A multiple-rendezvous, sample-return mission to two near-Earth asteroids

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Abstract

We propose a dual-rendezvous mission, targeting near-Earth asteroids, including sample-return. The mission, Asteroid Sampling Mission (ASM), consists of two parts: (i) flyby and remote sensing of a Q-type asteroid, and (ii) sampling of a V-type asteroid. The targeted undifferentiated Q-type are found mainly in the near-Earth space, and to this date have not been the target of a space mission. We have chosen, for our sampling target, an asteroid from the basaltic class (V-type), as asteroids in this class exhibit spectral signatures that resemble those of the well-studied Howardite–Eucrite–Diogenite (HED) meteorite suite. With this mission, we expect to answer specific questions about the links between differentiated meteorites and asteroids, as well as gain further insight into the broader issues of early Solar System (SS) evolution and the formation of terrestrial planets. To achieve the mission, we designed a spacecraft with a dry mass of less than 3 tonnes that uses electric propulsion with a solar-electric power supply of 15 kW at 1 Astronomical Unit (AU). The mission includes a series of remote sensing instruments, envisages landing of the whole spacecraft on the sampling target, and employs an innovative sampling mechanism. Launch is foreseen to occur in 2018, as the designed timetable, and the mission would last about 10 years, bringing back a 150 g subsurface sample within a small re-entry capsule. This paper is a work presented at the 2008 Summer School Alpbach, “Sample return from the Moon, asteroids and comets” organized by the Aeronautics and Space Agency of the Austrian Research Promotion Agency. It is co-sponsored by ESA and the national space authorities of its Member and Co-operating States, with the support of the International Space Science Institute and Austrospace.

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1. Introduction

Sample-return missions to other bodies in the Solar System (SS) are of vital importance to access scientific data that are impossible to obtain remotely or with meteoritic samples. Many of the unresolved science questions related to asteroids stem from detailed knowledge obtained from high-precision and high-sensitivity measurements of meteorites. The anticipated scientific advances, with a new sample from an asteroid, will only be achievable with the level of analytical capability provided by laboratory instruments. The ability of in situ or remote-sensing instruments to emulate lab-based instruments in providing high-sensitivity, high-precision or high spatial-resolution measurements is compromised by constraints due to limitations of size, mass, power, data rate, and reliability imposed by the practical aspects of space missions. We propose a dual-rendezvous, sample-return mission, targeting near-Earth asteroids (NEAs). We present both the scientific motivation of the proposed sample-return mission and some key aspects of the mission design and associated trade-offs, including an innovative sampling mechanism.

The 2008 Summer School Alpbach, “Sample return from the Moon, asteroids and comets” brought together 60 students and 20 professors from all over Europe for 10 days. The Summer School program also addressed the important topics relevant to the technical implementation of sample-return missions. The most important engineering topics were covered during a series of lectures. The work presented here is the result of the “Green Team”, comprising 14 students and two advisors who designed a sample-return mission to targeted NEAs.

1.1. Scientific background

Our current model of early SS evolution begins 4.566 Gyr ago with the formation of refractory inclusions (Calcium Aluminium Inclusions) and chondrules from the dust and gas of the protoplanetary disk (Shukolyukov and Lugmair, 2002). This primitive material accreted to form planetesimals (asteroids), some of which differentiated and in some cases formed magma oceans (Greenwood et al., 2005), before runaway accretion occurred culminating in planetary formation.

A revised scenario for the formation of meteorite parent bodies has recently gained broad acceptance in the scientific community, based on many important results derived from precise isotopic dating (Kleine et al., 2004, 2005; Misawa et al., 2005; Wiechert et al., 2004; Trieloff et al., 2003). These works seem to indicate that the differentiated parent bodies formed before, or at least contemporaneously with, the chondrite parent body, although we still lack a complete understanding on the growth mechanisms and formation times of asteroids (Scott, 2006). Differentiated bodies were subject to sufficient internal heat to allow heavier material, like iron, to accumulate at the center of the body as a nucleus, with the rest of the material forming a silicate mantle and a basaltic crust. Terrestrial planets and the big asteroid (4) Vesta exhibit this internal structure (Ruzicka et al., 1997).

