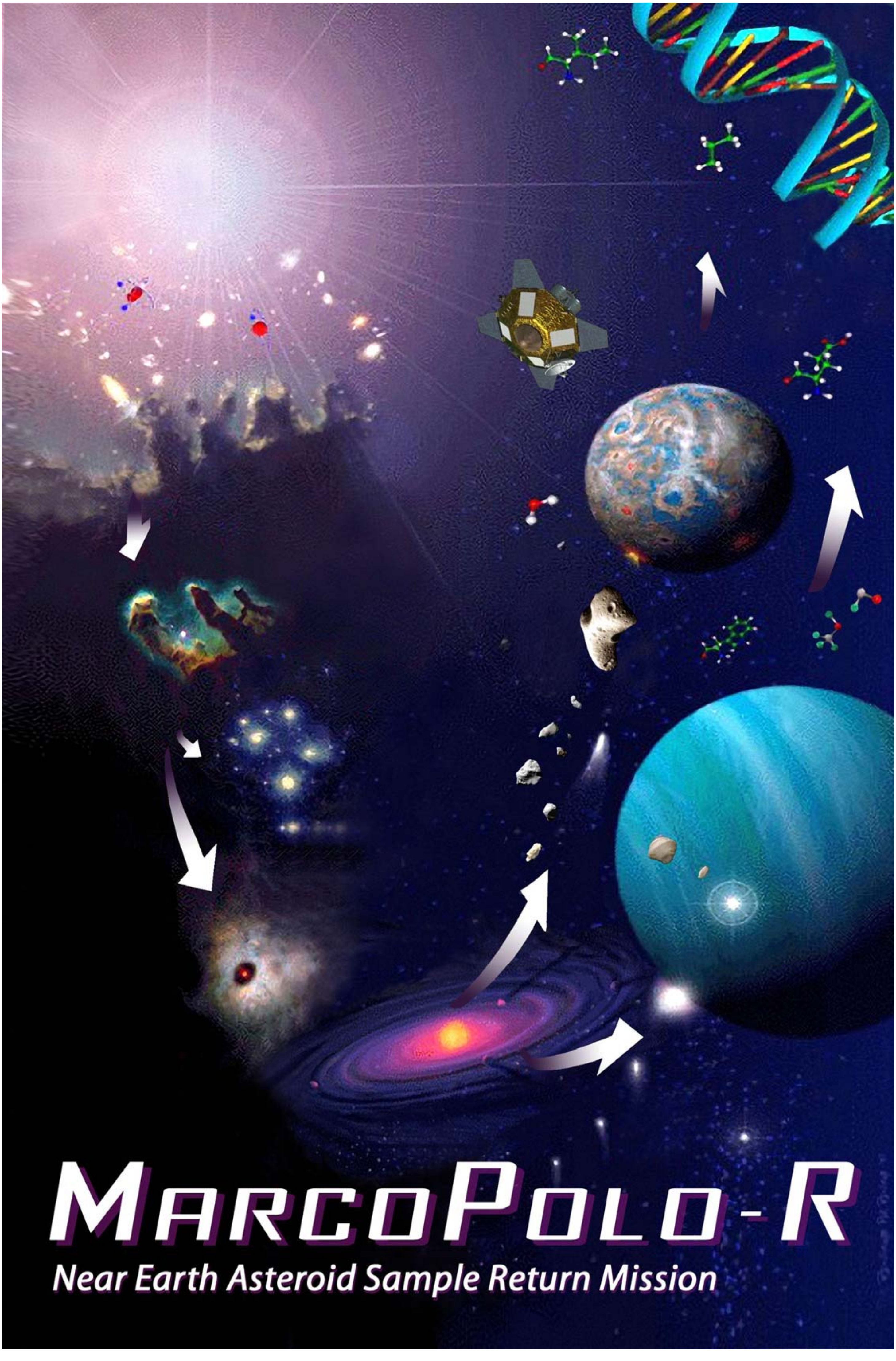
MarcoPolo-R
Near Earth Asteroid Sample Return Mission

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We are grateful to all European supporters of MarcoPolo-R (527 on Dec. 1st, 2010). The list is continuously updated on the following web site: http://www.oca.eu/MarcoPolo-R/ (click on Community).

The mission design takes advantages of the ESA assessment study phase of the former Marco Polo project in 2008-2009 including the related three industrial studies. For this proposal, we acknowledge the contribution of the following European industrial teams: Astrium Ltd, OHB, GMV, Thales Alenia Space.
We are also grateful to our US partners for their contributions.

The front page shows an artistic view of the 15-billion-year-long chain of events from the birth of the universe at the Big Bang through the formation of chemical elements, galaxies, stars, planets, asteroids and comets, the mixing of chemicals and energy that cradles life on Earth, to the earliest self-replicating organisms — and the profusion of life (inspired from NASA/JPL-Caltech image). ***The MarcoPolo-R spacecraft is shown travelling through time to investigate the birth of our planetary system.***

Content

EXECUTIVE SUMMARY

MarcoPolo-R is a sample return mission to a primitive Near-Earth Asteroid (NEA). It will rendezvous with a primitive NEA, scientifically characterize it at multiple scales, and return a unique sample to Earth unaltered by the atmospheric entry process or terrestrial weathering.

This proposal is based on the previous Marco Polo mission study (ESA/SRE (2009)3), which was selected for the Assessment Phase of the first round of Cosmic Vision. Its scientific rationale was highly ranked by ESA committees and it was not selected only because the estimated cost was higher than the allotted amount for an M class mission. The cost of MarcoPolo-R will be reduced to within the ESA medium mission budget by collaboration with APL (John Hopkins University) and JPL in the NASA program for coordination with ESA's Cosmic Vision Call for Proposal (Appendix 1).

Small bodies, as primitive leftover building blocks of the solar system formation process, offer clues to the chemical mixture from which the planets formed some 4.6 billion years ago. In addition, they retain material that predates the solar system and contains evidence for interstellar processes and its original formation in late-type stars. Current exobiological scenarios for the origin of life on Earth invoke an exogenous delivery of organic matter: primitive bodies could have brought these complex organic molecules capable of triggering the pre-biotic synthesis of biochemical compounds on the early Earth. Moreover, collisions of NEAs with the Earth pose a finite hazard to life. For all these reasons, the exploration of such objects is particularly interesting and urgent.

The main goal of the MarcoPolo-R mission is to return unaltered NEA material for detailed analysis in ground-based laboratories. The limited sampling provided by meteorites does not offer the most primitive material available in near-Earth space. More primitive material, having experienced less alteration on the asteroid, will be more friable and would not survive atmospheric entry in any discernible amount. Moreover, the small sample successfully returned by the JAXA mission Hayabusa is confirmed as coming from a highly processed S-type asteroid.

MarcoPolo-R will allow us to study the most primitive materials available to investigate early solar system formation processes. Moreover, MarcoPolo-R will provide a sample from a known target with known geological context. Direct investigation of both the regolith and fresh interior fragments is also impossible by any means other than sample return.

MarcoPolo-R will provide scientific results that are crucial to answer the following key questions:

1. What were the processes occurring in the early solar system and accompanying planet formation?
2. What are the physical properties and evolution of the building blocks of terrestrial planets?
3. Do NEAs of primitive classes contain pre-solar material yet unknown in meteoritic samples?
4. What are the nature and the origin of the organics in primitive asteroids and how can they shed light on the origin of molecules necessary for life?

Answers to these fundamental questions require measurements with exceptionally high precision and sensitivity. Such measurements cannot be performed by a robotic spacecraft and therefore require a sample returned to terrestrial laboratories, which are unconstrained by mass, power, stability etc. The most demanding measurements are those required to date the major events in the history of a sample, and to investigate the organic components.

Laboratory techniques determine the time interval between the end of nucleosynthesis and agglomeration, the duration of agglomeration, time of accumulation, crystallization age, the age of major heating and degassing events, the time of metamorphism, the time of aqueous alteration, and the duration of exposure to cosmic radiation.

MarcoPolo-R will answer the fundamental scientific questions listed above and outlined in Figure 1.

NEAs are among the most accessible bodies of the solar system. For several tens of NEAs, the Δv required to transfer and insert a spacecraft in orbit around them is lower than that required for the Moon. The binary asteroid (175706) 1996 FG3, baseline target of MarcoPolo-R, offers a very efficient operational and technical mission profile. A binary target (15% of the NEA population are binaries) also provides enhanced science return. The choice of this target will allow new investigations to be performed more easily than at a single object, and also enables investigations of the fascinating geology and geophysics of asteroids that are impossible at a single object. Several launch windows have been identified in the time-span 2020-2024. A number of other possible primitive single targets of high scientific interest have been identified covering a wide range of possible launch windows consistent with Cosmic Vision 2, e.g. 1999 JU3, 1999 RQ36.

MarcoPolo-R takes advantage of three industrial studies completed as part of the previous Marco Polo mission (see ESA/SRE (2009)3).

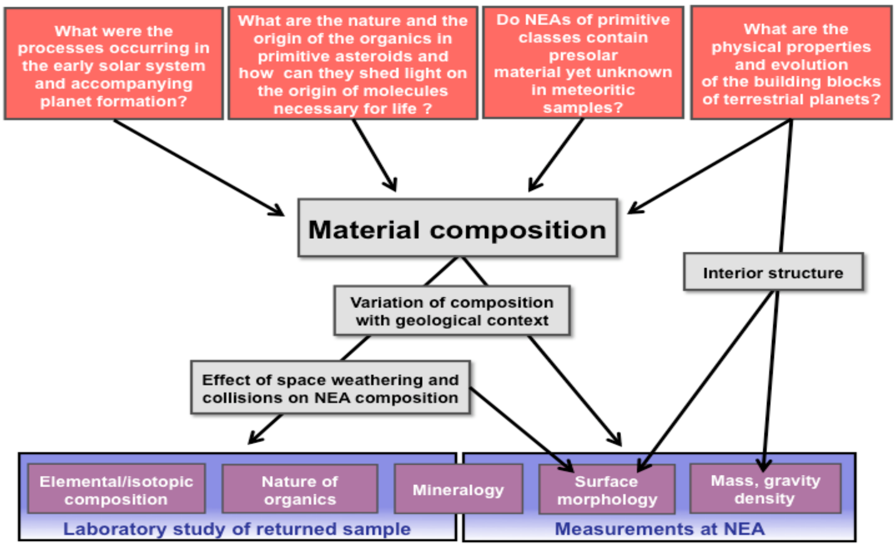

Figure 1. *Logical flow to answer to the fundamental question*

The baseline mission scenario of MarcoPolo-R to 1996 FG3 is as follows: a single primary spacecraft provided by ESA, carrying the Earth Re-entry Capsule (ERC), sample acquisition and transfer system provided by NASA, will be launched by a Soyuz-Fregat rocket from Kourou into GTO and using two space segment stages. Two similar missions with two launch windows, in 2021 and 2022 and for both sample return in 2029, have been defined. Earlier or later launches, in 2020 or 2024, also offer good opportunities. All manoeuvres are carried out by a chemical propulsion system.

Once at the NEA, a number of potential sampling sites (up to 5) are characterized by remote sensing measurements. The spacecraft will then attempt to sample surface material (up to ~2 kg) on the most suitable site (*i.e.* the location yielding the best compromise between science return and risk-mitigation). The sample mechanism will consist of brush wheel samplers and rock chippers designed and tested to collect the required sample in less than one second. If the sample collection is not confirmed, up to two additional samplings can be attempted.

The spacecraft will then continue performing orbital science, or will wait in a safe position until it departs from the asteroid and returns to Earth. The ERC is then released and undertakes a high-speed Earth re-entry at $v_{entry} \sim 12\text{-}15$ $km\,s^{-1}$ depending on the adopted mission scenario.

The scientific payload includes state-of-the-art instruments, e.g. a camera system for high resolution imaging from orbit and on the surface, spectrometers covering visible, near-infrared and mid-infrared wavelengths, a neutral-particle analyzer, a radio science experiment and optional laser altimeter. If resources are available, an optional Lander will be added to perform in-situ characterization close to the sampling site, and possibly internal structure investigations.

In addition to addressing the exciting science goals, the MarcoPolo-R mission also involves technologies for which technical development programmes are well under way. It is the ideal platform to (i) demonstrate innovative capabilities such as: accurate planetary navigation and landing, sample return operational chain; (ii) prepare the next generation of curation facilities for extra-terrestrial sample storage and analysis; (iii) pave the way as a pathfinder mission for future sample returns from bodies with high surface gravity. MarcoPolo-R will ensure that European laboratories involved in sample analysis remain world class facilities spanning the entire breadth of expertise required for the science success of the mission.

The public outreach possibilities of MarcoPolo-R are considerable because of the enormous fascination of the general public for asteroids. On the strategic and political front there is also a considerable interest in prediction and mitigation of an NEA impact.

MarcoPolo-R will return bulk samples from an organic rich, binary asteroid to Earth for laboratory analyses, allowing us to:

- explore the origin of planetary materials and initial stages of habitable planet formation;
- identify and characterize the organics and volatiles in a primitive asteroid;
- understand the unique geomorphology, dynamics and evolution of a binary NEA.

Moreover as a possible precursor for the MarcoPolo-R mission, there is an appealing possibility for participation as an ESA Mission of Opportunity to the NASA sample return mission OSIRIS-REx (Appendix 2). This mission is currently in the proposal competition phase within NASA's New Frontiers program. The final selection will take place in mid-2011.

1 INTRODUCTION

Unlike the planets, small bodies can retain evidence of the primordial solar nebula and the earliest solar system processes that shaped their evolution. They may also contain pre-solar material as well as complex organic molecules which led to the development of life. For these reasons, asteroids and comets have been targets of interest for proposals and missions for over three decades. Fly-bys provided the first close-up views of these objects and led to major advances in our knowledge of their physical properties and evolution. However, remote sensing gives only the most superficial information on the surface composition, and even in-situ measurements that could be made by a lander are severely limited by the resources available. Only in the laboratory can instruments with the necessary precision and sensitivity be applied to individual components of the complex mixture of materials that forms an asteroid regolith, to determine their precise chemical and isotopic composition. Such measurements are vital for revealing the evidence of stellar, interstellar medium, pre-solar nebula and parent body processes that are retained in primitive asteroidal material, unaltered by atmospheric entry or terrestrial contamination. It is no surprise therefore that sample return missions are considered a priority by a number of the leading space agencies.

Cosmic Vision 2015-2025 lays out four fundamental questions to be addressed by ESA's mission programme (ESA 2005). For the second of these, "How does the Solar System work?", it states: "The natural next step in ESA's exploration of small Solar System bodies would be a sample return mission of material from one of the near-Earth asteroids." Sample return from a primitive NEA also addresses the Cosmic Vision question "What are the conditions for life and planetary formation?". Marco Polo (ESA/SRE (2009)3) was selected for the Assessment Phase of the first round of Cosmic Vision and the scientific rationale was highly ranked by ESA committees (SSWG, SSAC, SPC).

The JAXA Hayabusa spacecraft made touch-and-go sampling attempts from the NEA Itokawa in 2005 and the return capsule was successfully recovered in Australia in June 2010. Tiny grains, with total mass <<1 mg, have been recovered and appear to be of a highly processed S-type asteroid, with composition consistent with that of thermally-processed ordinary chondrite meteorites. A follow-up mission, Hayabusa 2, is proposed to the primitive NEA 1999 JU3 for launch no later than 2015.

A number of NEA sample return mission concepts have been proposed for NASA's Discovery and New Frontiers programmes. OSIRIS-REx is one of three missions shortlisted for selection in 2011 for a New Frontiers launch in 2016 to the primitive NEA 1999 RQ36.

Despite this strong international interest and activity, there is currently no asteroid sample return mission that is selected for flight. We therefore propose a European-led mission, MarcoPolo-R, based on the former Marco Polo mission study, but with a revised approach that allows access to a unique target, the primitive binary NEA (175706) 1996 FG3 (1996 FG3 hereafter). The cost to ESA will be reduced within the medium mission budget by collaboration with an international partner. A consortium led by Dr. A.F. Cheng (PI of the NEAR NASA mission) of the Johns Hopkins University Applied Physics Laboratory, including JPL, NASA ARC, NASA LaRC, and MIT, has formally responded to the NSPIRES solicitation #NNH11ZDA005J (NASA Coordination with ESA's Cosmic Vision Call for Proposals). An official letter by NASA (see Appendix 1) states that NASA is aware of the proposal and acknowledges that its scientific objectives are aligned with the 2010 Science Plan for NASA's Science Mission Directorate. The proposed NASA contribution to MarcoPolo-R comprises the following mission elements:

- *Sample acquisition and transfer*, including active sample acquisition devices and robotic mechanisms to transfer samples reliably into a canister;
- *Earth re-entry capsule*, including sample canister;
- *Sample recovery,* including recovery operations at Utah Test and Training Range (UTTR) and sample canister delivery and opening.

These elements provide a well-defined interface with a European spacecraft and save to ESA development costs of a high-velocity Earth re-entry capsule and sampling mechanism.

In addition, there is an appealing possibility for participation, as an ESA Mission of Opportunity, in the OSIRIS-REx mission. Agreement in any participation will depend on final selection of OSIRIS-REx in the NASA New Frontiers programme although preliminary agreements have been defined with the mission PI (see Appendix 2).

In this proposal we provide an overview of the new MarcoPolo-R mission and the scientific objectives that can be addressed using the combination of returned samples and in-situ measurements.

2 SCIENTIFIC OBJECTIVES AND REQUIREMENTS

2.1 Scientific objectives

Small bodies of the solar system are believed to be the remnants - either fragments or "survivors"- of the swarm of planetesimals from which the planets were formed. In contrast to the planets, which have experienced major alteration during their history, most asteroids and (dormant) comets, primarily due to their small sizes, experienced less internal heating and so are believed to have retained a record of the original composition of our solar system's proto-planetary disk (Figure 2). Abundant within the inner solar system and the main impactors on terrestrial planets, small bodies may have been the principal contributors of the water and organic material essential to create life on Earth. Small bodies can therefore be considered to be equivalent to DNA for unravelling our solar system's history, offering us a unique window to investigate both the formation of planets and the origin of life. Moreover, in the current epoch, these small bodies also represent both a potentially rich resource for future space exploration and a threat to the very existence of humankind on Earth.

Figure 2*: A proto-planetary disk during the early phase of planetesimal formation (from W. K. Hartmann).*

Near-Earth asteroids are a continuously replenished population of small bodies with orbits that come close to the Earth's orbit. Their median lifetime is 10 Myr (Gladman et al. 2000). Most of them end up in a Sun-grazing state, or are ejected from the solar system, while about 10-15 % collide with a terrestrial planet, in particular the Earth or Venus. Objects in near-Earth space are a precious source of information as they represent a mixture of the different populations of small bodies, *i.e.* main-belt asteroids and cometary nuclei, and a link with meteorites (Morbidelli et al. 2002, Binzel et al. 2004, DeMeo and Binzel 2008). They have the orbital advantage 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, an NEA offers the particular advantage of being related to a specifically known birth region, which from dynamical studies, places most between Mars and Jupiter (Bottke et al. 2002). Hence, understanding NEAs will provide insights required to sharpen our scientific picture of the formation of a planetary system – our own – in the terrestrial planet region.

A space mission to an NEA therefore provides major opportunities for advancement in our understanding of some of the fundamental issues on the origin and early evolution of the solar system. NEA missions enable an entirely new approach for investigating the primordial cosmochemistry of the solar protoplanetary disk and the formation and properties of the building blocks of terrestrial planets. Moreover, considering the threat represented by those NEAs classified as potentially hazardous objects, knowledge of the physical properties of NEAs (composition and internal structure) is the first essential step towards developing efficient methods to deflect an object whose trajectory leads to a possible collision with the Earth.

