MARCOPOLO-R ASTEROID SAMPLE RETURN MISSION: TRACING THE ORIGINS

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ABSTRACT

MarcoPolo-R is a sample return mission to a primitive Near-Earth Asteroid (NEA) selected for the Assessment Phase for the M3 mission of ESA's Cosmic Vision (CV) program. The assessment study started in May 2011 and will end in the Spring of 2013 with the submission of a study report. MarcoPolo-R will rendez-vous with a binary primitive NEA, scientifically characterize the object at multiple scales, and return a unique sample to Earth unaltered by the atmospheric entry process or terrestrial weathering.

A CDF (Concurrent Design Facility) study has been completed at ESA and two independent industrial studies started in February 2012 for one year. A technical study starting in July 2012 is specifically dedicated to the sampling mechanism.

The main goal of the MarcoPolo-R mission is to return unaltered primitive material from a unique binary asteroid for detailed analysis in European ground-based laboratories. The mission will address the fundamental CV questions "How does the Solar System work?" and "What are the conditions for life and planetary formation?".

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 [1]. They may also contain pre-solar material as well as complex organic molecules that led to the development of life [2,3,4]. For these reasons, asteroids and comets have been targets of interest for proposals and missions for over three decades. Only in the laboratory can instruments with the necessary precision and sensitivity be applied to individual components of the complex mixture of materials that form 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. It is no surprise therefore that sample return missions are considered a priority by a number of leading space agencies. 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 [5,6]. 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.

Near-Earth asteroids are a continuously replenished population of small bodies with orbits that come close to or cross the Earth's orbit. Their median lifetime is 10 Myr [7]. 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 provide a link with meteorites [8,9]. They have the orbital advantage of being much more accessible for scientific research and space missions than small bodies of other more distant populations (comets and main-belt asteroids) from which they have originated [10]. Hence, achieving an accurate knowledge of NEAs will provide insights required to sharpen our scientific picture of the formation of a planetary system – our own – in the terrestrial planet region. Moreover, the NEA population presents a high degree of diversity as revealed by ground-based observations. More than 10 major spectral classes have been identified [11].

The main goal of the MarcoPolo-R mission is to return primitive 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. The small sample successfully returned by the JAXA mission Hayabusa is confirmed as coming from a processed S-type asteroid.

The large international interest for sample return missions to primitive asteroids is demonstrated by recent selections made by space agencies: NASA selected the OSIRIS-REx mission in the New Frontiers program for launch in 2016 and a return to Earth in 2023, while JAXA selected the Hayabusa 2 mission for launch in 2014/2015 and a return to Earth in 2020. Given the diversity of the targeted objects and the different sampling strategies adopted by various missions, different kinds and amounts of material will be sampled. It is important that several sample return missions are sent to different objects using a variety of sampling approaches, so that we can enhance our knowledge on the diversity of primitive bodies.

MarcoPolo-R will allow European scientists to study the most primitive materials available to investigate early Solar System formation processes, returned from a known target with known geological context. Moreover, it will have an increased science return thanks to the choice of a binary object as its baseline target. 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 planetary 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?**

Remote sensing gives only the most superficial information on the surface composition. Consequently, answers to these fundamental questions require measurements with exceptionally high precision and sensitivity. Samples returned to terrestrial laboratories, which are unconstrained by mass, power, stability etc. are definitely required. In particular, laboratory techniques can date the major events in the history of a sample and investigate the organic components.

2. *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 to 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.

3. MISSION BASELINE

The baseline target is (175706) 1996 FG3 (a particularly interesting C-type binary asteroid), which offers an efficient operational and technical mission profile.

Several launch windows have been identified in the time-span 2020-2024. The baseline mission scenario of MarcoPolo-R to 1996 FG3 is as follows: A single primary spacecraft, carrying the Earth re-entry capsule and sample acquisition and transfer system, will be launched by a Soyuz-Fregat rocket from Kourou.

