieval procedure is performed as explained in section3.9.2. Once the sample is retrieved, the lower thrusters are turned on and the spacecraft returns to orbit.

5.4 Re-entry and Earth Return Capsule

Figure 9 shows the nominal re-entry mission phases. The recovery phase starts around $T_0 - 10$ days prior to atmospheric entry. The spacecraft performs a correction maneuver targeting the Earth atmosphere. $T_0 - 36$ hours prior to entry, the spacecraft performs an additional correction to further enhance the entry accuracy. The spacecraft then spins up and deploys the Earth Return Capsule (ERC) $T_0 - 4$ hours after towards its final destination and continues its deflected hyperbolic trajectory surpassing the Earth. The capsule then enters the Earth atmosphere with an approximate re-entry speed of 12.15 km/s and a flight path angle of -15^o.

Shortly afterwards, the maximum heat flux is experienced followed by maximum deceleration. The proposed capsule then performs a direct impact on the ground without the use of any parachute. This impact preference is chosen as there has been numerous studies and testing performed in the past decade showing a high reliability compared to other parachute retrieval options and no considerable mass increase (Kellas, 2017; Yamada and Tanno, 2016; Carvalho et al., 2017) . This last aspect was tested by designing a capsule with a parachute system, showing a difference in the order of 0.2 kg. Therefore, although planetary con-

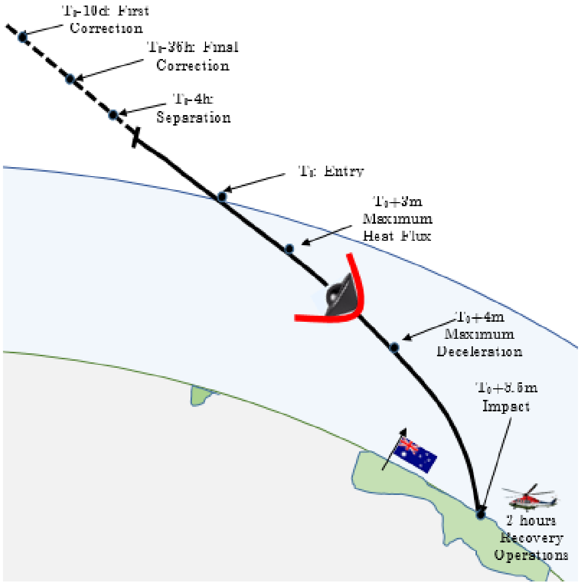

Fig. 9. Re-entry and Recovery Phase

tamination protocols are not as critical compared to Mars sample return missions, the reduced system complexity and low flight time, enabling quick retrieval and higher reliability makes this recovery option considerably more attractive. Carvalho et al. (2017) mentioned continuous work being performed to improve the TRL. A the time of this proposal, a TRL of 4 can be assumed. Table 4 shows feasible preliminary design results for the trajectory and impact. For landing sites, terrain landings in Australia, Ohio (USA), and Kazakhstan are considered.

Table 4. Re-entry Dynamics

a_{max} [g]	q_{max} [MW/m^2]	Q/A [MJ/m^2]	a_i [g]
84	10.5	127	419

The chosen capsule shape with a low center of gravity experiences adequate stability margins during re-entry, allowing for a lower spin rate of 2 rpm provided by the spacecraft prior to re-entry (Desai et al., 2000). This configuration was studied in previous Mars/Asteroid Sample Return missions such as the Marco Polo proposals (Barucci et al., 2012). Additionally, it can transport a maximum payload sample of 2.2 kg, enclosed in a container of approximately 4.8 kg. The TPS system uses PICA and a crushable cTPS system using a PMI Rohacell grade material (Carvalho et al., 2017). As primary structure, a CFRP layer is used. Some recovery equipment is included, in order to localize the ERC in a short time-frame of 2 hours enabling a quick access to the samples. This recovery time baseline was used in an analysis of a similar capsule performed by (Carvalho et al., 2017) showing temperatures lower than 20 degrees during re-entry and after impact in the payload container surface. The total mass and capsule geometry is given in Table 3.

6. DEVELOPMENT SCHEDULE

The development schedule is shown in Figure 10.