The NEA population presents a high degree of diversity as revealed by ground-based observations. More than 10 major spectral classes have been identified (Barucci et al. 1987, Bus and Binzel 2002a, b). The most intriguing objects, which represent the highest priority for NEA missions, are those having the most primitive compositions. These objects have the most direct link to the chemistry and conditions of the early solar system and are widely believed to have preserved materials that witnessed the condensation of the early phases of the formation of the solar system. These may also contain pre-solar grains[1] that retain information on the interstellar medium (ISM) and even their genesis in evolved stars. Therefore, a mission to a primitive NEA (dark C, D, and similar spectral classes) can provide crucial elements to answer the following key questions:

1. What were the processes occurring in the early solar system and accompanying planet formation?
2. What are the physical properties and evolution of the building blocks of terrestrial planets?
3. Do NEAs of primitive classes contain pre-solar material yet unknown in meteoritic samples?
4. What are the nature and the origin of the organics in primitive asteroids and how can they shed light on the origin of molecules necessary for life?

Answers to these fundamental questions can only be derived by use of laboratory

[1] A 'grain' is dominated by a single mineral crystal, c.f. a 'particle' is composed of several or many grains.

instrumentation, and therefore MarcoPolo-R will return a sample from a low-albedo, primitive NEA. Only one low-albedo asteroid, namely (253) Mathilde, has been observed by spacecraft to date (Yeomans et al. 1997) and only during a brief fly-by and with limited instrumentation. MarcoPolo-R will return fundamental and exciting science, within a mission that will excite the public during all phases, in particular during the in-situ observations and laboratory-based investigation of the returned material. Orbital observations will provide a characterization of the target necessary for sample selection and for relating laboratory samples to the asteroid population as a whole.

2.2 Fundamental science questions addressed by MarcoPolo-R

What were the processes occurring in the early solar system and accompanying planet formation?

The solar system formed from a disk of gas and dust orbiting the Sun. These dust grains then collided with each other, growing into larger objects, called "planetesimals", which eventually reached a size of tens to a thousand kilometres, although some key aspects of this process are not fully understood. Details of the formation of the principal components formed in the solar protoplanetary disk, and the timing of these events relative to the formation of different asteroidal bodies, are beginning to emerge. However, the precise chronology of events is still poorly understood. Planetesimals represent the building blocks of the planets, and in this respect their analysis is expected to bring us crucial information on the nature of the protoplanetary disk.

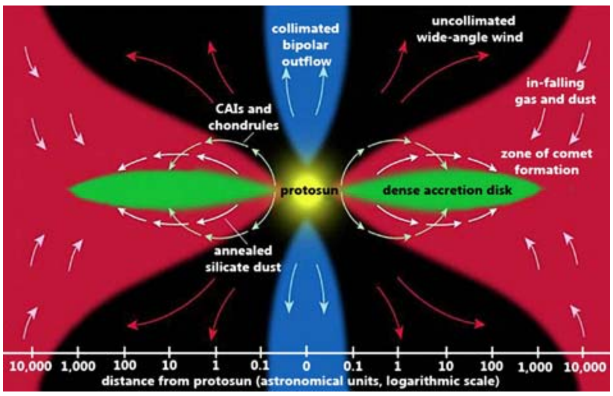

Figure 3: *A schematic diagram of the solar nebula as it was still accreting dust. Planets have not yet formed. Materials heated near the Sun circulate to the outer solar system (from Nuth 2001).*

Primitive objects are expected to include the earliest condensed material (Calcium-Aluminium Inclusions (CAIs) and chondrules) and material made and/or modified by stellar outflows, the ISM, and the solar protoplanetary disk (Figure 3), as well as by parent-body processing (e.g. thermal metamorphism; Figure 4). MarcoPolo-R, by returning primitive material from a small body and knowing the geological context in which it was residing, offers the possibility of distinguishing between effects of solar-nebula processing and effects of alteration from asteroidal parent-body processing.

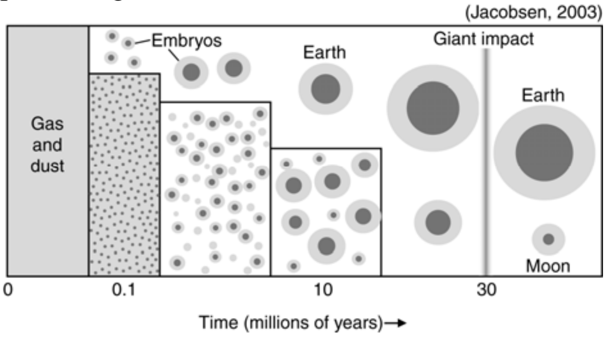

Figure 4: *In the primordial solar nebula dust and ices condensed to form planetary embryos that accumulated to larger protoplanets eventually forming bodies of the sizes of the terrestrial planets.*

Primitive material also permits determination of the abundance of a number of short-lived radionuclides present at the time of formation of a variety of early solar-nebula components that are essentially free from the concerns of partial re-setting or secondary process effects. They therefore offer a clear insight into the timing of the formation of these components and their origin, whether it is local (*e.g.* irradiation and ejection by X-wind) or remote (*e.g.* stellar nucleosynthesis). The abundance of the various short-lived nuclides provides an important constraint on possible triggering mechanisms for the collapse of the proto-solar molecular cloud.

What are the physical properties and evolution of the building blocks of terrestrial planets?

The current physical and chemical properties of an asteroid have been shaped by its evolution since the condensation and agglomeration that formed its parent planetesimal in the asteroid belt. This evolution includes some or all of: thermal metamorphism, aqueous alteration, collisional disruption, re-accumulation, regolith processing and space weathering. For the most primitive asteroids, the effects of these processes are expected to be minor, or even minimal, and will not obliterate the record of early nebular conditions at formation. The sample of mixed NEA regolith returned by MarcoPolo-R will likely contain components displaying varying degrees of asteroidal processing that must be accounted for to permit study of the earliest stages of solar system formation, but will also allow detailed investigation of the evolution of the solar system from its formation to the present day.

Thermal heating of asteroids for extended periods, as documented in meteorite analyses, results in considerable modification and even obliteration of the accreted primitive material. Such thermally altered materials are thought to be found on bright (high albedo) asteroids unlike the MarcoPolo-R target. Temperatures greater than 800 °C in the ordinary chondrite meteorites (see Figure 5), or even higher temperatures in the achondrite meteorites, result in melting or re-crystallisation of minerals and loss of volatiles, including water and organics. We can be confident that the low-albedo target of MarcoPolo-R will not have suffered such processes, because these processes result in higher albedo and different spectral features.

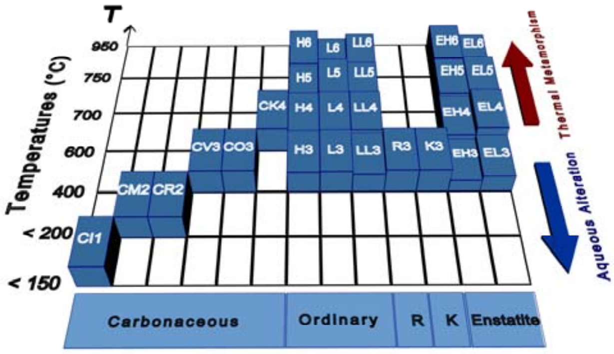

Figure 5 *The chondrite classification of meteorites as a function of the estimated temperature required for producing the petrographic types. Arrows on the right indicate the degree of aqueous alteration or thermal metamorphism. Most meteorites have experienced extensive aqueous alteration or significant levels of thermal metamorphism (Dotto et al. 2005).*

Aqueous alteration is a low-temperature chemical alteration of compounds by liquid water which acts as a solvent and produces secondary minerals such as phyllosilicates, sulphates, oxides, carbonates, and hydroxides. It also plays a major role in the modification and synthesis of organics. Several transfer transitions are only possible in the presence of liquid water on the surface of the object. Related spectral features, found for several meteorites and low-albedo main-belt and outer-belt asteroids, indicate that liquid water was present on their surface during some previous epoch. Moreover, water ice and organics were recently observed on the surface of the two asteroids of the C-complex, (24) Themis and (65) Cybele (Campins et al. 2010, Rivkin and Emery 2010, Licandro et al. 2011).

About 60 % of the C-class asteroids, at heliocentric distances between 2.5 and 3.5 AU, are thought to have undergone some kind of aqueous alteration process (Barucci et al. 1998). While D-class bodies have no clear relation with any kind of meteorites (with the tentative exception of Tagish Lake), C-classes appear to be related to carbonaceous chondrite meteorites, which are the best preserved witnesses of the early phases of the solar-system formation on the Earth that we have in our collections. The sample of mixed regolith returned from an NEA by MarcoPolo-R will likely contain a number of components sampling regions of the parent asteroid with different geological histories. It will therefore offer a unique opportunity to follow the effects of progressive aqueous alteration on the mineralogy and organic inventory of a suite of rocks.

It remains unclear from where the water for the Earth's oceans came. Models of the early solar system indicate that accretion at 1 AU and the energy released during this process would have led to a body poor in water. Comets are a major available source of water in the solar system, but the D/H ratio of water measured in a number of comets is much higher (by a factor of 2-3) than that of the Earth's oceans (Dauphas et al. 2000, Robert 2006; new results for 8P/Tuttle by Villanueva et al. 2009). The mean D/H ratio of carbonaceous chondrites appears to be much closer to that of the oceans – and therefore primitive asteroids originally from the main belt may be considered as the potential delivery mechanism for the abundance of water now present on the Earth that is so essential for all life. A sample of a primitive NEA will provide further insight to the abundance and isotopic signatures of water originally accreted at 3-5 AU.

All but the largest asteroids (diameter > ~100 km) are part of a collisionally evolved population (see Figure 6). The bulk density (porosity), shape (*e.g.* spheroidal to highly elongated), rotation rate and morphology (grooves, crater shapes and abundance, crater chains, slope variation) provide clues about the internal structure. This could range from monolithic objects (mostly sizes ~ tens of m), through fractured or shattered objects or contact binaries, to true "rubble piles" of re-accumulated fragments with porosities up to 40 % (Richardson et al. 2002).

Space weathering, the physical and chemical alteration of materials exposed to the space environment (solar wind irradiation and impact processing), starts to affect the surface layers of NEAs as soon as they are exposed by collisional disruption or subsequent surface movements. The effects are most apparent on the extreme surfaces of grains (solar radiation and particle flux) and can significantly affect the light-scattering properties. Dating of disruption or resurfacing events is possible via sample analysis (exposure ages from more deeply penetrating cosmic rays) or asteroid imaging (cratering rates).

The returned sample from the asteroid which has undergone negligible thermal alteration will allow us to study the chemical evolution of material from the formation of planetesimals (the building blocks of the terrestrial planets) to its current state in NEAs. In-situ observations of the known source object will provide the large-scale properties as well as surface and regolith features and their variation across the whole body that define the physical evolution of the NEA and place the collected sample in context.

Do NEAs of primitive classes contain pre-solar material yet unknown in meteoritic samples?

Primitive material is expected to contain pre-solar grains, in particular silicates, and offers the best opportunity for obtaining pristine grains.

One of the major achievements in meteoritics over the past 20 years has been in the isolation and detailed analyses of a wide range of different pre-solar grains found in primitive meteorites. They have offered insight, which was previously undreamed of, into specific nucleosynthetic processes and the thermo-physical conditions of the accompanying circumstellar shells associated with a wide variety of such processes. The latest and potentially the most important group of grains identified in meteoritic material is the one composed of interstellar silicates. MarcoPolo-R will offer the opportunity to investigate the abundance of pre-solar grains accreted in the parent body and to search for new, less robust grains which have not survived the meteorite formation processes.

An area of meteorite interstellar grain research that is starting to open up with a range of analytical tools capable of generating samples and performing complex measurements on much less than micron-scale features is the study of mantles and reaction rims around the grains (*e.g.* Bernatowicz et al. 2003, Lyon et al. 2007). Such features should record a wealth of information about the environments and processes the grains experienced since their formation – offering insight into the ISM and early nebula. However, by their very nature these rims or mantles are likely to be particularly susceptible to modification or destruction during meteorite formation on the parent body. Once again, primitive material collected from the surface of an NEA offers the best opportunity for obtaining pristine grains.

What are the nature and the origin of organics in primitive NEAs and how can asteroids shed light on the origin of molecules necessary for life?

Current exobiological scenarios for the origin of life invoke an exogenous delivery of organic matter to the early Earth. It has been proposed that carbonaceous chondrite matter (in the form of planetesimals down to cosmic dust) could have imported vast amounts of complex organic molecules capable of triggering the prebiotic synthesis of biochemical compounds (*e.g.* Maurette 2005 and references therein). For example, amino acids are abundant in meteorites and have recently been discovered in returned Stardust samples (Elsila et al. 2009). The organic compounds found in meteorites display great structural diversity.

Current investigations of the most primitive organic materials available from samples such as the Stardust cometary samples, interplanetary dust particles (IDPs) and micrometeorites are limited to a few techniques – *i.e.* those offering exceptional spatial resolution or sensitivity, but due to the very small sample size, lacking detailed abundance and isotopic information available from the meteorite samples.

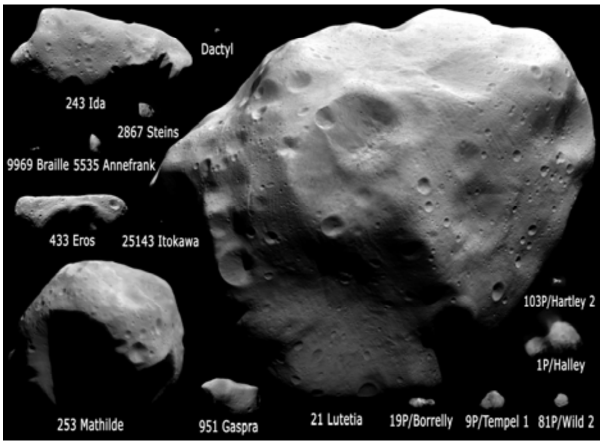

Figure 6: *Images to scale of all small bodies (asteroids and comets) visited so far by space missions, showing the great diversity in size, shape and surface characteristics. The largest body in the image is the 100 km-size Lutetia observed by the ESA mission Rosetta. The smallest, not visible in the image, is the 320 m-size Itokawa visited by the JAXA mission Hayabusa.*

One of the most important observations to date has been the identification of chiral excesses in the soluble fraction of meteoritic organic matter (*e.g.* Pizzarello and Cronin 2000). It was demonstrated that some of the most abundant amino acids display an excess of up to 15% in the L-enantiomer (left-handed molecular symmetry) over the D-enantiomer (right-handed). It has been suggested that the observed preference for left-handedness may be related to the left-handedness of biological molecules in life forms on Earth, strengthening the possibility that the meteoritic organics played a role in the origin of life on Earth.

Understanding the origin of the amino acids and their distribution in the early solar system will contribute to assessing the likelihood of this scenario, and indeed its applicability to planets or other bodies around other stars. An even greater analytical challenge is determining the presence and origin of nucleobases in primitive materials. Like amino acids, the nucleobases are fundamental building blocks of life, being integral parts of DNA and RNA. There is evidence that such compounds are present in meteorites (*e.g.* Martins et al. 2008), but their detection and study are hindered by their ubiquitous presence in life on Earth and low abundances in meteorites. Contamination is a major problem, particularly as all nucleobases are involved in terrestrial life processes. The delivery of carbonaceous chondrites, loaded with amino acids, nucleobases, sugar-related compounds, carboxylic acids and other organic materials could have had a major influence in the initial stages of the development of life on Earth. Measurements of such pre-biotic compounds in samples from beyond our own world will trigger a tremendous discussion on the origin of life and its ubiquity in the universe.

A sample of mixed regolith from a primitive NEA containing a number of components with varying degrees of aqueous alteration would give definitive answers on the formation processes of carbonaceous matter in interplanetary material. It would help to determine the origin of compounds such as the amino acids – by monitoring how the abundance of the amino acids, and their possible precursor, evolves with the degree of aqueous alteration (as determined by mineralogy). By returning a sample free from terrestrial contamination, any ambiguity created by life on the Earth is eliminated.

2.2.1 Why a sample return?

Many of the science questions we are attempting to resolve stem from detailed knowledge obtained from high-precision and high-sensitivity measurements of meteorites. The anticipated scientific advances with the new sample from a primitive 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.

A recent press release by JAXA (Nov. 16, 2010) indicated that the Hayabusa mission returned successfully some particles from the evolved S-type asteroid Itokawa; however, only tiny grains have been recovered and their preliminary analysis suggests that their composition (e.g. olivine and pyroxene) is consistent with the one expected from remote-sensing data of such a non-primitive surface.

The NASA Stardust mission to comet 81P/Wild 2, a periodic comet captured from the outer solar system onto its current orbit only recently, is the first space mission to return solid extraterrestrial samples other than those from the Moon. Several thousand micron-sized dust particles from the coma were trapped during the fly-by on 2 January 2004, in a collector made of silica aerogel, and returned in a capsule to Earth on 15 January 2006 by direct re-entry. Their analysis highlights the wealth of information that can be achieved from sample return (Brownlee et al. 2006). For instance, the presence of high-temperature minerals (forsterite and CAIs), that formed in the hottest regions of the solar nebula, provided dramatic evidence for extensive radial mixing at early stages of the solar nebula (Brownlee et al. 2006, Zolensky et al. 2006). The organics present in the cometary samples display considerable variability and complexity, even at a very fine scale, indicating multiple formation processes (see Figure 7; *e.g.* Cody et al. 2008, Rotundi et al. 2008).

Nevertheless, the samples collected by Stardust experienced considerable heating, modification and contamination during capture in aerogel and therefore are far from ideal when attempting to understand the incredibly complex materials and organic compounds found in primitive materials.

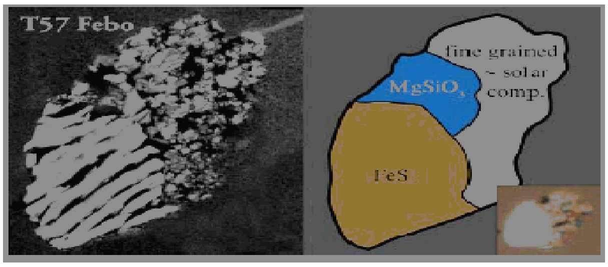

Figure 7*: Stardust 8-µm particle from comet 81P/Wild 2. Laboratory analyses show the presence of three major components: sulphide pyrrhotite, enstatite grain and fine-grained porous aggregate material with chondritic composition (Brownlee et al. 2006). Therefore, in a single particle, materials which formed in different regions in a protoplanetary disk can co-exist, which was not expected.*

> The science questions addressed by MarcoPolo-R require many different types of analyses, providing a framework of understanding about the history of the sample, the parent asteroid, the solar nebula and beyond.

Examples of the types of analyses include the detection of elemental abundances at the ppm-level or even ppb-level, with a precision of a few percent, of components within the sample that are required to provide context between components and with known meteorite groups. Laboratory-based techniques such as mass spectrometry and neutron activation are routinely employed for such measurements. Even more challenging is the need to understand diffusion/exchange processes (*e.g.* gas-dust in nebula, aqueous alteration on parent asteroid, *etc.*) operating over <<mm scales which requires analyses to be performed at scales of the order of microns or even less – again readily achieved by techniques in the laboratory such as LA-ICPMS, SIMS, XAFS, EMPA, but generally not possible by in-situ techniques with the required sensitivity or precision.

Isotopic measurements are a key tool in understanding the processes in the solar nebula and parent asteroid. One of the major goals of MarcoPolo-R is to provide a detailed understanding of the chronology of early solar system events, which we know to span only a few million years from the analysis of meteorites.

Organic analyses require a wide array of techniques – based on the use of liquid solvents to extract key life-implicated compounds such as amino acids and nucleobases. Detection of such compounds, and those from thermal decompositions could be performed using space flight instruments. Precise isotopic measurements are far more demanding. Investigation of the insoluble organic macromolecules would require use of NMR (with large super-conducting magnets) and synchrotron radiation, neither of which could ever be envisaged for space flight.

Notwithstanding the technical requirements of individual measurements and the high levels of stability (thermal, vibration, power, *etc.*) that the instruments demand, multiple analyses of the same sub-sample employing a range of techniques are usually necessary in order to unravel the history of each component and to understand the earliest process involved in their formation. In order to achieve high quality measurements, careful sample selection is required along with complex sample preparation – *e.g.* production of very flat, polished surfaces for precise spot elemental and isotopic measurements, irradiation with high neutron fluxes for Ar-Ar and I-Xe dating of asteroidal and early solar-system processes, demineralisation by harsh acids for NMR investigation of the macromolecule and concentration of interstellar grains.