2.1 Launcher requirements

For the selected target and launch vehicle, feasible missions can be found using chemical propulsion by launching into Geosynchronous Transfer Orbit (GTO) and two space segment stages or using electric propulsion by launching directly into the correct interplanetary trajectory. Electric propulsion offers attractive alternatives to chemical (lower escape velocity, no planetary assist). It may allow a decrease of the mission duration (and associated operation costs) and an increase of the mass available for payload. A detailed study of both propulsion systems will allow determination of which is the most suitable. In the preliminary mission definition phase however, an electric propulsion scenario has been defined and is presented here.

2.2 Orbit requirements

Several potential mission scenarios were identified within the 2020-2024 launch timeframe. Following the ESA CDF study the electric engines will provide the velocity impulse (ΔV) to reach the target via planetary fly-bys of Venus. This will be followed by the asteroid approach phase during which the spacecraft will perform the targeting maneuvers 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 maneuvers are executed to reduce the approach velocity and increase the knowledge of the spacecraft relative state with respect to the asteroid. This phase 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 Guidance Navigation Control/Attitude and Orbit Control System/Failure Detection, Isolation and Recovery (GNC/AOCS/FDIR) system has been developed in a Technology Research Program activity at ESA (called NEO-GNC) led by GMV...

This technique assures safe station keeping using a wide-angle camera. Only light curves taken from ground observatories (prior to launch) and refined using on-board observations during the approach phase are needed.

During this phase, 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 better characterization and eventually a more precise estimate of the gravity parameters 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 maneuvers for perturbation control. The duration of this phase shall allow for radio science experiment operations 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 will be performed for some potential landing sites. 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 fulfills all constraints to achieve safely the required landing accuracy. At a given altitude, the spacecraft shall perform the D&L phase autonomously.

Surface operations start as soon as the spacecraft contacts the surface, with spacecraft stabilization, sampling and transfer of the collected material to a canister inside the Earth Re-entry Capsule (ERC). This is followed by the ascent phase, which ends when the spacecraft is in the desired safe haven. 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 ending with ERC release and Earth atmospheric entry.

2.3 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 spacecraft design.

The Science requirements for the sampling device are the following: it should have the capability to acquire a minimum mass of the order of a hundred grams; with a selection of cm-sized fragments, plus a large number (minimum several grams) of small (hundreds of µm-sized to mm-sized) particles.

A Sample and Acquisition System (SAS) was proposed by the US partner of the MarcoPolo-R proposal (see [12]). The ERC would then be developed by NASA Langley Research Center (LaRC). The SAS comprised two arms (from the Jet Propulsion Laboratory, JPL), each with a Brush Wheel Sampler (BHW, from JPL), two rock chippers (from the Johns Hopkins University Applied Physics Laboratory, APL), a sample canister with a sample verification mechanism, and hinge latch and spin eject mechanisms (all from JPL). The BWS has been designed and tested in air and vacuum in Earth and low-gravity environments to collect the required sample (between 0.35 and 2.1 kg) in less than one second (Fig. 1). If the asteroid surface is assessed to contain no loose regolith, pyrotechnic rock chippers are fired during the sampling event in order to break the material into collectable pieces.

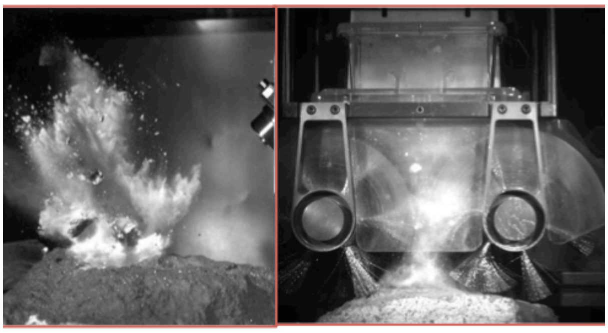

Fig. 1. Possible concept of a sampling device. Left: test with a Rock Chipper that has been shot; right: Brush Wheel Sampler and Bandelier tuff rocks.