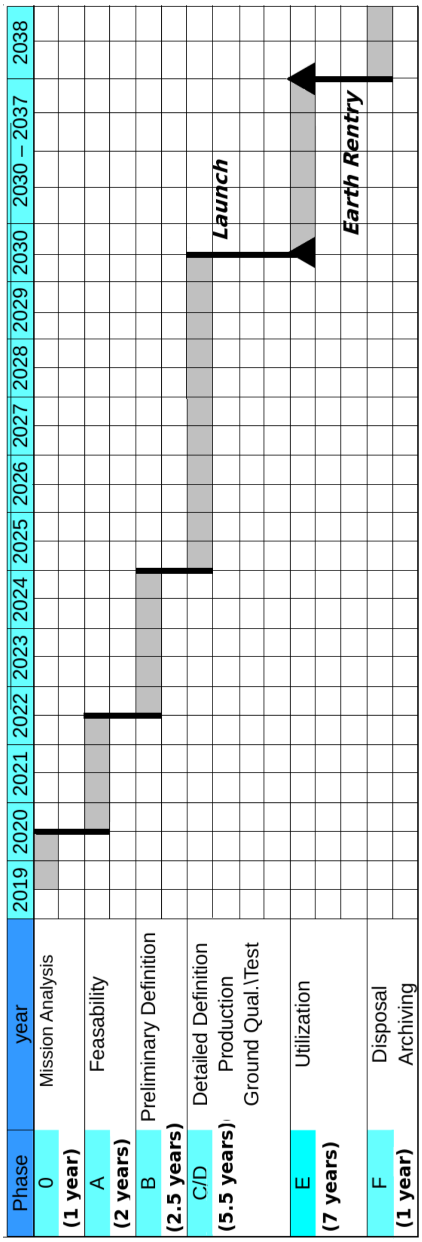

Fig. 10. The image above shows the schedule planned for the development of technology and launch of CARINA

6.1 Curation and contamination management

Our mission and samples do not qualify for restricted sample return based on guidance from the planetary protection policy (Kminek and Rummel, 2015). When the sample capsule has returned on Earth, qualified personnel will remove and catalogue the samples in secure facilities. These facilities need to be away from populated centers and in proximity to science centers. Our curation facility is the University of Oxford. Other option from the Euro-Cares centers are in Nancy and University of Pisa. The curation of the extraterrestrial samples must be in agreement to national requirement and with UN's requirement. Location site, personnel and samples must be under correct security regulations. The samples must be declared for biohazard. If there are detection of extraterrestrial organism, only sterilized samples can be distributed. If no biosignals, the samples can be allowed for controlled distribution. Lunar and asteroid samples needs to be kept in ultra clean containers and are non restricted. Contamination of the samples should be of the same temperature as the asteroid they are taken from (Pottage et al., 1917). For planetary protection there must be clear sample transfer methods for inside the facilities and for transportation between different facilities. For biohazard testing there must be a clear protocol and sample selection. For samples needed sterilization the integrity of the samples must be minimized, and there must be clear protocol for cleaning of the instruments (Aurore Hutzler, 2017).

6.2 Risk assessment

Table 5 shows the risk assessment of the space mission.

Table 5. S: schedule, C: cost, M: mission, P: performance. The likelihood $\mathcal{L}$ column scale goes form A - acceptable to E - not acceptable

angle = 90°

	Impact	Severity	$\mathcal{L}$
Launcher 62 n.a.	S/C	6	E
Bristle sampler mech. n.a.	S	6	D
Harpoon sampler mech. n.a.	S	6	C
Reentry capsule n.a.	S/M/P	2	C
Solar panel clearance	S/M/P	5	D
Sampling mechanism failure	M	6	C
Reentry capsule failure	M	6	D
HGA failure	M	6	E
Sampling ring failure	M	2	D
Sample recovery issues	M	6	E

6.3 Costs

To calculate the cost of the CARINA, some assumptions are made;The space craft consist of three parts, mechanical and thermal architecture, electrical instruments and scientific payload. The reentry capsule consist of the mechanical and thermal architecture. The rough order of magnitude costs are based on dry mass, degree of innovation/heritage and complexity. The operation cost of the mission profile is driven by duration, maneuvers, distance from the sun. All costs of curation facilities and laboratories are not included. Table 6 shows the cost of the mission Possible

Table 6. Cost

Object	Cost [M€]
Main S/C	375
Earth Return Canister	18
Operations	160
Launcher	75
Payload	280
Total cost	**908**

ways to reduce the cost are to have cooperative partners providing parts for the system of the space craft in exchange of samples. Other ways to reduce cost are focusing on the most important requirements, improve the mission analysis methods. By descoping the costs and complexity and keeping the mission goals intact, the contamination of the samples can be compromised after interaction with the sample container. This comes form vibration, gravity and temperature differences in the sample container. Also initial characterization of the samples can be reduced, meaning no information of the sample are known before the capsule is examine.

7. SUMMARY

This space mission aims for improving our understanding of the early solar system and the evolution of the planetesimals, look for possible relations between asteroids and comets and the origins of life. In order to do this the space mission is to visit the asteroid 2002 AT_4, where the space craft is designed to take samples from the surface and subsurface of the asteroid, for the return to Earth with the samples in a capsule sent to Earth. This gives the opportunity to investigate the stated mission goals in great detail from the sample return.

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