Although some planetesimals differentiated and formed metallic cores like the larger terrestrial planets, the parent bodies of undifferentiated chondritic meteorites experienced comparatively mild thermal metamorphism that was insufficient to separate metal from silicate (McCall et al., 1998, 1999). Today, there is still plenty of debate within the scientific community about the nature of the heat source, as well as the structure and cooling history of the parent bodies (Trieloff et al., 2003, and references there in).

To date, we have observed and characterized the surface of many asteroids and several dozens of meteorites. Some of these asteroids and smaller meteorites are fragments of those bodies (some of them differentiated, some others undifferentiated). Survivors from these disrupted and dispersed differentiated objects could produce several different asteroid taxonomic types: iron-rich asteroids from the core might be analogous to some M-type asteroids, olivine-rich metal-free silicate asteroids from the mantle might be analogous to A-type asteroids (de Leon et al., 2006), and basalt-rich asteroids from the crust might be analogous to V-type asteroids (Bottke et al., 2005; Duffard et al., 2006).

Initially, all the V-type asteroids and basaltic (Howardite–Eucrite–Diogenite; HED) meteorites were thought to come from a single body, the big main belt asteroid (4) Vesta (Lazzaro, 2009, and references there in). But currently, there are problems with the scenario of considering all the HED to have come from Vesta. The meteorite Northwest Africa 011, despite its texture and mineralogy being similar to some basaltic Eucrites, shows an $^{16}$O-rich isotopic composition, which suggests that this it is genetically unrelated to the other HED meteorites (Yamaguchi et al., 2002). More recently, Wiechert et al. (2004) have reported more evidence of oxygen isotopic heterogeneity among HED meteorites, indicating sources that have not been mixed completely. New high-precision oxygen isotope measurements of a large sample of HED meteorites provide evidence that although most of them derived from a common, well-mixed pool, there are some that are inconsistent with an unique origin. In total, the meteorite collection could represent several dozen parent bodies, considering also the abundance of iron meteorites, which should have been part of the nucleus of distinct differentiated bodies (Lazzaro, 2009; Canas et al., 2008; Duffard et al., 2004).

NEAs belong to a continuously replenished population of small bodies with orbits that come close to the Earth’s orbit. Their median dynamic lifetime is 10 Myr (Gladman et al., 2000). They have the advantage from a mission perspective of being much more accessible for scientific research and space missions than small bodies in other more distant populations (comets and main belt asteroids). Moreover, a NEA offers the particular advantage over the main belt asteroids of being directly related to a specifically...
known birth region, which from dynamical studies, places most between Mars and Jupiter (Bottke et al., 2002; de Leon et al., 2010).

Given that it is now commonly accepted that there were many differentiated objects in the former asteroid belt, and most of them were destroyed, this poses the following question: “do all HED meteorites originate from Vesta?”. Dynamical models suggest that the NEA population samples different parts of the belt (Bottke et al., 2002), so V-type NEAs could have originated from any of these differentiated objects, not necessarily only from Vesta (Duffard and Roig, 2009).

Ordinary Chondrite parent bodies, on the other hand, are less thermally altered, unlike differentiated objects. The most intriguing objects, which represent the highest priority for NEA missions, are those having the most primitive compositions with the most direct link to the chemistry and conditions of the early SS. Typically, such compositions are also found among NEAs.

The main reason to study these two asteroidal taxonomic types and take samples from them in our proposed mission, is that they were formed at the very beginning of the SS, maybe at the same time, but they underwent significantly different thermal processing. A timeline of the formation processes is given in Fig. 1. We can see in the figure that chondrite material and also the differentiation of the HED, Mesosiderite and Angrite parent bodies took place in the 7 first Myr. Mesosiderites and Angrites are differentiated meteorites. Also is shown the time of formation of two differentiated planets, Mars and Earth (Kleine et al., 2004).

1.2. Main objectives

Small SS bodies, as primitive leftover building blocks of the SS formation process, can offer clues to the chemical mixture from which the planets formed 4.6 billion years ago. They contain records of early events in the history of planetary formation, which have been erased from the terrestrial rock record by plate tectonics. Asteroids represent a significant population of these primordial objects that reside throughout the SS. Exploration of asteroids can therefore greatly enhance our understanding of the planetary formation process and constrain current relevant theories. The asteroid population is highly diverse with regards to orbital, physical, chemical and mineralogical properties. This degree of diversity is thought to be the result of both the original accretion location of the bodies in the primordial nebula and their subsequent evolutionary history.