It will therefore be important to compare the sample returned by MarcoPolo-R from a primitive asteroid, with its geologic context, to the dust sample from comet Wild 2 returned by Stardust, as well as the collections of meteorites, micrometeorites and IDPs, across the full range of compositional and physical properties.

MarcoPolo-R will collect at least 5 orders of magnitude more material than Stardust, permitting more sample-specific selection from the expected complex mixture of asteroid regolith. Most importantly, MarcoPolo-R will be able to collect the sample such that its physical content is not modified during its collection. Moreover, contrary to the sampling strategy of Stardust and similarly to Apollo missions, the sampling area will be selectable after inspection from orbit. There will also be a strong control on any possible contamination, particularly by and for the organics.

It is clear that in order to answer the science questions that MarcoPolo-R seeks to address, laboratory analysis of a sample of a primitive asteroid is required. The great added benefit of sample return is that the analyses can be refined to account for unexpected features of the sample, and that material is available to address new scientific questions which may arise or for new techniques that are developed during the long lead time up to the return of the sample in such a mission.

The study of the MarcoPolo-R sample within the larger context of extraterrestrial primitive materials will greatly advance the understanding of the nature and origins of primitive materials in the solar system.

Why can meteorites in our collections not answer these key science questions?

Approximately 40,000 meteorites now exist in collections across the world (including large collections from Antarctica and the hot deserts), although the number of individual falls is much lower – reflecting the presence of unidentified shower falls and mechanical break up of single bodies into numerous fragments. However, even after correcting for such effects, we have strong scientific indications that our terrestrial record is biased. Various clues point to an abundance of material that does not survive atmospheric entry. The C-class asteroids account for ≈ 75 % of all main belt asteroids – and while largely located in the mid/outer asteroid belt, their nearest meteoritic equivalents, the somewhat friable carbonaceous chondrites, are present in our meteorite collections at the level of less than 5 %. Although carbonaceous meteorites belonging to the so-called CM class constitute by far (~35 %) the majority of carbonaceous chondrites, it is possible that they come from one asteroid only (Morbidelli et al. 2006).

Since only the strongest material reaches the Earth, it is not known whether this material is representative of the dominant material in space. For instance, the measured compressive strength of the Murchison meteorite is 50 MPa (Tsuchiyama et al. 2008), which is an order of magnitude higher than the compressive strength of porous materials on the Earth. This could explain the apparent overrepresentation of ordinary chondrites in the meteorite collections compared to dominant interplanetary matter as inferred from populations of asteroid classes.

The strength of meteorites is the result of metamorphism and/or aqueous alteration on the parent asteroids – with effects that extend well beyond the mechanical properties of the meteorites as they mobilise elements and isotopic ratios within and between minerals, re-set radio-isotope chronometers, destroy and modify primitive materials, and synthesise and mobilise organic compounds. IDPs display mineralogical, chemical and isotopic signatures, not found in meteorites. This strongly indicates formation and/or residence in the ISM or solar accretion disk. Such primitive material must have been stored somewhere for the past 4.5 x 10^9 years. On a more macroscopic scale, the Tagish Lake meteorite is perhaps the most friable carbonaceous chondrite recovered to date. Recovery of useful amounts of material was only possible as the fall was witnessed and happened over a frozen lake. In some respects it appears to be a particularly primitive meteorite, with high carbon content and unusual organic inventory. It has been linked with the very primitive D-class asteroids (*e.g.* Hiroi et al. 2001), but the high levels of aqueous alteration affecting this meteorite are not consistent with the fact that water features in D-class spectra are rarely observed (*e.g.* Kanno et al. 2003).

Moreover, the recent experience of the Sudan meteorite 2008 TC3 emphasises the uncertainty and incompleteness of our understanding. This fall is the first instance where an object was observed astronomically as an asteroid and then was recovered as a meteorite. It was identified as an F-class object, similar to C-class (bluer in the visible), but the meteorite is unexpectedly a friable breccia of mostly ureilite and enstatite chondrite clasts (Jenniskens et al. 2009, Horstmann and Bischoff 2010). These rare and unique samples demonstrate that mechanically weak material does exist in significant quantities within the inner solar system and that the existing meteorite collection is significantly biased towards heavily processed material. Nonetheless, we still miss primitive materials that are probably even weaker and would not survive atmospheric entry.

The spectacular falls mentioned above highlight two crucial lessons, in addition to the obvious one that our knowledge from the current meteorite collection is incomplete. First, carbonaceous chondrites preserve material and information from the solar nebula as well as from the pre-solar environment. However, most carbonaceous chondrites have undergone some thermal and aqueous processing on their parent body and we will never fully understand such processing of primitive materials unless we return a sample from a primitive asteroid. Clearly, we do not have access to all the information recorded in primitive materials too fragile to be recovered on the Earth.

Until we return a sample from a primitive asteroid, which is the primary goal of MarcoPolo-R, we will never know what a primitive material is.

2.2.2 Why an NEA?

The near-Earth population includes both asteroids and comet nuclei in orbits with perihelion distances q < 1.3 AU, which periodically approach or intersect the Earth's orbit. NEAs are therefore the most accessible targets containing primitive materials for scientific research. They offer two main advantages: (i) most of them come from the asteroid belt, which makes them representative of the whole asteroid population, and (ii) contrary to more distant main belt asteroids, they are highly accessible targets for spacecraft missions (low Δv).

Several thousand objects in near-Earth space are currently known. According to model estimations, the whole near-Earth population contains somewhat more than 1000 objects with diameter larger than 1 km and hundreds of thousands greater than 100 m (Morbidelli et al. 2002, Stuart and Binzel 2004). Numerical studies have determined that the main sources of the near-Earth population are located in the inner solar system (Mars crossing zone and main belt; Michel et al. 2000, Bottke et al. 2002) with a small component coming from Jupiter Family Comets.

Numerical analysis of the orbital histories of thousands of particles from each source has allowed, as a by-product, the estimation of the most likely reservoir of a real object before its transport to its current orbital position. Thus, it is possible to estimate the relative probability that a body with known orbit in near-Earth space comes from a particular reservoir and consequently to relate the target from which a sample will be taken to its most likely source region in the solar system.

The study of the physical nature of NEAs is also relevant to the assessment of the potential hazard imposed by NEA impacts on our planet. Whatever the scenario, it is clear that the technology needed to set up a realistic mitigation strategy depends upon knowledge of the physical properties of the impacting body, regardless of whether it is a single object or a binary.

The return of a surface sample from an NEA by the MarcoPolo-R mission and its subsequent laboratory analysis will not only help to answer questions related to planetary formation, but will also provide for the first time a good knowledge of the material properties of a potential impactor. Improved knowledge of the physical properties of a whole object and its material properties would then allow a better optimization of mitigation strategies, and MarcoPolo-R can provide a significant contribution to this objective.

2.2.3 Why is a binary favoured?

Binary objects represent about 15% of both the NEA and main belt populations and their formation mechanism is still a matter of debate, although several scenarios have been proposed to explain their existence. In particular, rotational disruption of an NEA, assumed to be an aggregate, as a result of spin-up above the fission threshold due to the YORP effect (a thermal effect which can slowly increase or decrease the rotation rate of irregular objects) has been shown to be a mechanism that can produce binary asteroids with properties that are consistent with those observed (shape of the primary, size ratio of the primary to the secondary and circular equatorial secondary orbit: Walsh et al. 2008). Other fission scenarios have been proposed which imply different physical properties of the binary (Jacobson and Scheeres 2010). Binary formation scenarios therefore place constraints on, and implications for the internal structure of these objects. One of the most important implications of the model by Walsh et al. is that the pole of the primary should be composed of fresh material that was originally at some depth in the progenitor. In effect, when spun-up, the material of the pole of the progenitor migrates to the equator and when the centrifugal force exceeds the gravity of the body, this material escapes from the surface to form the secondary (see Figure 8). Collecting samples from the pole of the primary can therefore provide a means of obtaining material that was originally inside the body without having to drill into it.

Thanks to its binary nature, the sizes, mass and orbit pole direction of the system can be estimated from Earth-based observations. This knowledge of basic physical parameters will enhance navigation accuracy and lower mission risk during the rendezvous; it will reduce the time required for initial characterization before entering into close-in, bound orbits.

A visit to such a binary system will allow several scientific investigations to occur more easily than they would at a single object, and others that would be impossible regarding the fascinating geology and geophysics of asteroids.
1. Precise measurements of the mutual orbit and rotation state of both components can be used to probe higher-level harmonics of the gravitational potential, and therefore internal structure.
2. A unique opportunity is offered to study the dynamical evolution driven by the YORP/Yarkovsky thermal effects (see Section 3.3.3).
3. Possible migration of regolith on the primary from poles to equator allows the increasing maturity of asteroidal regolith with time to be expressed as a latitude-dependent trend, with the most-weathered material at the equator matching what is seen in the secondary.

Moreover, a sample return would bring us, in addition to the primitive materials discussed above, crucial information: i) that may allow discrimination between the most likely formation mechanisms, ii) about the internal composition of the progenitor (as part of the surface of the primary may well correspond to some material that was located in the interior of the progenitor).

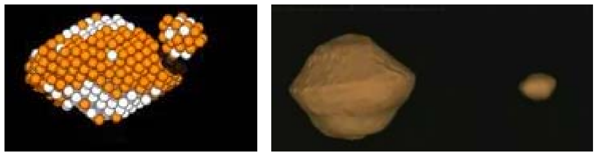

Figure 8: *Left: image of a simulation of binary formation by YORP spin-up; orange particles were originally located at the surface of the progenitor while white particles were originally below the surface; right: radar model of the asteroid 1999KW4, whose properties resemble those of the simulation (e.g. oblate primary shape, secondary to primary size ratio, etc.). Note that the pole of the primary is essentially composed of fresh material that was originally inside the progenitor (Walsh et al. 2008, Ostro et al. 2006).*

2.2.4 Solving the missing links

Considerable effort has been made linking reflectance spectra obtained from asteroids with those of meteorites. Comparatively good matches have been achieved for highly evolved (melted) bodies (*e.g.* (4) Vesta and the basaltic achondrites), but become increasingly more tenuous with decreasing albedo (increasing organic content) and other characteristics of more primitive mineralogy. For instance, spectra of the E-class asteroid (2867) Steins obtained by the ESA Rosetta spacecraft do not match any existing reflectance spectra of meteorites (Keller et al. 2010). However, from spectral observations of asteroid 2008 TC3 and the analysis of fragments recovered on Earth, we now have evidence that there is a discrepancy between the expected composition of a small body based solely on its spectral properties and the actual one from recovered fragments (Jenniskens et al. 2009).

A significant complication comes from space weathering which can alter the surface properties of airless bodies. The effects of space weathering are very difficult to simulate in the laboratory, but have been studied in great detail using returned lunar samples. However, the composition of the space environment at the lunar surface is quite different from that of asteroids.

Interpretation of all remote observation data will be greatly enhanced by "ground truth" analysis. Laboratory reflectance spectra of individual components from a returned sample of a primitive NEA can be compared with telescope spectra. The level of space weathering each component has experienced can also be determined mineralogically and geochemically (*e.g.* noble gas studies), by comparison with the mineralogy and chemistry of known meteorite types. Only on the basis of MarcoPolo-R sample analysis will it be possible to apply the knowledge obtained from meteorites to the vast amount of information available from asteroid observations.

2.3 Scientific requirements

MarcoPolo-R will provide fundamental elements to answer the key science questions described in the previous Section and reported in Table 1 together with the related scientific objectives.

To reach these objectives, the main goal is: ***to return a sample from a near-Earth asteroid belonging to a primitive class*** that will allow the analysis of asteroid material in ground-based laboratories to study the formation of the solar system and its planets, the characterization of an NEA as a representative of a primitive solar system body, and contribute to the field of astrobiology.

The sample provides a legacy for future generations of scientists with the potential for application of new analysis techniques and instrumentation to address as yet unexplored aspects of planetary science.

In addition, in-situ observations, and possible surface measurements shall be made to provide local and global geological and physical context for the returned sample.

Table 1: *Science questions and objectives, with measurements and methods to be used to address them (optional: *).*

Science questions	Science Objectives	Measurements	Method
1. What were the processes occurring in the early solar system and accompanying planet formation?	A. Characterize the chemical and physical environment in the early solar nebula B. Define the processes affecting the gas and the dust in the solar nebula C. Determine the timescales of solar nebula processes	Bulk chemistry. Mineralogy, petrology. Isotopic chemistry in inclusions (*e.g.*, chondrules or CAIs), matrix; pre-solar grains and volatiles, water.	Sample analysis.
2. What are the physical properties and evolution of the building blocks of terrestrial planets?	D. Determine the global physical properties of an NEA E. Determine the physical processes, and their chronology, that shaped the surface structure of the NEA F. Characterise the chemical processes that shaped the NEA composition (*e.g.* volatiles, water) G. Link the detailed orbital and laboratory characterization to meteorites and interplanetary dust particles (IDPs) and provide ground truth for the astronomical database	Volume, shape, mass. Surface morphology and geology. Mineralogy, petrology. Isotope geochemistry & chronology. Weathering effects. Thermal properties. Radar absorption *. Seismic waves *.	Imaging. Laser altimetry *. Radio Science. Visible and Near-IR spectrometry. Sample analysis. Neutral particle analysis. Mid-IR spectrometry. LIBS *. Penetrating radar *. Seismic Exp. *.
3. Do NEAs of primitive classes contain pre-solar material yet unknown in meteoritic samples?	H. Determine the interstellar grain inventory I. Determine the stellar environment in which the grains formed J. Define the interstellar processes that have affected the grains	Bulk chemistry. Mineralogy, petrology. Isotopic chemistry in inclusions (*e.g.*, chondrules or CAIs), matrix; pre-solar grains and volatiles, water.	Sample analysis.
4. What are the nature and origin of organics in primitive asteroids and how can they shed light on the origin of molecules necessary for life?	K. Determine the diversity and complexity of organic species in a primitive asteroid L. Understand the origin of organic species M. Provide insight into the role of organics in life formation	Abundances and distribution of insoluble organic species. Soluble organics. Global surface. distribution and identification of organics.	Sample analysis. Visible and Near-IR Imaging-spectrometry.

2.3.1 Target selection

A *primitive asteroid* is considered to be a low-albedo object of spectral class B, C, D, P or T including sub-classes, according to the taxonomic classification by Barucci et al. (1987) and Bus and Binzel (2002a, b).

The primitive C-type binary 1996 FG3 has been chosen as the baseline target of MarcoPolo-R, primarily because it is a relatively accessible binary NEA. Indeed, the science return is maximised by choosing a binary as in this case, there is also the possibility of observing evolutionary processes still in action as well as striking geophysical effects, such as regolith motion (as suggested for the binary 1999KW4 observed by radar; Scheeres et al. 2006). Moreover, one can better understand the potential outcome of YORP spin-up and test models of formation of a system that represents a non-negligible fraction (15%) of asteroid populations.

The current orbit of 1996 FG3 ranges from 0.69 to 1.42 AU from the Sun. It will be observable by radar in 2011, and observations by L. Benner (US core member) have been programmed at Goldstone and Arecibo. A probabilistic model (Bottke et al. 2002) of its orbital evolution shows a 93% probability that it entered near-Earth space via the ν6 resonance after forming in the 2.1-2.5 AU region of the main asteroid belt. Optical lightcurve observations reveal its binary nature (Pravec et al. 2000; Mottola and Lahulla 2000; Scheirich and Pravec 2009), with a 16 hour mutual orbit period and a 3.6 hour primary rotation period. Table 2 summarizes the main known physical properties of 1996 FG3.

Table 2: P*hysical properties of the baseline binary target 1996FG3 (estimated from ground-based observations).*

Primary diameter:	1.4±0.2 km
Primary geometric albedo:	0.035
Primary spin period:	3.595±0.002 hrs
Primary density:	1.4±0.3 g.cm^{-3}
Primary taxonomic type:	C
Secondary to primary diameter ratio:	0.28±0.02
Secondary orbital semimajor axis:	3.1±0.5 km
Secondary orbital eccentricity:	0.1±0.1
Secondary orbital period around primary:	16.14±0.01 hrs

In addition to 1996 FG3, other primitive asteroids can be considered as appropriate back-up targets that are easy to reach and that altogether offer a wide range of launch opportunities. All are single objects that can allow us to achieve the science objectives of a sample return mission to a primitive asteroid, except the additional ones specifically linked to binaries.

2.3.2 Sample requirements

There is a vast array of analytical tools for the characterization of returned materials encompassing many techniques spanning the principal approaches of microscopy and spectroscopy/spectrometry. These are shown in Table 3, together with the mass of selected material for a given measurement and an estimate of the mass of original sample required.

The required mass has been derived in such a way as to guarantee the scientific success of the mission. Different aspects have been taken into account to evaluate the returned mass, specifically: the probability that an amount of each sample component is sufficient for analysis was estimated; a statistical analysis of the returned sample has to be done in the laboratory (*e.g.* at least three different measurements in three different laboratories have to reproduce the same results); and finally 1/3 of the returned mass has to be stored for an indefinite time in the Curation Facility for future analysis. A few tens of grams of sample will guarantee the scientific success of MarcoPolo-R.

> In almost all cases no single measurement, or type of measurement, will provide the complete answer to any of the questions. Instead, our understanding will be derived from the results of many analyses of different components of the returned sample, and by a plethora of techniques.

2.3.3 Remote sensing analysis

The scientific requirements and associated measurements at the asteroid are structured in three phases: *'global characterization'*, *'local characterization'*, and *'sample context measurements'*:

- *'Global characterization'* means to measure the properties of the whole NEA, on a global scale;
- *'Local characterization'* is the characterization of dedicated areas which are identified as potential sampling sites;
- *'Sample context measurements'* are measurements being performed at the actual sampling site.

Table 4 gives an overview of the required orders of resolution for the different phases.

The global characterization of the body is required to obtain as complete a picture as possible of the physical nature of the NEA in order to relate the properties of the sample to those of the parent body. This characterization includes the following investigations.

Sampling site selection

For the overall success of the mission, the global characterization will allow the selection of a number of surface areas as potential locations for the intended surface sampling.