In the current study of a mission entirely developed by ESA, alternative sampling approaches are investigated by the two industries selected to perform the assessment study. Moreover, an independent technical study will start in July 2012 concentrating on “Touch and Go” sampling mechanisms. Cutting wheels, scoops and gaseous transport devices are among the mechanisms that will be considered.

The ability to perform an efficient sampling of the surface and to return the minimum required amount of material is crucial for the success of the mission.

2.4 Earth Re-entry Capsule (ERC)

The design proposed for the MarcoPolo-R ERC is entirely passive. In order to save costs it does not include a parachute but instead lands at around 45 m/s with the energy being absorbed by a crushable structure. This parachute-less approach is derived from the Mars Sample Return (MSR) mission design. However, the planetary protection requirements for MarcoPolo-R are much less harsh and therefore such a capsule has a much simpler design than for MSR as no bio-container needs to be accommodated. The design (see an example on Fig. 2) was optimized to meet MarcoPolo-R mission needs while preserving key characteristics for high reliability.

The final configuration of the ERC will depend on the study by the European industries.

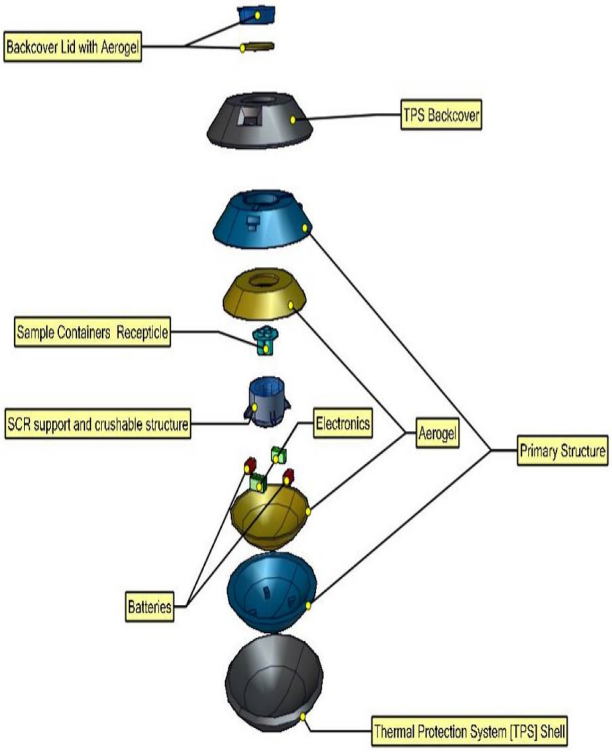

Fig. 2. Exploded view of possible MarcoPolo-R Earth Retrun Capsule.

3. MODEL PAYLOAD

3.1 Nominal payload

The baseline payload includes a Wide Angle Camera (WAC), a Narrow Angle Camera (NAC), a Close Up Camera, a Visible Near-Infrared Spectrometer, a Mid-Infrared Spectrometer, a Radio Science Experiment and a Neutral Particle Analyser. All these instruments are defined based on the scientific requirements and associated measurements at the asteroid, which 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 that are identified as potential sampling sites;
- ‘Sample context measurements’ are measurements being performed at the actual sampling site.

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. Moreover, 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.

3.2 Optional payload

Optional instruments have been identified that would provide additional science return. A Laser altimeter can be considered to measure the two-way travel time of a pulse between the instrument and the surface of the asteroid. Topographic profiles can then be produced even when the surface is unilluminated, from which the global shape model (derived in conjunction with WAC and NAC images) can be improved.

An optional micro-lander package is also being considered, with a total mass of about 10 kg, capable of carrying small instruments to characterize physical properties (e.g. electrical, magnetic, thermal) of the landing site, as well as the surface and subsurface fine structure and composition. 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? 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. A seismic experiment might also be considered that can provide information on the internal and surface properties of the asteroid.