In the last decade, asteroids have become primary targets for space missions geared towards improving our understanding of SS formation. The Galileo mission, in 1991 (Russell, 1992), was the first to perform an asteroid flyby. On its way to Jupiter, it performed a flyby of the asteroids Gaspra and Ida, including its moon Dactyl. The NEAR-Shoemaker mission (Veverka et al., 2001) made a flyby of the asteroid Mathilde, and performed a rendezvous mission to Eros. Deep Space 1 (Nordholt et al., 2003) made a double fly-by of the asteroid Braille and comet Borelli. The Stardust mission (Brownlee et al., 2003) returned a sample of Comet Wild 2’s coma material, and completed a flyby of asteroid Anne-Frank. In 2003, the Japanese Space Agency’s (JAXA) Hayabusa mission was the first to focus on an asteroid with an aim to return a sample (Fujiwara et al., 2004). With only a basic scientific payload onboard Hayabusa, data gathered on the S-type asteroid Itokawa have nevertheless yielded unexpected results. Whilst waiting for the publication on the results of the sample-return in 2010, JAXA conducted mission planning for a new mission known as Hayabusa II, aimed at sampling another primitive asteroid; a C-type asteroid. In 2011, the
Dawn mission (Russell et al., 2007) will commence a remote-sensing mission to asteroid Vesta and then in 2015 to dwarf planet Ceres. Despite these endeavors to study asteroids, there remain many taxonomic types that have never been studied.

On the other hand, there are several proposed missions to study asteroids or comets. Barucci et al. (2009) proposed the Marco Polo mission with sample-return from a NEA. Previous to that proposal, there was the Hera NEA sample-return mission, twice proposed to NASA and not selected (Sears et al., 2004, 2008). The Triple F (Fresh from the Fridge) mission is a comet-nucleus, sample-return mission, which has been proposed to ESA’s Cosmic Vision program (Kuppers et al., 2009).

Meanwhile, several other (proposed) missions are aimed at characterizing certain taxonomic asteroid classes. We are proposing a complete study of two different classes that would provide us valuable insights into condition at the very beginning of the SS.

1.3. Science goals

Physical and chemical characterization of multiple small bodies is important in this context for threat evaluation, mitigation and potentially for identification of resources in the longer term. For all these reasons, the exploration of NEAs is particularly interesting, urgent and compelling. The main aim of NEA research is to set strong constraints on the link between asteroids and meteorites, to achieve further insight into the processes of planetary accretion; and to achieve a better understanding of the origin of life on Earth and its distribution in the SS. In the short term, after flyby and landing missions on NEAs, the next goal should be sample-return, enabling a detailed investigation of primitive and organic matter from one or several selected small bodies.

There are a number of important questions with regards to the formation of the terrestrial planets that can be addressed by sample-return missions to NEAs:

- What are the initial conditions and evolutionary history of the solar nebula?
- What was the nature of differentiation in the early SS?
- What are the timescales of accretion and differentiation in planetesimals?
- How important are processes such as agglomeration, heating, aqueous alteration, etc., in the history of planetesimals?
- What heat source was responsible for planetesimal melting?
- What are the building blocks of terrestrial planets, in particular the Earth?
- What are the elemental and mineralogical properties of NEA samples and how do they vary with geological context on the surface?
- Do primitive classes of NEAs contain pre-SS material that is absent in meteoritic samples?
- How did NEA and meteorite classes form and acquire their present properties?
- What are the nature and origin of organic compounds on asteroids?
- Can asteroids help shed light on the origin of organic molecules necessary for life?
- What is the role of asteroid impact in the origin and evolution of life on Earth?

2. Mission statements

The main goal of the proposed mission is to visit a body of basaltic V-type asteroidal class and establish genetic links with one of the suites of differentiated meteorites. Differentiation of planetesimals is a key stage in formation models of the early SS and there is, as yet, no planned sample-return mission to a differentiated asteroid. We have targeted the V-type class, as asteroids belonging to this class show a basaltic spectral signature resembling that seen in the well-studied HED meteorite clan.

The primary objective is to return a subsurface sample from a V-type NEA after characterizing the body from orbit. The oxygen isotope signatures of differentiated meteorites (Scott et al., 2008) show that there could have been at least six parent bodies for the differentiated meteorite groups. A returned sample would allow us to confirm a genetic relation between our target V-type asteroid and HED meteorites using oxygen isotopes and other geochemical markers that can only be analyzed by Earth-based laboratory techniques.