Table 3*: Scientific information obtained from analysis of various types of materials expected in the returned sample, sample requirements to achieve the scientific result, and estimate of the required mass for a given measurement. For each science area, the range for the minimum amounts of consumed material is shown in column 'single analysis mass'.*

Component	Scientific aspects			Measurement requirements			
	Goal	Objective	Theme	Measurement type	Techniques	Required mass	Single analysis mass
Chondrules, refractory inclusions, matrix	1	C	Age	Isotopic abundances	SIMS, LA-ICPMS, MC-ICPMS, TIMS	Gram	10s pg (SIMS) to 10s mgs (TIMS) per analyses
	1	B	Disk dynamics	Mineralogy & mineral chemistry	EMPA, SEM, TEM, XRS, FTIR, Raman, SIMS, LA-ICPMS	Gram	ng (EMPA) to µgs (LA-ICPMS) per analysis
	1	A	Volatility fractionation	Elemental and isotopic abundances	SIMS, LA-ICPMS, GS-MS, NG-MS	100s mgs	10s pg (SIMS) to 100s µgs (NG-MS) per analyses
	1	B	Processing	Elemental and isotopic abundances	SIMS, LA-ICPMS, MC-ICPMS, GS-MS, NG-MS	Gram	10s pg (SIMS) to 10s mgs (MC-ICPMS) per analyses
	1	B, C	Thermal history	Mineralogy and mineral chemistry	EMPA, SEM, TEM, XRS, FTIR, Raman, SIMS, LA-ICPMS	Gram	ng (EMPA) to µgs (LA-ICPMS) per analysis
	1	A, B, C	Accretion dynamics	Mineral chemistry	EMPA, SEM, TEM, XRS, FTIR, Raman, LA-ICPMS, SIMS	Gram	ng (EMPA) to µgs (LA-ICPMS) per analysis
	2	L	Interstellar processes	Elemental and isotopic abundances	SIMS, CS-GS-MS, NMR, GC-MS, XANES, STXM, μL^2MS	10 grams	10s ag (GC-MS) to gram (NMR) per analyses
Organics	1	A, B	Early solar-system processes	Chemical analyses, elemental and isotopic abundances	SIMS, GS-MS, NMR, Raman, XANES,	Several grams	10s ag (GC-MS) to gram (NMR) per analyses
	3	K, L	Asteroidal processes	Chemical analyses	NMR, Raman, XANES, HPLC, GC-MS, μL^2MS	100s mgs	10s ag (GC-MS) to gram (NMR) per analyses
	3	K, L, M	Origin of life	Chemical analyses	Laser GSMS, NMR, Raman, XANES, HPLC, GC-MS, μL^2MS	Several grams	10s ag (GC-MS) to gram (NMR) per analyses
	3, 4	D, L	Collisional history	Mineral composition	EMPA, SEM, TEM, XRS, FTIR, Raman	100s mgs	10s pg (Raman) to ngs (EMPA) per analyses
Lithologies & breccias	4	F	Aqueous alteration	Mineralogy	EMPA, SEM, TEM, XRS, FTIR, Raman, GS-MS, SIMS	Several grams	10s ag (GC-MS) to 100s µgs (GS-MS) per analyses
	4	D	Shock processes	Mineralogy	EMPA, SEM, TEM, XRS, FTIR, Raman	Several grams	10s pg (Raman) to ngs (EMPA) per analyses
	4	F, L	Thermal alteration	Mineralogy	EMPA, SEM, TEM, XRS, FTIR, Raman, SIMS, GS-MS	Several grams	10s ag (GC-MS) to 100s µgs (GS-MS) per analyses
	4	F, G, L	Space weathering	Mineralogy	EMPA, SEM, TEM, XRS, FTIR, Raman, Opt. spectro., ESR, NG-MS, SIMS, GS-MS, susceptometer	Gram	10s pg (SIMS) to mgs (susceptometer) per analyses
	4	D	Physical properties	Strength, porosity, thermal diffusivity	Helium pycnometer, differential scanning calorimeter.	Gram	mgs (differential scanning calorimeter) to 100s mgs (Helium pycnometer)
	4	D, L	Age	Mineralogy & isotopes	EMPA, SEM, TEM, XRS, FTIR, Raman, SIMS, NG-MS, ICPMS	Gram	10s pg (SIMS) to 10s mgs (ICPMS) per analyses
Pre-solar grains	2	H, I	Nucleosynthesis	Elemental and isotopic composition	SIMS, NG-MS, TEM, SEM	Several grams	10s pg (SIMS) to 100s µgs (NG-MS) per analyses
	1, 2	B, H, I	Circumstellar processes	Mineralogy and mineral chemistry	SEM, TEM, Raman, SIMS, Auger spectr.	Gram	10s pg (SIMS) to 100s µgs (NG-MS) per analyses
	2	H, J	Interstellar processes	Isotopes and mineralogy	SEM, TEM, Raman, SIMS, Auger spectr.	Gram	ags (Auger) to 10s pgs (SIMS)
	1, 2	C, I, J	Age	Isotopes	SIMS, NG-MS	Several grams	10s pg (SIMS) to µgs (NG-MS) per analyses

Size, shape, and rotation

The size, shape, and rotation of the baseline primitive binary target 1996 FG3 are already known within the limitations of ground-based observations. However, precise measurements will be obtained from combinations of imaging and laser ranging data. The determination of these parameters is also crucial for sampling site selection and safe navigation at close proximity.

Mass, density, and gravity field

From spacecraft tracking, mass estimates of the asteroid will be improved from the already estimated values exploiting the binary properties. Using volume information in combination with mass, the bulk density can be estimated. The porosity index of the body, which is an indicator for the internal body structure and associated formation scenarios, can then be determined by comparison with meteorite analogues.

Table 4: *Resolution requirements for global characterization, local characterization, and context measurements.*

	Spatial resolution		
	VIS imaging	VIS/IR spectrometer	Mid-IR instrument
Global characterisation	Order of dm	Order of m	Order of 10 m
Local characterisation	Order of mm	Order of dm	Order of dm
Context measurements	Hundred µm	-	-

Morphology and geology

Imaging maps of the whole body from a closer distance (order of a few hundred metres to two kilometres) provide the database for the detailed and synoptic geological analysis and interpretation of the NEA surface. Such information is important in order to place the returned sample into a geological environment and to relate it to the surface history.

Regolith

Regolith on an asteroidal surface can be envisaged as being a porous random medium of particles, with rough interfaces towards the exterior and solid rock towards the interior. Regolith can be subjected to gardening and turnover; regolith motion has been seen on Eros and Itokawa. Particles can range from fine sub-micron to centimetre, decimetre and even metre sizes. Regolith is present, at least to a varying extent, on all asteroids, natural satellites, and terrestrial planets. In the case of a binary, particular locations are expected to show regolith accumulation (e.g. at the equator) from formation and evolution models.

Composition and mineralogy

Global compositional characterization of the entire target by MarcoPolo-R is important primarily for the sample site selection but also for the investigation of the object surface.

Space Weathering

The effects of space weathering are different according to the heliocentric distance of a body and its surface composition. In particular, it is important to study the effects of space weathering on an NEA because it can give hints on how surface spectral properties are altered in the space environment, to provide ground truth for astronomical observations of reflectance and thermal emission. In the case of a binary, great variations in the degree of weathering are expected from formation models that suggest the pole of the primary to be composed of material freshly exposed and therefore less weathered than in other locations.

Thermal properties

The thermophysical properties of an NEA's surface are of fundamental importance in determining the surface temperature distribution. Its diurnal and seasonal cycles and variation with depth provide further constraints on surface composition and dictate the magnitude of the Yarkovsky and YORP thermal effects.

Yarkovsky and YORP effects

Knowledge of the thermal inertia (combined with a detailed shape model, spin properties, and mass) is essential to characterize thermal effects on the motion of an asteroid. Asymmetries in thermal radiation reaction forces can yield both a net force (Yarkovsky force) and a net torque (YORP effect) of fundamental importance for the orbital and spin histories of asteroids, in particular in the case of a binary whose formation involves these thermal processes. The size-dependent Yarkovsky effect slowly moves asteroid orbits (by changing semimajor axes) and is believed to be the dominant mechanism for injecting small asteroids into gravitational resonances which causes their escape from the main belt and replenishes the NEA population. The YORP effect (Rubincam 2000) influences the orientation of the spin axis and/or spin frequency of small asteroids and has been directly measured recently for four NEAs (*e.g.* Lowry et al. 2007).

3 MISSION PROFILE

There are a wide range of options available when defining a mission profile for an asteroid sample return mission. Mission design choices have to be made taking into account the main constraints and design implications, which for MarcoPolo-R are summarised below:

- Preferred target: the binary 1996 FG3
- Launch vehicle: Soyuz/Fregat
- Minimum stay time at the asteroid: 3 months
- Maximum entry velocity: 15-16 km.s^{-1}, limited by the ERC heatshield material capabilities.

3.1 Launcher requirements

For the preferred target and selected launch vehicle, feasible missions can be found using chemical propulsion by launching into GTO and using two space segment stages. The use of a GTO launch with a large propulsion capability enables more mass to be delivered to the asteroid and therefore a feasible return mission. A direct injection trajectory was ruled out to meet the Δv requirement for the target 1996 FG3. Electric propulsion may offer attractive alternatives to the chemical one (lower escape velocity, no planetary assist) though at higher cost. This can be decided during the mission assessment study. A staged space segment, adopted during the preliminary assessment, has shown that the inclusion of a separate propulsion module to perform the escape manoeuvres from GTO and the outbound transfer leads to a lower launch mass and therefore greater launch margin.

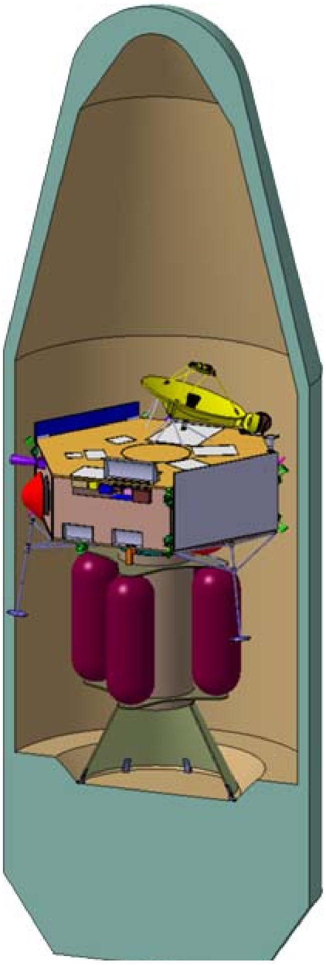

Figure 9: *Mission composite in Soyuz Fairing (Astrium design)*

3.2 Orbit requirements

An initial assessment of the transfer opportunities to 1996 FG3 has been carried out (Tables 5 and 6) and several potential mission scenarios were identified within the 2020-2024 launch timeframe. Earlier launch windows (e.g. in 2018) also offer good opportunities. The mission (for an overview, see Figure 10) will be launched from Kourou on board a Soyuz/Fregat launcher. The propulsion module will then provide the Δv to inject the composite into an interplanetary transfer that would include planetary (Venus or Venus-Earth) fly-bys. This is followed by the asteroid approach phase during which the propulsion module will be jettisoned, with the science module performing the targeting manoeuvres required to rendezvous with the asteroid.

When the spacecraft is close enough to the asteroid, the interplanetary cruise ends and the approach phase begins. An on-board star sensor or narrow angle camera is used to detect and track the NEA. Some braking manoeuvres are executed to reduce the approach velocity and increase the knowledge of the spacecraft relative state with respect to the asteroid. This phase is similar to the Rosetta approach phase, that typically lasts one month.

When the spacecraft is at a few tens of km from the asteroid, the proximity operations start. The first sub-phase of the proximity operations is Far Station Keeping. The on-board GNC/AOCS/FDIR system is currently being developed in a TRP activity at ESA led by GMV company (called NEO-GNC) and ending in February 2011.

This technique assures safe station keeping using a wide angle camera without any altimeter. Only light curves taken in ground observatories (prior to launch) and refined using on-board observations during the approach phase are needed.

Table 5: *Possible baseline mission scenarios (as defined according to the designs of OHB/GMV* and Astrium). Prime and backup baseline mission scenarios are indicated in bold.*

Launch	Mission duration (yrs)	Stay time (months)	Δv (km.s^{-1})	Entry v (km.s^{-1})
10.03.2020*	6.98	10.5	2.07	12.0
10.03.2020*	4.70	3.5	1.9	15.0
23.02.2021*	9.09	13.7	2.93	12.0
24.04.2021	**7.99**	**16.1**	**2.81**	**13.6**
09.01.2022	**7.28**	**9.3**	**2.88**	**13.6**

Table 6: *Backup mission scenarios for 1996FG3 and mission scenarios for backup targets (as defined by Astrium and OHB/GMV*).*

Target	Launch	Mission duration (yrs)	Stay time (months)	Δv ($km.s^{-1}$)	Entry v ($km.s^{-1}$)
1996 FG3 *	2024	8.3	5.7	2.95	15.0
1996FG3	2024	11.1	8.3	2.92	15.4
1996FG3 *	2024	10.13	4.2	3.45	12.0
1999 JU3	2022	7.9	14.0	2.56	11.9
1999 JU3	2023	6.0	15.6	2.90	11.8
1999 JU3	2024	5.0	13.0	2.50	11.9
1999 RQ36	2023	6.0	14.2	2.74	12.8
1999 RQ36	2024	5.0	3.9	2.80	12.8

During this phase, a known landmark database is built. Enough time to observe a large portion of the surface of the asteroid should be allocated (~1 month). To ensure good visibility of the asteroid, the Far Station location should be close to the Sun-asteroid line. Several station positions at closer distances are foreseen, that allow a robust identification of landmarks on the surface and eventually a more precise estimate of the gravity parameter of the asteroid.

When the distance is close enough, the spacecraft can be injected into a Self-Stabilised Terminator Orbit (SSTO), which requires very sparse manoeuvres for perturbation control. The duration in this phase shall allow for radio science experiment and for identification of the landing site. Remote sensing activities are performed, characterizing the asteroid in different levels of detail and determining its main gravitational, thermal and topographic characteristics. Local characterization shall be performed for some selected potential landing sites.

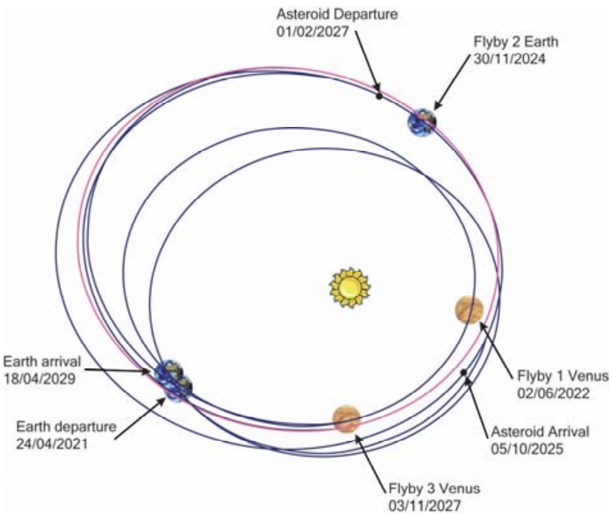

Figure 10: *Example of MarcoPolo-R overall trajectory with launch in 04/2021 (from Astrium).*

After a landing site is selected, the descent & landing phase (D&L) can start. Up to three sampling attempts are considered. The D&L can be preceded by some rehearsals, which are essentially a D&L procedure stopped at a certain altitude. The spacecraft will follow a predefined descent profile that fulfils all constraints to achieve safely the required landing accuracy. At a given altitude, the D&L phase shall be performed by the spacecraft autonomously

After touch-down, the surface operations shall start, beginning with the spacecraft stabilization, then execution of the sampling phase, transfer of the collected material to a canister inside the ERC and the ascent phase, which ends when the spacecraft is in the desired safe haven (a station position or a SSTO). From this point, the mission can perform additional science observations and prepare for the return flight (inbound trajectory).

The spacecraft will be injected on to the return trajectory, which may include a Venus fly-by, ending with ERC release and Earth atmospheric entry.

Back-up missions have been identified for alternative targets 1999 JU3 and 1999 RQ36 (Table 6).

3.3 Ground segment requirements

The ground segment will consist of a comprehensive flight dynamics operation centre (ESA) and will require a very complete simulator with an important NEA environment modelling component. Deep Space Network (DSN) will be used during specific phases of the mission (rendezvous, landing, sampling, asteroid departure and Earth re-entry).

3.4 Special requirements

1. The ERC will return to the USA, at the UTTR site which has been used for previous US sample return missions.
2. Capsule confinement is required with internal thermal control for preservation of volatile components.
3. Continuous, 24-hour deep space link during rendezvous burns, landings, and sampling phases, asteroid departure and Earth return will be required.

4. Interface assurance and procurement of safety and quality control standard will be agreed by ESA and NASA.

3.5 Critical Issues

The proximity operations of the spacecraft at the asteroid are generally considered critical from the point of view of the operations, both ground-based and on-board (GNC). However, the mission profile has been designed in accordance with the findings of NEO-GNC ensuring the safe achievement of each sub-phase, mainly for Far Station keeping, SSTO, transfers, and D&L. The output of NEO-GNC is a prototype of the GNC system with TRL 4. The emphasis is on cost reduction while assuring a high level of safety. Moreover, if the spacecraft is injected in SSTO over the asteroid and the observation of a particular area that is not available from SSTO is needed, there are two possibilities: fly-over or hovering above the region of interest. Both techniques are possible with the GNC design.

4 MODEL PAYLOAD

4.1 Overview of proposed payload

As requested for an M class mission, the proposed instruments (Table 7) are based on existing/under development technologies (TRL ≥4), and have already been assessed as a result of the assessment study phase of the former Marco Polo Mission in 2008-2009; details of the payloads can be found in the resulting Payload Definition Document (PDD, ESA/ESTEC, SCI-PA/2008).

Table 7: *Overview of the nominal payload complement and main resource budgets.*

	Wide Angle Camera (WAC)	Narrow Angle Camera (NAC)	Close-Up Camera (CUC)	Visible Near Infrared spectro. (VisNIR)	Mid-Infrared spectro. (MidIR)	Radio Science Experiment (RSE)	Neutral Particle Analyser (NPA)
Mass [kg]	2.0	8.92	0.82	3.6	3.0	Contained in the resources of the radio subsystem	2.2
Volume [mm]	237x172x115	520x380x197 250x170x120	364x78x68	270x110x90 150x180x82	160x220x370	Contained in the resources of the radio subsystem	200x200x100
Power [W] average	11.5	13.5	12.5	18	2		11
Data volume single measur.	67 Mbit	67 Mbit	67 Mbit	0.45 Mbit	360 Mbit	Data recorded in the ground station in real time	0.72 kbit
Heritage	Rosetta, ExoMars, ISS, Bepi Colombo	Rosetta, ExoMars, ISS, Bepi Colombo	Rosetta, ExoMars, ISS, Micro-rover (ESA)	Mars/Venus Express, Rosetta	SMT, TechDemSat		Bepi Colombo

4.2 Summary of each instrument's key resources and characteristics

4.2.1 Wide Angle Camera (WAC)

Images provide important information on the morphology and topography of the NEA surface and are necessary to choose the landing site. WAC imaging will provide the data:
- to obtain the first bulk characterization of the NEA (size, shape, rotational properties) during cruise phase
- to map the entire surface
- to identify the landing site (elaboration of a Digital Elevation Model)
- to map the secondary of the baseline target or search for moonlets in the other cases
- to support spacecraft navigation.

The WAC is a small-aperture camera for the visible wavelength range providing wide angle low resolution images of the target (or other fields).

Filter optics are not required although it is possible to include them. The same detector system is used for the NAC and the CUC design.

Wide Angle Camera (WAC)	
Mass: 2.0 kg	**Volume:** 237x172x115 mm^3
Detector: APS	**Data volume single measurement:** 67 Mbit
FoV: 11.2 deg	**Power:** 11.5 W

OBDH: The baseline for the command and data management is an integrated approach for the WAC, NAC and CUC into a single Command and Data Processing Unit. The three cameras are complemented by a general electronics package (for voltage, power, harness).
Co-alignment: Knowledge of accurate alignment with the WAC is required for other imaging and spectroscopic instruments.
Operating modes: The WAC will be used for:

- nadir pointing for body shape imaging and rotation monitoring
- limb pointing for special applications like shape model details and activity search
- any pointing direction for in-flight calibrations and special applications at the target (satellite search) and for navigation purposes.

WAC operations are performed in quasi-continuous and snapshot modes at the target. Full orbit operations must be possible.

Pointing requirements: The WAC optomechanics plus detector are fixed nadir-pointing.

4.2.2 Narrow Angle Camera (NAC)

The asteroid is intrinsically a dark object. The low contrast resulting from the low albedo makes it difficult to obtain high contrast images that are necessary to study the regolith properties well. A high contrast image can be obtained only if the optical contrast performance of the camera, including the residual diffraction contribution, is very high. One of the main scientific objectives of the NAC is the generation of the Digital Terrain Model (DTM) of specific regions, in particular of the potential and the actual sampling area. The NAC optical design is based on an off-axis three mirror anastigmatic configuration which follows the heritage of the OSIRIS cameras for the Rosetta mission. According to preliminary calculations it is not necessary to have a panchromatic filter covering the entire spectral range. One filter with broad-band coverage of 100 nm, and up to 7 filters with bandwidths of 5-10 nm provide coarse spectral resolution for composition/colour diagnostics. Their central wavelengths will be selected according to specific scientific simulations.

Narrow Angle Camera (NAC)	
Mass: 8.92 kg	**Volume:** 520x380x197 mm^3 250x170x120 mm^3
Detector: APS	**Data volume single measurement**: 67 Mbit
FoV: 1.7x1.7 deg	**Power:** 13.5 W

OBDH: See WAC.

Co-alignment: Knowledge of accurate alignment with the WAC, and therefore with other imaging and spectroscopic instruments is desirable.

Operating modes: The NAC will be used for:
- nadir pointing during global mapping;
- nadir and off-nadir pointing (0-60 deg) for the DTM application of the target;
- limb pointing for special applications like shape model details and activity search;
- any pointing direction for in-flight calibrations and special applications at the target (satellite imaging).