4. MISSION PHASES, OPERATIONS, AND CURATION FACILITY

Currently, the following mission phases are foreseen, each accompanied with science operations activities that are described in [12]: near-Earth commissioning and calibration phase, cruise phase, asteroid characterization phase, lander delivery phase (optional), “Touch and go” phase, lander relay phase (optional), in-situ measurements done by the Lander (optional), return cruise phase, Earth re-entry, sample distribution and ground measurement phase.

The aim of the mission operations is to ensure the monitoring and the control of the complete mission. The control of the MarcoPolo-R mission will take place at ESOC. For the entire mission duration, ESA will provide facilities and services to the scientific experiment teams through a MarcoPolo-R Science Ground Segment.

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 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. 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 the preservation of the sample in its pristine condition, avoiding chemical and physical alteration of materials by the Earth’s environment 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.

Considerable expertise exists within Europe for the curation and distribution of sensitive extraterrestrial samples – e.g. numerous large national meteorite collections, Antarctic meteorite collections and cosmic dust collection programs.

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. 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. A description of the ground-based sample analysis that will be performed to reach the science objectives of MarcoPolo-R can be found in the assessment study report (called Yellow Book) of the former Marco Polo study (see the ESA web site: http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=46019).

5. SCIENCE VALUE OF A BINARY NEA

Binary objects represent about 16% of both the NEA and main belt populations [13] and their formation mechanism is still a matter of debate, although several scenarios have been proposed to explain their existence [14, 15]. In particular, rotational disruption of a rubble pile NEA 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, [14]). Other fission scenarios have been proposed that imply different physical properties of the binary [15]. 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. [14] is that the pole of the primary should be composed of fresh material that was originally buried at some depth in the progenitor. In effect, in this model, when the progenitor is spun up, material from the poles 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 Fig. 3). According to this model, 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 deeper.

Moreover, 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 a binary system will thus allow several scientific investigations to occur more easily than through a single object, in particular 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.
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.

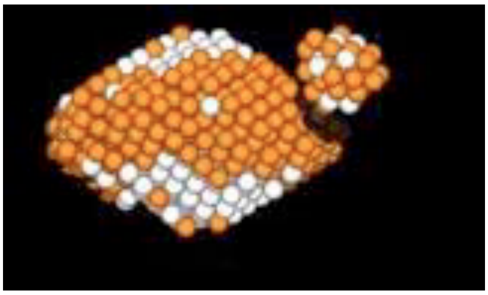

Fig. 3. Image of a simulation of binary formation by YORP spin-up; orange particles were originally located at the surface of the progenitor; white particles were originally below the surface [14].

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).

6. CONCLUSIONS

MarcoPolo-R is one of the four candidates selected by ESA (February, 25, 2011) for the M3 mission in the ESA Cosmic Vision program to proceed for an assessment study. The target cost for ESA is 470 million Euros. The aim of the assessment study is to design the best mission to reach the science objectives, while keeping the budget below the cost limit.

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 geophysics, dynamics and evolution of a binary NEA.

The development of sample return technology represents a crucial element for Europe’s science community and space industry to remain at the level of other agencies developing these capabilities. The sample will provide 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 to addressing the exciting science goals, the MarcoPolo-R mission also involves European technologies for which technical development programs 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) develop a high-speed re-entry capsule; (iv) 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. MarcoPolo-R will also involve a large community in a wide range of disciplines (Planetology, Astrobiology, Cosmochemistry, etc…) and will generate tremendous public interest.

The choice of a binary asteroid as the baseline target for the first time will provide enhanced science knowledge and complement in a unique way the science return of the two other sample return missions under development, namely the NASA OSIRIS-Rex and the JAXA Hayabusa 2 missions. The returned sample (a first for ESA) will then be of inestimable value. Given the expected richness of small body compositions, until we return a sample from various primitive asteroids, to which MarcoPolo-R will contribute, we will not achieve a comprehensive knowledge of primitive materials.

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.

7. ACKOWLEDGEMENTS

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