Another reason for going to a basaltic asteroid is because Dawn will rendezvous with Vesta in 2011, the potential parent body of most of the V-type bodies. Hence, sampling from a V-type is a way to potentially analyze a fragment of a parent body that will be well characterized by a current space mission. Further, we propose an additional rendezvous with a fragment of a Q-type body. This spectral type is associated with the primitive, undifferentiated ordinary chondrite (OC) meteorites (Trierloff et al., 2003). There is little spectral information on Q-type NEAs and no evidence of their existence in the main belt. However, all four S-complex asteroids for which measurements have been obtained by previous space missions (Gaspra, Ida, Dactyl and Eros) have surfaces that are more OC-like in recently excavated terrain. This leads to the question as to whether Q-type asteroids are derived from recent impacts on S-type bodies.

A secondary aim of the mission is to gather information on the physical parameters of the two selected NEA asteroids and provide constraints on their threat to Earth. The specific questions to be answered by this mission are:

- How are the V-type NEAs genetically linked to the, at least, six different differentiated meteorite suites?
- What is the formation history of the basaltic NEAs?
- When were the V-type objects ejected from their parent body and was it related to the Late Heavy Bombardment?
2.1. Why sample-return?

The most significant problem when studying meteorites is that we lack geological context for the sample, which limits the extent of our interpretation of laboratory analyses. Also, as a meteorite passes through the Earth’s atmosphere, its mineralogical, chemical and isotopic signatures can be modified. Some of the previously stated scientific objectives require chemical composition and mineralogical information, as well as physical property measurements (gravity, density, mass) that can be acquired in situ. However, several of the main goals require information on the age of the target, accompanied by detailed petrology, trace element and isotopic information. There are a number of requirements of these kinds of analysis, such as sample preparation techniques, large instrument geometries and high-energy sources that mean that miniaturization of these instruments for a spacecraft is simply not feasible. Some of the key analysis and instruments that would be required are the use of a optical and electron microscopy for imaging with millimeter to nanometer resolution. An ion microprobe or/and a X-ray source techniques can be used to obtain information on the mineralogy, chemistry and atomic structure of the sampled material. The thermal and plasma ionization mass spectrometry will be used for radiometric dating and finally, a laser-fluorination and double-focussing mass spectrometry should be used to obtain information on the oxygen isotopes and other isotope systems (<0.1‰). All this instruments are too complex to be carried on the spacecraft compared with the information that the imaging cameras, the visible and near infrared spectrograph or/and the X-ray spectrometer can obtain on the asteroid.

Some of these techniques require at most a few grams and others only nanograms of material from the target asteroids (Barucci et al., 2009).

2.2. Mission target selection

A detailed search for the selection of the targets was done. From the NEOs spectroscopic surveys database, all the Q and V-type objects were identified. Objects with known rotational period and shape were selected with higher priority. After that, the ΔV’ necessary to rendezvous with the asteroids and return to Earth was determined and several targets were selected. We need to mention here that our selection for this work was fixed to the known and characterized NEOs at the moment of the selection. In the future, more objects will be discovered and spectroscopically classified so another scientific selection of the final targets should take place. The first targeted asteroid (152560) 1991 BN \( (a = 1.444; \ e = 0.398; \ i = 3.447^\circ) \), which we would only study from orbit, is a small (400–900 m) Q-type NEA. The second asteroid (5604) 1992 FE \( (a = 0.927 \text{ AU}; \ e = 0.405; \ i = 4.797^\circ) \), which would be sampled, is a V-type basaltic NEA. This NEA is 500 m in diameter, has a rotation period of 6.026 h and light-curve amplitude of 0.1 mag. Surface temperatures in the sub-solar point of the object are 270 K in the aphelion and 400 K in the perihelion. We chose a V-type NEA with a relatively small diameter, rather than targeting an object that is large enough to be the parent differentiated body of differentiated meteorites. From the knowledge gained through previous missions, we can expect the structure of the NEA to be either a solid body or a rubble pile with parts comprised of solid rock. In either case it is likely that the surface would be covered by some regolith material.

The scientific competitiveness of our mission is characterized by being the first sampling mission to a differentiated asteroid. In addition, we would rendezvous with two classes of NEAs (Q-type and V-type) that have not been previous visited by space missions. The Hayabusa and Marco Polo sampling missions are targeting primitive asteroids, while Dawn will only be studying Vesta and Ceres from orbit. Therefore, our mission complements the existing and proposed missions to asteroids.