NAC operations are done in quasi-continuous and snapshot modes at the target. Full orbit operations must be possible.

4.2.3 Close-Up camera (CUC)

Images acquired with a close-up camera are needed to perform the local characterization of the sampling site. Images must be taken before the sampling to study the surface structure (i.e. the arrangement of larger and smaller particles and dust). The structural property of the surface will likely be destroyed during the sample acquisition. Images of the sampling site after the sample collection will allow an estimate of the friction coefficient of the regolith from observations of slumping of material. The CUC is a compact imaging device for the 400-900 nm wavelength range designed for microscopic resolution (better than 100 nm).

Close-Up Camera (CUC)	
Mass: 0.82 kg	**Volume:** 364x78x68 mm^3
Detector: APS	**Data volume single measurement**: 67 Mbit
Wavelength range: 400-900 nm	**Power:** 12.5 W

The instrument consists of three key components: (1) optics, (2) a multi-colour illumination device, (3) a hybrid APS detector with readout electronics (similar to those used with the WAC and NAC). Furthermore, due to the intrinsically small field depth of microscopic designs, a focusing device is needed. The current design uses a linear translation stage that moves the lens with respect to the focal plane.

OBDH: see WAC.

Operating modes: The CUC will operate before and after each sampling operation. WAC and NAC are assumed to be out of operation while the CUC images are taken at the surface of the asteroid.

4.2.4 Visible Near-Infrared Spectrometer

Spectroscopy in the VisNIR range is a powerful technique for the characterization of the chemical and mineralogical surface composition. The proposed instrument (Figure 11) is a classical slit imaging spectrometer composed of a reflecting telescope imaging the scene at the entrance slit of the spectrometer.

Visible Near-Infrared Spectrometer	
Mass: 3.6 kg	**Volume:** 260x128x84 mm^3
Power: 18 W	**Data volume single measurement**: 0.45 Mbit
Spectral resolution: 200	**Wavelength range:** 0.4-3.3 μm

On a 2D detector, this kind of imaging spectrometers records a 1D image and a full spectrum of each point of the 1D image. Either the motion of the spacecraft with respect to the asteroid or a scanning mirror is needed to recover the second spatial dimension.
Electronics: ASIC and FPGA
Operating modes: Internal spectral calibration system using Fabry-Perot, allows checking the spectral registration before each session. The scanning system is used to point the calibration device. External calibration by pointing at stars and the Moon is foreseen after launch. The instrument can observe at all operation phases.
Thermal constraints: the typical detector temperature will be 150 K.

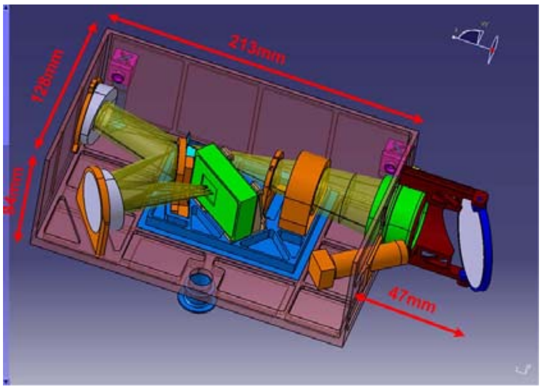

Figure 11: *VisNIR spectro. optomechanical scheme.*

4.2.5 Mid-Infrared Spectrometer

The Mid-Infrared spectrometer analyses the thermophysical properties of the surface (thermal inertia) by measuring changes in thermal emission due to the day/night temperature cycle. It provides information on surface mineralogical and chemical composition and the combined results are important in addressing sample site selection.

The proposed instrument is an imaging Fourier transform mapping spectrometer utilising a beam-shearing interferometer to generate a set of spatially resolved interferograms that are imaged onto a detector array. This allows spectral image cubes of the target body to be measured. The instrument uses a mid-infrared beam splitter and all reflective optics to image the interferogram onto a 640x480 micro-bolometer array.

Mid-IR Spectrometer	
Mass: 3.0 kg	**Volume:** 160x220x370 mm^3
Power: 2 W	**Data volume single measurement**: 360 Mbit
Maximum resolution: 10 cm^{-1}	**Spectral range:** 400-2000 cm^{-1} (5-25 µm)

Operating modes: The target is mapped by scanning the 480 cross track pixels across the surface. To maximise signal to noise, the measurements along the 640 pixel axis do not correspond to the same point on the target. Instead these must be scanned to assemble the interferogram of each single point.

4.2.6 Neutral Particle Analyser (NPA)

The NPA is designed to detect neutral particles released from the asteroid's surface and to investigate the effect of space weathering. Discrimination of the major components of the escaping flux will add important information also on surface composition. Detecting and characterizing neutral atoms in the energy range of interest, <1.0 eV to 1.0 keV, in an environment of photon, electron and ion fluxes, requires 1) highly effective suppression of photons, electrons, ions, and 2) two sensors for particles above and below 10 eV. The incoming radiation made by neutrals, ions and photons impinges upon an aperture. The ions and electrons are deflected by an electrostatic lens before the entrance. The neutral particles pass through an entrance of about 1 cm^2 divided for detecting both low energies and higher energies separately.

Neutral Particle Analyser (NPA)	
Mass: 2.2 kg	**Volume:** 200x200x100 mm^3
Power: 11 W	**Data volume single measurement**: 0.72 kbit
FoV:5x30°	**Angular resolution of the high energy distribution:** 5x2.5° (high ang. res. mode) 5x5° (low ang. res. mode)

Operating modes: The FoV will be oriented towards the target surface. Hence, the spatial resolution on the target surface can be computed via the angular resolution and the distance between the spacecraft and the target.

4.2.7 Radio Science Experiment (RSE)

Radio Science will use the radio subsystem of the main spacecraft for its observations. The goal is to derive the mass of the target body and if feasible low order gravity harmonics by observing the Doppler shift of two downlink radio carrier frequencies at X-band and Ka-band caused by the perturbation of the spacecraft motion.
Operating mode: each time the spacecraft is tracked from ground, the radio signal may be recorded in the two-way mode at X-band uplink and X- and Ka-band downlink.
Pointing requirements: the HGA needs to be pointed to Earth.

4.2.8 Optional laser altimeter

A Laser altimeter measures, with high precision, the distance of the spacecraft from the surface of the NEA. The instrument will measure the two-way travel time of a pulse between the instrument and the surface. A topographic profile along the ground track of the spacecraft will be produced from which a global shape model will be derived (in conjunction with WAC and NAC images). By measurements of pulse amplitude and shape, the reflectivity of the surface, as well as slope and surface roughness (within the footprint of the laser) can be modelled. Laser altimeter also provides information on the gravity field and the position of the centre of mass.

The suggested instrument is based on BELA (BepiColombo Laser Altimeter) but with performance parameters specifically designed for MarcoPolo-R. This will reduce the size, total mass, and required power compared to BELA.

Laser Altimeter	
Mass: 4.0 kg	**Volume:** 150x100x100 mm^3
Power: 22 W	**Data volume single measurement**: 80 bit/shot

Orbit, operations and pointing requirements: The instrument will operate during approach to the asteroid and during the spacecraft orbit phase. It will typically fire at a rate of 1 Hz, which ensures a seamless ground pattern in the along-track direction.

Night and day observations are equally possible. The divergence of the laser beam is 200 µrad, which results in a laser spot diameter of 1 m at a range of 5 km. At lower ranges, the footprint decreases below 1 m and the pulse repetition rate will be increased in order to obtain the seamless along-track spacing, which results in a finer grid spacing, e.g. 0.1 m from 1 km range.

4.3 Optional lander and associated payloads

4.3.1 Lander

The Lander package (Tables 8 and 9) has the means to characterize physical properties (*e.g.* electrical, magnetic, thermal) of the landing site, as well as the surface and subsurface fine structure and composition (elemental, mineralogical, molecular). Complementary data from a lander science package can address questions such as: are the returned soils and rocks representative of the bulk of the parent body? What are the macroscopic physical properties of the terrain from which the samples have been extracted?

Table 8: *overview of Lander*

Mass [kg]	10.3 *
Volume [mm]	300x300x250
Power [W] average	10 (cruise ops)
Data volume single measurement	800 Mbit for overall mission
Heritage	MASCOT, Philae

** Excluding 2 kg for mechanical and electrical interfaces on the orbiter.*

A Lander could also act together with the spacecraft to support the global characterization of the asteroid, e.g. by microwave sounding, and thus, enhance our understanding of the formation process of the target.

The proposed surface package would have an overall mass in the range of 10 kg including about 3 kg of scientific payload (Table 9). Such a design is scalable to some extent (allowing trade-off between mass of lander and orbiter instruments). The package would be delivered by the mother spacecraft to the asteroid surface. During cruise it would be connected via an umbilical for power supply and communications link. This strategy is applied e.g. for Philae, the Rosetta Lander (Ulamec and Biele 2009).

Table 9: *Lander mass break down.*

Element	mass [kg]
Structure	2.9
Thermal Control	0.4
Mobility mechanism	0.4
Communications	0.4
CDMS	0.5
Power (incl. battery)	1.0
Payload	3.0
Margin (20%)	1.7
Total	10.3

Delivery to the asteroid surface is planned by a fairly simple spring ejection (Δv in the 5 $cm.s^{-1}$ range), no velocity adjustment (as for Philae) nor spin eject needs to be applied. The "impact speed" of the lander must be well below the asteroid's escape velocity (actually all velocities involved are low and consequently accelerations and shock loads are non-critical from a structural point of view; however bouncing is an aspect to be considered). Communications will be relayed via the spacecraft (no direct link to Earth). The data rate and volume are dependent on actual payload and mission timeline. For the proposed scenario an S-band or alternatively UHF solution is assumed.

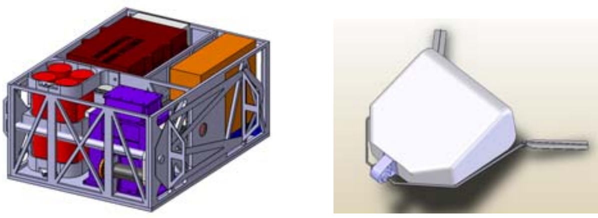

Figure 12: Possible Lander designs. Left: *design taken from a study (MASCOT, completed phase A, TRL=3); right: concept for alternative hopper (Ulamec et al. 2010).*

Although a 10 kg lander does not offer a large degree of flexibility regarding its technical complexity, different lander types can be adopted, such as a stationary or a mobile lander. In effect, due to the very low gravity on the surface of the asteroid, mobility can be achieved with mechanisms of very low mass and complexity. The investigation of several landing sites will characterize the degree of heterogeneity of the surface. Recent studies analysed various concepts for hoppers in the 10 kg range. Examples of two possible designs of either a stationary or a hopping lander are given in Figure 12. The design of the stationary lander is based on a box-like structure, containing all subsystems (including a primary battery allowing 16 hrs of on-surface operations).

4.3.2 Lander payloads

A lander in the 10 kg mass range could support a scientific payload of up to about 3 kg, including:
a) *Camera system* - A wide angle camera would provide the geological and general context for the MarcoPolo-R lander environment in addition to supporting the system (orientation, localisation, navigation during hopping). Surface features of the landing site from the mm (close up) to m (horizon) size would be investigated.
b) *Laser Induced Mass Spectrometer (LIBS)* - A LIBS measures the abundances of elements of the asteroid surface and would allow rock-type as well as mineral identification. Element concentrations from a few ppm to 40wt% can be measured with a lateral resolution of 50 µm. The instrument does not require particular sample preparation and is, by its design, capable of removing dust layers prior to the actual measurement. Laser ablation even allows depth profiling to a certain extent (down to a few 100 µm). The instrument uses a high power laser (e.g. Nd-YAG) beam focussing on the sample and generating a local plasma. As the plasma cools down it emits light with characteristic spectral lines, detected with a CCD detector (see as example Figure 13).

Figure 13: *Nd-YAG Laser of LIBS prototype for ExoMars, Pasteur.*

c) *Infrared/visible microscope* - An instrument imaging over an area of a few millimetres with an optical microscope as well as a hyperspectral IR imager (0.5 to 2.6 µm) will characterize rocks and minerals with a spatial sampling of a few micrometers.
d) *Thermal Probe* - Characterization of the thermal properties of the asteroid surface material is important in comparison between in-situ and returned samples and have implications for the quantification of Yarkovsky and YORP effects.
e) *Bi-static Radar Tomographer* – Using tomography techniques a radar can provide information on the target internal structure (monolithic/rubble pile/statigraphy). Figure 14 shows the measurement concept of a radar tomographer, based on the CONSERT-Rosetta instrument.

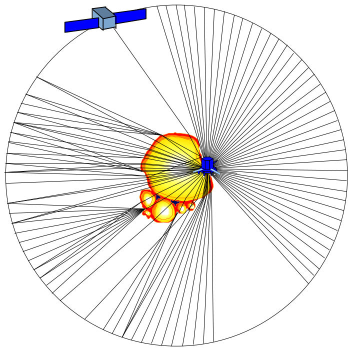

Figure 14: *Principle of bi-static radar tomographer (from CONSERT-Rosetta).*

Radiowaves are transmitted between lander and spacecraft. During an orbit (or asteroid rotation underneath the hovering spacecraft) the asteroid is scanned. Several such scans will allow three-dimensional modelling of the asteroid. The instrument consists of one unit aboard the lander plus a similar unit on the spacecraft.
Table 10 shows a possible instrument combination that can be accommodated aboard the lander.

Table 10: *Mass breakdown of possible payloads.*
** For the radar tomographer an additional 1.2 kg is required on the orbiter.*

Instrument	Mass
Camera	0.4 kg
LIBS	1.2 kg
Vis/IR microscope	0.7 kg
Radar	0.7 kg *
Thermal Probe	0.2 kg

4.3.3 Specific environmental constraints

The lander would be connected to the spacecraft by an umbilical during cruise. Heating power of 4.5 W is required constantly to keep the package at acceptable non-operation temperatures (> -40°C). During cruise and pre-separation activities also communications will be performed via this umbilical. Although separation requires a dedicated manoeuvre by the spacecraft, it will not place additional requirements on GNC performance as compared to the sampling activities. Communications with the landed package are relayed via the spacecraft. A dedicated RF communication unit is consequently required, in addition to the mechanical interface, staying on the orbiter.

4.4 Optional Seismic experiment package

The interior of the target asteroid can also be studied by an active and passive seismic experiment. The experiment is designed with a single type of sensor but in two configurations. The first seismic sensor will be deployed and serviced by the MarcoPolo-R lander. Note that in this case, a lander of about 14 kg will be necessary to host both the payloads described in Section 5.3 and the seismic sensor. It will perform long term monitoring during the lander's life time.

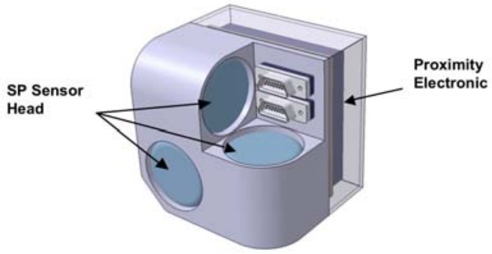

Figure 15: *Geophone package: size is 67x60x60 mm^3 and mass is 600 g including 20% margin. It encloses the 3 geophones and the proximity electronics.*

This seismic sensor (Figure 15) will be deployed jointly with thermal sensors and can use a deployment spike. The second type of seismic sensor will be mounted onboard a small autonomous egg which will be released from the orbiter to the asteroid surface. This egg has a mass of about 3.5 kg, with a battery power system compatible for one day of cumulative operations, transmitting the data to the orbiter. It will be ejected from the orbiter by a spring device for a free fall onto the asteroid surface. It will include a charge of about 250 g that will be activated upon command to generate an active seismic source. The activation will be done by electrical discharge, the latter being inhibited prior to eggs deployment and performed by a timer activated at the separation. The full mass is provided in Table 11.

Table 11*: Mass breakdown of sub-systems of the seismic experiment.*

Sub-system	Mass (kg)
Egg	3.5
Egg deployment	0.5
Lander sensor head and digital electronics	1.0
Lander sensor deployment system	1.0
Total orbiter (+margins)	4.0 (+ 1.0)
Total lander (+margins)	2.0 (+ 0.5)
TOTAL including margins	7.5

The science goals of the seismic investigation are:
• to characterize the seismic efficiency and quantify the mass of ejecta through measurement of the amplitude of the ground acceleration;
• to constrain the efficiency of seismic shaking (e.g. Richardson et al, 2005) and improve asteroid surface age determination;
• to provide information on the deep interior and shallow surface of the asteroid.

4.5 Current heritage and TRL of optional payloads

The TRL of the MASCOT lander is 3 (completed phase A) and all its instruments described in the previous section have TRL between 5 and 6. All components of the seismic experiment are based on high TRL: sensor electronics are based on the SEIS-Humboldt electronics (TRL>5), geophones sensors are qualified for harsh environments (including launch) and are furthermore in qualification process for radiation (TRL>4), batteries have flown on Rosetta and the UHF system has flown on small nanosats (TRL>6).

4.6 Curation Facility

While spacecraft operations end once the ERC has safely returned the samples to the surface of the Earth, a major phase of the overall mission remains before the sample science phase in the community can commence. Many different laboratories across Europe and around the world will be required to undertake the full range of studies necessary to answer the scientific questions MarcoPolo-R seeks to address. This demands that carefully selected portions of the returned material are identified and distributed to appropriate laboratories. In order to achieve this, a sample Receiving and Curation Facility is an essential element of the mission, and is required for the long term archiving of such a valuable resource.

First and foremost, the facility must guarantee to preserve the sample in its pristine condition, avoiding chemical and physical alteration of materials by the Earth environments in order that none of the key analyses are compromised, ensuring the highest scientific return. The key activities of the facility are to provide:

- secure and appropriate long term storage,
- preliminary characterization of the sample,
- preparation and distribution of sub-samples,
- accurate documentation of the samples

Security - The returned samples will command very high scientific and public interest. Therefore, high levels of protection against natural events and theft are essential aspects of the Curation Facility. However, the location and security must also permit ready access for visiting scientists, required to aid sample characterization and selection. No bio-containment of the sample is required as MarcoPolo-R will only be a COSPAR designated "unrestricted" sample return mission.

Contamination Control - In order to preserve the samples in the same condition as when collected, it is essential to strictly limit the addition of terrestrial materials through the selection of materials and control of the ambient environment the samples experience. Key parameters that must be controlled are exposure to particulate material, volatile organics and moisture. All storage and initial handling and characterization of materials will need to be conducted in Class 4 (ISO 14644-1) environments under moisture-free inert gas atmospheres (Ar or N_2) and low levels of volatile organic compounds. In order to provide the appropriate environments for all the activities, a suite of clean laboratories are required for sample receiving, handling, and storage, as well as support labs for preparation and additional characterization.

A range of continuous monitoring and witness plates are required to ensure that the environment conditions are maintained.

Sample Storage - A fraction of the returned sample will be preserved for posterity – which can be best achieved under high vacuum. The remainder of the sample will be stored in a clean environment with a controlled atmosphere composed primarily of inert gas (argon or nitrogen). As multiple operations on any one sub-sample will likely be common, an integrated sample storage and handling area is required in order to ensure that samples are not cycled through different conditions. In order to access the large number of sub-samples that will result from a sample of NEA regolith and stored under inert gases, robotic handling of the sample is required in the main storage area.

Sample Characterization - The returned sample will be heterogeneous, containing a variety of different lithologies from the parent asteroid. Prioritization of analysis sequences for any one sub-sample, or even if a sub-sample may be appropriate for any specific analysis, requires some knowledge of its mineralogy and composition (*e.g.* organic rich material may be prioritized for organic studies, low aqueous alteration for interstellar grain and early solar-system studies, *etc*.). Non-destructive and non-contaminating analytical tools will be required within the cleanest areas of the sample Curation Facility:

- Optical microscopes - for initial overview;
- FTIR/Raman spectrometer microscopes – for characterizing mineralogy and organics;
- High precision balances – for sample mass.