2.3. Science drivers

The main purpose of the mission is to return a sample from the surface of an asteroid. There is a vast list of analytical tools for the characterization of returned materials encompassing many techniques spanning the principal approaches of microscopy and spectroscopy/spectrometry, some of them mentioned in Section 2.1. A sample returned from the surface of an asteroid is expected to be a mixed regolith, containing components from different parts of the body, each having experienced a unique geological history on the asteroid. The sample should be 150 g, be obtained from a depth of at least 3 cm, and preserve stratigraphy and grain-size distribution. The limitations on the maximum depth of the sample is given by the sampler mechanism itself. As mentioned before, the minimum mass requirement for the sample stems from the minimum mass needed for analysis by various Earth-based laboratories. During rendezvous with the first asteroid and the initial orbiting phase of the second asteroid, we plan to conduct the following experiments remotely:

- Imaging of surface features/topography to 1 m resolution.
- Macro scale mineralogy and composition (to 20 m resolution).
- Size, shape, mass, density, gravity of asteroidal bodies.

At the sample site we intend to conduct the following experiments:

- Imaging of the sampling site (field-of-view 1 mrad).
- Chemical composition and mineralogy (field-of-view <1 mrad).
Based on the COSPAR Planetary Protection Policy categorization scheme, our sample-return mission is classified as Category V. With (5604) 1992 FE as the landing target, it fulfills the criteria for an unrestricted Earth-return, as it is a differentiated body. For the flight from Earth to the asteroids the mission is classified as Category II. As for the degrees of concern, we specify that the impact probability is 1 and also that the contamination control measures would be recorded. In terms of documentation, pre-launch-, post-launch-, post-encounter-, and end-of-mission reports would be written.

3. Mission and spacecraft design

Our spacecraft would be launched as secondary payload on an Ariane V ECA into geostationary transfer orbit (GTO). From there it would perform a low-thrust Earth escape. To avoid similar problems to those suffered by SMART-1 (Foing et al., 2001) during its flight within the van Allen belts, our mission’s onboard avionics should be radiation protected. To avoid flight within the inner van Allen belt, the spacecraft orbit pericenter would be raised to 6000 km, using the chemical attitude control thrusters. After that, the spacecraft would only have to withstand lower radiation doses of the outer van Allen belt during low-thrust Earth escape.

After escaping the Earth’s sphere of influence, the low-thrust transfer to 1991 BN would be performed using two pairs of solar panels with an electrical power of 14 and 10 kW. As rendezvous criteria, we assume a maximal distance of 5000 km and a relative velocity of 50 m/s. The remaining relative velocity would be compensated by an attitude control thruster burn during target approach. After investigating 1991 BN for about 275 days, the spacecraft would perform another low-thrust transfer to 1992 FE. Due to the smaller distance to the Sun, the 10 kW solar array would no longer be required and would therefore be jettisoned. When remote-sensing and sampling operations are completed at 1992 FE after 113 days, the spacecraft would return to Earth using its electrical engines. At the end of the primary mission, the return capsule would be detached during Earth approach. In principle, the spacecraft could use an Earth gravity assist for a mission extension to a third target. This mission scenario is illustrated schematically in Fig. 2. Table 1 summarizes the preliminary \( \Delta V \) budget assessed for our mission, detailing the different legs of the mission.

To establish the final science orbit at the two asteroids, extensive analysis is required. With regards to rendezvous and remote-sensing, the following sequence of events is planned:

1. Optical identification of the target asteroid (≈100 km).
2. ‘Formation’ flight with asteroid on edge of Hill’s region in the neighborhood of the \( L_1 \) Lagrange point.
3. Initial acquisition of the geometry of the asteroid provides input for first-order analysis of its gravity field.

![Fig. 2. Mission scenario.](image-url)
The required power consumption of a spacecraft for this type of mission must be assessed in detail. Table 2 summarizes the peak power budget for our mission. Most of the power units would not be used all the time, hence the power generation system can be scaled appropriately to cater to the actual operating power requirements of the spacecraft.