Additional analytical facilities (FIB-ASEM, GC-MS and XPS) will be required within the Curation Facility to support aspects of the sample preparation and operation of the facility:

Sample Preparation - Many of the analytical techniques employed by the scientific community demand special preparation of the sub-samples – *e.g.* polished sections, homogenized powders, electron transparent sections. Preparation of such samples must be performed within the Curation Facility in order to ensure optimum use of materials and control of contamination.

Documentation - Detailed descriptions of each fragment within the sample will be generated by the Curation Facility for distribution to the scientific community in order to facilitate sample requests. The facility will be required to document all activities for each part of the sample, including all movements and processes within the facility and to track and monitor usage and movement once allocated. A database will manage the vast amount of information associated with these tasks, and feed a sample catalogue that will be readily accessible to the scientific community.

Sample Analyses - It is anticipated that virtually all scientific studies of the samples will be conducted by the dispersed analytical laboratories in Europe and around the world. However, a number of important analyses are particularly susceptible to terrestrial contamination – particularly those involving biologically important molecules likely to be present in low abundance in the samples and those relating to the nature of any aqueous alteration the samples may have experienced. In such cases some additional sample preparation and/or analyses should be undertaken within the sample Curation Facility to minimize sample contamination. Examples include:

- Extraction and concentration of some soluble organics (*e.g.* amino acids, nucleobases);
- Analyses of some soluble organics (upgraded of support GC-MS systems);
- Isotopic measurements (O and H) of alteration products (requires isotope mass spectrometer);
- Characterization of alteration mineralogy (TEM).

Considerable expertise exists within Europe for the curation and distribution of sensitive extraterrestrial samples – e.g. numerous large national meteorite collections (e.g. London, Paris, Vienna, Berlin), Antarctic meteorite collections (e.g. Milton Keynes, Siena) and cosmic dust collection programs (e.g. Paris, Aix-en-Provence, Siena).

Presently, no single facility exists within Europe that has the capability to curate, characterize and distribute returned samples in the way required for this mission. In addition to the samples from the NEA, the Curation Facility will act as a repository and distribution centre for a further two sets of material that will be important in confirming that the samples have not been affected by contamination. The first set is of materials collected during the construction of the spacecraft that may contribute volatiles or directly contact the sample. The second set is of witness plates recording the sample collection process and sample storage that will be returned by the ERC along with the NEA sample.

The new ESA centre at Harwell (UK) contains a proposed sample receiving facility (as part of Mars sample return), although a decision on whether this will go ahead (or indeed if it is appropriate for an asteroid sample return) has not yet been finalized and alternative sites within Europe may be equally viable.

5 SYSTEM REQUIREMENTS AND SPACECRAFT KEY ISSUES

The MarcoPolo-R system requirements and drivers are derived from the mission science objectives:

- Sample-return mission: The key science driver is to return a sample of at least a few 10s of grams; this drives the mission profile, specifically the number of mission phases and their type.
- Target: the selected asteroid will drive the trajectory and Δv required for the mission and also impact the power and communications system design, with the corresponding implications in terms of equipment selection, mass and cost.
- Asteroid characterization: the required remote sensing activities drive the operations schedule, observation orbit selection, data volume and thus communications subsystem sizing.
- Sampling: the selected sampling collection and transfer concept will drive the spacecraft design and operations. The need to perform landing operations is a major driver in the GNC design.

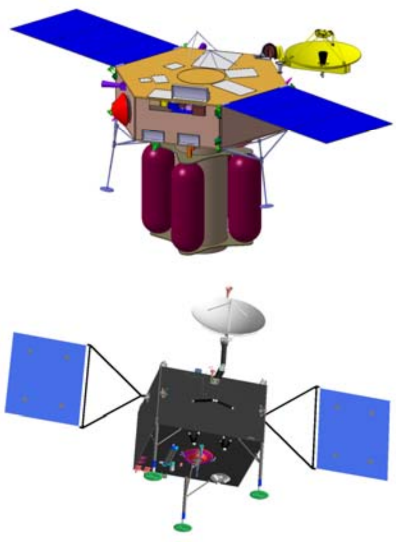

Figure 16: *Main Spacecraft designs from Marco Polo assessment study by Astrium (top, with propulsion module) and OHB (bottom).*

The science priorities and mission requirements for MarcoPolo-R can be met by a large number of mission architecture options which will need to be carefully analysed and traded-off to select the optimal baseline. A preliminary analysis based in part on the results of the previous Marco Polo assessment study has led to a feasible reference solution. Spacecraft designs suggested by Astrium and OHB are shown in Figure 16 (see Marco Polo Yellow Book, ESA/SRE (2009)3), for details of proposed designed, including a third by Thales Alenia Space). In the following we use as an example the solution by Astrium, although a much more detailed analysis is expected to be carried out in the future.

5.1 Attitude and orbit control

5.1.1 Propulsion Subsystem

The suggested propulsion subsystem in the Astrium design consists of two parts: a bi-propellant propulsion module using a main 400N engine, to perform the outbound transfer and manoeuvre corrections up to the asteroid (total $\Delta v \sim 2.8\ km.s^{-1}$); and a mono-propellant system using 22N thrusters, which is part of the science module, responsible for the asteroid operations and inbound transfer (total $\Delta v \sim 0.5\ km.s^{-1}$). This staging approach results in duplication of some hardware but the associated propellant mass savings enable the spacecraft to be launched with Soyuz. Use of mono-propellant in the vicinity of the NEA also reduces impact of any uncontrolled contamination of the surface/sample.

The propulsion module design shown in Figure 17 uses off the shelf components including the Eurostar 2000++ tanks. The proposed configuration is based on the design for the LISA Pathfinder PRM.

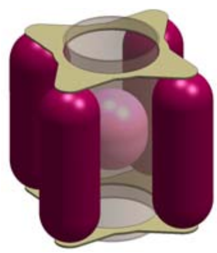

Figure 17: *Overview of tanks arrangement and support structure for the propulsion module (Astrium).*

5.1.2 Guidance, Navigation and Control (GNC) Subsystem

A classical ESA approach (i.e. Rosetta) is envisaged for the interplanetary transfer. MarcoPolo-R would have a 3 axis-stabilised spacecraft, with a combination of reaction wheels and thrusters as actuators and Sun sensors. For navigation, the sensors suite includes redundant star-trackers, WAC, and a set of radar altimeters, covering all phases of the mission.

In order to provide full 3-DoF control for the science module, sixteen (2 sets of 8 thrusters, one for redundancy) 10N thrusters will be used for correction attitude manoeuvres during the science phase. Attitude thrusters will also be needed during the composite mission phases and for these operations eight (4 prime and redundant) 22N thrusters will be used on the propulsion module.

5.2 Space Segment Mass Budget

For the prime and backup missions (2021 and 2022 launch years, see Table 5) proposed to 1996 FG3 the space segment requirements are very similar. A preliminary mass budget for the worst case back-up mission, including a propulsion module, is presented in Table 12.

Table 12: *Preliminary mass budget summary*

Sub-system	Mass (kg)	Margins
Science Spacecraft		
Structure	83.3	
Thermal Control	28.4	
Sampling system	34.7	
Capsule spin-ejection mechanism	7.4	
Earth Re-entry Capsule	27.5	
Other mechanisms	27.2	
Communications	28.2	
Data Handling	21.2	
AOCS	41.3	
Propulsion	41.4	
Power	83.5	
Harness	36.5	
Science instruments	20	
Main spacecraft nominal mass	480.6	
Spacecraft total dry mass	**576.7**	**20%**
Pressurant + propellant mass	118	20%
Spacecraft total wet mass	**694.7**	**20%**
Propulsion Module		
Structure	214.6	
Propulsion	144.4	
Total dry mass	359	
Prop. Module total dry mass	**430.8**	**20%**
Pressurant + propellant mass	1830	20%
Prop. Module total wet mass	**2260.8**	**20%**
Total composite wet mass	**2955.5**	**20%**
Adapter mass	54	20%
Launch mass (including adapter)	**3009.5**	**20%**
Launch vehicle performance	3200	
Launch margins	**190.5**	**6.0%**

The total launch mass of 3009.5 kg (including 20% system margins) is compatible with the Soyuz capability into GTO of 3200 kg resulting in a launch mass margin of 6%.

Another mission design (OHB) leads to a different mass budget, that does not involve necessarily a propulsion module. Although an accurate estimate cannot be provided at this stage, the design is similar to that proposed for Marco Polo (see ESA/SRE (2009)3).

The assessment study will improve the accuracy of the whole mission design.

For the baseline target 1996 FG3, differences with the former Marco Polo scenario concern essentially the Δv, re-entry velocity, and mission duration, and a mass increase that remains within the launcher capability, including margins.

5.3 On-board data handling and telemetry

The on board data handling system will consist of an on-board computer, a mass memory system and the electronics necessary to communicate with and control the spacecraft.

The estimated memory capacity required is around 500 Gbit, which would lead to a real implementation of mass memory of 1.2 Tbit as outlined in the previous assessment study.

The ground system assumed for the mission uses the DSN. A 35 m ground station is baselined for nominal operations with availability for eight hours per day during proximity operations. A 70 m ground station can be made available in case of emergencies.

The requirements for the MarcoPolo-R communication subsystem include: telemetry and telecommand during all mission phases; peak data downlink during the remote sensing phase; navigation images during characterization and proximity operations and in-situ instrument data.
The remote sensing phase is the most demanding in terms of required data rate. Therefore, the sizing of the communication subsystem is driven by the data rates and volume of that phase (see Table 13). For the appropriate range of distance of the spacecraft to the Earth, during the proximity operations, assuming an HGA of diameter 1.36 m and a high output power transponder a data-rate of 22 kbps can be sustained in X band.

The baseline communication hardware includes a prime and redundant LGA, providing omni-directional coverage for LEO phase; a steerable HGA, responsible for the main data transmission; and an MGA, providing useful telemetry during descent and landing and emergency communication in safe mode with a reasonable-sized DSN antenna.

Table 13: Example of remote-sensing data rates and volume for a campaign of 27 weeks over the asteroid

	Total Compressed Data Volume [Mbit]	Total Compressed Data Volume [Gbit]	Duration of Campaign [weeks]	Duration of Campaign [days]	Average Production Data Rate [kbit/s]	Average Data Rate [kbit/s] for 10h/day G/S Availability	Average Data Rate [kbit/s] for 8h/day G/S Availability	Average Data Rate [kbit/s] for 6h/day G/S Availability
Far Characterization	5311.2	5.3	2	14	4.39	10.54	13.17	17.56
Global Characterization	380222.7	380.2	12	84	52.39	125.74	157.17	209.56
Local Characterization	6279.4	6.3	5	35	2.08	4.98	6.23	8.31
Gravity Field Campaign	9004.3	9.0	8	56	1.86	4.47	5.58	7.44
Remote Sensing Total	**400817.58**	**400.82**	**27.00**	**189.00**	**24.55**	**58.91**	**73.64**	**98.18**

5.4 Estimated overall resources (power subsystem)

The distance to the Sun during the proximity operations phase is between 0.7 and 1.42 AU, with the solar constant ranging between 2794 and 698 W.m^{-2}. This leads to a significant solar array area of ~10 m^2. There is no credible alternative to solar arrays in Europe in the mission timescale, so a large area of solar arrays will have to be accommodated. This will have implications for the spacecraft configuration.

Lithium Ion batteries are selected as the baseline. The sizing case (descent, sampling and ascent manoeuvres) leads to an energy requirement of 750 Wh resulting in a total battery mass of approximately 10 kg.

5.5 Specific environmental constraints (thermal system)

The thermal environment of the spacecraft is influenced by radiation from the Sun and the asteroid (and Venus during the transfer phase). The most demanding phase for the thermal system is the landing phase where the spacecraft could need to operate on a surface at 190°C.

The proposed thermal design makes use of MLI to isolate the spacecraft from the hot thermal environment, with some radiators to dissipate heat in particular from exposed components. Heaters are also needed to maintain the spacecraft temperature when in a cold environment or to compensate for any equipment which is not operating.

5.6 Landing, sampling and transfer systems

There are a number of options for the landing and sampling systems and the selected option has a strong influence on the overall spacecraft design.

For the landing, a simple leg design is proposed with a crushable damper integrated into each of the three legs, which corresponds to the design proposed by Astrium during the former Marco Polo assessment study phase (ESA/SRE (2009)3).

The Sampling, Transfer and Entry (STE) subsystem is responsible for the acquisition, verification, transfer, and containment of the sample from the asteroid to the surface of the Earth. The key elements of the STE are: (1) two block redundant arms with Brush Wheel Sampler (BWS) end effectors and (2) an ERC. All of the STE hardware is mounted on a single panel of the spacecraft as seen in Figure 18.

The ERC is comprised of a vault in which the sample canister is inserted prior to Earth return, and a capsule which facilitates a safe sample return during Earth entry and landing. The ERC is mounted to the spacecraft via a Hinge Latch device that allows the ERC to be opened for sample canister insertion by both of the block redundant arms with the SAS.

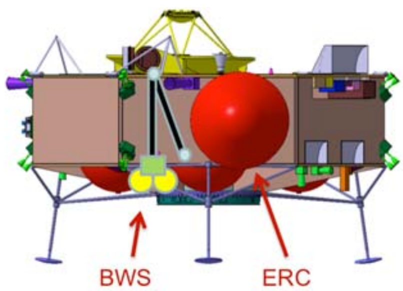

Figure 18: *Arm, ERC, and BWS in stowed position.*

All components are secured to the spacecraft via pyrotechnic launch locks and are released after the launch. The 3-DoF robotic arm is reconfigured to its nominal deployed position (Figure 19) in preparation for sampling operations. A contamination shield is jettisoned from the BWS before landing.

The arms are made of aluminum and designed to tolerate surface contact and ascent burn plume impingement. Electrostatic discharge problems during contact will be mitigated by standard practices such as using conductive and grounded exterior spacecraft surfaces, and sampling in sun-light, where photoelectron emission will reduce potential differences to a few volts, well below the electrostatic discharge threshold.

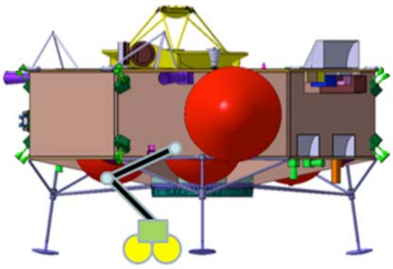

Figure 19: *BWS in deployed position for sampling.*

Once the sampling process is complete, the arm rotates to verify sample acquisition via cameras on the panel supporting the ERC. The BWS head is jettisoned after confirmation that the required sample has been acquired. This jettison event locks the canister, containing the sample, in a rigid axially aligned position on the end of the arm ready for insertion into the vault.

The ERC-mounted vault is based on the JPL-designed Genesis mission container and sealing design. A door on the canister is used only to ensure that the sample stays in the canister. The vault seal controls the contamination of the canister and sample once the canisters are inserted and the vault is sealed shut for Earth return. The vault is an integral part of the ERC and serves as the structural tie between the fore and aft-bodies. The vault remains sealed except during the time of canister insertion to mitigate contamination. Prior to canister insertion into the ERC, the vault seal is released and the ERC support structure hinge latch actuator opens the vault/ERC by separating the fore and aft-bodies as shown in Figure 20.

Once the canister is fully seated in the bottom of the vault via latches, the canister release actuator releases the canister from the arm. The arm is then commanded to retract out of the vault. The arm is then re-stowed, the hinge latch is closed, and the vault re-sealed.

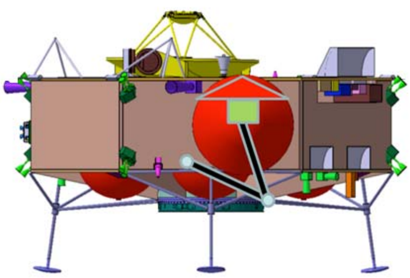

Figure 20: *Canister insertion into vault.*

When the spacecraft is ready to release the ERC, a pyrotechnic cable cutter severs the electrical connections between the spacecraft and the ERC. Once the ERC is disconnected, a spring is able to transfer its preload to the whole ERC. This release mechanism allows the spin-up of the ERC to 1-2 rpm and a separation velocity of 25 ± 2.5 $mm.s^{-1}$.

5.7 Sample Acquisition System (SAS)

The SAS is part of the STE subsystem and performs sample acquisition, verification, and transfer into the ERC from LaRC. The SAS comprises two arms (from JPL), each with a BWS (from JPL), 2 rock chippers (from APL), a sample canister with a sample verification mechanism, and hinge latch and spin eject mechanisms (all from JPL). The STE is integrated and tested as a system at JPL. After sample collection, the BWS is jettisoned allowing insertion of the sample canister into a vault within the ERC. After the canister is inserted, the vault is sealed, and the ERC is returned to UTTR.

The BWS has been designed and tested to collect the required sample in less than one second. Alternative collection approaches were studied, including sticky pads, drive tube coring, augers, projectile ejecta collection (as in Hayabusa's rock chippers), cutting wheels, scoops, drag line bucket and gaseous transport devices. The BWS with pyrotechnic rock chippers was selected as the most reliable sample collection approach given uncertainties in surface properties and contact conditions (relative velocity and positioning). It is moreover amenable to high fidelity verification and validation by testing and analysis.

Before sampling, the brush wheels are spun up, and the canister door opens, allowing entry of sample. The rotating brushes, designed to comply with the surface, sweep regolith into the sample canister through a 3 cm opening. The sample canister is shaped to create a vortical flow to dissipate particle kinetic energy and trap the sample. It has an internal volume of 700 ml, for a returned mass between 0.35 and 2.1 kg, depending on sample density. If the asteroid surface is assessed to contain no loose regolith, pyrotechnic rock chippers are fired during the sampling event. This determination is made prior to sampling and activated by ground command. The canister door is shut after two seconds of asteroid contact. The BWS can be reused in subsequent sample collections.

The BWS has been tested in air and in vacuum, in Earth gravity and in low gravity on the KC-135A, with many regolith stimulants, including one using the modified lunar regolith size distribution (Figure 21). Rock chipper testing with

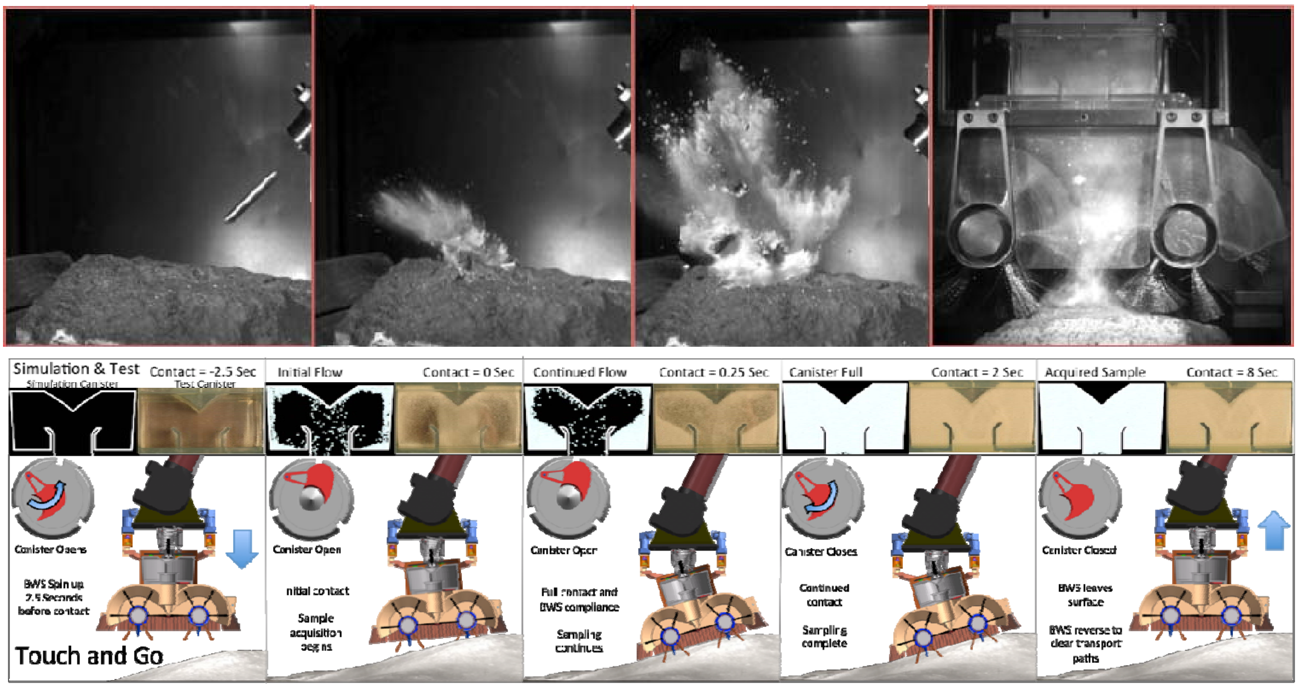

Figure 21: *Sampling: Top test with Rock Chipper and Brush Wheel Sampler and Bandelier tuff rocks; Bottom test, simulation, and diagram of BWS collecting lunar regolith simulant.*

an operating BWS has demonstrated the capability to generate and collect 15 g of sample per single rock chipper firing into Bandelier tuff rocks (two chippers are fired during a sample collection event). Testing has shown that sample collection by the BWS is largely insensitive to both gravity and atmosphere. JPL has developed and validated numerical models of BWS particle transport and collection dynamics. Testing and analysis confirm robust sample collection in flight-like and ground test conditions. Most verification and validation testing of the BWS will be done in gravity and ambient conditions.

5.8 Earth re-entry capsule (ERC)

The MarcoPolo-R ERC is derived from a unique NASA-developed, chute-less design (Mitcheltree et al. 2001) for Mars Sample Return. This design is optimized to meet MarcoPolo-R mission needs while preserving key characteristics for high reliability. These are: the elimination of all active systems, a well-understood forebody shape, and a well-characterized flight heritage thermal protection system (TPS). NASA LaRC will be responsible for the design, development, integration, test and delivery of the ERC. NASA ARC will partner with LaRC and be responsible for the design, development, and delivery of the ERC aeroshell element (TPS and carrier structure).

The ERC (Figure 22) has an axisymmetric external shape, and consists of a core (primary structure, impact system, etc.), TPS and carrier structure, and payload element (provided by JPL). A completely passive design, spin-stabilized at 2 rpm with no parachute, the total diameter is 0.9 m, and the maximum expected mass (including payload) is approximately 33 kg (including 20% contingency), for a ballistic coefficient at entry of about 72 kg.m^{-2}. The entry state assumed has a nominal inertial Entry Flight Path Angle (EFPA) near -10º velocity of 13.63 km.s^{-1}.

The ERC core consists of the primary structure, the impact foam, which supports the payload element, thermal insulation, spacecraft attachment hardware, and a small radio beacon. This beacon is self-contained, activated at landing using a g-trigger, and acts as a backup to visual and radar tracking of the ERC to determine its location at landing.

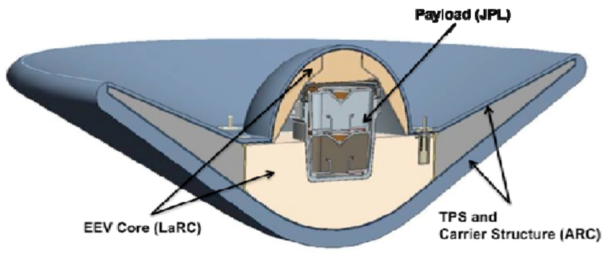

Figure 22: *Illustration of MarcoPolo-R ERC (cross section).*

The baseline ERC forebody TPS is unipiece PICA (Tran et al. 1996, 1997; Willcockson 1999). Manufactured by FMI (with ARC insight and oversight) for Stardust. It was flown in 2006 at entry heating conditions twice those expected by MarcoPolo-R. The unipiece PICA TPS will be manufactured to the same specifications as

Stardust, using components with traceability to Stardust, thus providing full flight heritage. After detailed analysis of the recovered Stardust PICA (Stackpoole, et al. 2008), both Orion and MSL (Beck et al. 2009) invested heavily at both ARC and LaRC to further improve the reliability of the PICA thermal response models and understand its thermostructural performance and material properties through extensive test and analysis. This gives PICA qualification heritage far beyond Stardust. If required, unipiece PICA could be manufactured up to a diameter of 1.2 m.

The ERC main seal/vent is located at the lid - aftbody TPS interface. The "breathing" design allows pressure equalization during ascent and entry, while eliminating hot gas ingestion during entry. To evaluate the overall performance of the ERC, a 6-DoF Monte Carlo analysis, considered expected dispersions in entry states (including attitude), aerodynamics (based on a database developed for Mars sample return, which also included data from Stardust and Genesis), vehicle mass properties, and atmosphere (including winds).

Sample mass is small compared to the total system mass, so sample loading has little to no impact on the ERC performance or landing footprint size. As sample mass decreases, the footprint moves up-range, with a maximum shift over the configurations considered of approximately 8.4 km. With proper targeting at UTTR, these variations are easily accommodated (Figure 23). Lateral center of gravity offsets due to uneven distribution of the sample have little effect on ERC performance or aerodynamic stability. All expected vertical center of gravity location variations remained within the limit needed to ensure sufficient subsonic stability.

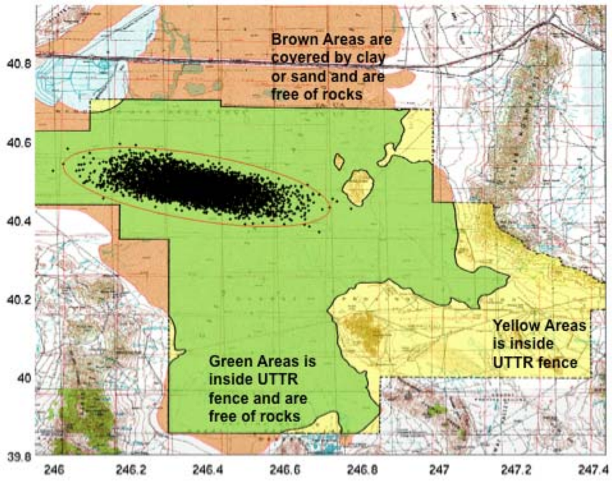

Figure 23: *Illustration of MarcoPolo-R ERC Landing Footprint at UTTR.*

The design of the ERC impact system provides ample margin to the 1500-g payload impact load requirement. Preliminary analyses examined two approaches to the impact dynamics problem: ground penetration and crushing. With ground penetration, it is assumed that the vehicle is sufficiently rigid such that all impact energy is absorbed through ground penetration, resulting in no crushing of the vehicle. Based on UTTR penetrometer testing performed by MSR (Fasanella et al. 2001), the MarcoPolo-R ERC would experience, at worst, approximately 520-g at landing. With a compressive strength of 1.7 MPa, the impact foam provides margin against the 1.3 MPa compressive strength required to ensure vehicle stiffness during ground penetration. If the vehicle were to instead experience an off-nominal impact near the maximum allowable load of 1500-g, crushing with no ground penetration is more likely to occur. An energy balance approach shows that the required stroke of the payload into the impact foam is 5.2 cm. With a stroke efficiency of 60%, the required foam thickness is 10.3 cm. The impact foam ensures meeting the payload landing load requirement if either ground penetration or crushing, or some combination of both, occurs.

The thermal design provides significant thermal insulation of the payload during the entry heat pulse, as well as post landing. For example, a 2-D axisymmetric thermal soak analysis using a design similar to that of MarcoPolo-R showed the maximum temperature of the sample canister interior surface during entry or after landing never exceeded 42 ºC, providing 28 ºC margin against the 70 ºC science temperature requirement, thus allowing for an indefinite period of time for recovery of the ERC.

TPS sizing was performed using a Mass Estimating Relationship Model, which was developed and validated against high fidelity, highly validated NASA-standard tools (DPLR, LAURA, NEQAIR). Aerothermodynamic environments are predicted by the NASA LaRC entry simulation, using models developed over many years, which are well validated against NASA ARC thermal analysis tools.

To accommodate any unexpected changes in mass, science or system requirements, or estimated performance, the ERC diameter can grow in order to maintain, or even lower, the ballistic coefficient if needed. Growth beyond the 1.2 m unipiece PICA diameter limit is possible with the use of the tiled PICA or Avcoat forebody TPS option. The risk of TPS damage due to micro-meteorite and orbital debris (MMOD) hazards is considered low. The Stardust TPS was designed and qualified for a similar space environment, and no damage from MMOD was observed during post flight TPS analysis.

5.9 Mission operation concept (ground segment)

The ground segment will be set up similar to current planetary missions performed by ESA. The scientific instruments will be operated by the responsible PI teams via a Science Operations Centre (SOC). SOC is part of the Science Ground Segment (SGS) which coordinates the scientific input. The SGSs are located at ESAC, close to Madrid (Spain). The spacecraft operations, flight dynamics and ground station activities will be performed at the Operational Ground Segment (OGS) which includes the Mission Operations Centre (MOC). The OGS is located at ESOC in Darmstadt (Germany).

5.10 Current heritage and Technology Readiness Level (TRL)

The system requirements and spacecraft key issues benefit from the heritage of the former Marco Polo assessment study phase by three industrial consortia in 2008-2009. Moreover the GNC-NEO activity has been developed (TRL 4) and TRL 5 can be achieved in a short time (<1 year).

TRL for the sample mechanism and the ERC are addressed in Section 8.2.3.

5.11 Critical Issues

No critical issues are expected regarding the interface between ESA and NASA components. Indeed, to simplify the interface, the sample transfer to the ERC will be included in the NASA package.

6 SCIENCE OPERATION AND ARCHIVING

6.1 Mission phases

Currently, the following mission phases are foreseen. For each phase, the main goals of the science operation activities are indicated:

Near-Earth commissioning & calibration phase – Early operation phase will include spacecraft checkout and trajectory correction manoeuvre to remove injection error.

Cruise phase – Regular instrument checkouts are planed, typically in 6-month intervals. Some science observations should be done, e.g. of star fields or bright stars for functional testing, geometric and radiometric calibration.

Asteroid phases – Asteroid approach and encounter mission phases consist of: 1) approach and rendezvous leading to distant station-keeping; 2) target characterization phase from orbit around the asteroid; 3) proximity operation phase leading to touch-and-go landing (TAG). As MarcoPolo-R approaches the target system, Earth-based radar and optical observations of the asteroid will be combined with spacecraft optical navigation and radiometric data to refine the spacecraft position relative to the asteroid. These navigation observations will be used to design and execute the rendezvous manoeuvre which will be split into a series of smaller burns of decreasing magnitude, in order to control approach errors.

Target characterization phase – In this phase the NEA is mapped and characterized such that the best landing site, both from an engineering and from a scientific point of view, can be selected. As 1996 FG3 is a binary system, the initial characterization refines the determination of system mass (already measured from Earth-based observations) and masses of the primary and secondary from imaging of the mutual orbit. From a station-keeping position over the dayside of the target system, the sizes, shapes and rotations of the two components will also be determined. After initial characterization, the spacecraft is injected into high inclination (to the binary orbital plane) stable orbits around the target system barycentre. From the stable orbits, the spacecraft will map the surfaces of the primary and secondary to determine morphology and topography. These data enable selection of the landing site and certification that it meets science requirements as well as safety requirements for landing.

Lander delivery phase (optional) – There will be at least one rehearsal descent prior to landing for sample acquisition. The spacecraft will briefly hover at fixed low altitude and can release the lander package from that position.

"Touch and go" phase – The spacecraft will approach the NEA surface and collect the surface samples. During the TAG landing, the spacecraft remains in contact with the asteroid surface for at most a few seconds before autonomous lift-off occurs. TAG landing will occur only over sunlit portions of the surface. TAG landing may occur at the surface of either member of the binary system; the choice of landing site will be made after target characterization.

Lander relay phase (optional).

In-situ measurements done by the Lander and communicated to Earth (optional) – Most likely this will be done via the spacecraft antenna.

Return cruise phase – as *Cruise phase*.

Earth re-entry phase – The ERC re-enters and is recovered at the US Utah Test and Training Range (UTTR). The UTTR is located where previous sample return missions like Stardust returned and were successfully recovered. The MarcoPolo-R entry strategy will be similar to that of Stardust where a series of small manoeuvres will be performed, starting 30 days before atmospheric entry, to target the entry safely within UTTR.

Sample distribution and ground measurement phase – The collected samples are distributed to ground laboratories and analyzed.

6.2 Science Operation Architecture and proposed shares of responsibilities

The aim of the mission operations is to assure the monitoring and the control of the complete mission. The control of the MarcoPolo-R mission will take place at ESOC, in conjunction with the ESA DSN.

The scientific data will be acquired during the NEA acquisition/approach, the near NEA phase before and during the optional lander delivery (and relay) phase, and after the sampling, during an extended monitoring phase. Some cruise science will also be done with only a very small impact on operation cost. Particularly important are the operations governing the sample collection phases, the sample transfer to ERC, the round trip cruise phases and the ERC delivery. During critical mission phases (launch, cruise, sampling, Earth return, ERC recovery), support for tracking, telemetry and command by the ESA ground stations and the NASA DSN could be foreseen.

For the entire mission duration, ESA will provide facilities and services to the scientific experiment teams through a MarcoPolo-R Science Ground Segment (MPSGS). Its tasks will be:

- planning and execution of scientific data acquisition, in particular the long-term scientific mission planning and experiment command request preparation for consolidation and submission to the Mission Operation Centres;
- generating and providing complete raw-data sets and the necessary auxiliary data to the Principal Investigators. The MPSGS will make pre-processed scientific data and the long-term scientific data archive available to the scientific community after a proprietary period for the PI teams;
- optionally, the Lander Science Ground Segment will support operations of the Lander, in particular before and after completion of the landing, sampling and relay phases.

6.3 Data Archive approach

The goals of the Data Archiving are to preserve both data obtained by the scientific payload and Curation Facility and materials collected during the mission. The instrument payload PI will provide support and the inputs for the data processing pipeline. Final long-term data archive products will be made available to the scientific community via the Planetary Science Archive (PSA). Moreover, supplementary information acquired in the sample Curation Facility and laboratories would also be archived, as well as samples of contaminating materials collected during spacecraft build and witness plates from the spacecraft itself.

The returned sample will be the principal resource used to address the scientific goals outlined in this proposal. Great care has to be taken to ensure that the sample is properly curated so that the scientific goals of the mission are achieved, and indeed that the science return is maximised.

The breadth of highly specialised measurement requirements means that a large number of laboratories will participate in the analysis of the sample. Equally, any regolith sample from the surface of an NEA will contain multiple lithologies. Accurately cataloguing each of the main components, and distributing the most appropriate sample parts to each of the participating laboratories is a key function of the sample Curation Facility. This work requires full tracking of sub-sampling to permit subsequent cross referencing of unexpected results, and at the same time minimising contamination for many different types of analysis. Analyses performed outside the Facility by qualified laboratories require that samples are prepared in order to fulfil specific analytical needs. Once samples are retrieved from external laboratories, their state may need to be checked according to analyses performed (destructive, partially or non-destructive). Data archiving activity is, thus, split up into two phases:

- *Cataloguing phase*: the definition of the number of particles, their size, morphology, type (mineral aggregate or individual mineral, presence of carbonaceous content), identification of unusual features, attribution of a particle identification number for curatorial purposes, image collection for curatorial purposes, definition of sample categories for curatorial and analytical purposes.
- *Classification phase*: the identification of mineralogical phases, definition of mineralogical texture.

The sample data archiving will be created as database logbooks to ensure tracking and documentation of all the actions performed on samples, inside the Facility or in external laboratories. All this information will be stored using dedicated software according to the following data sets: identification; attribution; location; preparation; documentation. The sample data archiving will be based on the development of standards and tools for the cataloguing and documentation.

A Preliminary Examination (PE) of the returned samples will be organized and performed in order to catalogue them and to support sample allocation. A portion of the sample will be allocated to NASA as will be negotiated between ESA and NASA. A joint ESA-NASA team will perform the PE, and it will implement a well-defined series of analyses, beginning with non-destructive tests followed by more destructive procedures. It is anticipated that the PE shall not consume more than 10% of the returned sample.

One of the great benefits of a sample return is that material can be retained for future generations to address scientific problems not known at the present time or to apply new analytical techniques that offer greater insight into processes than we can currently investigate. Therefore, a significant portion of the returned sample should be retained for future study, demanding that some level of operation of the Curation Facility will be required for many years. Other applications for this facility could of course potentially include future Mars sample return and any other materials returned by ESA, NASA, or even national agencies.

6.4 Proprietary data policy

The science data archive will be compatible with the Planetary Data System (PDS). It will be based on and part of the PSA developed for Smart-1, Rosetta, Mars Express and Venus Express. Data will also be provided to the International Planetary Data Alliance (IPDA).

A Memorandum of Understanding between ESA and NASA will be needed to fix:

- the portion and the disposition of the returned sample that will be allocated to NASA;
- details of PE programme, including timetable;
- the criteria that will be adopted for the selection of the proposals of the study of the NEA samples resulting from a call to the worldwide scientific community on a competitive basis;
- the data policy rules, the selected format and the length of the period after which the data have to become available to any user of the PSA.

In the framework of a Mission of Opportunity linked to the NASA mission OSIRIS-REx, the amount of sample provided to ESA will be negotiated directly between ESA and NASA after OSIRIS-REx selection.

7 TECHNOLOGY DEVELOPMENT REQUIREMENTS

7.1 Payload technology challenges and technology development strategy

The proposed payload, as already quoted in Section 5, is based on existing /under development instruments, and has been assessed during the assessment study of the former Marco Polo project. The TRL is in the range 4-9 for the priority instruments, all the quoted instruments will be at TRL>5 much before the end of Definition Phase foreseen at the end of 2014.

7.2 Mission and Spacecraft technology challenges

The Spacecraft is the heritage from the assessment study of the former Marco Polo project. The GNC benefits from deep studies at ESA, showing that in particular for the accuracy of approach required during the sampling phase (order of tens of meters), there are no critical issues.

For the optional Lander, the key technology area is the landing precision.

In the previous assessment study for Marco Polo, four critical technologies were identified: GNC for proximity operations, landing gear, sampling and transfer system, and the ERC. For each of these technologies a development plan was created showing how the TRL could be increased to 5 by 2012.

A summary of the development activities is provided in the following sections.

7.2.1 GNC for Proximity Operations

The GNC for proximity operations has two critical technologies involved: the vision-based navigation function required for landing and the FDIR strategy and safe mode definition. The detailed design of GNC/FDIR is already covered by the GNC-NEO activity. The demonstration in a real time environment to achieve TRL 5-6 will come next.

7.2.2 Landing Gear

The current design for the landing gear is simple with the majority of components off the shelf with a TRL of 9. Some development activity is needed however for the crushable dampers which absorb the landing energy and to test the overall performance of the system under representative conditions. The technology development road map would include an initial selection of damping elements, followed by proof of their efficiency on one landing leg and a final demonstration of the landing gear on a complete landing gear system with varying landing and surface conditions.

7.2.3 Sample, Transfer, and Entry System

Novel application of proven components allowed the successful development and zero-g and vacuum testing of the BWS. JPL and APL internally funded R&D efforts have brought the BWS to TRL-5 and the Rock Chipper to TRL-4. Continued R&D funding will bring the integrated BWS and Rock Chipper to TRL-6 by PMSR. To do this, verification testing will be performed in flight environments including thermal-vacuum, low-g (additional KC-135A or equivalent flights) and margin testing on slopes with varying types of regolith.

The development of a 3-DoF motion simulator with already committed R&D funding will allow testing of the BWS performance during a representative sampling environment (see Figure 24).

This environment will provide realistic sampling surfaces and closed-loop reactions from the motions simulator that represents the dynamic reaction forces that the arm and spacecraft would provide during sampling. Generation of surface interaction models can also be done in this facility.

The only new technology development required for the ERC is the application of the ROHACELL®71WF impact foam, used in the Delta IV launch vehicle fairing. To develop this foam for the impact application, high fidelity impact dynamic modeling and simulation analyses will be performed. To anchor these models, UTTR testing is planned, including additional ground characterization tests bounding the expected MarcoPolo-R landing conditions (e.g. time of year, weather conditions, etc.) and full scale helicopter drop tests. These tests will verify that the impact system design for the ERC is sufficient to meet mission requirements for a range of impact surface types and bring the impact foam development to TRL-6 by PDR.