The power would be provided by 50 m$^2$ of third generation, bare-cells solar arrays, divided in two 2.4 × 6.8 m wings. This technology, developed by the European Space Agency (ESA) program for the Mars exploration missions, has 28% efficiency and is effective out to 2.5 AU. The mass of the latest generation panels amounts to 100 kg. For use of the instruments during the asteroid sampling phase (up to 4 h) 52 kg of Li-ion batteries would be used. They can provide peak power of 2150 W for 4 h. These lithium batteries have already been selected for the Galileo, Optus D3 and Alphabus missions. Their minimum specific energy is 175 W h/kg and they exhibit acceptable degradation levels, although a decrease in power output of 20% is expected in 18 years, which is less than the duration of our proposed mission.

### 3.2. The spacecraft

The basic mission concept for ASM is as follows: a single spacecraft would be sent to the target asteroids, rendezvous with the first target, orbit the second target, acquire a sample, and finally return to Earth. Apart from the sampling device, a basic payload is required to fulfill the following objectives: (i) characterization of the surfaces of the target asteroids, primarily their topography, with sufficient spatial resolution to identify appropriate sampling sites on the second target and (ii) mapping of the target sampling location to derive important physical properties to establish the context of the sample. An overview of the payload is given in Table 3. The total mass of this payload is less than 20 kg.

The high-resolution camera provides global monitoring of the target asteroid during the approach phase and when the spacecraft is further than several tens of kilometers away. The frame camera would consist of a moderate angular resolution framing imager. This instrument would be responsible for global mapping for distances between 5 and 20 km, corresponding to a resolution range of 0.5–2 m. The two wide-angle cameras would be active during the descent and ascent phases, working in tandem with the laser altimeter. Finally, the close-up camera is located in the sample mechanism to obtain a detailed image of the sampling site.

The main scientific drivers of the infrared spectrometer are: (i) to support the selection of the sampling sites by searching for surface rocks and (ii) to determine the nature of the surface composition in the visible and near-infrared range (0.5–2.5 μm).

The X-ray spectrometer would produce the first global view of the two asteroidal surfaces, with X-ray fluorescence (XRF) giving elemental abundances of Mg, Al and Si (and Fe plus others such as Ca, Ti, if solar activity permits) across both bodies. The complete design of the spacecraft with the scientific payload can be seen in Fig. 3.

#### 3.2.1. Thermal control system

This mission poses two problems that the thermal control system (TCS) has to handle:

- An electrical propulsion system with an estimated efficiency of 70% is used for long periods during the transfer phases. A 13 m$^2$ radiation area is required to compensate for the 4.2 kW heat generated by the propulsion system, due to the power system rated at 14 kW.
- The heat input from internal and external heat sources varies greatly over the mission duration. When the spacecraft is at a distance of 0.5 AU from the Sun, the electrical propulsion system is also in use. This results in a high amount of heat input to the spacecraft (hot case). In contrast, there is a longer period at a distance
of 2 AU when the electrical propulsion system is not used. This results in a low heat input to the spacecraft (cold case).

The TCS mainly uses passive components: the structure of the spacecraft, variable heat-pipes with diode function, louvers, radiators and Multi-Layer Insulation (MLI). The total calculated radiator area needed is 15.5 m². Heaters capable of delivering a total of 1560 W (incl. 20% margin) are installed to regulate the temperature for critical instruments that have a small operational temperature range. These heaters and the temperature sensors employed constitute the active part of the TCS.

There are a number of special measures that have been developed to cope with the mission challenges. At a distance greater than 0.7 AU, the area of solar panels would be orthogonal to the solar flux. From 0.7 AU to the minimum distance of 0.5 AU the solar panels would be rotated such that the effective area is generating the same energy and temperature as at 0.7 AU. The maximum temperature for solar panels would be $170 \pm 10$ °C. The largest angle between the rectangular position and the rotated position

<table>
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<th>Weight (kg)</th>
<th>Power 133.1 (W)</th>
<th>TRL</th>
<th>Data rate (Mb/s)</th>
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<td>1560</td>
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<tr>
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<td>7</td>
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<tr>
<td>Dry weight with margin (20%)</td>
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<td></td>
<td></td>
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<tr>
<td>Propellant</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Total</td>
<td>3755</td>
<td></td>
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Fig. 3. Design of the spacecraft configuration with main sub-systems. Scale is shown at the left.
would be 60°. The electrical propulsion system would be fixed directly to a radiator so the generated heat would not be routed through the spacecraft. To reduce heat input by radiation on the radiators, louvers would be used to change the $\alpha/e$-ratio and the radiators would be connected to variable diode heat-pipes.