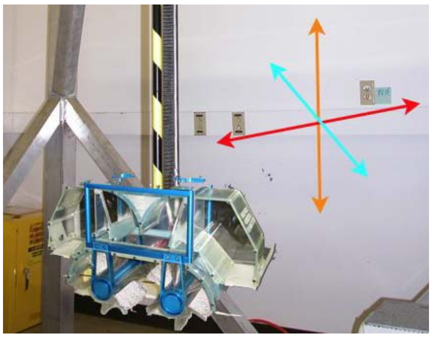

Figure 24: *Existing 3-DoF Motion Simulator enables realistic sample acquisition testing.*

An option exists to increase the allowed ERC entry velocity from the current 13.63 km.s^{-1} to about 16 km.s^{-1} by replacing the ERC unipiece PICA forebody material with carbon phenolic. This effort would require a new process qualification which will be evaluated in the next proposal phase.

8 PRELIMINARY PROGRAMMATICS/ COSTS

8.1 Proposed mission management structure

A Memorandum of Understanding (MoU) to be signed by ESA and NASA will define the respective responsibilities of the two agencies. The science and project management will follow the current practices of ESA science missions. NASA will appoint:

- a project manager for all the NASA technical contributions (sampling and Earth atmospheric re-entry);
- a project scientist who will have the responsibility of the science management of all NASA contributions.

A science management plan will be submitted for approval to ESA. A MarcoPolo-R Science Working Team (MPSWT), comprising the principal investigators (PIs), the Interdisciplinary Scientists (IDSs), chaired by the ESA and NASA project scientists, will be established to support the project. The prime task of the MPSWT is to maximize the scientific return of the mission within the established resources.

In the case of a participation as an ESA Mission of Opportunity in the OSIRIS-REx mission, we will provide Deep Space Network and Curation Facility. OSIRIS-REx is proposed for a launch in September 2016 and sample return in September 2023, during which European DSN will be provided. The Curation Facility will have to be operational when the sample is returned in 2023.

8.2 Mission schedule drivers

Owing to the fact that the baseline as well as possible backup targets have several launch windows, the mission drivers concern essentially the operations after the NEA rendezvous (sampling phases and optional Lander separation). In fact, the results of the exploration phase of the NEA, which will characterize its properties, will allow the mission project manager to define the approach trajectory for the optional Lander release, to choose the landing and sampling site.

Important items are also i) the optimization of the mission analysis for avoiding conjunctions (Earth, Sun and spacecraft alignments) during critical phases such as gravity assist, rendezvous, sampling and optional Lander release, and ii) interface and functional tests between the European and American parts.

8.3 Payload/Instrument Costs

The instruments included in the Strawman payload are assumed to be supported by the national agencies, on the basis of competitive selection following an AO issued by ESA. Preliminary costs for an instrument cannot be easily provided because in general, national agencies have direct contact with commercial companies and the results are often private and classified. Moreover, instruments developed in public Research Laboratories are in general much cheaper than the ones produced by commercial companies. Thus, in Table 14 we indicate a rough estimate of the total payload cost. The former Marco Polo PDD (ESA/ESTEC, SCI-PA/2008) contains detailed information on the model payload, including the Curation Facility, with their cost estimates for National Agencies.

8.4 Cost for Mission of Opportunity

The guiding principles for the preliminary cost assessment of the ESA Curation Facility layout are: systems, scientific instruments, technical infrastructures, operations and maintenance. The economic cost of the Sample Curation Facility is estimated of about 13 M€ initially, with operational costs averaged for 10 years starting two years before sample return estimated to be approximately 12 M€. Moreover, special analytical instruments and associated staff required to perform the contamination-critical analyses such as biologically important organics and volatiles (e.g., TEM, GC-MS, isotope-MS plus the necessary additional sample preparation laboratories) will add an estimated 5 M€.

European Deep Space Network time to NASA, for a cost of ~ 40 M€, will also be provided.

8.5 Overall mission cost analysis

The overall mission cost accounts for the cost reduction with respect to the former Marco Polo study.

Table 14: Estimated *costs (M€) for the ESA-led mission (assuming a 8 year duration and continuous operations) and for the Mission of Opportunity with the NASA mission OSIRIS-REx.*

Baseline Mission ESA-led	ESA	NASA	National Agencies
Launcher Soyuz/Fregat	67		
Total spacecraft industrial activity Project Int & Science Sample Transfer Entry system Re-entry capsule Model Payload[1]	200	7.7 47.2 32.2	42
Optional Lander (payload excluded)			20
Operations	80	4.4	
ESA Project	40		
Total	**387**		**62**
Contingency 10%	39		
Total (M€)	**426**	**91.5**	**62**
Mission of Opportunity			
DSN Curation facility	40 30		
ESA Project	7		
Total	**77**		
Contingency 10%	8		
Total (M€)	**85**		

[1]The cost of the Curation Facility (not included) is assumed to be financed by European National Agencies, and detailed in the former Marco Polo PDD (ESA/ESTEC, SCI-PA/2008).

This cost reduction originates from:

- the supply of both the sampling system and ERC by our US partner;
- the robustness of the supplied sampling mechanism (tested both in Earth and micro-g environment), that can cope with a wide range of soil properties;
- the output from the TRP for a possible on-board GNC/AOCS/FDIR system (called NEO-GNC), which is a prototype of the GNC system with TRL-4. TRL 5-6 can be reached in a real time environment demonstration;
- the landing accuracy on the asteroid relaxed to a few tens of meters (instead of 5 meters).

Note that long GNC autonomy periods can be achieved with the proposed timeline and GNC design from the NEO-GNC activity. Thus the cost can be minimized for operations and GNC, while maintaining the safety and science performances.

For the Mission of Opportunity linked to the NASA mission OSIRIS-REx, the sample Curation Facility layout is developed in order to accomplish all the facility purposes and protocols. The preliminary design is based on the development of architectural design, plants design, functionality and consistent approach to curation protocols.

An estimate of the overall mission cost is given in Table 14 both for the baseline ESA-led mission and the Mission of Opportunity.

9 COMMUNICATIONS AND OUTREACH

The public outreach possibilities of a mission like MarcoPolo-R are considerable for two main reasons:

1. The enormous fascination of the general public for challenges such as the landing of a terrestrial robot on an alien world, expressed at each new step of the planetary exploration (from the Surveyors on the Moon to Mars Pathfinder, from Spirit and Opportunity on Mars to Huygens at Titan). The probe is perceived as belonging to all of us and its performance is seen as our own performance (after the Huygens mission, you could often hear “We landed on Titan”);

2. The impact hazard and the interest of the media and people for this subject due to its link to the extinction of the dinosaurs and several catastrophic movies. On the strategic and political front there is considerable interest in prediction and mitigation of a NEO impact: Society has the right to expect that the scientific community will make a significant contribution to these efforts: we can do so, while still addressing the demands of fundamental planetary science, by a mission like MarcoPolo-R.

Reaching out to the culturally different people from across the Earth (North and South America, Europe, Japan, China, India …) to provide a better understanding of the mission challenges/

achievements is an important objective. Furthermore, a communication network will be set up allowing provision of clear and correct information, without scare-mongering, to the general public about Earth-crossing asteroids, the risks represented by a possible impact and about the actions under consideration in the event of emergency.

Images, photos and reports can seep into every house thanks to the great instrument that is the media, thus informing almost everyone about the activities related to the MarcoPolo-R mission. Newspapers, magazines and scientific publications are extraordinarily powerful tools for spreading news. The internet gives everyone the possibility of accessing an immense range of information regarding discoveries as well as new and old projects. Public events associated with scientific conferences are also effective in approaching the general public and increasing their involvement in the mission.

We intend to set up an Outreach and Public Affairs (OPA) Team composed of one representative from each scientific and technical team involved in the mission, to support the public relation services and/or press offices of both ESA and NASA with material and activities especially devoted to public outreach and education. The OPA team will organize at least one workshop per year designed to provide opportunities for MarcoPolo-R team members to discuss and propose new tools and initiatives in the mission outreach activity.

From previous experience, it was found that rapid and regular release of news and information is very important to attract people's interest. We will develop and update continuously MarcoPolo-R science multimedia tools such as images, video, animation, sounds, documents (producing posters, CD, DVD) to be distributed to the media, teachers and the general public. An important experience in that sense has been acquired in Japan during the Hayabusa mission. From the phase of approach of the asteroid to the end of the exploration, information from the Hayabusa mission was continuously updated on the JAXA website. During the two touchdown events, the mission status was reported on the web in real time.

The MarcoPolo-R mission web page (http://www.oca.eu/MarcoPolo-R/) and a list-server will be maintained for both internal communication among the various scientific/technical teams participating in the mission and outreach to the general public. The web page content will include the following:

- mission description and mission status;
- upcoming meetings and workshops;
- links to other relevant conferences, workshops and societies;
- an image gallery.

10 REFERENCES

Barucci M.A., et al. 1987. Icarus 72, 304.
Barucci M.A., et al. 1998. Icarus 132, 388.
Beck R.A.S. et al. 2009. AIAA-2009-4229
Bernatowicz T.J., et al. 2003. GeCoA 67, 4679.
Binzel R.P., et al. 2004. Icarus 170, 259.
Bottke W.F., et al. 2002. Icarus 156, 399.
Brownlee D., et al. 2006. Science 314, 1711.
Bus S. J., Binzel R.P. 2002a. Icarus 158, 106.
Bus S.J., Binzel R.P. 2002b. Icarus 108, 146.
Cody G.D., et al. 2008. MAPS 43, 353.
Campins H. et al. 2010. Nature 464, 1320.
DeMeo F., Binzel R.P. 2008. Icarus 199, 436.
Dauphas N., et al. 2000. Icarus 148, 508.
Dotto E., et al. 2005. CRPhy 6, 303.
Elsila J.E., et al. 2009. MAPS 44, 1323.
Fasanella E.L. et. al. 2001. AIAA-2001-1388.
Gladman B.J., et al. 2000. Icarus 146, 176.
Hiroi T., et al. 2001. Science 293, 2234.
Horstmann M., Bischoff A. 2010, LPSC abs#1784.
Jacobsen S.B. 2003. Science 300, 1513.
Jacobson S.A., Scheeres D.J. 2010. LPI , 41, 2098.
Jenniskens P., et al. 2009. Nature 458, 485.
Kanno A., et al. 2003. Geophys. Res. Let. 30, PLA 2-1.
Keller H.U., et al. 2010. Science 327, 190.
Licandro et al. 2011. Astron. Astrophys. 525, A34.
Lowry S.C., et al. 2007. Science 316, 272.
Lyon I., et al. 2007. MAPS 42, 373.
Martins Z., et al. 2008. EPSL 270, 130.
Maurette M. 2005. Micrometeorites and the mysteries of our origins. Springer-Verlag.
Michel P., et al. 2000. Icarus 145, 332.
Mitcheltree R., et. al., 2001, AAAF, ARVS-102.
Morbidelli A., et al. 2002. Icarus 158, 329.
Morbidelli A., et al. 2006. MAPS 41, 875.
Mottola S., Lahulla, F. 2000. Icarus 146, 556.
Nuth J.A. 2001. Am. Sci. 89, 230.
Ostro S.J., et al. 2006. Science 314, 1276.
Pizzarello S., Cronin J. R. 2000. GeCoA 64, 329.
Pravec P., et al. 2000. Icarus 146, 190.
Richardson D.C., et al. 2002. In Asteroids III, Univ. of Arizona Press, 401.
Rivkin A. and Emery J. 2010. Nature 464, 1322.
Robert F. 2006. In Meteorites and the Early Solar System II, Univ. of Arizona Press, 341.
Rotundi A., et al. 2008, MAPS 43, 367.
Rubincam D.P. 2000. Icarus 148, 2.
Scheeres D., et al. 2006. Science 314, 1280.
Scheirich P., Pravec P. 2009. Icarus 200, 531.
Stackpoole et. al. 2008. AIAA 2008-1202.
Stuart J.S., Binzel R .P. 2004. Icarus 170, 295.
Tran H. K. et al. 1996. PICA Patent 5,536,562
Tran H. K. et al. 1997. PICA Patent 5,672,389
Tsuchiyama A., et al. 2008. IPEWG Abstract Book.
Ulamec S., Biele J. 2009. Adv. Space Res. 44, 847.
Ulamec S., et al. 2010. *J. Adv. Space Res.*, in press.
Villanueva G.L., et al. 2009. ApJ. Let, 690/1, L5.
Walsh K., et al. 2008. Nature 454, 188.
Willcockson W. H. 1999. JSR 36/3.
Yeomans D., et al. 1997. Science 278, 2106.
Zolensky M.E., et al.. 2006. Science 314, 1735.

11 TECHNIC. DOCUMENTATION

ESA 2005- Cosmic Vision - Space Science for Europe 2015-2025, ESA BR-247.
ESA/SRE(2009)3, Marco Polo Yellow Book.
MASCOT 2009, MSC-RY-ES-RP-0001.
ESA/ESTEC, SCI-PA/2008/002/Marco-Polo PDD.

12 ACRONYM LIST

AO	Announcement of Opportunity
AOCS	Attitude and Orbit Control System
APL	Applied Physics Laboratory
APS	Active Pixel Sensor
ARC	Ames Research Center
ASIC	Application Specific Integrated Circuit
BWS	Brush Wheel Sampler
CAI	Calcium aluminium rich inclusion
CDMS	Command and Data Management System
COSPAR	Committee on Space Research
CS-GS-MS	Compound specific gas source mass spectrometer
CUC	Close-Up Camera
D&L	Descent and Landing
DNA	DeoxyriboNucleid Acid
DoF	Degree of Freedom
DPLR	Data Parallel Line Relaxation
DSN	Deep Space Network
DTM	Digital terrain model
EFPA	Entry Flight Path Angle
EMPA	Electron Microprobe Analyzer
ERC	Earth Re-entry Capsule
ESAC	European Space Astronomy Center
ESOC	European Space Operations Centre
ESR	Electron spin resonance
FDIR	Failure, Detection, Isolation and Recovery
FIB-SEM	Focussed Ion Beam – Scanning Electron microscope
FoV	Field of View
FPGA	Field-programmable gate array
FTIR	Fourier-transform infrared spectroscopy
GC-MS	Gas chromatograph – mass spectrometer
GNC	Guidance Navigation and Control
GS-MS	Gas source mass spectrometer
GTO	Geosynchronous Transfer Orbit
HGA	High gain antenna
HPLC	High Performance Liquid Chromatography
ICPMS	Inductively Coupled Plasma Mass Spectrometry
IDP	Interplanetary Dust Particle
IPDA	International Planetary Data Alliance
ISM	Interstellar Medium
ISO	International Organization for Standardization – or: Infrared Space Observatory
JPL	Jet Propulsion Laboratory
LA-ICPMS	Laser Ablation – Inductive Coupled Plasma Mass Spectroscopy
LaRC	Langley Research Center
LAURA	Langley Aerothermodynamic Upwind Relaxation Algorithm
LEO	Low Earth Orbit
LGA	Low-Gain Antenna
LIBS	Laser Induced Breakdown Spectroscopy
MC-ICPMS	Multiple Collector Inductively Coupled Plasma Mass Spectrometer
MGA	Medium Gain Antenna
MIT	Massachusetts Institute of Technology
MLI	Multi-Layer Insulation
MMOD	Micro-Meteorite and Orbital Debris
MOC	Mission Operations Centre
MPSGS	MarcoPolo-R Science Ground Segment
MPSWT	MarcoPolo-R Science Working Team
MSL	Mars Science Laboratory
MSR	Mars Sample Return
NAC	Narrow Angle Camera
Nd-YAG	Neodymium-doped Yttrium Aluminium Garnet
NEA	Near-Earth Asteroid
NEQAIR	Non Equilibrium Air Radiation
NG-MS	Noble Gas Mass Spectrometer
NMR	Nuclear Magnetic Resonance
NPA	Neutral Particle Analyzer
OBDH	On Board Data Handling
OGS	Operational Ground Segment
OPA	Outreach and Public Affairs
PE	Preliminary Examination
PICA	Phenolic Impregnated Carbon Ablator
PDR	Preliminary Design Review
PDS	Planetary Data System
PMSR	Project Mission System Review
PRM	Propulsion Module
PSA	Planetary Science Archive
R&D	Reasearch & Development
RF	Radio Frequency
RNA	RiboNucleid Acid
RSE	Radio Science Experiment
SAS	Sample Acquisition System
SEM	Scanning Electron Microscopy
SGS	Science Ground Segment
SIMS	Secondary Ion Mass Spectroscopy
SOC	Science Operations Centre
SPC	Space Programme Committee
SSAC	Space Science Advisory Committee
SSEWG	Solar System Exploration Working Group
SSTO	Self-Stabilised Terminator Orbit
STE	Sampling Transfer and Entry
STXM	Scanning Transmission X-ray Microscope
TAG	Touch And Go landing
TEM	Transmission Electron Microscopy
TIMS	Thermal Ionization Mass Spectrometer
TPS	Thermal protection system
TRL	Technology Readiness Level
TRP	Technology Research Programme
UHF	Ultra-High Frequency
UTTR	Utah Test and Training Range
WAC	Wide Angle Camera
XAFS	X-Ray Absorption Spectroscopy
XANES	X-Ray Absorption Near the Edge Structure
XPS	X-Ray Photoelectron Spectroscopy
XRS	X-Ray Spectroscopy/Spectrometer
YORP	Yarkovsky-O'Keefe-Radziewski-Paddack
μL^2MS	2-step Laser Mass Spectroscopy.

13 APPENDIX 1

National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

Reply to Attn of: Science Mission Directorate

NOV 1 2010

NASA has received a description of the following mission, which has been identified as a mission that will be proposed to the European Space Agency (ESA) for consideration as a Cosmic Vision mission, as well as a description of the mission's science objectives.

Mission: Marco Polo-R (MPR)

Letter requested by: Andrew Cheng (JHU Applied Physics Laboartory)

NASA is aware of this proposal and acknowledges that its science objectives are aligned with the 2010 Science Plan for NASA's Science Mission Directorate (available at http://science.nasa.gov/about-us/science-strategy/).

This letter may be included in the proposal that is submitted to ESA. NASA has not provided ESA with a copy of this letter. NASA will enter into discussions with ESA about support of selected proposals at an appropriate time.

Sincerely,

Paul Hertz
Chief Scientist
Science Mission Directorate

14 APPENDIX 2

Office of the Head and Director
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Lunar and Planetary Laboratory
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TUCSON ARIZONA

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16 November, 2010

Observatoire de Paris
5 Place J. Janssen
92195 Meudon Principal Cedex
France

Dear Dr. Antonella Barucci:

I am writing to you as the Principal Investigator for the mission *OSIRIS-REx*, a mission currently in the proposal competition phase within NASA's New Frontiers Program. *OSIRIS-REx* is an asteroid sample return to the primitive body (101955) 1999RQ36 with a proposed launch date of September 2016 and sample return in September 2023. The purpose of this letter is to respond to your interest in proposing a Mission of Opportunity (MOO) of the European Space Agency (ESA) to augment the *OSIRIS-REx* mission.

ESA Mission of Opportunity options involving spacecraft hardware cannot be accommodated at this late stage of the *OSIRIS-REx* proposal development. On a positive note, NASA allows for Science Enhancement Opportunities (SEO). Generally such SEOs are introduced as part of the mission proposal. Time precludes incorporating an SEO as part of the *OSIRIS-REx* proposal. However, you could propose SEO to ESA as an MOO, which could lead to negotiations between NASA and ESA after *OSIRIS-REx* selection.

An example of an MOO would be to provide European deep space network time to NASA at no charge, effectively reducing the cost of *OSIRIS-REx* to NASA. What ESA would get in return would have to be negotiated directly between NASA and ESA.

Sincerely,

Michael J. Drake
OSIRIS-REx Principal Investigator
Regents' Professor
Head, Department of Planetary Sciences
Director, Lunar and Planetary Laboratory
Director, Arizona Space Grant Consortium

c. Prof. Dante Lauretta, *OSIRIS-REx* Deputy Principal Investigator