3.2.2. Power, telecommunications and data handling

The propulsion systems onboard the mission are ion, bi-propellant and cold-gas thrust systems capable of providing $\Delta V$ for maneuvering and attitude control. The system is capable of delivering pure torques and pure forces for maneuvering around an asteroid with a weak gravitational field. The cold-gas thrust system uses nitrogen as an inert gas and would be employed during landing and lift-off from the target asteroid, so as to minimize contamination of the sample field.

Attitude determination uses star trackers, a fine ADCOLE miniature spinning sun sensor, and a Inertial Measurement Unit (IMU) containing a Ring Laser Gyro (RLG). Some star trackers enables high-accuracy inertial reference acquisition. We assessed that reaction wheels are sufficient for normal attitude control (Carpenter and Mason, 2007). Before the final approach, we would release optical target markers. The final approach would have combined information from an onboard advanced Microwave Sounding (MS) unit and a Light Detection And Ranging (LIDAR) system.

The major challenges for the GNC system are the operations in the proximity of the asteroid, including landing on the surface of 1992 FE. However, years before the launch of the ASM mission, extended experience of operating in near-asteroid environments will have been accumulated by Hayabusa, Hayabusa II and possibly Marco Polo. The spacecraft would be equipped with a redundant, coherent transponder system, enabling telemetry and tele-command communications and radio science (Doppler) experiments for navigation and orbit determination purposes. The proposed antenna concept is based on two requirements: (i) guaranteed command reception during all mission phases and (ii) energy saving while maintaining a high downlink rate.

These two requirements led to the choice of two omnidirectional Low Gain Antennae (LGA), to ensure permanent telecommand access, and a High Gain Antenna (HGA) to provide high downlink data rates. The HGA is mounted on a two-axis Antenna Pointing Mechanism (APM). The two LGAs are located on opposed sides on the spacecraft to provide full coverage of the celestial sphere. In standard operation, the communication link is based on the HGA using X-band for uplink and telemetry downlink, and Ka-band for scientific downlink. The downlink would be capable of transmitting at a maximum data rate of 50 kbit/s. For the radio science (Doppler) experiment, the HGA data transmission is switched off and the uplink is immediately re-transmitted coherently with reduced power to the Earth over X- and Ka-band. In emergency situations, the two LGAs ensure a telecommand uplink for risk reduction reasons. As the data rates are too high for online-transmission during descent, sampling and ascent, and because of no HGA communication due to trajectory reasons, all non-high-priority telemetry data are temporarily stored and transmitted later.

We would use two cross-strapped computers with solid state recorders. The communication with the sensors and other devices would be via SpaceWire. There are two 35-m deep-space antennae at New Norcia, Australia and Cebreros, Spain in ESA’s tracking network ESTRACK. Since the launch is planned after 2015, the third ESA deep-mission antenna will be ready to work in Malargüe, Argentina, mutually separated from the existing pair by 128°. These three deep-space antennas are proposed to be used as receivers for the ground segment.

3.3. Return capsule

The return capsule follows a ballistic re-entry trajectory with an entry velocity of 12.3 km/s and an entry angle of 11° at the Earth. During the hot re-entry, the 50 kg capsule is protected by an ablative heat shield that is subject to a stagnation point peak heat load of 11.4 MW/m² and an overall heat load of 254 MJ/m². The maximum deceleration has been estimated to be about 47.3 g. During final

Fig. 4. Sampling sequence by PSS: (a) terrain approaching, (b) sample capture and (c) sample extraction.

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2 http://www.esa.int/esaTQM/1176186230669_electrical_0.html.
descent, a 10-m diameter parachute is deployed to ensure a landing with a velocity of 4.6 m/s on the Earth.

3.4. Sampling system

In this section, a Piezoelectric Sampling System (PSS) for the collection of the material from asteroid’s surface, mainly based on ultrasonic technology for the mechanical actuation and with a new coring geometry, is described. The principle of operation behind ultrasonic actuators is resonance vibrations (at very high frequency) induced by piezoelectric ceramic on a rigid stator structure, so that the naturally amplified displacements can be used to perform the desired task. The ultrasonic devices were recently used by the Jet Propulsion Laboratory to design a new generation of drills and corers. Prototypes were developed and patented at the beginning of 2000, and considered the future for sampling in planetary exploration missions (Bar-Cohen et al., 2001). The tested devices were demonstrated to: (i) pierce ice and various rocks including granite, diorite, basalt and limestone, (ii) operate at low and high temperatures, (iii) operate at low average power using duty cycling and (iv) be lightweight and finally (v) not require intensive preloaded forces.

The eroding action of the Piezoelectric Sampling System, with relative low penetration and force but at very high frequency, is guaranteed by the continuous impacts of an ultrasonic hammer on a coring penetrating Pyramidal Sampling Tool PST (Fig. 4). The forcing action over the PST blades should be imposed by an impacting mass, that is excited in high frequency resonance condition by piezoelectric elements. The vibrating system could be positioned along the blade sliding axis (Fig. 5a), or with a radial configuration of cantilever elements with natural bending modes (Fig. 5b); their intermittent impacts on blades, reproducing the typical action of the manual hammer–chisel system, make the percussive assembly suitable also for coherent hard soils sampling. The PSS allows collection
different kind of materials, preserving stratigraphy, even analysis to penetration in material with different compressive strength are necessary. Although the PSS was theoretically demonstrated to be suitable in low coherent Mars and Moon soils sampling (Pirrotta, 2010), the basic high-frequency hammering action makes the PST blades potentially able to erode or fracture hard rocks of planetary bodies. The penetrating head can be also conceived to be actuated by non-piezoelectric linear devices (Fig. 5c) or one-shot blasting charges (Fig. 5d).

A serial robotic arm is then designed to handle the penetrating head from the asteroids surface to the housing in the re-entry capsule (Fig. 6). Depending on allowable volume, a different design with two sample containers could be adopted; the robotic arm could leave the full container into the capsule and then replace it on its free tip with other empty one. Two harpoons would be used for anchoring the S/C on the asteroid. The special shape of the harpoon allows the anchoring on different types of material. The harpoons are connected via a cable which would be

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**Fig. 7.** Risk map of the mission.

**Fig. 8.** The timeline envisioned for the mission.
tensioned by a rewind system within seconds after the firing. The extreme environmental conditions present on the asteroid (5604) 1992 FE require no special precautions for sample containment from a scientific point of view; we do not expect a volatile component, that has to be preserved. The container does not have to be hermetic and pressure-tight. No temperature control above the asteroid’s temperature range and no radiation protection is required. Items to consider are: there should be no contamination with terrestrial material and no temperatures higher than 325 K.

4. Management aspects

Fig. 7 illustrates a risk map for the mission. From this figure it is clear that the ultrasonic hammer and sampling head technologies pose the greatest risk to the overall mission. Hence, care must be taken during the subsequent development phases to dedicate sufficient resources to mitigate these risks.

The concept study can be commissioned in 2009 and a Mission Design and Definition one year later. After nearly a 10-year period of manufacturing and integration, the spacecraft would be ready for launch in 2018. After another 10 years of operations, the sample-return is planned in 2028 with a possible extension of visiting a third asteroid.

The timeline of the mission is provided in Fig. 8. The total mission cost is estimated at approximately 1556 million Euros, which includes a contingency of 20% on the total nominal mission cost. The cost estimate is based on first-order estimates for L-class missions conducted by ESA. Table 3 provides a summary of the key systems engineering budgets for the mission.

5. Conclusion

The present analysis shows that a scientifically interesting, highly demanding, dual-rendezvous mission to NEAs, including sample-return, is feasible and can be undertaken within the next 10–20 years. The mission would last less than 10 years, have a cost cap of approximately 1500 million euros and employ technologies that are available or can be developed within the considered time-frame. It is therefore recommended to plan and undertake the next step for understanding SS history and evolution of the Earth by realizing this mission.

Finally, the selection of the target asteroids is not fixed. We outline two taxonomic classes of asteroids worth investigating, however the specific targets can be changed. In recent years, photometric surveys have led to the discovery of new, smaller objects, with accompanying spectroscopic surveys leading to their classification. Ours should therefore be considered as a reference concept, which aims to assess the technological complexity and challenges for NEA sample-return missions, but can also be tailored to fulfill an alternative set of scientific objectives.

The mission concept presented here represented a promising basis for a challenging yet affordable mission with high science return. The scientific potential, technology readiness levels, cost and programmatic suitability of the mission merit further investigation.

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